Citation: Hackney, Philip (2007) An investigation into the characteristics of materials and processes, for the production of accurate direct parts and tools using 3D rapid prototyping technologies. Doctoral thesis, Northumbria University.

northumbria
UNIVERSITY
*great **learning** great **experience** great **future***

"An Investigation into the Characteristics of Materials and Processes, for the Production of Accurate Direct Parts and Tools using 3D Rapid Prototyping Technologies"

PHILIP MARK HACKNEY
BEng, MSc, PgCEd Dev, ILTM

A thesis submitted in partial fulfilment
of the requirements of the
University of Northumbria
for the degree of Doctor of Philosophy

Research undertaken in the
School of Computing, Engineering and Information Sciences

June 2007

I. DEDICATION

To both my two wonderful daughters, my mother, my late father, especially Fiona. Also I would like to thank all who have helped advised, cajoled and put up with me in the last decade or five.

II. PREFACE

"God made the world in six days and on the seventh day he rested" Gen 2:1-3, over many centuries the world has become increasingly more "man made"

God has an exemplar record in new product development that most try to achieve, this body of work is focused around methods, technologies and processes that has caused a step change in human methods of new product development and manufacture in the last decade.

The technique is similar to God's methodology that instead of being subtractive as in the past, it is creative and additive. The theme is called "Rapid Prototyping and Rapid Tooling", the goal is "Rapid Manufacture" the production of components with either No or Quick tooling.

The author has been the manager of the Centre for Rapid Product Development at the University of Northumbria since its inception in 1996. He was awarded the degree of MSc in 1999 for his work using a Laminated Object Manufacture machine which in 1996 cost £125k. The two processes used in this research cost in the region of £30k and reflect the rapidly changing commercial Rapid Prototyping Industry.

This thesis investigates two processes of rapid prototyping and tooling, understanding their operation, establishment of operating criteria and developing new and innovative products.

III. ABSTRACT

The work reported here reflects the fundamental research undertaken by the author into the technologies of Rapid Prototyping, Rapid Manufacturing and Rapid Tooling.

This research was undertaken over 4 years, in a period when these technologies were experiencing huge change, through innovation and development, to produce viable and reliable industrial processes.

The research presented here deals with the two low cost, high speed Rapid Prototyping manufacturing processes. The first technology produces concept models for verifying design intent in the early stages of the product development cycle – referred to as the Z-Corps 3D Printing, 3DP process. The second technology investigated was the EnvisionTec 3D Digital Light Manufacturing, DLM process. This is machine capable of producing final parts in real engineering materials.

In both cases the default manufacturing settings and materials were evaluated for accuracy, finish and material properties and an experimental test methodology was developed. Each process was then optimised utilising Taguchi techniques and applied to industrial projects. Finite Element Analysis (FEA), has been used to predict best build orientation for these non-isotropic materials.

This work investigating the Z-Corps 3D printing process has improved the accuracy by 2%, part strength by 25% using new infiltrates and has been applied to both production of polymer injection mould tool inserts and electrode manufacture. The EnvisionTec Digital Light Manufacturing build parameters have been optimised and characterised for accuracy, hardness, part strength, surface finish. The application of FEA analysis using Non-isotropic properties has been shown to improve product performance by 14% and the optimised process has been applied to Rapid Tooling applications.

In all twelve case studies are presented here, several of which have been turned into successful commercial products, and for one case over 1 million products have been sold.

IV. COPYRIGHT

V. ACKNOWLEDGEMENTS

I would like to thank the following in assisting the Author with his research and compilation of this report; Prof M Sarwar, Dr TJ Bond, Dr K Tan, Ms F Ward, family and friends.

VI. AUTHORS DECLARATION

I declare that this work has not been submitted for any other award and that it is the work of the author alone.

VII. CONTENTS PAGE

Chapter Five: Research into Analysis and Development of the Envisontec Digital Light Manufacturing Process 88

Chapter Eight: Conclusions and Further Work 144

APPENDICES

VII NOMENCLATURE

- 3-Dimensional Printing (3DP) : a rapid prototyping process developed at the Massachusetts institute of technology (MIT). Layers of powder are bonded by inkjet to form a part. The term is also used generically as synonym for rapid prototyping.
- Absolute accuracy / precision : defined as the difference between an intended final dimension and the actual dimension as determined by a physical measurement of the part. In addition to those for linear dimensions, there are accuracy specifications for such features as hole sizes and flatness.
- Adaptive slicing : the use of variable layer thickness in an additive fabrication process, generally thinner layers being used where part detail is greatest.
- Additive fabrication : fabrication of a part by adding materials to a substrate or previously formed portions of a part. The most common additive fabrication methods utilize a layered approach, but other geometries are possible. The term is also used generically as a synonym for rapid prototyping.
- Anisotropic : refers to the fact that parts may have different physical properties depending on which direction measurements are made, and such differences can also arise if the exact same part is made in a different way. This can happen if the building orientation of the part in the machine is changed, and from the sequence in which the part's elements are fabricated.
- Ballistic particle manufacturing (BPM) : a rapid prototyping process, which deposits materials by means of inkjet technology. At one time, the term was used to refer to a specific company's technology, bpm, inc., now defunct, but prior to that, it was an early generic term for inkjet-based rp. The term is not often used at present.
- Bridge tooling : tooling which is typically capable of producing quantities of several tens to several hundreds of parts. That is to say, it "bridges" the quantity between very low volume prototype tooling and full production tooling. In some cases bridge tooling may offer sufficient volume to meet production requirements.
- Brown part : a part, which has been sintered or had other secondary operations performed on it to bring it from the loosely bonded, as-formed "green" state. Parts in the brown state are generally dimensionally stable, but are often porous and usually must be infiltrated with another material before use.
- Computer numerical control (CNC) : refers to a machine tool, which is operated under automatic control, as opposed to manually by an operator.
- Computer-aided design (CAD) : also sometimes called computer-aided drafting, is a computer program, which implements the functions of geometric design, drafting and documentation.
- Computer-aided engineering (CAE) : a computer program which automates one or more engineering analysis functions to determine the mechanical, thermal, magnetic or other characteristics or state of a system. CAE programs may use a geometry definition from a cad program as a starting point, and usually utilize some form of finite element analysis (FEA) as the means to perform the analysis.
- Computer-aided manufacturing (CAM) : a computer program that generates tool paths or other manufacturing data to fabricate tooling, usually by subtractive means. Cam programs may use a geometry definition from a cad program as a starting point.

- Concept model / conceptual model : a part intended primarily for form or appearance study, but which typically cannot be used to either check fit to other parts, or provide functionality of the final part in an application.

- Direct (fabrication) processes : generally refers to tooling which is made directly by a rapid prototyping system, as opposed to using the rp part as a pattern in a secondary process.

- Direct AIM tooling : 3d systems' trade name for a process of producing injection-mould tooling directly by stereolithography. AIM stands for aces injection moulding, where ACES stands for accurate clear epoxy solid, another 3d trade name.

- Direct composite manufacturing : 3d systems' trade name for Optoform technology, a stereolithography process that utilizes paste-like photopolymers to fabricate useable parts.

- Digital Light Manufacturing (DLM) : EnvisionTec's rapid prototyping, similar to 3D systems SLA process utilising a digital Light Processing chip (DLP), sometimes also known as Digital light Processing manufacturing (DLP)

- Direct manufacturing (DM) : a synonym for rapid manufacturing. It refers to parts made directly for end-use by an additive rapid prototyping process.

- Dots per inch (dpi) : a measure of the resolution of a printer. The number of discrete and distinct printed marks that an instrument is capable of producing in a linear inch. Also sometimes used in rp to describe the ability of an RP system to produce discrete voxels in the x-y axial directions.

- Final machining : a secondary operation in which parts formed by a rapid prototyping method are brought to acceptable final finishes and tolerances typically by subtractive CNC technology.

- Finish (part finish) : a qualitative term for the appearance of a part. For example, technologies based on powders have a sandy or diffuse finish; some inkjet technologies produce a smooth finish due to use of extremely thin layers; sheet-based methods might be considered poorer in finish because stair stepping is more pronounced.

- Freeform fabrication (FFF) : a synonym for rapid prototyping. The term is more precise and wider in scope, and somewhat favoured by the academic community. One variant is freeform manufacturing (FFM), but a more common one is solid freeform fabrication (SFF).

- Fused deposition modelling (FDM) :a thermoplastic extrusion-based rapid prototyping technology provided by Stratasys.

- Green part : a part that has been formed by a rapid prototyping process, but is in a loosely bonded state. For example, metal or ceramic parts formed by some selective laser sintering systems are in a "green" state when removed from the machine. They are then sintered by a secondary operation to a "brown" state.

- Indirect (fabrication) processes : generally refers to tooling which is made by using an RP-generated part as a pattern for a secondary process as opposed to directly fabricating a tool using the RP process itself.

- Initial graphic exchange specification (IGES) : a standard neutral format for the exchange of 2D and 3D cad data. STEP is follow-on to IGES and stands for standard for the exchange of product model data.

- Laminated object manufacturing (LOM) : Helisys, now defunct and succeeded by cubic technologies, was the first producer but also several other manufacturers provide this technology. Layers of paper or other materials are cut and bonded to form a part.

- Laser engineered net-shaping (LENS) : a rapid prototyping process which deposits metal powder into a pool of molten metal or other build material formed by a focused laser beam. There are several variants either commercially available or under development. Lens ® was developed by Sandia National laboratories and commercialized by Optomec. It can also be used for repairing and modifying existing parts and tools..)

- Mass customization : a process whereby small lots of individualized parts or products are produced. The opposite of mass production whereby large numbers of identical parts or products are produced.

- Minimum feature size : refers to the smallest detail of a part that can faithfully be reproduced. Mathematical definitions are usually based on a minimum curvature as a limit, but anecdotal values based on experience are more commonly utilized.

- Multijet modelling (MJM) : this is an inkjet rp method produced by 3d systems, inc. It uses a wide area head and is most often used for generating quick concept models. The materials available are wax-like plastics and accuracy is lower than that available from stereolithography.

- Pattern : an object or part which possesses the mechanical geometry of a final object or part, but which may not possess the desired mechanical, thermal or other attributes of the final parts. Patterns are used in secondary processes to form tools to make parts for end-uses.

- Photopolymer : material systems that change from a liquid to a solid state upon application of light (actinic) radiation. Light sources can be a laser or lamp, but related radiation-curable materials may be made solid by application of microwave or heat-based radiation sources. Photopolymers are typically complex mixtures of compounds rather than consisting of a single component.
- Rapid manufacturing (RM) : refers to the process of fabricating parts directly for end-use from a rapid prototyping machine. A synonym is direct manufacturing.

- Rapid prototyping (RP) :computer-controlled additive fabrication. Commonly used synonyms for RP are: 3-dimensional printing, additive fabrication, freeform fabrication, solid freeform fabrication, and stereolithography. Note that most of these synonyms are imprecise.

- Rapid tooling (RT) : most often refers to the process of fabricating tools from a rapid prototyping process. Rapid tooling may utilize direct or indirect methods: in direct methods, the part fabricated by the RP machine itself is used as the tool. In indirect methods, the part fabricated by the RP machine is used as a pattern in a secondary process. The resulting part from the secondary process is then used as the tool. In recent years, the term rapid tooling has been borrowed by practitioners of industry-standard methods such as subtractive CNC to refer to the ability to streamline these processes to compete with additive technologies.

- Resolution : refers to the minimum increment in dimensions that a system achieves. It's one of the main determining factors for finish, appearance and accuracy, but certainly not the only one.

- Reverse engineering (RE) : the process of measuring an existing part to create a geometric cad data definition of the part. In common non-technical usage, reverse engineering may also refer to measuring or analysing a part or a product for the purpose of copying it.

- Secondary operations : manual or machine-based operations, which must be carried out on a part, fabricated by a rapid prototyping system before use. Secondary operations may include, post curing, support-removal, sanding, machining, etc.

- Secondary process :any one of a large number of processes such as rubber moulding. Sprayform, ecotool, etc., that utilize a rapid prototyping-fabricated part as pattern to create a final tool or part.
- Selective laser sintering (SLS) : a rapid prototyping technology in which powders are fused laser fused layer wise by a laser. The technology produces accurate parts and models in engineering polymers, metals and polymer-coated sand for casting applications. Speed is similar to stereolithography, but material selection is wider.
- Solid freeform fabrication (SFF) : a synonym for rapid prototyping. The term is more precise and wider in scope, and somewhat favoured by the academic community. A variant is freeform fabrication (FFF).
- Solid ground curing (SGC) : this photopolymer-based technology was provided by Cubital. The company has been dissolved, but the process may still be available from a very few companies. A xerographically generated mask is used to cure an entire layer of photopolymer at one time. It offers good accuracy coupled with high throughput, but is considered quite expensive.
- Stair stepping : a type of inaccuracy, as well as a visual appearance artefact it refers to the stepped appearance of the edges of a part, a consequence of additive fabricating a part in layers of necessarily finite thickness.
- STEP : follow-on to the IGES neutral file exchange format. The acronym stands for standard for the exchange of product model data.
- Stereolithography (sl) (SLA) :a rapid prototyping process that fabricates a part layer wise by hardening a photopolymer with a guided laser beam. Stereolithography is frequently used as a general term for "rapid prototyping," but this is neither precise nor correct.
- Stl : a file format used in RP to define the geometry of the part to be made. Stl files are created by cad programs by translating their native or neutral files into the stl format. The stl file defines the coordinates of numerous triangular facets that approximate the shape of an object or part.
- Subtractive machining : the fabrication of a part by removing material from a stock shape of material. The stock shape may be a prismatic solid, cylinder, plate, etc. The removal of material may by cutting, turning, electro-discharge or other means. Common machinery such as millers, lathes and drills are subtractive tools.
- Support structure: many rapid prototyping machines need a means to hold in place unsupported geometries during fabrication, such as the top of a part in the shape of the letter "t." these supports are usually calculated and added to the part by the system's software and may be formed of the same material as the part, or from a different material entirely. Support structures are either mechanically removed or dissolved away in secondary operations before the part can be used.
- Virtual prototyping : computer-based prototyping without recourse to a physical part or object.
- Voxel : the three-dimensional equivalent of a pixel. A pixel is a "picture element," and a voxel is a "volume element." a voxel may also be defined as the minimum volume that a rapid prototyping system can fabricate.

IX. LIST OF FIGURES

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

X. LIST OF TABLES

Chapter 1

Chapter 2

Chapter 4

Chapter 5

CHAPTER ONE: AIMS AND ORGANISATION OF RESEARCH

1.1 Introduction to the Thesis

There is a revolution happening in the design world now[1]. Designers are now able to see the fruits of their designs as a physical model within hours or days. Previously they would have to wait weeks or months[2].

The driver for this revolution in the design world is the simultaneous development of several technologies; Low cost 3D Computer Aided Design (3D CAD), which completely defines the geometry of the product digitally, 3D Finite Element Analysis (3D FEA), which allows simulation of testing and processes, Rapid Prototyping (RP), which manufactures physical models directly from Digital 3D CAD data. Rapid Manufacturing (RM) is the application of RP techniques to produce end use parts directly for customers.

The effect upon the product development process of Time Compression Technologies (TCT) can clearly be seen in the Formula 1 Motor Racing sector. The application of 3D CAD, 3D FEA and RP has provided a 2% aerodynamic efficiency improvement per month for the Renault Formula 1 Team, due to the ability to assess new designs quickly[3]. In order for this revolution to continue, these processes need to be refined, developed and optimised.

The research presented here deals with the scientific evaluation, analysis, and development of two rapid prototyping technologies. Firstly, the Z-Corps 3D Printing (3DP) process uses a binder and powder materials to manufacture the part in layers. The research into this process concentrates on the process optimisation; material development; post build part infusion, and novel applications of this technology. Secondly, the EnvisionTec 3D Digital Light Manufacturing (DLM) process, the research into the DLM process covers the development of the process; process optimisation; materials development, and novel applications of this technology.

This thesis will present the details of the above research to date and the scope of further research.

The goal is to achieve a mass customisation capable Flexible Rapid Manufacturing system capable of producing reliable, usable components, quickly and economically without tooling.

1.2 Research Theme

Since the industrial revolution, manufactured goods have been "Mass Produced" in large numbers for a relatively small number of markets. Henry Ford was credited with revolutionising mass product methods at the turn of the century. In the 1950s a second major development was borne out of military requirements for repeatable high accuracy machined components for the aerospace industries, this led to the development of Computer Numerical Controlled (CNC) machine tools. These machines are capable of manufacturing one off products accurately and repeatable in engineering materials. The implementation of CNC machines into clusters led to "Group Technology" and "Flexible Manufacturing Systems" (FMS), capable of economical production of mass customised parts, replacing typically more expensive bespoke non flexible manufacturing systems.

The development of 2D and 3D CAD for product design has greatly assisted in the production of CNC programmes to drive these CNC machine clusters. However they are predominantly used to mass produce parts or assemblies in large batch sizes with the inherent costly processes of having large amounts of stock and work in progress. Polymer injection moulding is the manufacturing process of choice for many plastic components and products, however this process requires expensive inflexible tooling with large lead times (costing £10k to £100k and taking over several months to manufacture).

The rapid rise of manufacturing capacity in previously third world countries such as India, China and Southern Africa has led to a major change to the UK manufacturing base. The UK is increasingly becoming a knowledge led design based economy with manufacturing being outsourced on a global scale. Now typically the WEST "Designs and Prototypes" and the EAST "Manufactures" with the economics of low material and labour costs.

This has meant that many companies have almost stopped manufacturing completely, for example House of Hardy based in Alnwick Northumberland UK, 5 years ago manufactured 85% in house and now only manufacture 15% of key items in house[4]. This has led to issues with quality, time to delivery, reworks and stunted product development. Intense competition and sophisticated demand trends for personalised products has rendered Mass customisation[5] (MC), imperative for all business. As customers become more aware of issues pertaining to design, quality and functionality of their products or services, they increasingly demand to take part in the design and production processes[6]. MC is the use of flexible manufacturing processes or services to produce varied and often individual products at the price of standardised or mass produced alternatives[7].

Rapid Prototyping (RP) was originally used, and still used today, as a proof of concept technology allowing companies to innovate and reduce time to market for their products whilst still maintaining quality and reliability. The application of RP for Rapid Tooling has been recognised as a methodology to achieve mass customisation on a small scale, however the application of RP to mass customisation has a greater potential to change the way designers think and the products they produce. The layer technology gives freedom to design products that previously were un-achievable by traditional manufacturing methods. For example polymer parts no longer require draft angles, constant wall thickness and non-overhanging geometry, this will result in more complex designs and a reduction in part counts[8].

The research undertaken by the Author is focused on the development of two of these RP processes into functional "Flexible Rapid Manufacturing" systems for a number of applications. This work may assist in the development of Rapid Manufacturing (RM) strategies that will enable the UK economy, in the future, to re-instate its manufacturing capacity, which is currently haemorrhaging away to low cost African, Indian and Asian countries.

1.3 Project Overview

Rapid Prototyping processes are the building blocks for Rapid Prototyping, Tooling and Rapid Manufacturing. This project aims to first understand, and secondly develop, two of the building blocks to enable the goal of Rapid Manufacture to be achieved for the selected processes.

The two processes chosen are:

- The powder based 3D Printing (3DP) process, first developed by the Massachusetts Institute of Technology (MIT) in the USA – since commercialised into Z-Corporation's Z-Corps ZP402 range of 3DP machines.
- EnvisionTec PerFactory process that utilises a Digital Light Processing (DLP) chip to project a layer image onto a photopolymer to cure an individual layer.

The project aims to:

- Critically review rapid prototyping processes, their characteristics, applications and limitations, for both part and tooling production.
- Critically evaluate and optimise the current status of two chosen processes through scientific evaluation.
- Develop new materials, binders, additives and processes in order to extend the current working envelope of the two processes.

The investigation begins by reviewing the technical literature currently available on RP processes, to establish the capabilities and applications of the chosen processes. The aim is to develop the materials and processes for new applications to enable the goal of accurate Rapid Prototyping, Rapid Tooling and Flexible Rapid Manufacturing to be achieved. The generalised structure of the project is shown in diagram Figure 1.3

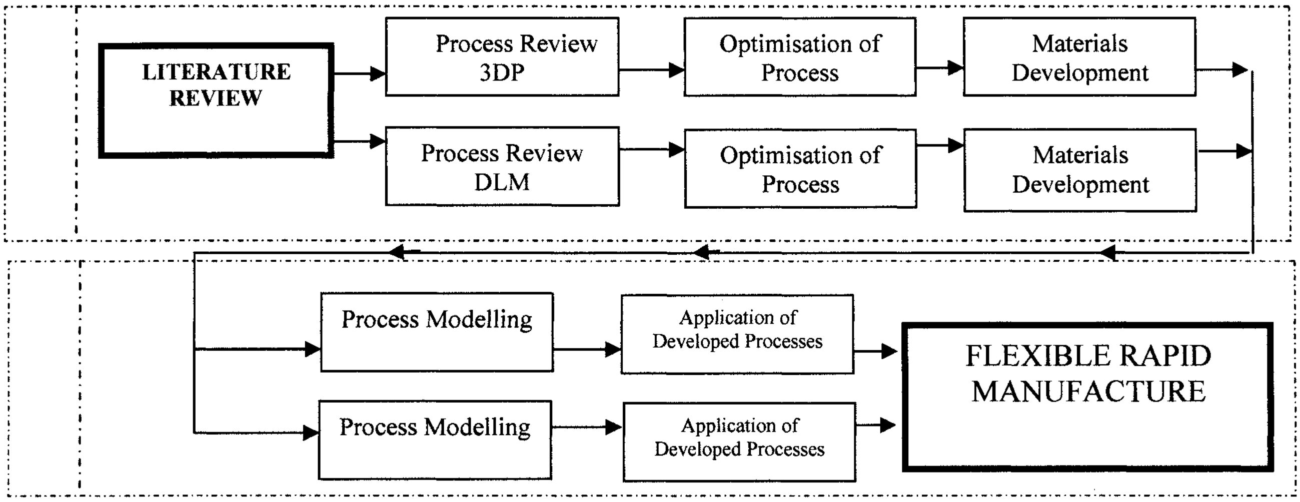


Figure 1.3. PhD Project Overview Block Diagram

1.4 Aim, Objectives and Methodology of Research

1.4.1 Aim of Research

The rational and motivation for this research is to first fully understand and then develop two rapid prototyping processes currently classified as "Concept Rapid Prototyping" systems, that previously were not considered capable of manufacturing accurate usable parts. This work has produced systems that can reliably manufacture "fit for function" engineering components and tools.

1.4.2 Research Objectives and Methodology

The research as stated above concentrates on two types of manufacturing processes, the powder based 3D printing process and the acrylate resin based photo-polymerisation Digital Light Manufacturing (DLM) process PerFactory system from EnvisionTec GmB.

1.4.3 Research Objectives for 3D Printing

The development of improved powder based rapid prototyping techniques will follow the research methodology below:

- Critical review of rapid prototyping techniques.
- Investigation into InkJet 3D printing techniques.
- Perform tests (geometrical, mechanical, material) to establish base line accuracy of current materials for powder based rapid prototyping.
- Perform tests to establish relationships between part orientations and build strength.
- Research alternative powders and binders for future test programmes.
- Investigation into infiltration techniques to enable part strengthening and improved mechanical properties.
- Investigation of the production of conductive powders for tooling production via electro discharge machining.
- Production of quantitative data for RP selection dependent on direct part requirements

1.4.4 Research Objectives for 3D Digital Light Manufacturing

The development of improved photo-polymerisation Digital Light manufacturing, rapid prototyping technique will follow the research methodology below:

- Critical review of DLM rapid prototyping techniques.
- Investigation into photo-polymerisation manufacturing techniques.
- Perform tests (geometrical, mechanical, material) to establish base line accuracy of current materials for resin based rapid prototyping using Taguchi methodology.
- Perform tests to establish relationships between part orientations, build strength, accuracy and surface finish and the key build parameters.
- Application of techniques to enable theoretical modelling of components for Rapid manufacturing applications by Finite Element and Photo-Elastic Analysis.
- Production of quantitative data for RP selection dependent upon direct part requirements.

1.4.5 Dissemination of Knowledge

- Publish results and findings in international refereed Conference papers.
- Write international technical Journal paper to publish findings.
- Attendance and contribute to the following Conferences and appropriate journals associated with rapid prototyping technologies.
    - Flexible Automation & Intelligent Manufacturing, Dresden, Germany
    - Time Compression Technologies, Manchester, UK
    - Rapid Design, Prototyping and Manufacturing, Buckinghamshire Chilterns University College, UK
- Dissemination of knowledge to students and industry via seminars and lecturers, i.e. master classes with Durham University students

1.4.6 Publications

The following is a list of titles written by the author, full versions of the most significant papers can be found in Appendix A.

Refereed Journal Papers

1. P M Hackney, M Sarwar, "An Evaluation of Rapid Prototyping "Concept Modelling" Techniques for New Product Development", International Journal of Manufacturing, Product and Process Devlopment IncorporatinComputer Integrated Manufacturing System, Volume 20 Issue 2, 2004 ISBN:0736-5845.

2. Danaher S., Datta S., Waddle I., Hackney P., "*Erosion modelling using bayesian regulated artificial neural networks*", Wear (Special Issue), (2003).

Refereed Conference Papers Published

1. "Spin Casting of Metal parts directly from RP masters"
2. "Getting started in Rapid Prototyping"
3. "The Revolution of Mid-Range Low Cost 3D Solid Modellers to Small Engineering Companies within the UK"
4. "Development of Time Compression Techniques to Assist SMEs with Product Competitiveness"
5. "Reverse Engineering: A Simple Concept, A Complex Process"
6. "Operating Characteristics of the Z-Corps 3D Printing Process"

7. “The Development of 3D Printing Techniques for “Concept Modellers” to Competitive Rapid Prototyping Systems”
8. “Production of Roughing Electro Discharge Machining Electrodes from the Z-Corps 3D Printing Process”
9. “A Study of Build Accuracy of the Z-Corps 3D Printing Technique and Related Seepage Control”
10. “A Comparison of "Concept Modelling" Techniques for Rapid Prototyping”
11. “Analysis of the EnvisionTec PerFactory Rapid Prototyping System”
12. “Application Of The Z-Corps 3D Printing Processes For Medical Bone Replacement Implants”
13. “Analysis of the EnvisionTec PerFactory System for Rapid Production of Components and Validation Utilising FEA and Photo elastic Analysis”
14. “Analysis of the application of the Z-Corps 3D-printing system for rapid tooling for plastic injection moulded components”
15. “Development of Systems to Increase the Green Part Strength of the 3D Printed Z-Corps Manufactured Parts by Infiltration Processes to Improve their Range of Application”
16. “The Application of the Z-Corps 3D-Printing System for the Manufacture of Rapid Tooling inserts, for the Production Polymer Injection Moulded Parts.”
17. “Investigation into Surface Finish of Parts Built by the EnvisionTec PerFactory® Rapid Prototyping Process”
18. “Development of a Build Monitoring System for the EnvisionTec PerFactory® Rapid Prototyping Process”
19. “Investigation into the EnvisionTec PerFactory® Rapid Prototyping Process for Production of Accurate and Strong Functional Parts”
20. “Reverse Engineering – Speeds up manufacture of thermoforming tools”,
21. “Implementing Time Compression Technologies to Assist Small to Medium Size Enterprises for Product Development”
22. “The Implementation of Off Line Programming for Multi-Axis CNC Machining of Precision Aerospace Components within a Small Manufacturing Business.”
23. “Rapid Manufacturing of Polymer Injection Mould Tool Inserts for Prototype Tooling Production”
24. “Product Enhancement with a systems approach, utilising Time Compression Technologies”
25. “Analysis of the application of the “digital light processing” rapid prototyping process for functional rapid manufactured component.”

1.5 Organisation of Thesis

This thesis is organised by Chapters, each Chapter relates to literature review, research work, investigation or discussion as outlined below;

- Chapter One outlines the research objectives and methodology used in this research.
- Chapter Two introduces the reader to the industry and range of rapid prototyping processes available. This chapter also focuses on the application of Rapid Prototyping for Rapid Tooling, this is the application of rapid prototyping processes to manufacture direct or indirect tooling for processes such as injection moulding and vacuum casting.
- Chapter Three details the research equipment used and the methodology of research.
- Chapter Four investigates the 3D Z-Corps powder (3DP) based printing process. Investigating the accuracy, part strength and the relationships of build parameters coupled with strengthening in-filtrates. The application of 3DP for tool production, for injection moulding and vacuum forming, is also developed along with the manufacture of direct electrode discharge machining electrodes.
- Chapter Five investigates the EnvisionTec Digital Light Manufacturing process (DLM). The first part of the chapter focuses upon optimisation of the build parameters for strength, hardness, dimensional accuracy and surface finish. The application of the DLM process for direct manufactured parts and tooling inserts is also investigated in this chapter. Finally a method to monitor the build process is designed and proved, which enables a build that has failed to be detected to be stopped before damage to the basement or wastage of materials occur.
- Chapter Six, this chapter uses several case studies to highlight how the Author has used the outcomes of this research for real applications of new product development.
- Chapter Seven, this chapter contains discussion on the research finding and concludes the thesis.

The Appendices contains the 17 of the 26 research papers written by the Author during this research project, together with supporting data.

CHAPTER TWO: REVIEW OF RAPID PROTOTYPING AND RAPID TOOLING

2.1 Introduction

From the early beginnings of mankind humans have shaped their environment with ingenuity and imagination. Inventions have often been developed through "play" (investigation), by learning from experience and applying this experience to solve new problems. As humans we have five senses: Sight, Touch, Taste, Smell and Hearing. The first senses two being particularly relevant to new product development.

The development of Computer Aided Engineering (CAE), relies heavily on the sense of sight to understand, integrate and develop new designs. Virtual prototyping (VP) refers to the creation of a digital model, often referred to as CAD/CAM/CAE[9]. No matter how good these techniques are, they ignore the other senses that, as humans, are necessary to understand our environment. Prototyping is the first stage of product refinement, it facilitates testing of some or all of the product's features or capabilities. Historical prototyping has been undertaken by creating mock-ups of the desired product in clay, wood, metal etc. These mock-ups were produced by non-production processes, in non-production materials, and rarely reflected fully characteristics of the product. These mock-ups allow all those involved in the product to apply their expertise to the product, the resultant physical model allows a higher level of communication compared to a flat 2D display or 2 dimensional technical drawings[9].

Rapid Prototyping (RP) technology is the physical manufacture of a design, directly from digital to 3D CAD data using additive processes. The technology has had, and continues to have, a major impact on the manufacturing industry[10]. RP affects the way products are modelled, prototyped, tooled, and even manufactured. Rapid Prototyping has in some instances replaced traditional subtractive manufacturing processes such as turning and milling, to produce designs, and products.

Rapid Prototyping Tooling (RPT) is the utilisation of RP processes to not only produce one part, but also tooling to produce multiple parts in realistic end use materials to provide a flexible manufacturing process.

The development of more reliable processes and robust materials has led to the term Rapid Manufacturing (RM)[11]. RM promises design and manufacture without the cost and time to produce low flexibility tools. This will lead to mass customisation on a grand scale, i.e. even design/production can be tailored to suit individual customer needs.

The new USA space station currently being built intends to have a RP process installed for the RM of components[12]. If a part fails, or a new component is required, instead of waiting for the next shuttle to arrive from earth, the part data can be sent electronically to the space station, and the part manufactured as and when required. Work is ongoing into the effects of RP processes when operated in zero gravity applications. Another example of the way Rapid Manufacturing is replacing traditional manufacturing techniques is the "Mobile Parts Hospital". The 8 Million dollar USA military R&D funding in 2002 from US Congress[13], will allow the Army to create replacement parts in the field rather than requiring them to be shipped into the conflict. Such a tool would enable vehicles to be repaired more quickly. The system comprises a reverse engineering, CNC machining, Selective laser sintering with future versions having the laser engineered net-shaping (LENS) technology to produce fully dense parts[14].

Another area of RP/RM under research and development is selective material deposition. For example, if after a visit to the car repair garage you find a wheel bearing has failed on your car, the mechanic can download the file, and a new bearing can be manufactured with different materials for bearing surfaces, and outer ring to suit the particular application[15].

Rapid Prototyping, Rapid Prototype Tooling and Rapid Manufacturing are revolutionising the design and manufacturing world.

The American automotive industry is credited as being the primary driver behind the early push to develop processes that could produce physical components quickly and without the need for tooling[16]. Such demands had previously been difficult to achieve primarily through the lack of computational capabilities however in the early 1980s, a step change occurred with the emergence of three-dimensional computer aided design (CAD) systems. The goal of shorter product lead times and more individually styled products is within sight as the concept of "free form fabrication" (FFF) or "rapid prototyping" begins to take shape.

Commercial RP systems began to appear in the UK in the late 1980s and some 20 years later America remains the dominant player in this global market. Alternate systems have been developed worldwide, notably in Japan, Germany, Russia, and China and more lately in Israel.

However, due to the patent position, the American equipment suppliers who initially developed the market subsequently maintain their dominant position.

Current successful RP equipment suppliers have developed partnerships and local agency agreements on a worldwide basis and almost without exception they are all represented in one form or another in the UK.

2.2 What is Rapid Prototyping

RP is a generic term for a number of technologies that enable components to be manufactured without the need for conventional tooling in the first instance or indeed without the need to engage the services of skilled model-makers.

Many manufacturing processes are subtractive, in that they modify the geometry of a mass of material by removing parts of the material until the final shape is achieved. Conventional milling and turning are good examples of subtractive processes. By contrast, RP techniques are additive processes. RP components are built-up gradually in layers until the final geometry is obtained. The way in which the layers are produced however, and the materials in which parts can be built, vary significantly between the different RP processes.

The starting point for the RP process typically is a 3D CAD model prepared once exported to meet the requirements of a technology. Various other inputs, in addition to CAD, can be used to create components; these include medical applications such as MRI and CAT scan data, as well as point cloud data generated by engineering scanning or digitising systems. Whatever the source of the original data, it is reformatted into a triangulated surface file (stl) and sliced horizontally, each individual slice is subsequently presented to the selected RP manufacturing process. The RP system subsequently reproduces the sliced data thereby creating a physical example of the original "CAD" data Figure 2.2.1

Each RP technique has its own advantages and disadvantages. These must be understood thoroughly before an RP process is selected, otherwise a part that does not completely fulfil the requirements of the end-user will be produced, and disappointment in the use of RP technology is likely to occur.

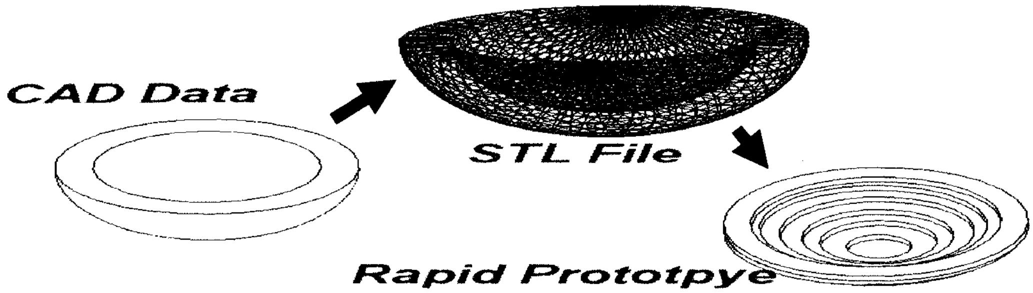


Figure 2.2.1; Digital to Physical route

2.3 What can Rapid Prototyping be used for?

Many organisations are new to RP, it is not always clear for what purposes the technology can be used or which is the most appropriate technology to achieve the required component.

Major uses documented to date include the following;

- Concept Models
- Functional or Semi Functional components
- Master patterns
- Direct tooling

Concept models

RP techniques allow prototypes of many complex parts to be made more quickly and cheaply than when using conventional manufacturing processes. Design teams can therefore check the design at an early stage and make any necessary modifications to the design before any commitment to produce tooling is made. An RP part can be used as a communication tool not only within the design team, but also with other interested parties. For example, RP parts can be given to sales teams so that an early response to a proposed design can be obtained from potential customers. In addition, the same component can be given to the production team to enable them to plan how best to manufacture the part[17].

Functional and Semi-functional components or Rapid Manufactured components

Some RP processes allow fully functional parts to be built directly, if the intended application for the part allows. RP parts can also be used in assemblies and may perform the function of a final production part satisfactorily. More often however, semi-functional parts are made using RP processes, as the RP materials used do not have adequate physical properties for the final application[18]. These semi-functional parts can still be used to check that parts can be easily assembled together, or to perform experimental tests that rely only on the part geometry and not on the limited material properties. The level of functionality of rapid manufactured parts is dependant upon the characteristics of both the RP process and the materials available for that process.

Master patterns

RP parts can be used as masters to make production tooling. For example, they can be used to produce silicon rubber moulds for the low volume production of functional parts using the vacuum moulding or reaction injection moulding processes[19]. RP parts can also be used as one-off patterns for investment casting moulds, though the RP parts are destroyed during this process. Additionally, RP parts can be used as masters in sand casting foundries.

Direct tooling

For some applications, RP processes allow production tooling to be made directly. "Soft" tooling that can only be used for low production volumes can be manufactured, for example soft injection mould tools can be made from thermosetting polymers, that allow up to several hundred shots to be produced. "Hard" or volume production tooling can also be made using relatively new RP processes[20]. For example, injection mould tooling can be made directly in a metal composite material that allows over one million shots.

2.4 Details of RP technologies

The RP industry is relatively young and it is therefore to be expected that some current processes will disappear and that others will emerge to become key players in the market in the future.

At present, the prototyping technologies are based on the following five main manufacturing processes[21].

- *Curing process* - where a photosensitive polymer is exposed to a light source in order to harden the polymer i.e. Stereolithography.
- *Sheet process* - where thin sheets of a material are cut to shape and stacked top of each other i.e. laminated object manufacturing.
- *Dispensing process* - where a material is melted and then deposited either as a filament or as individual hot droplets i.e. Fused deposition modelling.

- *Sintering process* - where a powdered material is sintered together using a source, typically a laser beam i.e. Selective laser sintering.
- *Binding process* - where a liquid binder is deposited onto a powdered material to bind the powder together i.e. 3D printing.

The market for RP systems remains at the formative stage and due to the dynamic nature of the process itself, it has encouraged many individuals and businesses to develop RP systems.

2.5 Major Rapid Prototyping Systems

The following provide a summary of some the most popular RP processes currently in use. A more comprehensive guide to Rapid Prototyping, Rapid Tooling and Rapid Manufacture can be found in the excellent "World Wide Guide to Rapid Prototyping" found on the CastleIsland.com web site[22].

2.5.1 Stereolithography

Stereolithography (SLA) is one of the first commercialised RP technologies dating back to 1988. SLA can be used to make parts with complex geometry and with a surface finish comparable to many conventionally machined components[23]. SLA parts are often used as masters to produce silicon moulds for vacuum or reaction injection moulding. When built with a honeycomb cross-section (known as "QuickCast" build style) they are also capable of being used as sacrificial masters in the investment casting process Table 2.5.1.

Method

A vat of polymer contains a platform on which the part is built. The platform can rise and fall within the vat. The platform moves until it is just below (0.050-0.250 mm) the surface of the liquid polymer. A laser traces out the cross-section of one slice of the part, Figure 2.5.1. Where the laser hits the polymer, it solidifies. The platform then moves down the distance of one slice (0.050-0.250 mm) of the part, and the laser draws the next slice on a fresh layer of liquid polymer. This slice of the part solidifies on top of the previous set slice. When all the slices have been traced by the laser, the platform is removed from the vat and excess liquid polymer is removed from the completed part. The completed part is then finally cured in an ultraviolet oven.

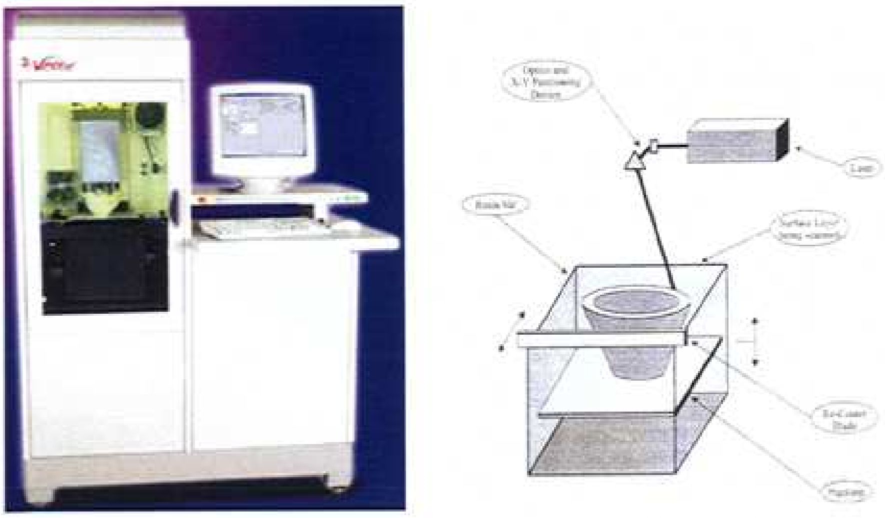


Figure 2.5.1 - Stereolithography Machine and Simplified Process

Advantages

- Good surface finish;
- Complex geometry, easily obtained;
- Generally there is a good accuracy of the geometry, easy to finish to high specification:

Disadvantages

- Models need support structures that must be removed as a finishing operation;
- Parts can warp, especially with acrylate resins;
- Resins are hazardous and need careful handling.

Table : Summary of the SLA process	
Materials available	Epoxy-based photocurable resins
Minimum laser beam diameter	0.200 mm
Layer thickness	0.050-0.250 mm
Finishing available	Models can be lightly sanded, sprayed with standard non-water based paints
Tooling methods available	Vacuum casting, reaction injection moulding, direct injection mould tooling, metal spray tooling, investment casting

Table 2.5.1 Summary of the Stereolithography process

Main suppliers: 3D Systems Inc

2.5.2 Selective Laser Sintering

Selective laser sintering (SLS) allows rapid prototypes to be built in a variety of materials so that semi-functional parts can be obtained directly. Parts of complex geometry can be made from the powdered materials. The fact that powder is used as the base material limits the quality of the surface finish of the final part. Production tooling can be made directly by using SLS parts made of metal powder in the RapidTool process[24] Table 2.5.2.

Method

A layer of powdered material is deposited on a platform. A laser beam traces out the cross-section of one slice of the part. Where the laser beam touches the powder, the affected particles are fused together or sintered, Figure 2.5.2. The bed drops a layer thickness, another layer of powder is then deposited on top of the previous layer using a roller mechanism, and another slice of the part is sintered onto the sintered material in the previous slice. The un-sintered material in each layer can act as a support structure for the part itself. When the part is complete, the un-sintered material can simply be brushed off in the de-powdering unit and recycled.

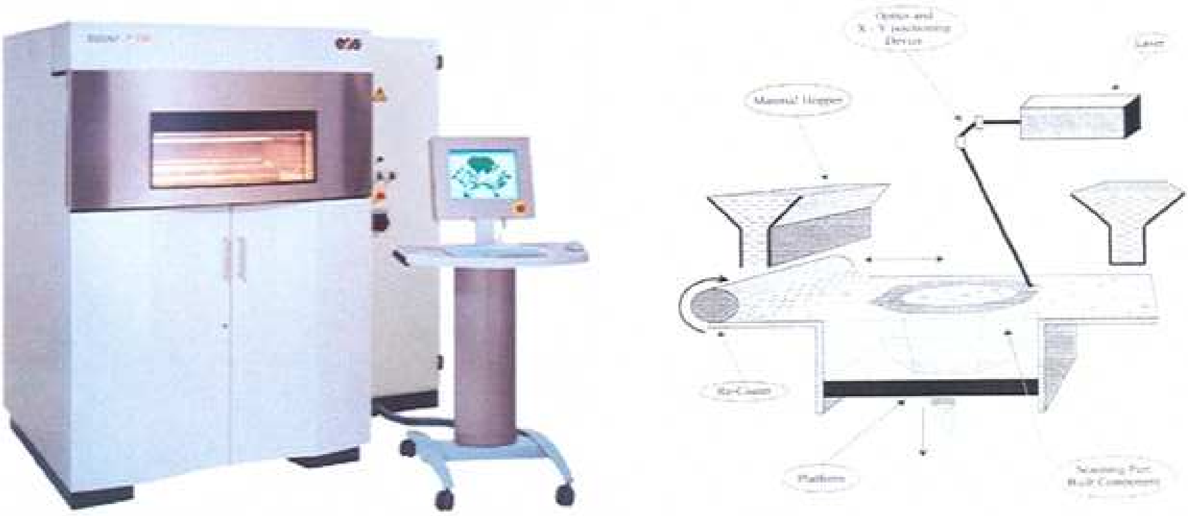


Figure 2.5.2 - Selective laser sintering machine and schematic of the Process

Advantages

- No post-curing of parts is needed, unless they are ceramic;
- Parts can often be built without additional support structures;
- Parts in a range of engineering end use materials can be manufactured.

Disadvantages

- Surfaces of the parts porous, and surface finish can be poor.
- Process can take a long time to heat up and cool down between builds.
- Investment casting requires the surface master parts to be sealed.
- Parts can warp significantly.

Table : Summary of the SLS process	
Materials available	Carbon steel with polymer binder, nylon, polystyrene, polycarbonate. investment casting wax, ceramics coated with binder, zirconium sand coated with polymer, flexible elastomer
Layer thickness	0.080-0.500 mm
Finishing available	Few
Tooling methods available	Investment casting, vacuum casting direct injection mould tooling

Table 2.5.2 Summary of the Selective laser sintering process

Main suppliers : EOS GmbH, DTM Corporation now 3D Systems, USA.

2.5.3 Laminated Object Manufacturing

Laminated object manufacturing (LOM) is often described as turning paper back into wood (though non-paper material is also available for the technique), as LOM is often used to make wooden patterns for sand casting. These patterns are durable, and therefore re-useable. LOM is one of the cheapest RP technologies and is excellent for making large parts with moderate geometrical complexity[25] Table 2.5.3

Method

A layer of material with an adhesive coating on one side is placed on a platform, adhesive side down. A heated roller passes over the material and adhered to the platform material. A laser beam then traces the outline of one slice of the part, cutting through the layer of the material Figure 2.5.3. The laser beam then crosshatches the material that does not form part of the cross-section, again cutting through the layer. The platform is then lowered one layer thickness, then another layer of material is stuck onto the previous layer and the procedure is repeated with the next cross-section slice of the part. When all cross-section slices have been added, the solid block of material is removed from the platform. The crosshatched areas of the block are then broken away to reveal the final part.

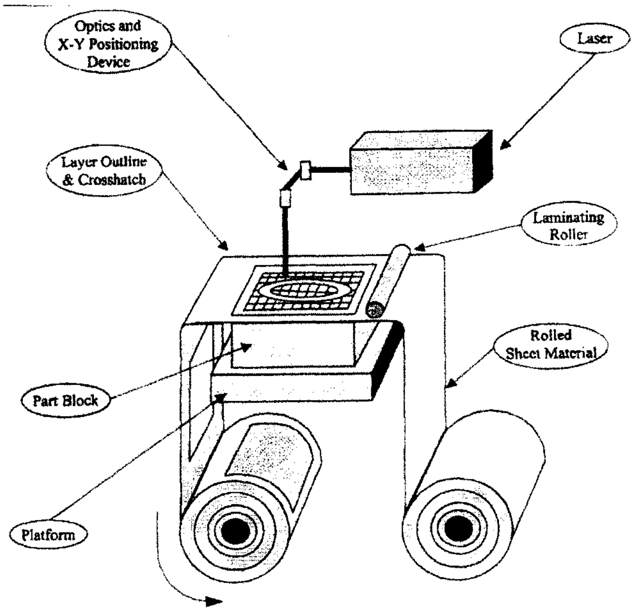


Figure 2.5.3 - Laminated Object Manufacturing process

Advantages

- Wooden parts can be sanded, drilled or tapped
- Large parts can be made quickly and relatively cheaply.

Disadvantages

- Wooden parts with thin cross-section often have poor strength; wooden parts absorb moisture unless surface is treated;
- Surface finish before post processing is poor compared to some other RP techniques; and
- Breaking out of parts can be difficult.

Materials available	Paper, polyester/polyethylene-based material, ceramic coated paper, polycarbonate composite
Layer thickness	0.080-0.250 mm, 0.111 mm standard
Finishing available	Components can be sealed with varnish and painted or resin impregnation, Components can be joined together by gluing, screwing, tapping etc,
Tooling methods available	Sand casting, investment casting, vacuum casting, vacuum forming

Table 2.5.3 Summary of the LOM process

Main suppliers : Helisys Inc. (now defunct) and Kira.

2.5.4 Fused Deposition Modelling

Fused deposition modelling (FDM) originally belonged to the class of RP technologies that are collectively known as "concept modellers". This was because the models created were generally non-functional in terms of their strength, and the surface finish was poor when compared to other technologies such as SLA[26]. Over recent years this has changed, as Stratasys have created machines such as the Dimension, Maxum and Titan. Concept modellers are intended to provide a fast and clean route to create a part that can be checked for any gross errors, and that can be used as a communication tool between the product development team Table 2.5.4.

Method

A filament of material is extruded from a fine nozzle and deposited onto a platform. The nozzle moves in the *X-Y* plane so the filament is laid down to form a thin cross-sectional slice of the part, Figure 2.5.4. The platform is then lowered relative to the nozzle and the next slice of the part is deposited on top of the previous slice. As the extruded filament is hot, it bonds to the material in the previous slice. A second nozzle is used to extrude a different material in order to build up support structures for the part where needed. Once the part is complete, the support structures must be broken away from the part.

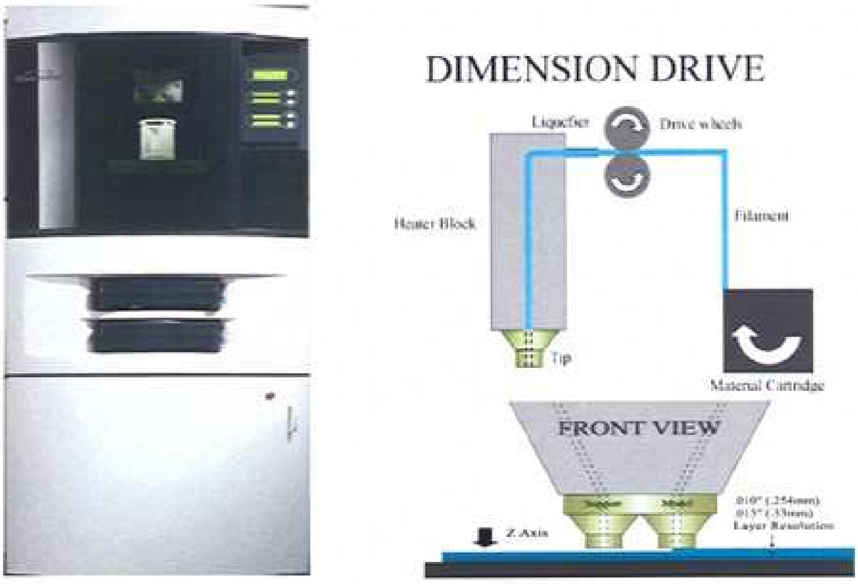


Figure 2.5.4 - FDM Machine and Process

Advantages

- Parts can be made from a variety of materials;
- Machine can be easily set up and used in an office environment.

Disadvantages

- Support structures are needed; parts have poor strength in the vertical direction;
- Process is slow on parts with large mass
- Poor surface finish makes tooling routes unattractive.

Table Summary of the FDM process	
Materials available	ABS, elastomer, investment casting wax, polycarbonate
Layer thickness	0.050-0.250 mm
Finishing available	Toluene to smooth and seal the surface

Table 2.5.4 Summary of the FDM process

Main supplier : Stratasys Inc.

5.5.5 Multi-jet modelling

Multi-jet modelling (MJM) also belongs to the class known as "concept modeller". The MJM technique has been likened to printing in three dimensions and is designed to allow design teams quick access to geometrically acceptable models in a material that would not normally be used for the final part[27] Table 2.5.5

Method

A "print head" containing 96 nozzles (or jets) in a linear array passes in the *X-Y* plane over a platform. Where material is to be deposited, a jet dispenses a droplet of a thermo-plastic polymer Figure 2.5.5. Any number of the 96 jets can be activated simultaneously, giving a rapid dispense rate when all jets are active. The hot droplets of material bond to the previous slice of the part that has just been printed. Thin support pillars must also be built-up slice by slice in the same material where they are needed. When the current slice of the part (plus slice support pillars) is completed, the platform is lowered relative to the print head and the next slice is "printed". When all the slices have been completed, the part is removed from the machine and the support structure is broken off. The Z-Corps, Objet and Invision technologies have developed with print head technologies to provide increase resolution by increasing the number of print nozzles to a resolution of 650 DPI. These print heads are now capable of depositing both build and support structures simultaneously and use UV curing of SLA type resins.

Table Summary of the MJM process	
Materials available	Thermo-plastic with UV Curing
Layer thickness	0.040-0.100mm
Finishing available	Toluene to smooth surface
Tooling methods available	Investment casting

Table 2.5.5 Summary of the MJM process

Advantages

- Machine can be used in an office environment;
- Strong and flexible parts can be obtained quickly by the design team
- Large improvement in materials and accuracy in recent years.

Disadvantages

- Support pillars must be broken off and bottom surface finish is very poor;
- Strength of finished parts is poor
- Bottom surface finish is pitted, limiting the potential use of investment casting.

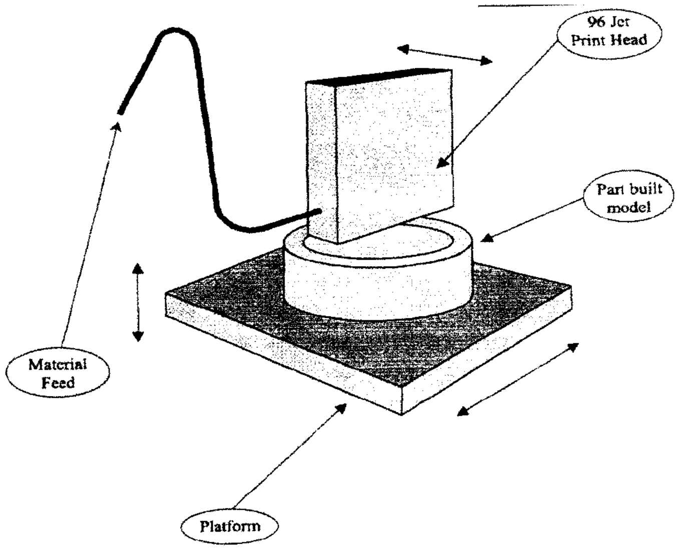


Figure 2.5.5 - MJM Process

Main suppliers : ObJet Technologies and 3D Systems (Actua/ThermoJet/InVision).

2.5.6 Three-Dimensional Printing

Three-dimensional printing (3DP) is one of the fastest modelling techniques. Developed by the Massachusetts Institute of Technology (MIT), the process was subsequently licensed to the Z Corporation for prototyping applications and ProMetal for tooling. 3DP components are typically used as ‘proof of concept" models however when impregnated appropriately, they can also be used as sacrificial master patterns in the investment casting process[28], Table 2.5.6

Method

A feed chamber contains a quantity of specially prepared cornstarch or plaster based powder, the vertical position of the upper surface of the build material can be varied by raising or lowering the feed piston. An adjacent build chamber operates in a similar manner whereby the vertical position of a piston determines the height of the build chamber. A horizontally reciprocating carriage, carrying a feed roller, spreads new material from the feed chamber evenly over the build chamber; excess feed material is swept down an overflow chute. Also mounted on the carriage, a "binder cartridge" travels over the surface layer of the build chamber material depositing a binder solution to match the current slice of CAD data, Figure 2.5.6. The build piston then descends a predetermined distance, this "layer thickness" can be varied between 0.100 and 0.250 mm; new material is then spread from the feed chamber over the build chamber surface and the printing process is repeated. When all the layers have been printed, the untreated material is cleaned of the component part and the component removed from the build chamber.

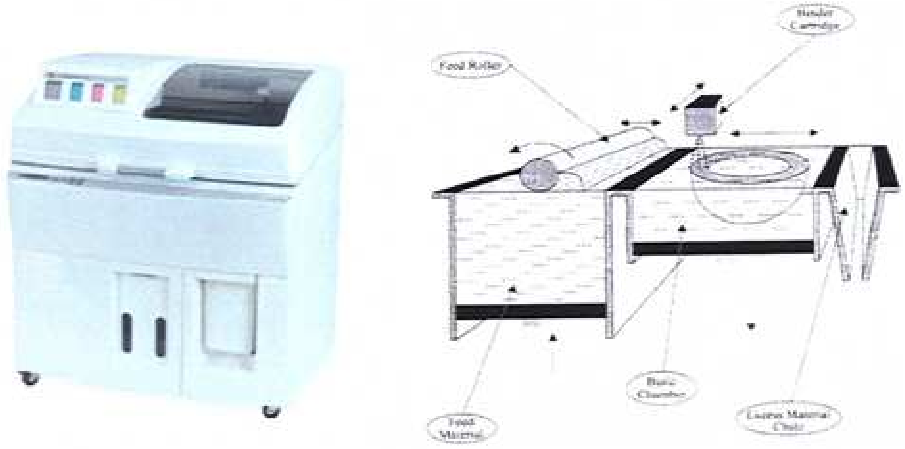


Figure 2.5.6 - 3D Printing Machine and Process

Advantages

- Shorter build times when compared to other RP technologies;
- Inexpensive raw materials when compared to other RP technologies; and
- No support structures allow complex geometry to be created.
- Support 256 bit colour output

Disadvantages

- Newly printed parts are fragile and require infiltration; and
- Surface finish is relatively poor.
- Very weak parts

Main suppliers: Z Corporation and ProMetal.

Table: Summary of the 3DP process	
Materials available	Corn starch, plaster
Layer thickness	0.080-0250 mm
Finishing available	Infiltrated with wax or cyanoacrylate
Tooling methods available	Vacuum casting, investment casting

Table 2.5.6 - Summary of the 3DP process

2.5.7 Selective Laser Melting

The Selective Laser Melting (SLM) is one of the first RP processes capable of manufacturing metal and ceramic components that are fully dense in a range of materials such as Zinc, Bronze, Stainless Steels, Tool Steel, Titanium, Chromium-Cobalt, Silicon Carbide and Aluminium oxide[29].

The process can build in layers of 30 µm accurate direct use, and tooling inserts for press tools, pressure die cast and polymer injection moulding applications at a deposition rate of 500 mm^3 per hour table 2.5.7.

The method is very similar to the Selective Laser Sintering method in that it uses powdered materials in an heated chamber flooded with an inert gas as per Figure 2.5.7. The platform drops and a layer of powder is spread across the build chamber. The high powered laser 100 cW then melts the powder to form a solid. The parts require no support structure other than the support to the build platform.

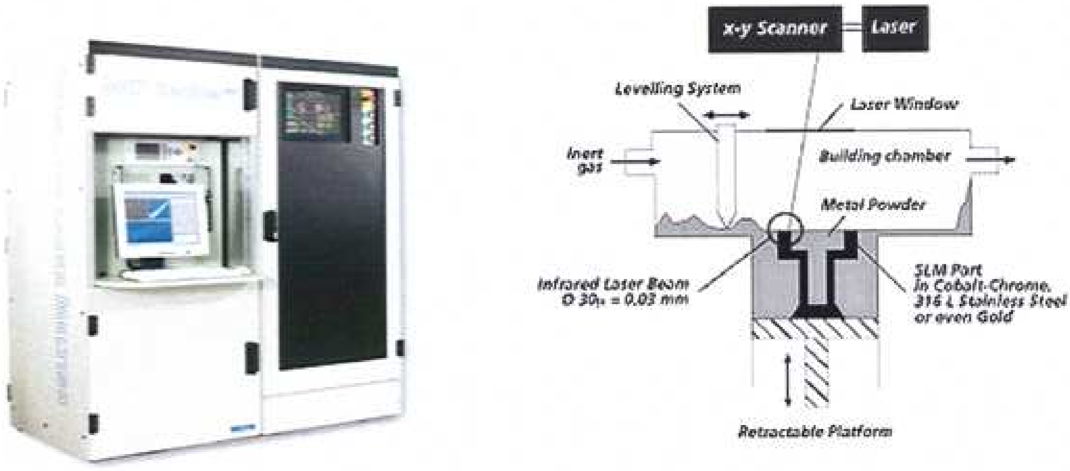


Figure 2.5.7 - Selective Laser Melting machine and Process[21]

Advantages

- Large Build envelope 250 * 250 * 240 (z), upto 120 kg steel
- 100% dense components
- Limited support structure therefore internal channels possible
- Range of metals
- Large build area

Disadvantages

- Build Speed

Table: Summary of the SLM process	
Materials available	Zinc, Bronze, Stainless Steels, Tool Steel, Titanium, Chromium-Cobalt, Silicon Carbide, Aluminium Oxide
Layer thickness	0.030 – 0.05 mm
Finishing available	Heat treatment and Polishing
Tooling methods available	Die casting, Injection Moulding, Sheet metal

Table 2.5.7 Summary of the Selective Laser melting process

Main Suppliers: MCP tooling Technologies (UK), Cost of machine (£300k)

2.6 Properties of Rapid Prototype Manufactured Parts

As RP parts are made by additive processes, they can process properties that are quite different from parts that are manufactured by conventional manufacturing processes. It is difficult to compare many properties of RP parts directly, as these depend not only on the material being used, but also on the direction in which the property is being measured. Nevertheless, it is important to have some understanding of the relative properties of parts made by the different RP technologies[30].

The following will assess several key properties namely:

- surface roughness;
- dimensional accuracy;
- mechanical properties.

2.6.1 Surface roughness of RP parts

RP parts are built-up slice by slice, and the surface roughness is affected by three main components Figure 2.6.1

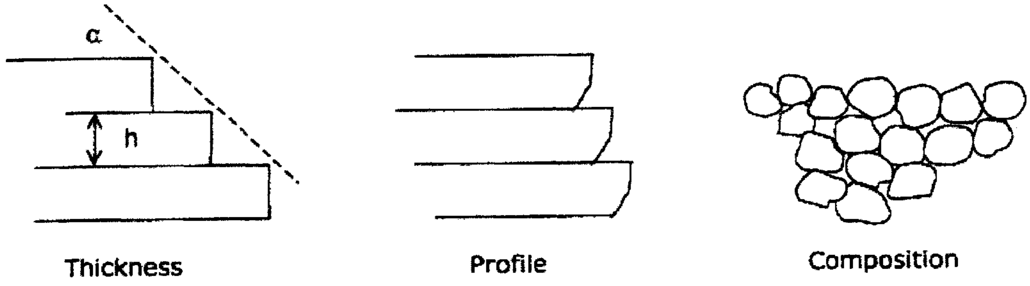


Figure 2.6.1 - Build effect on layer thickness

The thickness (h) of each layer of the RP part combined with the build angle of the surface (α) produces a staircase effect as shown. For α = 90° this component of surface roughness will be the best, but for other values of α, the surface roughness will be affected. This thickness component of roughness is essentially independent of the RP technology used[31].

The end profile of each layer then adds a second component of roughness to the surface. This component will depend on the RP technology used to produce the layer.

It can be seen that there is considerable variation in surface roughness depending on the technology, layer thickness and material used, and depending on the build angle of the surface. The build angle is particularly important and the RP user must specify which surface of an RP component should have the best surface finish to ensure that the part can be built in the correct orientation to achieve the desired result. The slicing as shown in Figure 2.6.1 rectangular produced layers will give the poorest surface finish when produced either upwards or downwards facing at 45°, however the profiled layers will be worst on the downward facing layers at 45°. Shallow angles say 10° or less provide the most visual surface stepping effect.

The material composition will then add a third roughness component to the surface. This component will depend on the material used in the RP process and the processing technique.

These three components combine to produce a total that is not easy to predict theoretically, and the surface roughness is best assessed by empirical means.

A standard test piece can be used to assess the surface roughness of RP test piece parts based on the geometry, Figure 2.6.2

The test piece is designed so that the surface roughness can be measured with values of α from zero to 90° and published papers have been combined to provide Table 2.6.1

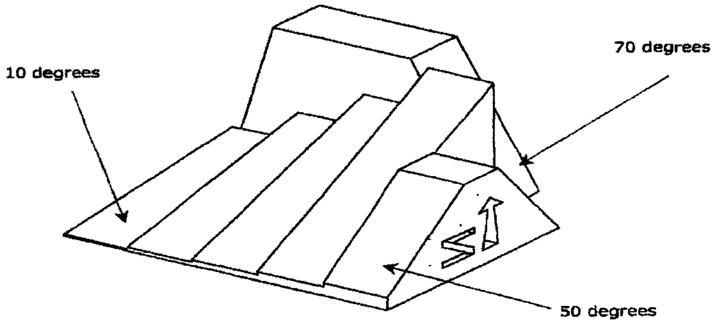


Figure 2.6.2 - Surface Roughness test piece

Surface roughness (μm Ra) for selected RP Technology		Build Angle α from horizontal				
Technology - material	Layer thickness	10°	30°	50°	70°	90°
SLA - Epoxy (ACES style)	0.20 mm	39.90	28.80	21.50	16.70	6.30
SLS - Polystyrene	0.10 mm	65.20	35.60	32.60	24.70	11.80
SLS - Nylon	0.10 mm	28.50	36.90	39.20	36.50	20.60
LOM - Paper	0.10 mm	29.20	27.70	25.30	23.30	16.90
FDM - ABS	0.25 mm	56.60	38.60	26.40	22.70	17.90

Table 2.6.1 Surface roughness (μm Ra) for selected RP Technology[28]

Table 2.6.1 shows the contribution of layer thickness has a significant effect to surface roughness, i.e. the higher layer thickness the greater contribution at lower angles. All processes exhibit the poorest surface roughness at 45° expect the large layer thickness of the FDM process.

2.6.2 Dimensional Accuracy of Rapid Prototype Parts

The same test pieces were also measured to establish the accuracy of linear dimensions for the different RP technologies, when compared to the intended dimensions in the CAD model of the test piece. The results are shown in Table 2.6.2.

As can be seen, the accuracy varies considerably depending on the RP technology used and on which dimension is being measured. Using this raw data, the average (un-weighted) linear dimensional accuracy for the different technologies is detailed in Table 2.6.2. This shows the characteristics of the different processes with some building over size whilst others build under size, generally the larger the dimension the larger the dimensional build error for the process.

Linear dimensional accuracy of different RP technologies								% Average accuracy overall
	Intended dimensions from CAD model (mm)							
	34.50	50.35	52.50	56.00	60.00	71.00	75.00	
Technology - material	Actual dimensions of test parts (mm)							
SLA - Epoxy (ACES)	34.83	50.57	52.77	55.85	59.97	70.97	74.94	97.70
SLS - Polystyrene	34.43	50.45	52.62	56.48	60.14	71.31	75.12	97.70
SLS - Nylon	34.77	50.37	52.59	55.99	60.39	70.65	74.99	97.80
LOM - Paper	34.67	50.61	5320	55.98	59.92	71.05	74.86	97.20
FDM - ABS	34.38	50.07	53.45	55.46	60.09	70.42	75.08	95.30

Table 2.6.2 Linear dimensional accuracy of different RP technologies[28]

It can be seen that none of the RP technologies considered are more accurate than 97.8 per cent. The RP user must take the linear dimensional inaccuracy and warpage of RP models into account when considering possible applications for the RP parts.

2.6.3 Mechanical Properties of Rapid Prototyped Parts

It is difficult to measure and compare the mechanical properties of RP parts for a number of reasons. The materials and processes used to make the parts are continually improving, therefore the mechanical strength and other properties of the parts are improving. The mechanical properties are also significantly anisotropic, and depend strongly on the direction in which they are tested. Finally, equipment manufacturers are often loath to supply material data for such comparisons and when they do, it is rarely directly comparable with that supplied by other manufacturers. For example, some manufacturers supply data obtained from test parts made on their RP machines, while others supply only data from tests on bulk samples of the source material.

Despite these reservations, it is useful to obtain some feel for the relative order of magnitude of the mechanical properties of the materials used in different RP processes.

Users of RP technology should ensure that they fully understand the mechanical properties of the selected RP process and material combination. This understanding can only be built-up with experience in using the technology[32].

2.7 Cost of RP machines

It is not possible to provide a definitive statement of the cost of particular machines as list prices and machine specifications change regularly, however an indication of machine purchase prices is given in Table 2.7.1. This table provides approximate prices of machines as sold in the UK in 2004.

Generally, over the past 5 years, the purchase price of RP equipment has significantly reduced, mainly due to increased competition. This highly competitive market has lead to a wealth of faster, more accurate machines, which are arriving with larger build envelopes and a wider range of build materials. This makes the selection of the appropriate RP system a more challenging one, whether it is for purchasing a machine or its prototypes[6].

Table : Typical purchase price of RP machines in UK				
Company	Technology	Model	Build volume (m3)	Purchase price £
3D Systems	SLA	SLA 250/30A	0.0166	£60,000
		SLA 250/40	0.0166	£90,000
		SLA 250/50	0.0166	£106,000
		SLA 350/10	0.0496	£237,000
		SLA 500/40	0.1525	£306,000
	SLS	Sinterstation 2000	0.0281	£187,500
		Sinterstation	0.0540	£250,000
	MJM	Actua 2100	0.0106	£40,000
Stratasys	FDM	FDM 1650	0.0166	£78,000
		FDM 2000	0.0166	£100,000
		FDM 8000	0.1289	£125,000
		Dimension	0.0166	£23,000
		Prodigy Plus	0.0166	£53,000
		Titan	0.0594	£163,000
Helisys	LOM	LOM 1015 Plus	0.0348	£57,500
		LOM 2030H	0.2335	£160,000
Sanders Prototype	DODI	ModelMaker - 6PRO	0.0036	£37,000
		ModelMaker - II	0.0107	£40,000
Cubital	SGC	SGC 4600	0.0455	£170,000
		SGC 5600	0.0929	£290,000
Z-Corporation	3DP	ZP402	0.0106	£23,000
Z-Corporation	3DP	ZP506 Colour	0.0106	£36,000
ObJet	3DP	Quadra	0.0159	£23,000

Table 2.7.1 - Typical purchase price of RP machines in UK[6] (2004)

2.8 The Future of Rapid Prototyping

Based on the experiences of the Author together with his working relationship with many RP system equipment suppliers, the following areas appear to present the major opportunities for change/development within the RP market place:

- office-based concept modellers will become "standard" PC peripherals;
- laboratory-based systems will reduce their build times and some processes may, in time, be replaced in total by "office systems";
- direct tooling processes will become mainstream, enabling prototype components to be produced in the correct production polymer;
- metal components will be produced directly by RP techniques this has started with limited impact to date.

Over the later years, one of the largest step changes in RP has been the ability to produce metal components directly. This requirement for "direct metal" led to several major ventures, investing large amounts of time and money into research and development in this field[33].

As the RP market matures, the opportunities for significant process development step changes will diminish; however, the dynamics of the market together with the general demand for quicker, cheaper and better products will continue to encourage innovative processing solutions that have the capability of "breaking the mould".

One such process is the EnvisionTec Digital Light Manufacturing process that cures the whole layer in one stage and utilises low cost data projectors instead of the high cost and high maintenance Lasers associated with the sterolithography process

2.9 Functional Parts and Tools From Rapid Prototyping

Parts made by rapid prototyping systems may be used directly in many final applications today. This was not true just a short while ago and reflects great strides in materials research that have been spurred by insistent market forces. Rapid prototyping generated parts may well offer a direct solution to application problems with material requirements ranging from plastics, ceramics and metallic materials. However, even the fastest RP systems are still far too slow and limited in other ways[34]. They simply can't produce parts in a wide enough range of materials, at a fast enough rate, to match the enormous spectrum of requirements of industry. However in small niche markets RP parts can provide a company with significant market advantage, one such application is in the production of hearing aids.

The patient has an impression taken of both ear canals, these are then digitised and shelled in CAD. The bespoke hearing aid shell is then manufactured on either an EnvisionTec Perfactory (Mini) or 3D Systems Invision machine. The electronics are added and dispatched to the customer, Figure 2.9 shows a build of hearing aids

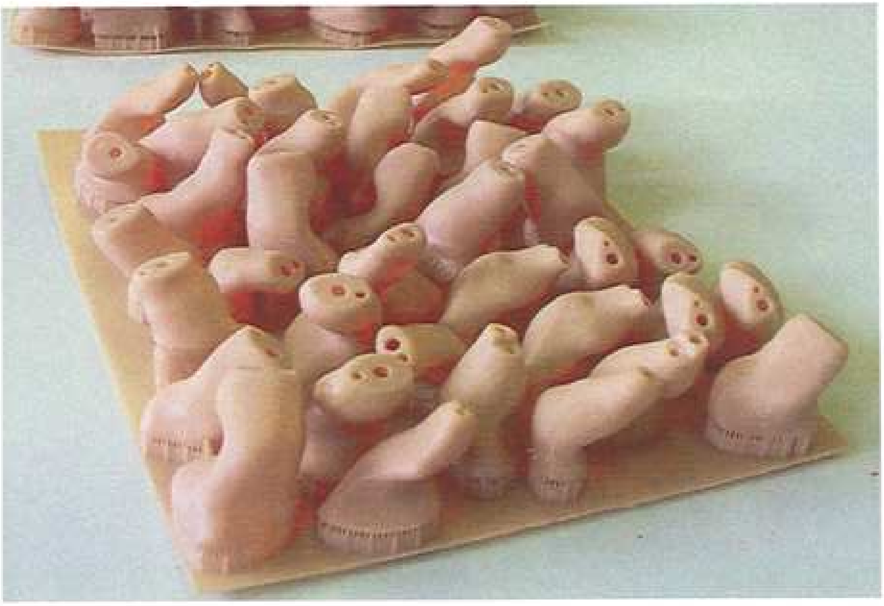


Figure 2.9 Hearing Aid Manufacture (courtesy of EnvisionTec)

Conventional processes such as moulding and casting are still the only means available to do that, but RP is often the starting point for making these processes faster, cheaper and better. Rapid prototyping is used in two ways to accomplish this: moulds may be directly fabricated by an RP system, or RP-generated parts can be used as patterns for fabricating a mould through so-called indirect or secondary processes.

2.9.1 Indirect or Secondary Processes

Although the properties of RP materials improve and expand continuously, a limitless array of applications means that there will always be a need to transfer parts formed in a material used in an RP process into yet another material. In addition, it's usually necessary to use very specific materials as the basis of most tool fabrication processes. Consequently, numerous transfer technologies have been developed. Typically a part made by the RP system is used as a pattern or model in these processes. While more than twelve processes are in various stages of development, just a few are common and commercially important today[35].

2.9.2 Direct Fabrication Processes

Specialised rapid prototyping processes have been developed to meet specific application and material requirements for moulding and casting. These may be forms of basic RP processes, such as stereolithography or selective laser sintering, or may be unique RP methods developed for a specific application. As in the case of indirect or secondary processes, there are a large number of technologies being explored, but only a few are commercially important today.

The net result is that there are a bewildering number of routes to get to a final functional part or tool starting from a CAD definition. The choice depends on the application, volume of parts to be produced, final material and accuracy requirements, rapid prototyping process used, and numerous other factors. Choosing isn't easy since most technologies are immature, have significant limitations, and there are usually several competing alternatives.

2.9.3 RP - Part Finishing

RP-generated patterns must undergo finishing operations before they can be used in any indirect or secondary process. No rapid prototyping technology today delivers surface finishes that are adequate for accurate applications such as injection mould tooling. Removal of the stair stepping inherent in the process and other surface artefacts is necessary before parts will eject from a mould, and may lead to additional errors being introduced. The accuracy of most secondary processes is ultimately limited by the precision of the pattern after finishing. Rapid prototyping patterns are best for applications with just a few critical dimensions: if many tight tolerances must be held, it's generally still faster and cheaper to use CNC.

2.9.4 Plastic or Polymer Parts

In the case of parts intended for use as prototypes, or for small production runs, different material properties may be required than those of the material used in the available RP process offers. While typically the target material is a plastic, the RP-generated pattern may belong to another family of materials. A principal means of making small quantities of polymer parts is with silicone rubber tooling. If larger quantities or specific material properties are required, an injection-moulding tool may be fabricated.

2.9.5 Silicone Rubber Tooling

This is a standard method of making small quantities of polymer parts[36]. Any rapid prototyping generated part can be used as a pattern to make silicone rubber tooling. These tools can be used to mould small to medium quantities of parts in a large variety of urethane, epoxy or other polymers. Some of these polymers have properties, which emulate particular engineering thermoplastics, and it's possible to fill them for added strength. The method doesn't produce a part, which is identical to an injection-moulded part however, because the conditions of manufacture aren't the same.

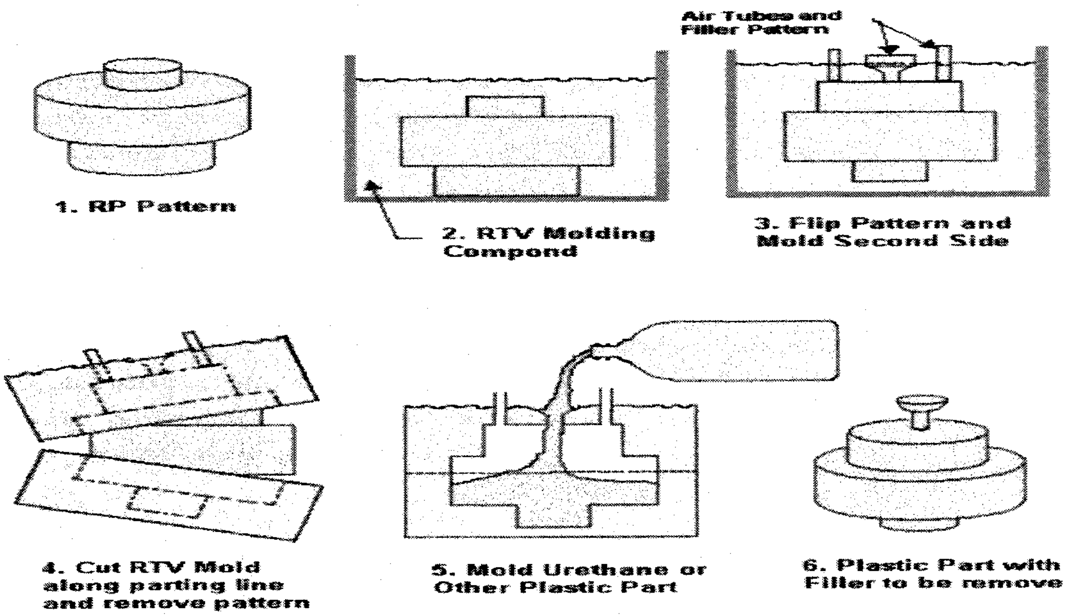


Figure 2.9.5 -The Silicon Tooling Process[37]

The materials are often used in a natural state, but painting and other secondary operations can result in parts that are very attractive. Silicone tools can typically be used to mould several parts before it becomes necessary to replace them. The number depends on accuracy and finish requirements and the specific geometry of the item produced. It may be possible to make many dozens of simple or non-critical parts from a single silicone rubber mould, but ten to twenty is typical if the parts are more complex. Wear of the mould occurs due to the reactive nature of the polymers, and because of the necessity to mechanically deform the mould to remove the part. It may often be necessary to replace the RP generated pattern as well, depending on the number of moulds to be made, similar accuracy, and geometric considerations.

The process is carried out by placing the RP-generated pattern in a frame, usually made of wood. The pattern itself usually must undergo secondary operations to bring it to the desired state of accuracy and finish before it can be used. See the section on RP-generated patterns. Silicone rubber room temperature vulcanising (RTV) moulding compound is then poured around the pattern. It may be necessary to apply a vacuum to the assembly to pull air bubbles out of the rubber and ensure fidelity to the pattern. Once the rubber has solidified the pattern is removed and the mould is ready to be used.

Silicone rubber tooling is most often used in manual casting processes, but in recent years more automated technologies have appeared. So-called reaction injection moulding (RIM) systems can produce several parts per hour from rubber moulds. Moulds also last longer because of the lower exposure time to chemical processes.

2.9.6 Why Use Rapid Prototype Tooling?

Making injection moulds by subtractive CNC or spark erosion methods is extremely slow and expensive. Skilled craftspeople are in short supply, product complexity is increasing and product cycles are growing ever shorter. This means that an ever-larger number of more precise tools have to be created by a declining population of toolmakers. There is therefore a great deal to gain from a process which provides both great time and labour savings, and addresses these limitations head-on. In addition, RP offers the tantalising prospect for improvement in mould performance beyond anything that can be accomplished with subtractive technologies[38]. The ability to fabricate complex conformal cooling channels to provide better thermal performance, or to use multiple or gradient materials to optimise each portion of a mould for performance and cost may ultimately lead to a revolution across the entire field. For example, Decreases in cycle times of 20% or more in experimental moulds have already been achieved[39]. Consequently, this application has been a major driving force in the development of rapid prototyping technologies that produce metal parts as well as in material transfer processes that use RP-generated patterns.

2.9.7 What are the Limitations?

The long-term prospect is for the direct additive fabrication of injection moulds with the same level of precision and durability as CNC methods. While great strides have been made in that direction, and important time and labour savings are being realised today by RP methods, the technology is still immature[40]. This means that the benefits realised are not universal and must be evaluated for each case. Rapid prototyping injection mould fabrication methods should be considered for projects in which the reduction of time to market is important, for prototype and short to medium volume production runs, and for parts which may be very hard to machine because of their geometry. The general limitations of RP methods compared to CNC today are that they produce somewhat less accurate and less durable tools, may have part size and geometry limitations, don't necessarily produce identical parts to hardened tooling, and tools may not easily be modified or corrected using typical toolmaking techniques. These limitations vary both as functions of the specific RP technology used and for each individual case.

2.9.8 Selecting a Process

Selection of the optimum RP-based process for each case is complex. Among the factors to consider are the final application, production volume, part size, accuracy and material requirements. The descriptions of the available technologies here provide a general guide for selection, as well as places to learn more. One important thing to keep in mind at the present state of the art is that while direct RP tool generation methods may offer faster turn-around, one of the transfer processes may offer lower costs and higher accuracy. Another thing to keep in mind is that it's sometimes appropriate to fabricate part of a tool with CNC technology and part using RP methods. The most economic and appropriate process must be selected for each portion of a tool, and not necessarily for the tool as a whole.

2.9.9 Other Competing Technologies

Many other competing technologies are being explored in corporate, university and government laboratories. There are also a number of methods which have not succeeded commercially over the course of several years, but are still being pursued on an experimental or limited commercial basis. The great majority of moulds today are still made using CNC and EDM this is due their understanding, acceptance and stability. Market acceptance for RP-based methods will continue to increase as business demands faster time to market, more individualised and shorter run products, and existing technical limitations are overcome.

2.10 Case Study - Application Of Rapid Tooling Methods

This example details the manufacture of Direct AIM™ tooling for the production of investment casting waxes. The end product is an impact driven square hole cutter, used to create the wall cavities required for 240 volt domestic light switches and sockets, Figure 2.10.1. This case study was undertaken by the author in collaboration with Design and Power Ltd, CADCAM Centre and 3D Systems Ltd

Figure 2.10.1 - The square hole cutter

The product is made of heat-treated cast steel, It's basic shape is square and it is driven through its centre, by a taper shaft. The driven end of the shaft has a universal fitting for connection to all commonly available impact devices.

The cutters underside comprises of a number of rows of serrated teeth, through the centre of the teeth is a steel pin, this pin locks the taper shaft in place and is used for location purposes.

The cutter will be made available in three forms. All forms have the same basic shape, but having different numbers of teeth and different masses, the three types are designed for specific power outputs of impact drill, Figure 2.10.2. The action is purely impact, i.e. no rotary action.

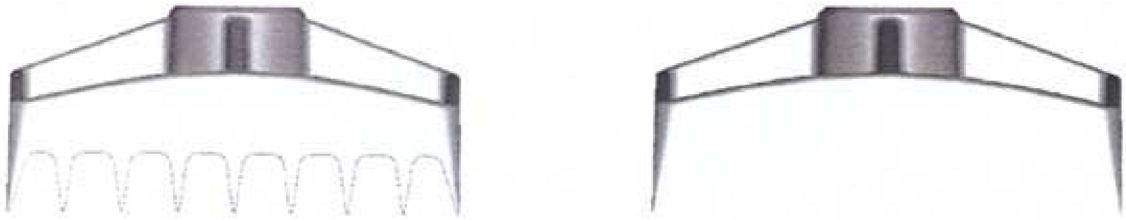


Figure 2.10.2 — Side views of cutter

The first prototype waxes were produced using Z-Corps 3DP at UNN and further masters made by Thermojet™ Printer. Using the Thermojet™ Multi-Jet-Modelling technology the component can be built up in layers in a material, which closely resembles investment-casting wax.

These wax models are then sent to the chosen foundry for investment casting. Many different design iterations were tested based on FEA information carried out at UNN, after each design modification, new waxes were created, castings made from these waxes were then tested until failure, this process continued until a satisfactory design was achieved.

Once the main design process had been completed, a larger number of components were needed for extensive field trials, and a quicker method of wax production was required. Using the Direct AIM™ method, the core and cavity inserts are built with stereolithography, using the ACES™ build style.

The CAD model data was then sent to 3D Systems, from the data the component split line was obtained. Using a 3D-CAD system, a block was created and the component geometry removed from it, effectively creating the reverse of the component. The block was then split to create the core and cavity sides of the tool; in this case, both halves of the tool were cavities Figure 2.10.3. This data is then used to build the tool using Stereolithography.

Investment castings were then made from these waxes; the castings were then used in extensive field trials, which proved to be successful.

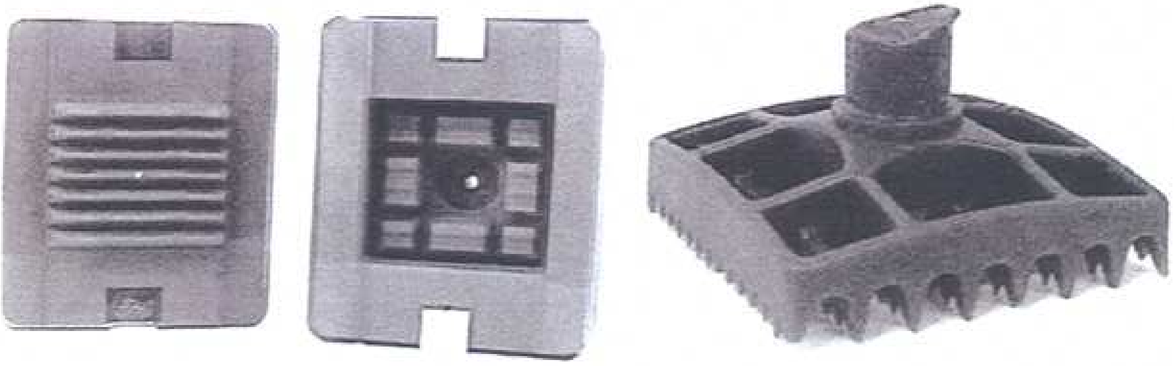


Figure 2.10.3 – Investment casting wax tool and wax master

The final stage in the product development is the creation of a traditional fully automatic multi--cavity aluminium tool; this tool is capable of creating waxes in sufficient quantity for full-scale production.

This example deals with two methods of creating shell mould tooling using RP technologies. Figure 2.10.4 shows the CAD model of the component in question, this component is the main body of an impact driven wall-chasing device, it is used to create the cavities in walls required for the installation of electrical cables and conduit.

Both methods result in a metal plate, the type of metal used influences the shrinkage factor. In this example a cast iron plate was required. On this plate is the male form of a number of the components, the number is calculated from the size of the plate.

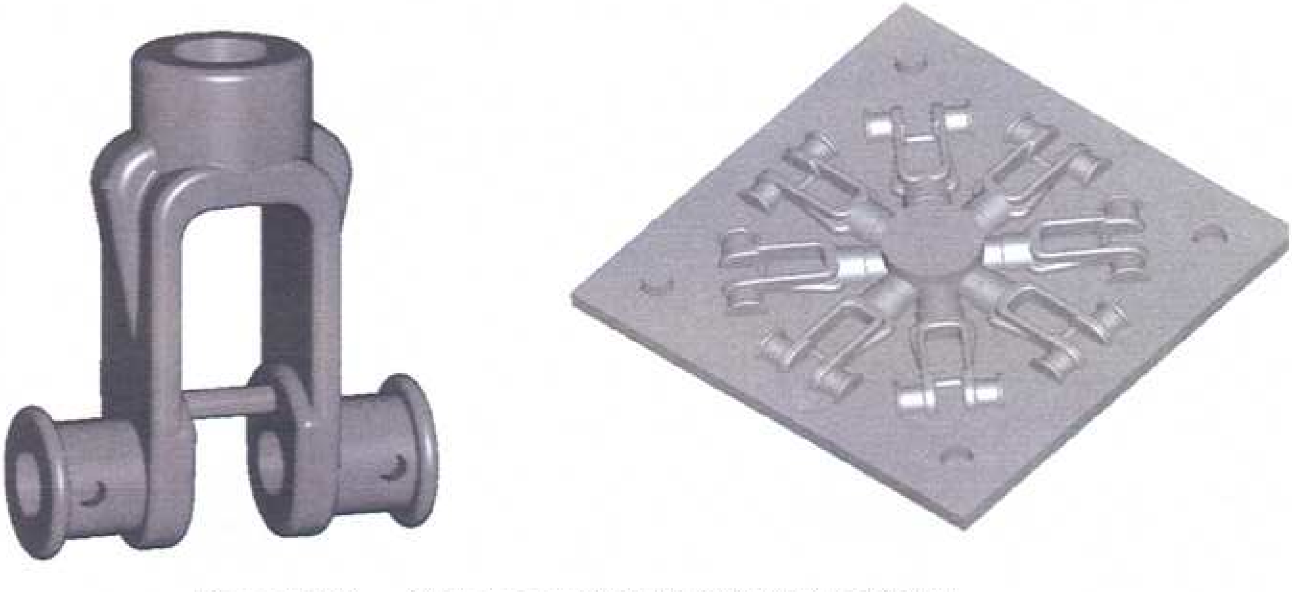


Figure 2.10.4 — Wall chaser main body and CAD tool layout

The components are split along their parting line and arranged on the plate together with location pillars and feeders. Figure 2.10.4 shows the Cad model of this plate before being sent for rapid Prototyping.

The plate is then used to create the shell moulds or "biscuits", as they are sometimes referred to, of the components. These shells are made by coating the plate in numerous layers of fine flyer sand. The coated the plates are then heated until the sand fuses together, this process is repeated until a sufficient thickness of sand has coated the plate.

The tool halves are manufactured in a 5mm thick shell in 100-micron thick layers. This saves time on the Stereolithography machine and money too. The SLA shell is then back-filled with a mixture of aluminium chips/aluminium powder/acrylic resin. This adds strength to the structure and the aluminium helps to draw heat away from the moulding face, finally the inserts are fixed with an aluminium back plate, this gives the tool much more rigidity and prevents wear to the tool faces. Figure 2.11.5 shows the Direct AIM™ tool and a wax produced from it.

Figure 2.10.5 - Stereolithography RP of the plate.

The finished tool was shipped to the foundry, which has an in-house wax production facility, the tool was successfully trialled and a sufficient quantity of waxes produced from it.
The first method trialled of the process to create the shell plate; uses a standard SLA RP model. This RP is then used to create an impression in sand; molten cast iron is then poured into to this impression to form the shell plate. Shrinkage allowances are calculated and built into the RP model. Figure 2.10.5 shows the RP of the plate.
The second method again uses an RP of the plate but this time uses a build method developed by 3D Systems called QuickCast. The QuickCast build style utilises a honeycomb-like internal structure that provides necessary structural integrity during pattern preparation, yet readily collapses and bums out during flash fire or autoclaving operations.

This QuickCast pattern is then used in the normal way and a casting of the plate is made using the investment casting process. The process for creating the shell mould is the same as for method one. The casting process requires two of these shell moulds clamped face to face and alignment is ensured by the locating pillars. A number of these pairs are then stacked on top of one another, the number is determined by volume of the parts i.e. the capacity of the ladle.

A feedhole is cut through the shells to allow the entrance of molten metal; the slight porosity of the shell enables trapped air to escape, the mould is then allowed to cool. Once cool the shell is broken away and discarded, the components are then fettled i.e. cut away from the feed channels, these parts are then shipped for final machining operations prior to assembly and sale.

CHAPTER THREE: RESEARCH EQUIPMENT AND EXPERIMENTAL PROCEDURES

3.0 Introduction

The previous chapters covered the generic technologies of Rapid Prototyping and Rapid Tooling in Chapter Two. An Authors example case study application of these RP and RT technologies was also included in Chapter Two. This chapter covers the equipment, test samples and test techniques utilised in Chapters Three and Four of the investigation.

3.1 Charactisation of ZP402 Material using Energy-dispersive X-ray spectroscopy

Energy dispersive X-ray spectroscopy (EDS or EDX) is an analytical tool predominantly used for chemical characterisation. It is a type of spectroscopy, it relies on the investigation of a sample through interactions between light and matter. Its characterisation capabilities are due to the fundamental principle that each element of the periodic table has a unique electronic structure and, thus, a unique response to electromagnetic waves.

Spectroscopy data is often portrayed as a graph plotting counts vs. energy. The peaks correspond to characteristic elemental emissions. To stimulate a measurable response from a specimen, an electron or photon beam is aimed down into the sample to be characterised. At rest, an atom within the sample contains ground state ('unexcited') electrons situated in concentric shells around the nucleus. The incident beam, however, excites an electron in an inner shell, prompting its ejection and resulting in the formation of an electron hole within the atom's electronic structure. An electron from an outer, higher-energy shell then fills the hole, and the excess energy of that electron is released in the form of an X-ray. The release of X-rays creates spectral lines that are highly specific to individual elements; thus, the X-ray emission data can be analysed to characterise the sample in question. This technique is used to characterise the ZP402 build materials.

This technique was utilised to characterise the un waxed and waxed ZP 11 starch based and the ZP100 ceramic based materials in section 4.4.2

3.2 ZP402 Material Hardness testing

Micro hardness testing of metals, ceramics, and composites is useful for a variety of applications for which 'macro' hardness measurements are unsuitable: testing very thin materials like foils, measuring individual microstructures within a larger matrix, or measuring the hardness gradients of a part along the cross section. Microhardness testing per ASTM E-384 gives an allowable range of loads for testing with a diamond indenter; the resulting indentation is measured and converted to a hardness value. The actual indenters used are Vickers or Knoop. The result for either Vickers or Knoop microhardness is reported in kg/cm^2 and is proportional to the load divided by the square of the diagonal of the indentation measured from the test.

The load on the Vickers microhardness indenter usually ranges from a few grams to several kilograms. In contrast, 'Macro' Vickers loads vary from 1 to 120 kg. The indentations should be as large as possible, within the confines of sample geometry, to minimize errors in measuring the indentation, hence the reported hardness. Vickers hardness is also sometimes called Diamond Pyramid Hardness (DPH) owing to the shape of the indenter.

The test samples should have a smooth surface and be held perpendicular to the indenter.

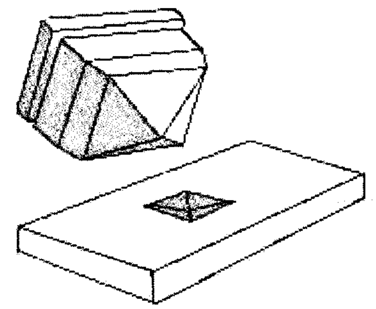


Figure 3.2.1 - Vickers Hardness Impression

Due to build characteristics parts were tested on all six sides, taken as a average of 10 readings as shown in Figure 3.2.2

Results can be seen in section 4.4.4

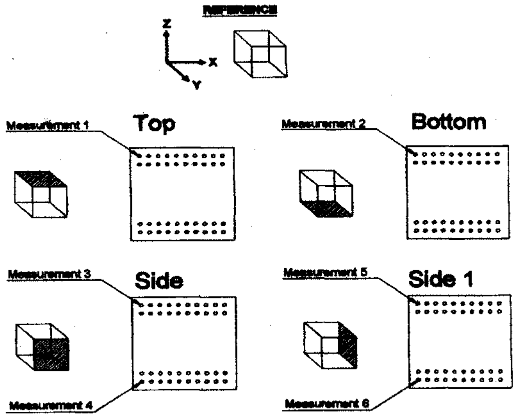


Figure 3.2.2 - Hardness Measurement Positions

3.3 Tensile strength test of 3DP materials

Standard test samples where prepared as shown in figure 3.3.1

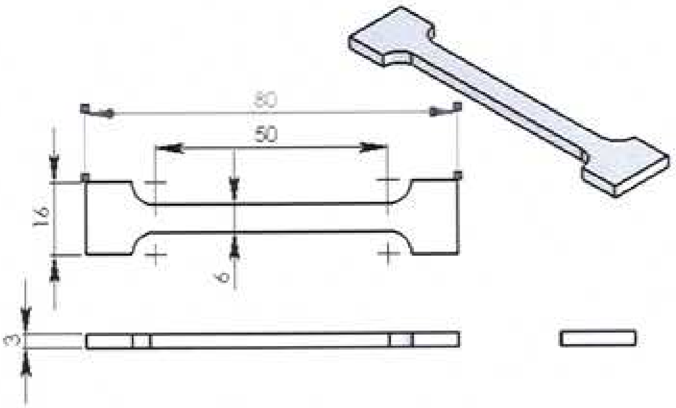


Figure 3.3.1 - Standard Tensile test specimen

Tensile test proceedure for section 4.4.4:

- Calibrate the load cell
- Locate test specimen in jaws of test machine
- Load specimen and record load versus extension
- Calculate the tensile strenght from cross section area and load at failure

Figure 3.3.2 - Instrone Tensile test machine

3.4 Three point bending test of 3DP process samples

The pieces were tested for their bending strength, set up for three point bending strength as show below in Figure 3.4.1. used in section 4.5.2

Figure 3.4.1 - Three point Bending Strength Test

To compare the infiltration experimental work, the present standard paraffin wax infiltration. Ten standard pieces of dimension 80 x 40 x 6 mm were in-filtered. The three point bending test method was carried out in order to find out the bending strength of this standard paraffin wax infiltrate pieces over at test length of 40 mm and was compared with other bending strength experimental readings obtained for the new proposed infiltration materials.

3.5 Accuracy Tests of 3DP and DLM specimens

Accuracy and surface flatness measurements were undertaken with an International Metrology System (IMS) Impact^{TM} Coordinate Measuring Machine (CMM) – accuracy of 3 µm.

The process uses a computer controlled gantry mounted highly sensitive and repeatable touch probe sensor accurate to ± 3 µmm..

A DMIS programe was developed control he CMM motion and selection of measuremnt points. This ensured repeatable measurement of all the sample parts.

Figure 3.5 - Visual Impact Co-ordinate measuring machine

3.6 Build Orientation, Dimensional Accuracy and Surface Flatness of DLM Specimens

3.6.1 Orientation: The part can be built in any of the three orientations x, y and z, as shown in Figure 3.6.1/2. The orientation is chosen considering the following factors:

- Geometry of the part
- Surface finish requirements
- Areas to be supported (Faces in contact with the support end up with a rougher finish)

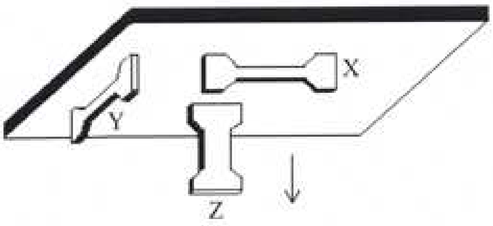


Figure 3.6.1.1 – Different build orientations

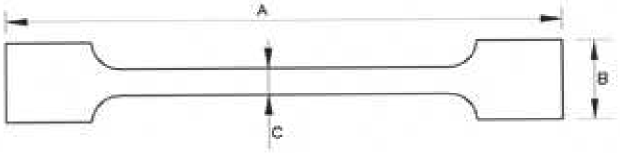


Figure 3.6.1.2 – The test specimen

3.6.2 Dimensional Accuracy

The test piece as shown in Figure 3.6.2.1 and 3.6.2.2 was designed to allow the measurement of multiple build axis to be assessed, coupled with part location within the build platform in a single part.

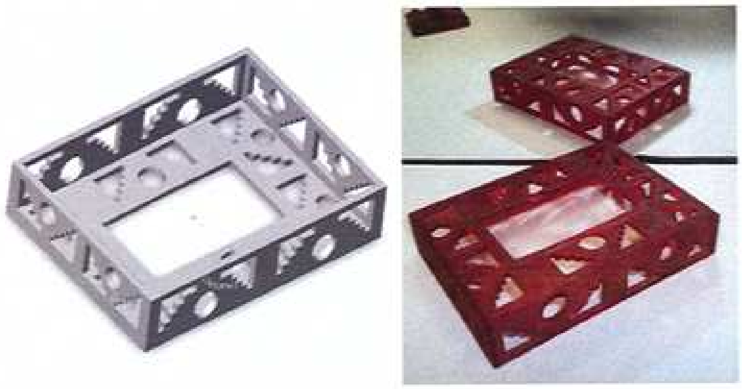


Figure 3.6.2.1 – Dimensional Accuracy Test Pieces

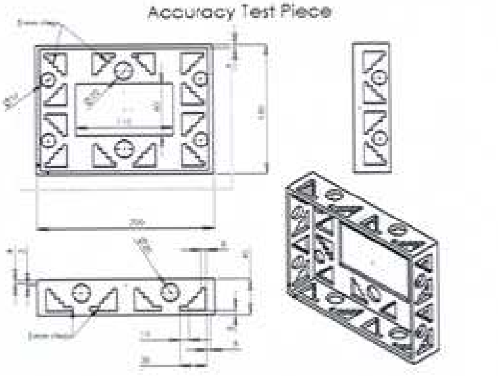


Figure 3.6.2.2 - Dimensional checks

The test piece in Figure 3.6.2.3 was design to allow the analysis of build features to be investigated.

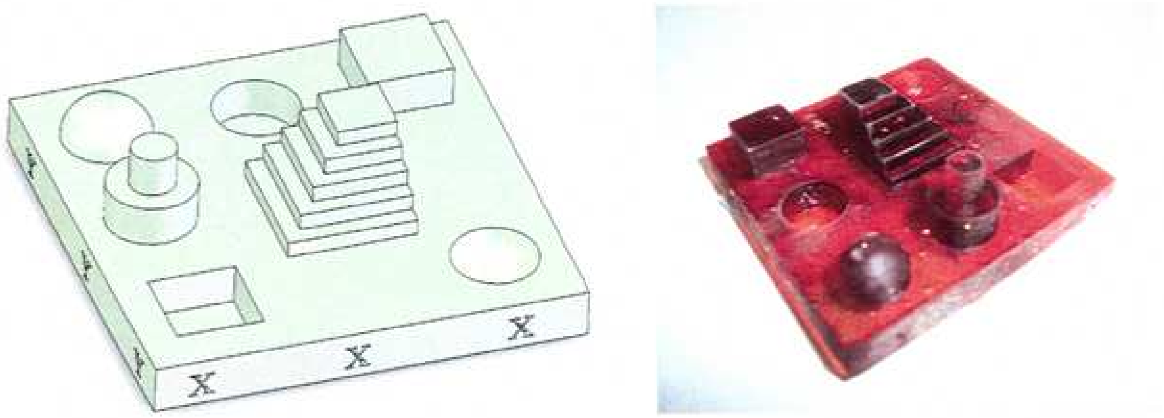


Figure 3.6.2.3 – CAD Geometry test piece and sample produced

3.6.3 Surface Flatness

The test pieces shown in Figure 3.6.1.2 were evaluated for surface flatness using the IMS Impact CMM along the full length of each specimen for each build orientation.

3.6.4 DLM Hardness and Tensile Testing Procedure

The equipment used to test the hardness and tensile strength of the specimens is shown in Figures 3.6.4.1. The values obtained form the Barcol Impressor are called Barcol Numbers and are universally accepted alongside Shore hardness values, for plastic materials.

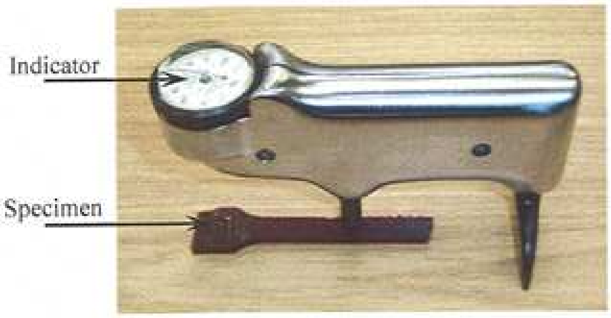


Figure 3.6.4.1 – The BARCOL Impressor

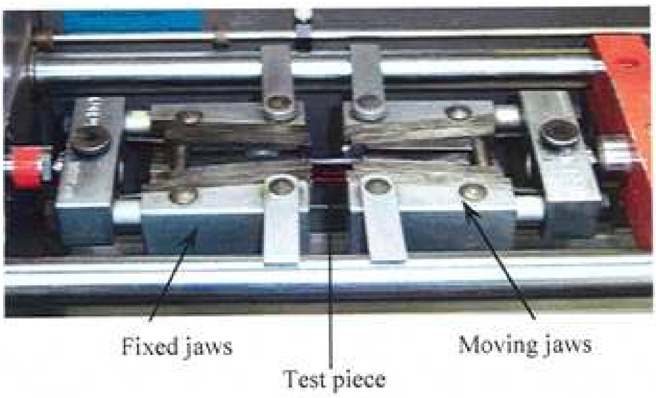


Figure 3.6.4.2 – The Tensometer

The tensile strength sample itself was used also for the accuracy measurements. Accuracy was determined by calculating the deviation of the part dimension from the actual, at different points across the sample. They are marked 'A', 'B' and 'C' in Figure 3.6.1.2. Two different types of accuracy can be obtained in the case of RP techniques in which the part is built layer by layer – XY and Z (dimension along build direction). The dimension obtained by building up of the layers is affected only by the accuracy of thickness of each layer. In this work, we focus on the XY accuracy, as that is the factor that is directly influenced by projector performance.

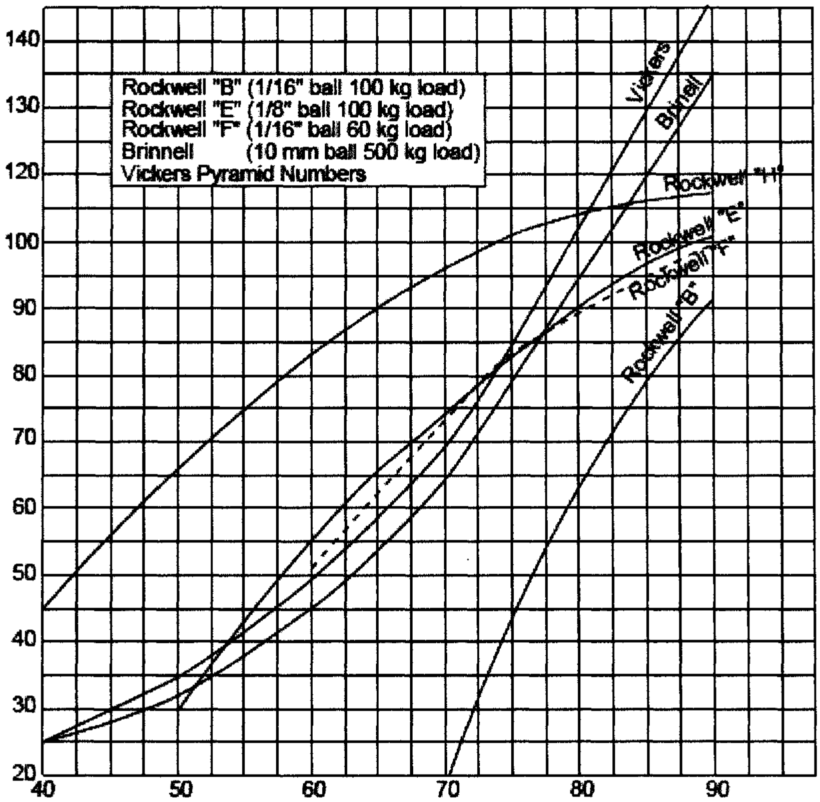


Figure 3.6.4.3 Barcol Number Conversion Chart[41]

3.6.5 DLM Building the surface finish test parts

Simple test parts were built with 30, 45, 60 and 75 degree slopes on them, to study how the surface finish varied with angle. The parts were built with both up and down-facing configurations of the aforementioned angles. They were built with a layer thickness of 0.05 mm. Example of up and down-facing angles can be seen in Figure 3.6.5.1.

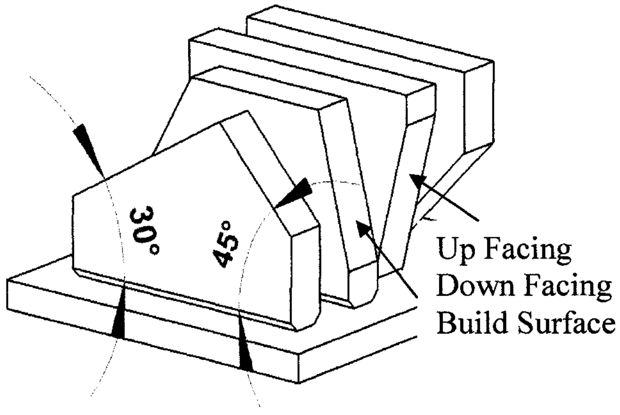


Figure 3.6.5.1 – The surface finish test sample

Testing the surface finish

The surface finish was measured with a Taylor Hobson Talysurf, for a cut-off length of 0.80mm for each measurement. The test set-up is shown in Figure 3.6.5.2.

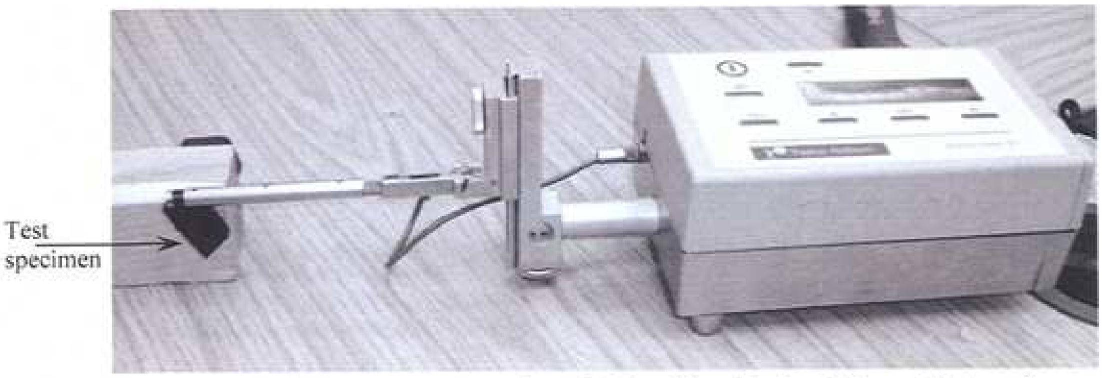


Figure 3.6.5.2 – Testing surface finish with a Taylor Hobson Talysurf

3.6.6 Level of Detail Tests – Filigree

The sample test piece as shown in Figure 3.6.6.1 and 3.6.6.2 were used to assess the finest detail that could be manufactured using the DLM™ with filaments of size 3 to 0.05 mm in the three build orientations.

Figure 3.6.6.1 - Filigree Test Piece

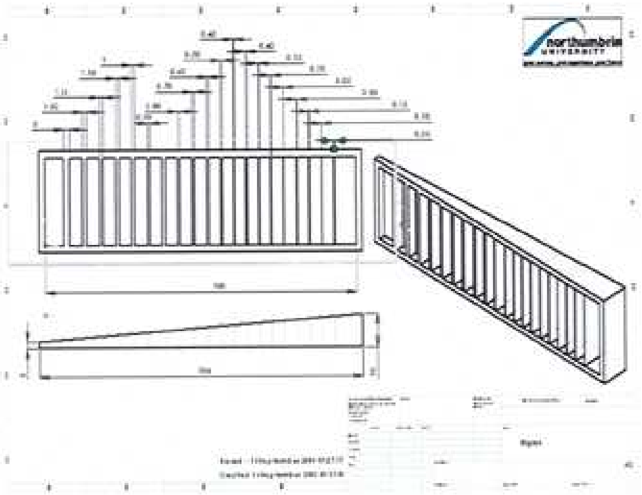


Figure 3.6.6.2 - Dimensional checks

3.7 The Finite Element Analysis (FEA) of DLM Components

3.7.1 Background to Finite Element Analysis

Design analysis is a software tool for simulating physical behaviour on a computer. Will it break? Will it deform? Will it get too hot? to understand the envelope of operation and ultimately the criteria of failure. These are the types of questions for which design analysis provides accurate answers. Instead of building a prototype and developing elaborate testing regimens to analyse the physical behaviour of a product, engineers can elicit this information quickly and accurately on the computer. The application of design analysis can minimise or even eliminate the need for physical prototyping and testing; the technology has gone main stream in the manufacturing world over the past decade as a valuable product development tool and has become present in almost all fields of engineering[42]. Design Analysis employs the finite element analysis (FEA) method to simulate physical behaviour of a product design.

The FEA process consists of subdividing all systems into individual components or "elements" whose behaviour is easily understood and then reconstructing the original system from these components. This is a natural way of performing analysis in engineering and even in other analytical fields, such as economics. For example, a control arm on a car suspension is one continuous shape. An analysis application will test the control arm by dividing the geometry into elements, analysing them, then simulating what happens between the elements.

The application displays the results as colour-coded 3D images, red usually denoting an area of failure, and blue denoting areas that maintain their integrity under the load applied.
Engineers use design analysis for just about every type of product development and research effort imaginable. Analysing machine designs, injection moulded plastics, cooling systems, products that emit electromagnetic fields, and systems that are influenced by fluid dynamics are just some examples of how companies leverage design analysis.

The design analysis procedure can be broken down into a series of steps

- Decide upon the analysis type i.e. static analysis, dynamic etc
- Generation of 3D CAD model of component
- Reduction of component to reduce complexity by looking for symmetry, removal of detail i.e. text etc

- Assigning material properties this case in x, y and z axis directions
- Applying restraints that hold the component
- Applying forces or deflections to reflect real world loading
- Creating a mesh of elements
- Running the analysis
- Refining the mesh in key critical areas
- Re-running the analysis
- Verification of analysis results by hand calculations or physical testing

3.8 Mould Tool Production using DLM

The material used to create the mould tool was orange coloured methacrylate release R5 . It solidifies by the process of photopolymerisation.

Parameters of the die:

- Diameter: - 43.5 mm
- Thickness: - 3 mm
- Time taken to build 5 replica parts: - 4.7 hrs

Injection Moulding

In this experimental test, the injection-moulding machine used to produce the plastic product is “Plunger injection machine” Manimould as shown in Figure 3.8.1. The temperature at barrel was set at 200^0C and the temperature at barrel head was set at 180^0C. The thermoplastic used was polystyrene with a melt temperature of approximately 200^0C.

The melt is forced into the mould through the injection nozzle of the injection unit. This operation is known as the shot rate. This shot rate can also refer to the pressure of the process. In this research, shot rate and various pressures are controlled in order to know the suitable shot rate and pressure for the DLM mould tools.

From the injection nozzle, the material passes through the sprue bush of the mould. It is then distributed to the cavities. When the cooling period has elapsed, the mould is opened and the finished parts are ejected.

The mouldings were tested with the different shot rate and various injection pressures. The shot rate used in this research can be divided into 2 shots, 1 shot, 3/4 shot, 3/5 shot, and 1/2 shot. Various pressures are used to force the melt material into the DLM mould. The temperature is set in the range of 180^0C to 200^0C.

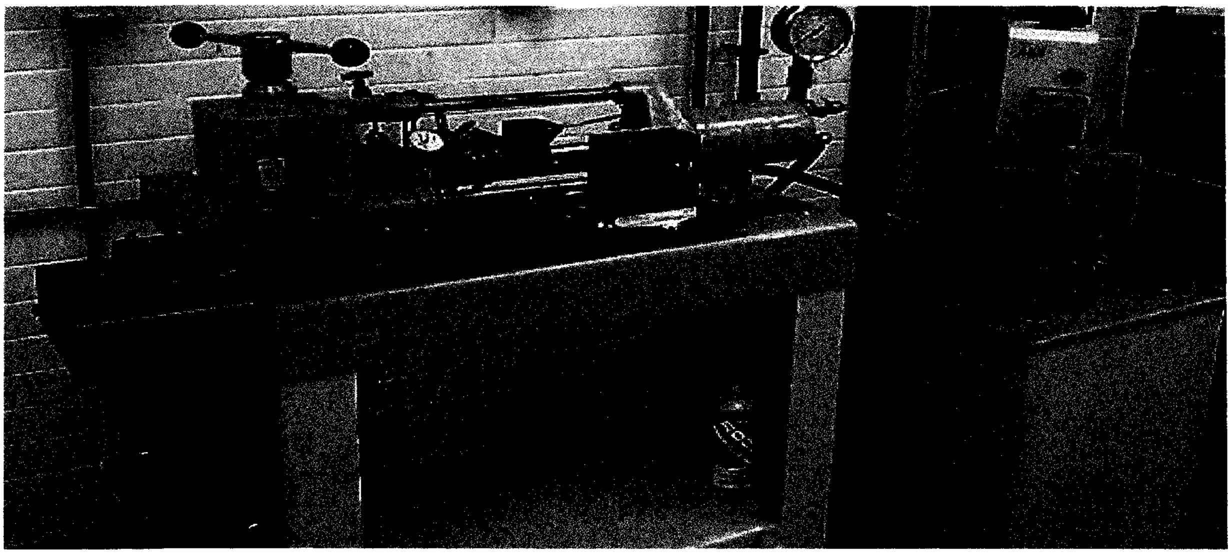


Figure 3.8.1 - Manimould injection moulding Machine

CHAPTER FOUR: RESEARCH, ANALYSIS AND DEVELOPMENT OF THE 3D PRINTING PROCESS

4.0 Introduction

The research into the development of the 3D printing process, which was first commercialised by MIT, focuses upon:

- Understanding the process
- Process interactions
- Materials development
- Post process materials improvement
- Novel applications of the process
  - Electro discharge machining
  - Polymer injection mould tool manufacture

This work builds upon the research carried out in chapters two and three and eight of the authors published research papers are focused on this area, full papers can be found in the Appendix A.

The first section presented in this chapter investigates the operating characteristics of the 3D printing process and materials, particularly focusing upon the build accuracy and materials strength.

The second section investigates increasing the green strength of the plaster-based 3D printing manufactured parts; the aim of this study was to increase the application of functional prototypes.

This is followed by research into the application of the 3DP process for manufacture of mould tools for polymer injection moulding similar to the 3D Systems AIM^{TM} tooling concept.
The final section investigates using a carbon ceramic composite material for the production of conductive electrodes for electro-discharge machining process. This research received a great deal of attention at the Time Compression technologies Conference 2002, being a novel application for 3D printing.

4.1 A Study of Build Accuracy of the Z-Corps 3D Printing Technique and Related Seepage Control

Rapid Prototyping techniques can create physical parts directly from accurate, desired shape, 3D models, which are typical un-toleranced desired size. As with all manufacturing processes there will be a deviation from desired size due to manufacturing parameters dependant upon process and operating conditions.

This section describes the Z-Corps powder-based 3D printing technique. The 3D printing process will be analysed so that the key operating parameters and mechanisms can, in the first instance, be understood, and thereafter be controlled in order to improve part accuracy.

4.2 Introduction to 3DP Build Accuracy

Rapid Prototyping (RP) refers to a group of technologies for the fabrication of physical objects directly from accurate digital 3D Computer Aided Design (CAD) data [43]. The designer normally models the desired component true size without any tolerances. The process of placing manufacturing tolerance is normally carried out during the detailed design stage, via annotation of the technical drawing. These tolerance attributes will define whether the part will be accepted or rejected. An alternative approach is to place an attribute on a 3D model dimension for later use within the technical drawing. All data translation mechanisms (IGES, DXF, STEP and STL) strip out these annotations from the 3D model as they only define geometry. It is a requirement of the manufacturing process to manufacture the part to the required geometry accurately.

The use of RP produced parts is restricted by three major parameters – part accuracy, part strength, and part definition;

- Part accuracy is a function of the process and the interaction with the build materials, and this research aims to further understand the interactive relationship of the two applied to the Z-Corps 3D printing process;
- Part strength is related to the build material or process parameters and the bonding produced during the process;
- Part definition is a combination of resolution of the process and the manufacturing process constraints, i.e. green strength, support requirements etc.

Over the last decade there has been significant advancement within the RP field in the above parameters, particularly in the area of Stereolithography (SLA) process whereby both process and material improvements have led to the acceptance of parts as end products as Rapid Manufactured parts[44 45]

3D Printing refers to a range of techniques characterised by the method of delivering build material or build adhesive via a series of nozzles that are translated across the build platform.

The Z Corps 3D printer is available in four machine versions. The basic build process is the laying down of a layer of powder (ceramic or starch based) 0.07 to 0.25 mm thick. The model is sliced and the solid sections printed via "Hewlett Packard print heads" in the *y*-axis, the carriage increments (similar to paper feed) in the *x*-axis and another strip of binder is deposited. The parts are formed in the build chamber that drops by one layer thickness as more material is deposited and bound above it. The machine is capable of building several layers per minute. As the powder supports the part, no support structure is required therefore allowing complex parts to be built. The binder can be coloured with a dye allowing coloured parts to be generated, for example the results of a Finite Element Analysis. The surface finish on the underside is poorer than the topside due to seepage of the binder into the surrounding material Figure 4.2.

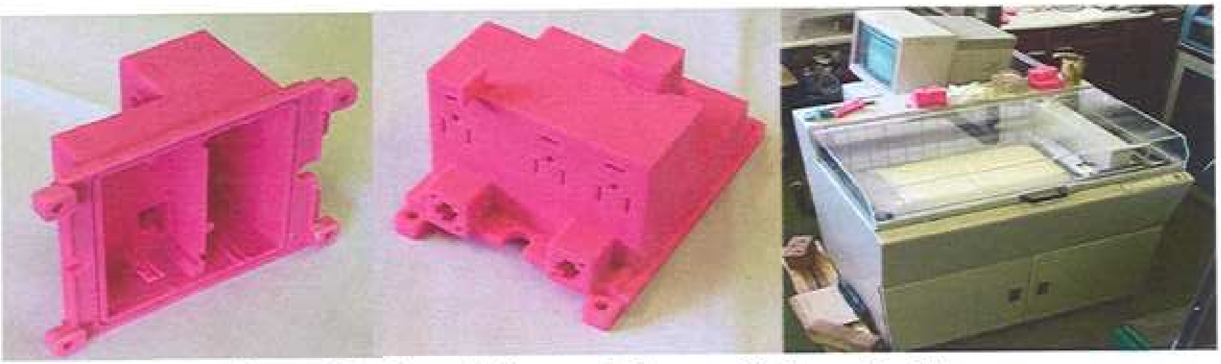


Figure 4.2 - Example Parts and picture of Z-Corps Machine

- Benefits

  Fastest build speed, No support structure

  Complex parts, thin walled parts,

  Two materials:

  - Starch - rubberising, investment castable
  - Ceramic - detail, definition strength

- Drawbacks

  Least accurate of concept modellers

  Underside surface finish – poor

  Poor strength

  Limited fit and function usage

Colour capable, Easy clean
New large build volume machine ZP810 (largest of concept modellers)
Alternative powders – metallic, conductive

Machines: ZP310, ZP406, ZP810, (ZP402 Now replaced by ZP310)

A benchmark of 3D printing systems revealed the various application areas for these concept-modelling processes. Namely: ThermoJet for investment casting, ObJet most accurate and strongest, and Z-Corps cheapest and fastest.

4.2 Z-Corps 3D Printing Process

4.2.1 The build process

The system software first converts a three-dimensional design built using 3D CAD (saved in STL format) into thousands of cross-sections or slices that can be between 0.07 – 0.25 mm thick. The three-dimensional printer then prints these cross-sections one after another from the bottom of the design to the top.

Inside the printer there are two pistons. The feed piston is filled with powder, the part is constructed within the build piston volume and a roller transfers the material from the feed piston to the build piston.

To begin the 3D printing process, the system first spreads a layer of ZP series powder in the same thickness as the cross section to be printed. The binder cartridge then applies a water based binder solution to the powder, causing the powder particles to bind to one another and to the printed cross-section one level below. The feed piston comes up and the build piston drops one layer thickness and the roller transfers one layer of material between the pistons. The system then spreads a new layer of powder and repeats the process, and in a short time the entire part is printed.

The system employs several techniques to quickly build great parts. First, binder solution is applied in a higher concentration around the edges of the part, creating a strong shell around the exterior of the part. Within parts, the printer builds an infrastructure by printing strong scaffolding within part walls with a higher concentration of binder solution Figure 4.2.1. The remaining interior areas are printed with a lower saturation, which gives them stability, but prevents over saturation, which can lead to part distortion.

After printing, the part is removed from the powder bed, de-powdered and dried. The part can then be infiltrated with wax, epoxy, or other materials to increase strength and durability. Because the powder layers support the structures being printed above, the system prints parts without support structures of any kind and can print parts with complex geometries that are impossible for other processes.

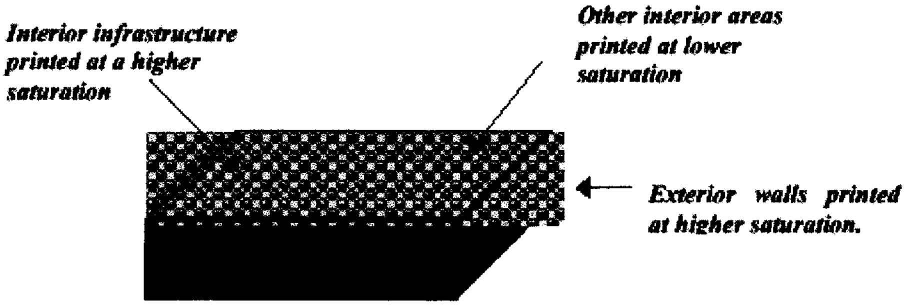


Figure 4.2.1 - Representation of the Z402 Shelling and Infrastructure Features.

4.3 Rapid Prototyping Accuracy

4.3.1 Positional accuracy of drop deposition

Accuracy is evaluated as dimensional error, form error and surface roughness of manufactured parts[46]. A large number of parameters limit the ability of RP systems to create parts as accurate as the CAD designs they are based upon. The major errors are:

- Mathematical errors due to forced approximation of part surfaces in the standard file input. These STL errors can be reduced by control of tolerancing and angle parameters during triangulation of CAD data;
- Process related errors affect the shape and definition of the part in *x-y* plane due to positioning errors due to head translation, and in the *z*-axis due to registration of different layers;
- Material related errors are related to shrinkage, distortion during and post manufacture, infiltration absorption during part processing and bleed or seepage of binder during production;
- Mathematical errors can be corrected using finer tolerances and more powerful algorithms to process the input data during slicing of 3D CAD data.

Process related errors as described by Jee & Sachs[47] ignore the practicalities of the 3D printing process, i.e. set print head resolution and linear axis of the print head and print head translation mechanisms[48].

4.3.2 Printing accuracy

Printing accuracy of the 3DP machine will also have to be considered as a contributor to the accuracy and conformity of a printed physical part from a designed CAD model. It is defined as the maximum deviation of a binder drop position from the numerical fabrication code along the three orthogonal printing directions as follows:

E_{fx}: maximum deviation error of drop placement along the fast y-axis.

E_{sx}: maximum deviation error of drop placement along the slow x-axis.

E_{zx}: maximum deviation error of drop placement along the z-axis.

The ability to reproduce fine surface textures relies heavily on the machine's accuracy. This accuracy depends on the errors introduced in the system by each component of the machine. The final combination of the machine errors, including the controller errors, can be made within an error budget. Manufacturing rules must reflect this printing accuracy to explain discrepancy in geometry between a designed CAD model and the physical part to be manufactured by 3DP process.

4.3.2.1 Printing style

Two different visually simulated models in accord with different printing styles of 3DP are possible in the CAD tool implemented using the proposed method. Binary deflection printing (BDP), for example, is a printing style in which the lines of drop placements are parallel to the printing direction as illustrated in Figure 4.3.2.1. Proportional deflection printing (PDP), on the contrary, is a different printing style in which the lines of drop placements follow the edge contour of the 2D layered CAD data, which provides smoother edges in the shape of a fabricated complex part.

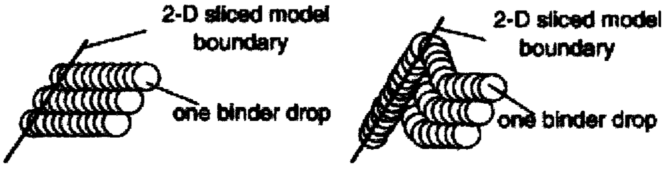


Figure 4.3.2.1 - Two printing styles of 3DP process – BDP (right) and PDP (left).

For example, the positive feature size along the fast axis is equals to $M_{pf}= (m_{pf}R_{fx}+D_p\pm\lambda_{pf}E_{fx})$, algebraic sum of drop placement primitive size D_p, total increment size of binder drops $m_{pf}R_{fx}$ and printing accuracy along the same axis $\pm\lambda_{pf}E_{fx}$ as illustrated in Figure 4.3.2.2.

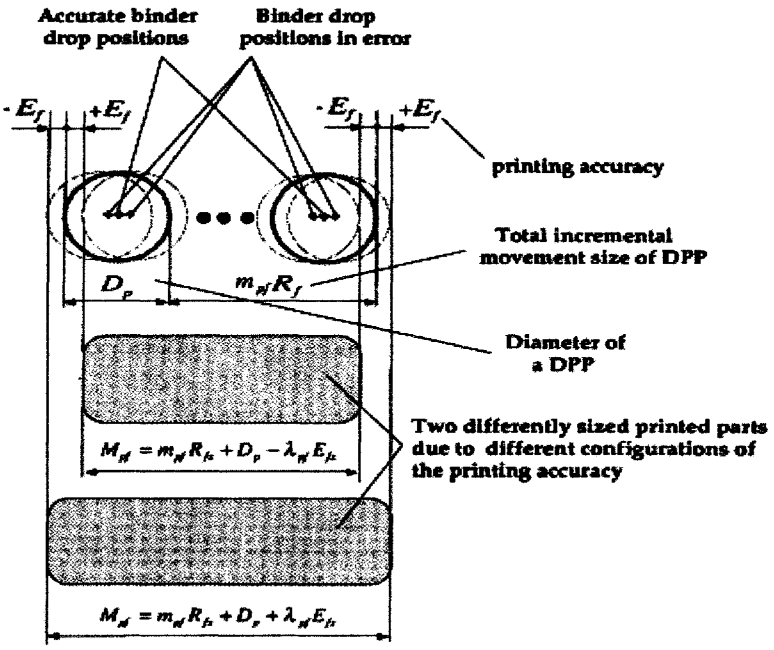


Figure 4.3.2.2 - Printing accuracy for a positive feature in 2D layers[48].

4.3.3.1 Material Related Errors

4.3.3.1 Material data

The bonding of the powder to form a layer and bond to the layer below is critical for part strength and this is controlled by the build shell and core saturation parameters.

The Z-Corps printer can use two major build materials, a starch based powder for speed and a plaster based powder for strength and resolution. The plaster-based powder was investigated, as this is the most commonly used material for the Z-Corps machine.

Plasters are manufactured from gypsum and anhydit. Gypsum is a fairly soft rock containing calcium sulphate, and the rock is crushed and semi-dried to form hemi-hydrate plaster, also known as plaster of paris.

When water is added to the plaster the water of crystallisation reforms to convert the plaster into gypsum. The growth and interlocking of crystals is the setting action of the plaster. Plasters can have retarders to reduce the speed of crystallisation.

$$C_a\,O + H_2O \rightarrow C_a\,(OH_2)$$

Setting – water dries and carbon dioxide is reabsorbed into the atmosphere – carbonation.

$$C_a\,CO_3$$

Absorption of the water in the surrounding and non-part designated areas means that the parts are built with a loss of accuracy and definition. This is of particular note with materials having low sorptivity similar to graphite/ceramic composite used for EDM electrode manufacture [49,50]

4.4.3.2 Mathematical background to sorptivity

One-dimensional capillary absorption is described by the non-linear diffusion equations,

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[D(\theta)\frac{\partial \theta}{\partial x}\right] \qquad (1)$$

Where θ is the water content and $D\theta$ is the unsaturated hydraulic diffusivity. This equation has a solution of the form,

$$\theta(x,t) = \phi(\partial)\sqrt{t} \qquad (2)$$

where Φ is the Boltzmann variable $xt^{-1/2}$. The total amount of water absorbed is,

$$i(t) = t^{1/2}\int_{\theta_0}^{\theta_s}\phi d\theta = St^{1/2} \qquad (3)$$

where S is the sorptivity. Note that the sorptivity is dependent on the initial and final water contents of the material, θ_0 *and* θ_s.

The sorptivity is established as the most useful parameter to describe the water absorption properties of porous media and defines the ability of a material to absorb and transmit water by capillarity[50]. In plaster the sorptivity is sensitive to variation in composition such as calcium content and water/gypsum ratio as well as to differences in density and compaction[51] [52]. As shown by equation (3) the sorptivity is also dependent on the water content of the material and decreases systematically with increasing (uniform) initial water content[52]. It is therefore important to know the water content of the material at the time of measurement.

The procedure of measuring the sorptivity has been standardised[52]. The most straightforward method of determining the sorptivity of any porous solid is to measure the increase in mass of the specimen during capillary absorption of water using one-dimensional absorption geometry. The specimen must be of constant cross-sectional area parallel to the absorbing surface, most conveniently in the form of a rectangular or cylindrical prism. Most materials are sufficiently fine pored, so that any effects of gravity on short-term capillary absorption may be neglected and the sorptivity may be measured in a simple vertical capillary rise experiment. After drying to constant mass (and therefore zero initial water content), the sample is placed on supports in a tray of water so that the lower surface of the solid is a few millimetres below the water surface. The sample is weighed at intervals (typically at t = 1, 4, 9, 16, and 25 min), with each weighing operation being completed as quickly as possible and without stopping the clock. The sorptivity is determined from the gradient of the straight line [equation (3)] obtained by plotting the cumulative absorbed volume of water per unit area, i against $t^{1/2}$. One-dimensional absorption is the only geometry to exhibit this linear absorption behaviour with $t^{1/2}$.

During *in situ* testing, it is clearly not possible to determine the sorptivity using the simple laboratory experiment described above, and various surface caps or drilled holes are used to hold sources of water in absorption experiments. In some cases relatively small hydrostatic pressures are applied to the water source. It is therefore useful to note the relationship defining the variation in sorptivity with pressure,

$$S(h) = \left[S_0^2 + 2hK_e f\right]^{1/2} \qquad (4)$$

where $S(h)$ is the sorptivity under an applied hydrostatic pressure head h, S_0 is the sorptivity without applied pressure and K_e is the effective hydraulic conductivity of the solid. For most cementitious materials, capillary forces are dominant for all but the largest hydrostatic heads and small pressures have a negligible effect on the measured sorptivity.

Geometry of the drop deposition layer and surrounding part affects the seepage to the surrounding area as per Figure 4.3.3.2

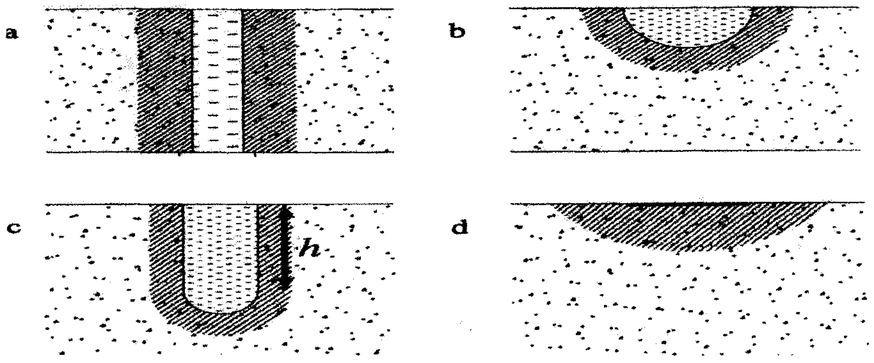


Figure 4.3.3.2 - Absorption geometries: (a) cylindrical source (with sealed end); (b) hemispherical source: (c) drilled hole with hemispherical end; (d) plane circular source.
The shaded area in each case represents the wetted region[53]

4.3.3.3 Bleed or seepage compensation

Bleed compensation comprises offsetting the print area inwards from the desired part size to compensate for the seepage into the surrounding material, refer to Figure 4.4.3.3. The offset can be set as bleed compensation as a scale factor inside and outside of the shell profiles. Typical values of 1.05 in *x*-axis and *y*-axis and 1.03 for the *z*-axis, but these are part geometry dependant and are derived from experimental work.

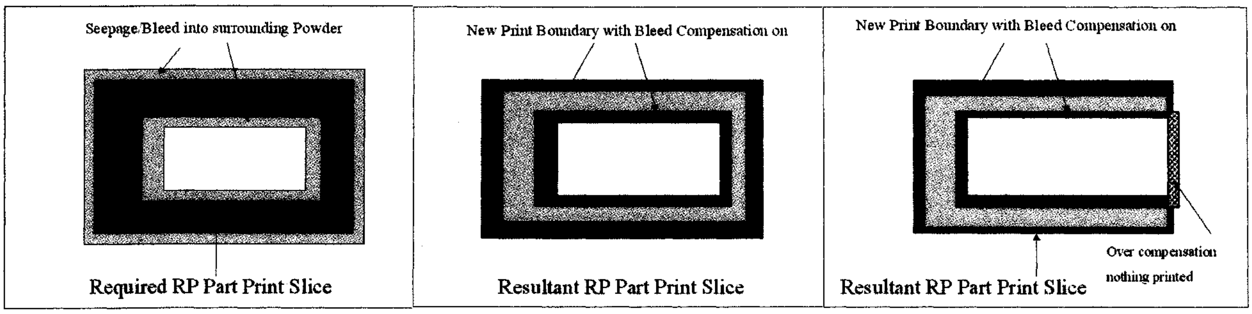


Figure 4.3.3.3 - Bleed compensation applied to 3D printing process

However, for thin walled parts this thinning of the print area leaves undesirable non-printed areas and as described above, the bleed is geometry and part orientation (gravity) dependant Figure 4.3.3.3.

4.3.3 Conclusions of Build Accuracy

The Z-Corps 3D printing process is one of the least accurate RP processes commercially available to date. However for speed of production and lack of part finishing (support removal) there is little to compare it to.

This section has shown the major causes of dimensional errors to be positional and material errors.

Positional errors can be compensated for within build software when machines are calibrated, in much the same way as when a new print head is fitted to a conventional printer to realign the unit. Material errors are much more complex than initially thought, and simple single bleed or seepage compensation will not remove them, although they can be improved.

This section has shown the seepage errors to be geometry controlled in three dimensions, therefore bleed/seepage compensation must look forward and backward at 3D build geometry to define the value of offset to build accurate parts.

4.4 Operating Characteristics of the Z-Corps 3D Printing Process

This section investigates the operating performance associated with the Z-Corps 3D printer and should prove useful to the potential users of this new technology and design engineers.

4.4.1 Z-Corps 3D Printer

The office compatible Z402 System claims to be the world's fastest rapid prototyping system[53] for the creation of 3D models directly from 3D CAD files. The 3D model is sliced into sections 0.1 mm to 0.3 mm thick. The machine consists of a feed chamber, a build chamber (z travel), powder spreader and a binder print head (x, y travel). The build platform drops the build depth and the feed piston travels up a corresponding amount. Powder is spread across at the required thickness to fill the build chamber. The print head (ex canon bubble jet) then prints the layer with the binder solution (ZP09), the outer shell has a higher binder density than the internal section, providing a hard shell and softer internal structure.

4.4.2 ZP402 Machine Material Characteristics

Energy-dispersive X-ray spectroscopy

Energy dispersive X-ray spectroscopy (EDS or EDX) was an analytical tool predominantly used for chemical characterisation of the ZP11 and ZP100 powders.

4.4.2.1 ZP11 – Starch Based

Starch is the common name given to white granular powder that is odourless and tasteless. Starch is a complex carbohydrate ($C_6H_{10}O_5$), which is abundant in cereal plants, also a significant amount of sucrose (sugar) ($C_{12}H_{22}O_{11}$) was found.

This material is water-soluble and the effect of heating above 180^{0}C results in the material becoming liquid.

4.4.2.2 ZP100 – Ceramic Based XRD revealed calcium sulphate ($C_aS_{04}ZH_20$), also called "Gypsum". It is very common in dried salt pans and sedimentary rocks such as limestone. The material is in hemi-hydrate form (C_aS_{04} ½ H_20) such as Plaster of Paris. This sets rapidly (10-20 minutes) by re-crystallising with water. A significant amount of calcium (C_a) was also found figure 4.4.2.2.

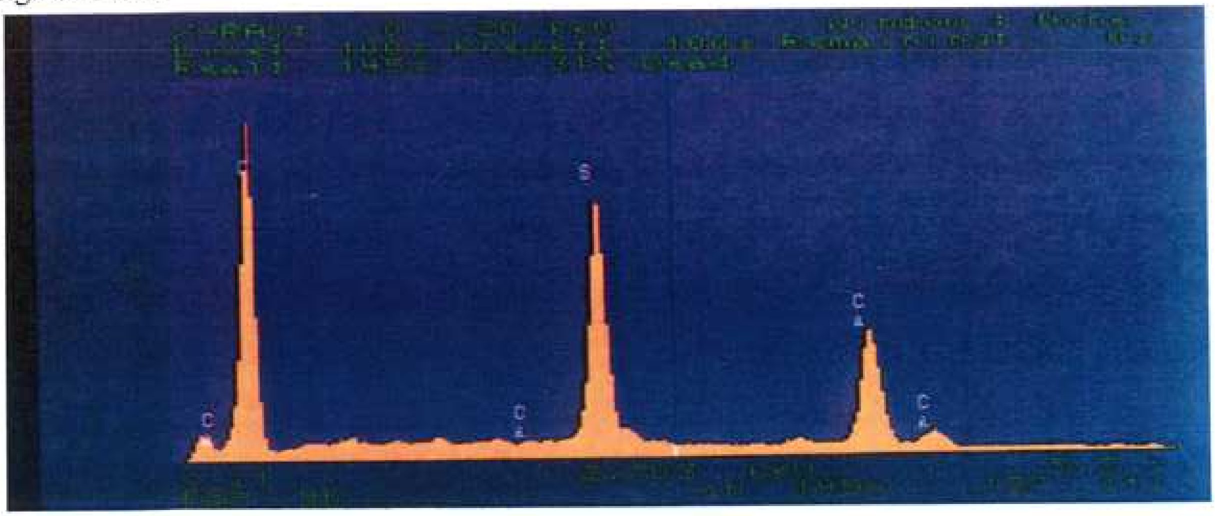


Figure 4.4.2.2- EDS Analysis ZP100 Ceramic Based Powder

4.4.3 Material Structure - A Scanning Electron Microscope were used to reveal the micro structures of the build samples before and after wax infiltration. Figures 4.4.3.1, 4.4.3.2. The starch based build material clearly has an open "candy floss" fibrous structure which latter tests revealed had lower hardness and strength. The ceramic build material is closer grained and this is reflected in the better part finish and strength.

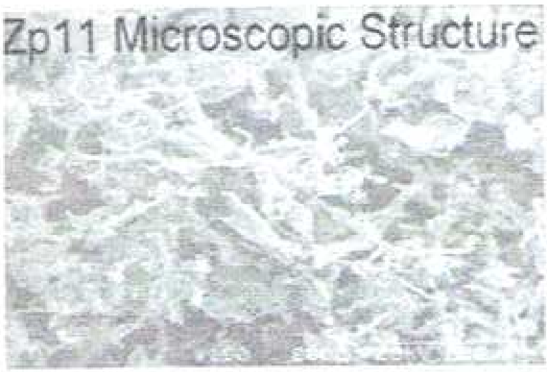
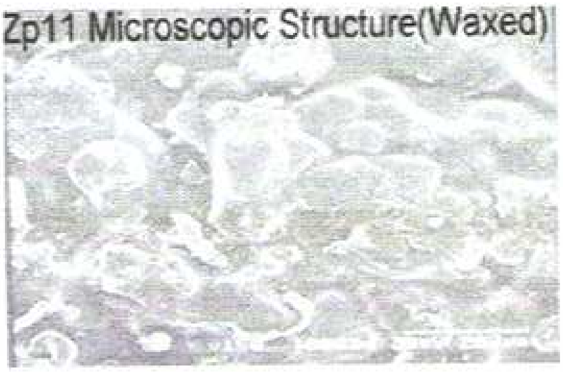


Figure 4.4.3.1 – SEM ZP11 Microstructure



ZP11 Microstructure (Waxed)

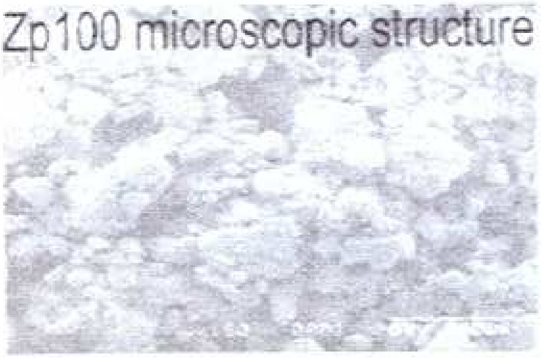


Figure. 4.4.3.2 – SEM ZP100 Microstructure

ZP100 Microstructure (Waxed)

The infiltratation of wax can be clearly seen to fill voids between the fibres ZP11 and particles for ZP100. This provides increased bonding, resulting in higher part strength. The effect of waxing can also be seen in reducing the stair stepping and improving surface finish as discussed later in this chapter.

4.4.4 Material Hardness

Due to build characteristics parts were tested on all six sides, taken as a average of 10 readings as shown in Figure 4.4.4

ZP11 Starch Based – The base was found to be the softest and the top hardest. The average hardness was 27 Vickers, with the highest 29 and lowest 25 for the base. The side's average hardness was found to be 27.6 Vickers

ZP100 Ceramic Based – The results were found to be similar to ZP11 in that the top layer was harder. The hardness was found to be 52.9 for the top and 31.2 for the base, and sides 49.2 Vickers. However the ceramic material is 180% harder overall.

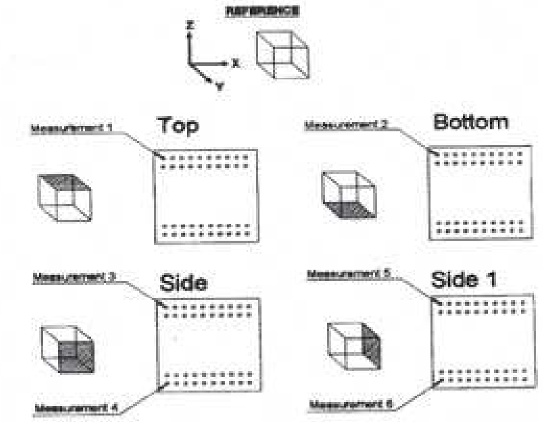


Figure 4.4.4 - Hardness Measurement Positions

4.4.5 Stress Analysis

Test specimens were produced and Finite Element Analysis carried out to assess the theoretical stress versus actual failure mode.

The orientation of the part on the build platform was investigated and the results are shown in Figure 4.4.5.1. This revealed that the highest strength is in either direction, in the x-y plane, and weakest is vertically across the build. The binder concentration was varied from the prescribed values and a variance of 15% can be obtained in part strength.

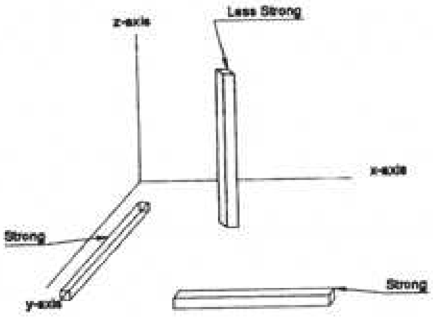


Figure 4.4.5.1 - Build Orientation effect on part strength

The binder concentration was varied from the prescribed values and a variance of 15% can be obtained in part strength.

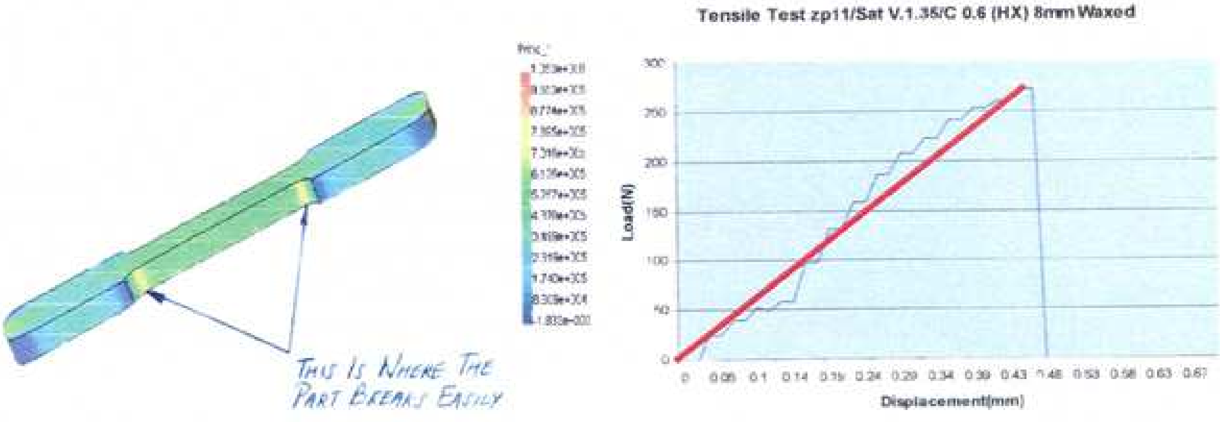


Fig. 4.4.5.2 - Tensile Test Results and FEA plot

The results sown in Table 4.4.5.2 compares the strengths of the two materials un-waxed and waxed for settings of core and shell concentrations of 1 and 2 respectively. The failure section dimensions were 8 x 4 mm section 32 mm^2.

Orientation/Material	ZP11	ZP11 Waxed	ZP100	ZP100 waxed
X - Axis	58.2 N	190.4 N	258.2 N	363.7 N
Y - Axis	55.7 N	183.9 N	205.8 N	344.1 N
Z - Axis	60.1 N	192.5 N	272.0 N	368.4 N
Average	58 N	188.9 N	245.3 N	358.7 N

Table 4.4.5.2 - Tensile test results for Z-Corps Materials in relation to build orientation

This shows that the ZP100 is 4.25 times stronger than the starch ZP11. It was also found that wax infiltration provides over 3 fold increase in strength for ZP11, but only 50% strength improvement for ZP100. Also note that the material in all cases is marginally stronger in the Z axis build orientation.

4.4.6 Accuracy Analysis

Fifteen test parts were built in three phases, in four quadrants of the bed. The build binder core and shell saturation and layer thickness was also varied. This comprised over 200 tests with both ceramic and starch based materials. The conclusions are as follows:

ZP11 Starch Based

Parts built consistently 0.7% to 2% smaller, an An-isotopic scaling factor of 1.0073, 1.0013 and 1.0025 in x, y, and z axis.

Build time directly proportional to binder and core saturation.

Wax infiltration reduces part size by 2%, this is due to wax being infiltrated hot and considerable shrinkage occurs as it cools and solidifies effectively compressing the part.

Raw parts absorb moisture and should be sealed to maintain accuracy.

Build location, particularly with contaminated build material affects parts' geometric shape and accuracy.

ZP100 Ceramic Based

Binder print area spreads outwards from print area causing the cylinder inner diameter to become too small, whilst its outer diameter is too large, therefore no single scale factor can be used.

Greatest error in Z direction, parts repeatable in x, y, but not z axis.

Wax infiltration has negligible effect on accuracy.

An-isotropic scale factor of 0.998 in x and y axis required for accurate parts dependent on cross-section area. Parts need to be left to harden in the machine for several hours to allow removal

ZP100 ceramic-based build material is superior to starch based materials in resolution, strength, hardness and accuracy.

4.5 Development of infiltrants to increase the green part strength of the 3D Printed manufactured parts to improve their range of application.

The ultimate goal of this research section was to improve green part strength and accuracy of Z-Corps manufactured parts by the infiltration process to improve its mechanical properties. An accurate 3D model of intricate parts can be produced using 3D printing technology but these produced parts do not have enough tensile and compressive strength since they are plaster based (powder and binder).

Previously, the parts are infiltrated with wax which results in reduced tensile and compressive strength, so the parts are very delicate. It is expected that by varying the different concentrations of highly viscous materials, relative *strength, Temperature, Resistance, Durability* of these green parts can be improved, in turn the tensile and compressive strengths can be increased. With the strength increased, parts produced could be used directly for operations such as Injection moulding, casting processes, replacing the requirement for the production of a limited number of expensive and large lead time metal moulds.

4.5.1 Introduction to Infiltration

Surface finish and strength in 3D printing is, however, one of the major technological constraints on its widespread utilisation. Surface finish and strength is an intrinsic limitation of powder-based processing[54,55] Surface finish in 3D printed parts can be greatly improved by using very fine powders as they allow the use of thinner layers and also provide improved finish within each layer. In addition to that if these powder parts are in-filtered with paraffin wax (present technology) good surface finish and strength can be obtained as shown in Figure 4.5.1.

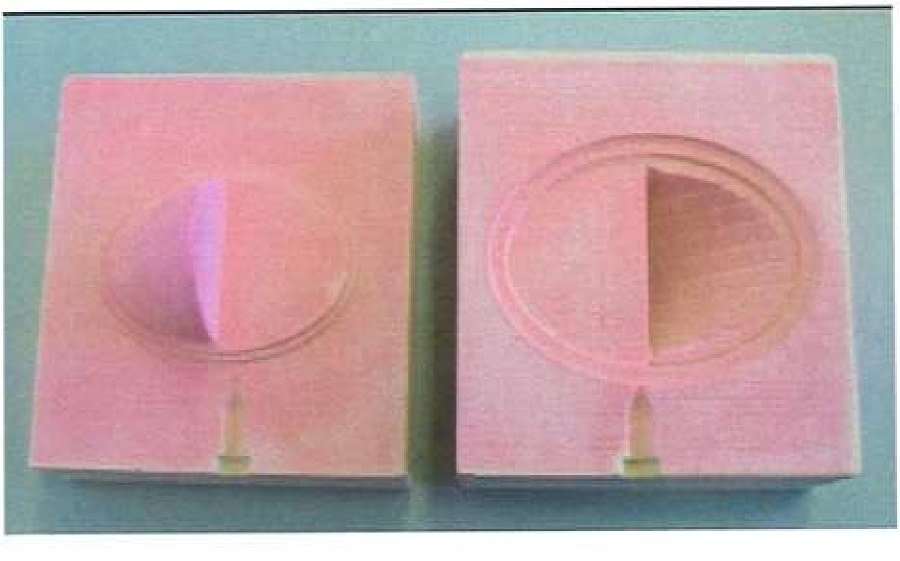


Figure 4.5.1 - Die set produced by 3D printing RP

High dimensional accuracy and part stability are significant elements of the end product in rapid prototyping (RP) processes, whether it is a component or a tool. This section of work is based on alternative infiltration process to increase strength and finish of those green parts produced from Z-Corps 3D printing machines i.e. infiltration of porous parts is generally performed by dipping the part in a liquid in-filtered bath, which rises into the open pores through capillary action. Different methods of infiltration were carried out with different combinations of highly viscous chemicals with wax as the base material. The bending strength are calculated and compared with normal paraffin wax in-filtered parts.

Infiltration research aims

Present Rapid Prototype, Z-Corps 3D printing machine produced green parts that are infiltrated with paraffin wax, are being partially replaced with the following two highly viscous materials, as these green parts produced from Z-Corps rapid prototype machine are plaster based and are 50% dense the remaining space is air. Since these plaster based green parts are porous in nature it is estimated that these highly viscous materials can fill these pores and give the component a good finish, strength and accuracy.

The following high viscous materials and were used for infiltration with wax as the base.

- Araldite (GT 1999)
- Polyvinyl Alcohol (PVA Fully Hydrolysed)
- Paints (Chosen Wood Polish)
- Combination of Araldite and Polyvinyl Alcohol

The above materials are infiltrated by using different processes.

- Spraying
- Dipping
- Brushing
- Compression

These are the highly viscous materials and different processes planned to carry out the infiltration operation, in order to partially replace the present wax infiltration for the plaster based rapid prototype green parts. These experiments were carried out in order to improve the green part strength, as this is the only main disadvantage with the Z-Corps 3D printing Rapid Prototyping system.

4.5.2 Experimental method

In this experimental procedure, initially the green parts were infiltrated with the combination of wax and resins (highly viscous materials), and in the second set-up the green parts were infiltered with wood polish, as wood polish is a highly viscous at elevated temperatures.

Paraffin Wax as Base material:-

In this experimental procedure, infiltration is carried out using wax as the base material along with a combination of high viscous material in order to increase the strength and accuracy of porous green parts produced by the Z-corps 3D rapid prototyping system.

Initially 100 g of total infiltrate materials taken consisting of 75 g of paraffin wax, with 12.5 g of PVA plus 12.5 g of araldite (GT-1999) was mixed. The wax was first heated in a beaker at a temperature of 60^0C, on a hot plate for 5 minutes. When the wax was totally melted, Araldite (GT-1999) was added and stirred continuously for 5 minutes. Finally 12.5 g of Poly-vinyl alcohol (PVA) was added and stirred for another 5 minutes maintaining the temperature of hot bath to 90^0C as the PVA chosen is fully hydrolysed and dissolves at 90^0C.

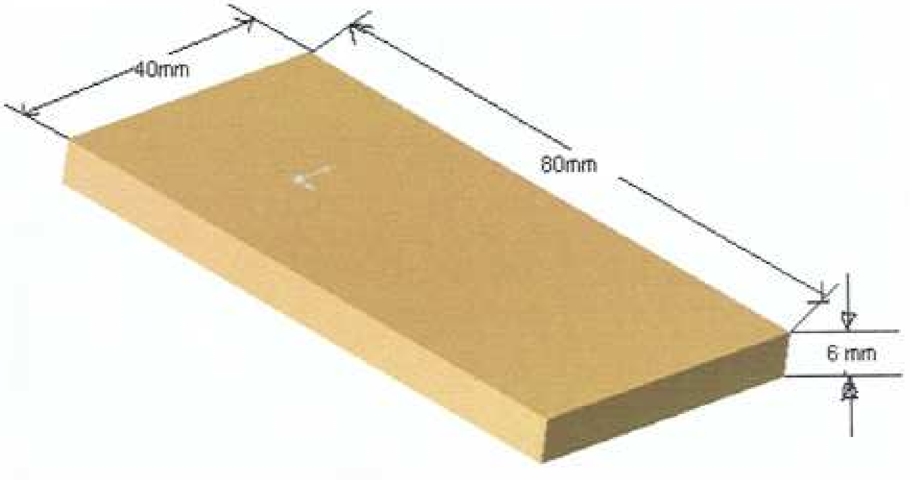


Figure 4.5.2.1 - Sample piece for testing

The above geometry shown in Figure 4.5.2.1 was used as the standard specimen throughout this experiment. It has dimensions of 80 x 40 x 6 mm, and these specimen's were dipped (Infiltrated) in to the prepared wax combination liquid with pressurised compressed air maintained at 1 bar pressure.

Compressed air was used in order to increase capillary action and this process was carried out for approximately 60 seconds and then these standard specimen infiltrate pieces were air dried for 2 hours before being tested for their bending strength using three point bending test.

Wood polish:

The green parts produced with Z-corps rapid prototyping system were directly infiltrated with wood polish by spraying, and the pieces were air dried for 12 hrs. This experiment was carried out in order to see if wood polish could have the potential as an economic process. The pieces were tested for their bending strength, set up for three point bending strength.

4.5.3 Results of infiltration

The following test results were obtained by using standard set up of three point bending test. To compare the infiltration experimental work, the present standard paraffin wax infiltration. 10 standard pieces of dimension 80 x 40 x 6 mm were in-filtered. The three point bending test method was carried out in order to find out the bending strength of this standard paraffin wax infiltrate pieces over at test length of 40 mm and was compared with other bending strength experimental readings obtained form the two new infiltrates.

Infiltrate materials	**Displacement in mm (Average of 10 pieces)**	**Bending strength N/m^2 (Average of 10 Pieces)**
Wax	0.73	3.68
Polish	0.71	3.42
Wax + PVA +Araldite	0.88	4.59

Table 4.5.3: Average values of Displacement and Bending strength

4.5.4 Infiltration Conclusions

From the above Table 4.5.3 it is very clear that with the combination of paraffin wax, polyvinyl alcohol and araldite used as infiltrate, the strength of rapid prototype parts can be increased by 25 % as compared to present paraffin wax infiltration. The combination provides improved part strength and infiltration penetration than the application of a single component alone.

4.6 The Application of the Z-Corps 3D-Printing System for the Manufacture of Rapid Tooling inserts, for the Production of Polymer Injection Moulded Parts.

This section investigates the utilisation of Z-Corps low cost 3D printing process to produce direct polymer injection moulding tool inserts for fast, low, cost aesthetic components.

Rapid Tooling using rapid prototyping methods such as SLAs' AIM and SLSs' Rapid steel has as discussed in chapter two have been used to produce plastic injection mould tools.

The application of 3D printing utilising plaster based materials and hardeners for direct injection moulding is investigated. The investigation focuses upon the feasibility, repeatability, accuracy and moulding process.

The application is to create low cost aesthetic parts in durable engineering polymers directly in hours rather than weeks.

4.6.1 Introduction

Current Rapid Tooling (RT) technologies can create moulds in days or weeks compared to traditional subtractive processes taking months, especially for complex components. However, these newly developed systems are expensive to purchase, operate and require specialist knowledge.

This section of chapter four, investigates the use of the low cost Z-Corps 3D Printing process with traditional build materials to manufacture moulds for early concept proving, testing and aesthetic parts.

Previously the design engineer designed his or her part with the manufacturing process in mind but didn't have to be concerned with the tooling to manufacture the component. The development of new features within mid-range 3D CAD systems such as mould designer whereby a complex mould can be generated by form filling to enable access to a catalogue of parts that are automated to generate your tool design. Other simulation packages such as Part Adviser^{TM} and Mould Adviser^{TM} can assist the designer to refine his design at a very early stage. This has led to a reduction in lead-time as now the mould tool is designed as the part is being designed in parallel. This reduces the time for both the quotation and production of new tooling, on the negative side the traditional external toolmakers skills need to be embedded within a company's design team.

Injection moulding is one of the most common processing methods for polymers. Injection moulding is a complex process that involves a series of sequential stages. The different phases of the injection moulding process include the mould filling phase, the packing phase, the holding phase, the cooling phase, and part ejection. Solid plastic is melted, and the melt is injected into the mould under high pressure (usually between 10 and 34.5 MPa)[56].

The investigation looked at the manufacture of a simple part first to establish which infiltrates and manufacturing settings were applicable. The results then being utilised to manufacture an aesthetic 3D component based upon both Northumbria University's logo and the Gateshead Millennium Bridge, this was used to validate the process. To verify the design of the mould tooling, Moldflow Plastics Adviser^{TM} software package was used to predict the quality of the plastic product in terms of accuracy, materials properties and surface finish. It was also used to analyse the best gate location of the injection sprue, pressure, flow analysis, and temperature in the injection moulding process.

The main disadvantage of the system is poor accuracy of parts built. The accuracy of the system depends on the material that is used and is affected by binder seepage, shrinkage, and geometry. In addition, the models produced are not particularly strong in tension especially without infiltrates, but compressive strength is higher. The surface quality of prototypes from the 3DP process is not high; a smoother surface can only be obtained by post processing.

4.6.2 Rapid tooling research investigation

4.6.2.1 Research Design

The aim of this research is an investigation into the use of Z-Corp 3D printer machine for sample plastic production. The method for this investigation can be divided into six stages.

1. Concept generation and 3D CAD model
2. Using rapid prototyping for part checking
3. Using Moldflow for injection mould analysis
4. Create mould tool design from 3D CAD
5. Using Z-Corp machine to build mould tool
6. Injection Moulding

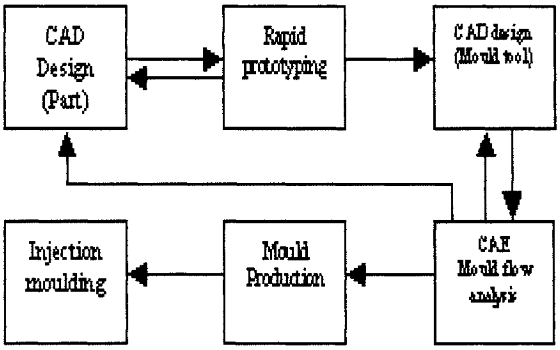


Figure 4.6.2.1 – Process flow diagram for Rapid Tooling

Stages 1 to 3 were undertaken to design, accurately manufacture and validate the test mould tooling for the sample parts and the desired design component as per Figure 4.6.2.1.1. Two standard infiltrates, cyanoacrylate and paraffin wax, were investigated.

The finished parts of the rapid prototyping process were then measured to identify any errors in build accuracy. From the measurements, the parts built from 3DP process were found to be lager than the original 3DCAD model dimensions by 1.63%. To solve this problem the anisotropic scaling factor was changed from 100% to 98.37%.

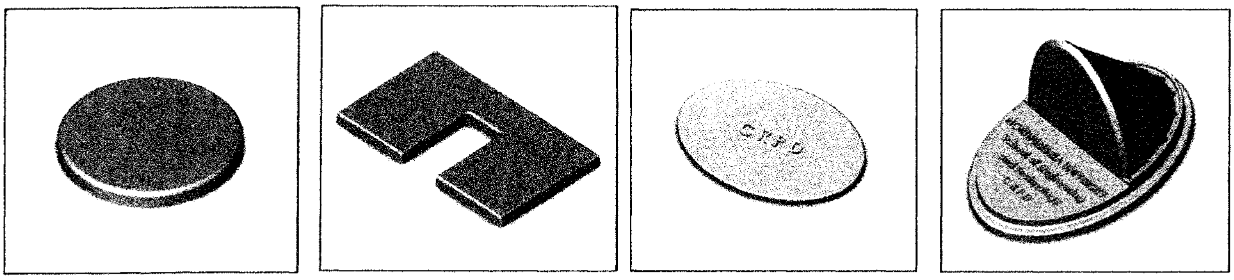


Figure 4.6.2.1.1 - 3D design of cylinder, U shape and ellipse test pieces and Millennium Bridge.

Plastic flow analysis involves an investigation of best gate location, flow analysis, confidence of fill, quality prediction of the parts as per Figure 4.6.2.1.2.

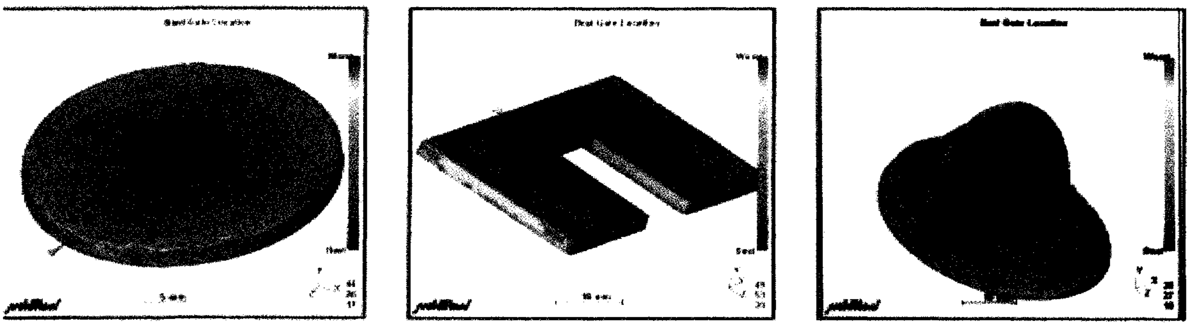


Figure 4.6.2.1.2 - The best gate location analysis, Circular model, U shape and Millennium Bridge

The Mould tools were then designed to fit the Manimould process and the bolster manufactured to support the 3DP inserts as per Figure 4.6.2.1.3.

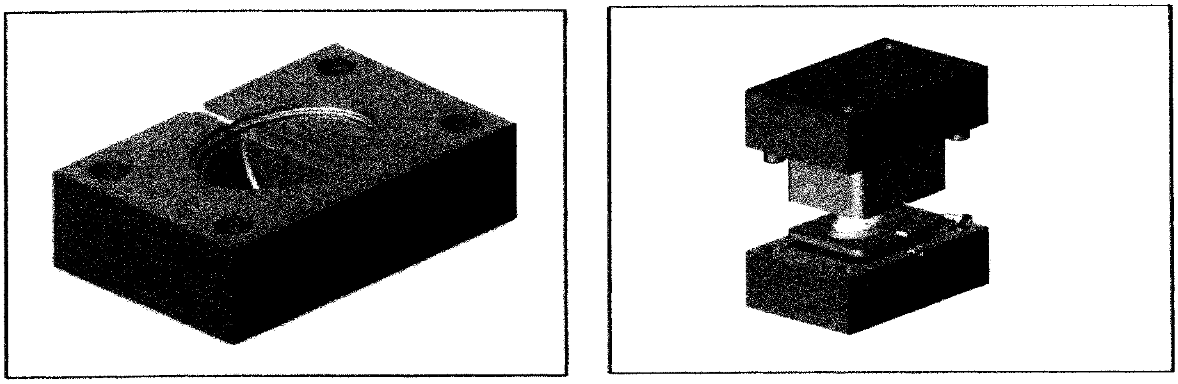


Figure 4.6.2.1.3 - Mould tool design of mould (female) and total tooling for Millennium Bridge

4.6.2.2 Mould Tool Production

The material used to create the mould tool is plaster-based powder ZP100. The setting of the Z402 machine is shown as follows:

- The build layer thickness 0.1 mm
- Binder shell saturation value 2, Binder core saturation value 1
- Anisotropic scaling factor 98.37% for X, Y, and Z-axis

The wax and cyanoacrylate infiltration was undertaken after part clean up, Figure 4.6.2.1 shows the sample of mould produced by the Z-Corp printer.

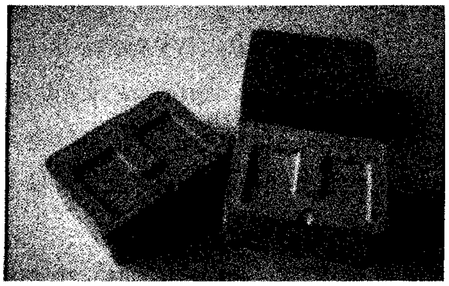


Figure 4.6.2.2 - Mould tool produced by 3DP U shape and Cylinder (female)

4.6.2.3 Injection Moulding

In this experimental test, the injection-moulding machine used to produce the plastic product is "Plunger injection machine" Manimould. The thermoplastic used was polystyrene with a melt temperature of approximately 200^{0}C.

The melt is forced into the mould through the nozzle of the injection unit. This operation is known as the shot rate. This shot rate can also refer to the pressure of the process. In this research, shot rate and various pressures are controlled in order to access the suitable shot rate and pressure for the Z-Corp mould tools.

From the injection nozzle, the material passes through the sprue bush of the mould. It is then distributed to the cavities. When the part has sufficiently solidified, the mould is opened and the finished parts are ejected.

The experimental test can be separated into two sections, which are:

1. Z-Corp mould tools with cyanoacrylate (ZR10) infiltration
2. Z-Corp mould tools with paraffin low melt wax infiltration

The different features of the Z-Corp mould block (Circular, U shape, Ellipse, and Gateshead Millennium Bridge) are tested with the different shot rate and various pressures. The shot rate used in this research can be divided into 2 shots, 1 shot, 3/4 shot, 3/5 shot, and 1/2 shot. Various pressures are used to force the melt material into the Z-Corp mould. The temperature is set in the range of 180^{0}C to 200^{0}C.

4.6.2.4 Rapid Tooling Results and Analysis

Z-Corp Mould Tools with Cyanoacrylate ZP10 Infiltration

Z-Corp mould tools used in this experimental test had improved surface quality and strength by using cyanoacrylate (ZR10) infiltration. The tests covered the quality of the finished part, and impact of the injection moulding conditions against the mould tools. The injection moulding results were divided into the ranges of F (Failed), N/F (Not Filled), A (Acceptable), and S (Satisfactory). The tests were divided into the four types of model parts to be manufactured; only the simple cylinder and bridge designs are evaluated.

Cylinder Model

Test	Temp of Head ^0C	Temp of Barrel ^0C	Temp btw Head and Barrel ^0C	Pressure MPa	Shot Rate	Result
1	193	198	160	4.96	2	F
2	193	198	160	4.55	1	F
3	193	197	160	4.20	3/4	F
4	195	197	165	4.06	1/2	A
5	195	198	165	2.75	1/2	N/F
Key: F = Fail, A = Acceptable, N/F = Not Full						

Table 4.6.2.4: The summary results of the injection-moulding test 1.

The results of tests 1 to 3 failed due the quality of the finished parts being unacceptable, as the plastic parts flowed material pierced into the mould tool. This was due to the high pressure and the shot rate. The quality of the finished parts of test 4 were acceptable, and shape of the mouldings were good. The accuracy of the model of test 4 for the diameter was 38.95 mm compared to design of 38.7 mm, error 0.64 %, and thickness 5.09 mm compared to design of 3 mm.

Figure 4.6.2.4 The finished “cyanoacrylate” part of Gateshead Millennium Bridge model.

Even though the shape of the finished parts was acceptable, the surface quality was poor. The surface quality of the finished part was dependent on the surface roughness of the Z-Corp mould. Part ejection was also a major problem in this test. The finished part stuck to the mould surface, therefore, the method to take the part out, was to destroy the mould.

Similar results were recorded for the other test tools, and a shot rate of 3/5 providing an injection pressure of 4.17 MPa was used to produce the bridge components Figure 4.6.3.1

Z-Corp Mould Tools with Wax Infiltration

In this test, mould tools produced by the Z-Corp printer were infiltrated by using paraffin low melt temperature wax. This study covered the quality of the finished part, affect of temperature, pressure, and shot rate against the mould. The experiment was divided into four tests according to the features of the mould block.

Cylinder Model.

Test	Temp of Head (^{0}C)	Temp of barrel (°C)	Temp btw Head and Barrel	Pressure (MPa)	Shot Rate	Result
T5.1	197	198	165	3.5	1/2	A
T5.2	197	198	165	3.93	1/2	S
T5.3	197	198	165	3.93	1/2	S
T5.4	197	198	165	3.96	1/2	A
T5.5	197	198	165	4.27	3/5	F
Key: A = Acceptable, S = Satisfactory, F = Failed.						

Table 4.6.2.4.1: Summary results of injection moulding of test 5.

From the injection moulding tests, the plastic parts from the mould with wax were more acceptable than those from the mould with cyanoacrylate infiltration.This was due to the cyanoacrylate expanding and then bubling when in direct contact with the hot polymer. The characteristics such as shape and roundness of the parts were superior and ejected easier, Table 4.6.2.4.1 refers to the cylindrical parts, other test moulds yielded similar results. Figure 4.6.2.4.1. the Gateshead Millennium Bridge, it can be seen that the products have plastic flash at the split line. Therefore, the parts require post processing to improve the quality and shape of the finished part.

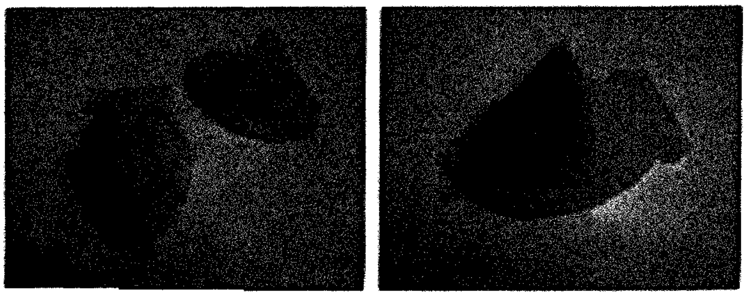


Figure 4.6.2.4.1 Sample picture of product

4.6.3 Conclusions of Rapid Tooling using 3DP

In this research, the Z-Corp 3D printing machine was used as a rapid prototyping technique to produce sample plastic parts. The focus of this study was on the part design, mould design, creation of sample part and mould tool using a Z-Corp 3DP machine, injection moulding process, and injection moulding conditions.

It can be concluded that injection pressure played a significant role in the process. Too high or too low injection pressure had a major effect on the finished parts, such as over filled "flash", short filled, distortion, sink marks, warpage, etc. The pressure also affected the dimensional accuracy of the finished parts, too high injection pressure resulted in increased part thickness.

Temperature has little effect on the finished part and mould tool. This is because the mechanical properties of the plaster base powder and infiltration method can resist high temperature. However, high melt temperature can cause problems with part ejection and shrinkage in the mould.

Infiltration material also had an influence on the part ejection and surface quality of the product.

The surface quality of the product produced by wax-infiltrated mould was better than on the product manufactured by cyanoacrylate-infiltrated mould.

Part ejection was the major problem of the Z-Corp mould with cyanoacrylate infiltration, as the plastic product reacted with the mould cavity material. The high temperature of injected material melted the cyanoacrylate to liquid; therefore, the part was adhered to the mould. Mould tools had to be destroyed in order to take the finished part out of the mould.

The accuracy and surface quality of the finished part were quite poor due to the Z-Corp printing machine.

In this study, it was found that plastic parts manufactured from a Z-Corp mould are acceptable, but still need post processing to improve the accuracy and quality. The Z-Corp rapid prototyping technology can be used as a mould tool to produce plastic parts. However, this manufacturing technique is not suitable for complex geometry or delicate products. This technology is more suitable for a simple products or parts, which do not require high accuracy.

4.7 Production of Roughing Electro Discharge Machining Electrodes from the Z-Corps 3D Printing Process

In the manufacture of complex components and hard tooling for plastic injection mouldings, Electro Discharge Machining (EDM) techniques are often used, to achieve the geometry and accuracy required for the designed component.

Traditional techniques require the CNC machining of a set of electrodes from copper or graphite blocks for each stage of the manufacturing process, this takes time out of the tooling production process, (typical, 75% of actual 4-12 weeks process is manufacturing time). Therefore any progress in the production of EDM electrodes would shorten lead times and reduce the need for soft tooling.

Several attempts to fabricate EDM electrodes from rapid prototyping and rapid tooling techniques have been attempted, with limited success, mainly electro plating of conductive coatings on stereolithography parts. The major problems being coating adhesion, thickness and life of the coatings and substrate.

This section investigates the use of the Z-Corps 3D printing process to produce roughing electrodes using composite graphite powders as the build material in place of the traditional build materials of ceramic and starch materials. It highlights the problems encountered in producing accurate, conductive robust electrodes for the EDM process.

4.7.1. Introduction to tool making methods

The production of plastic injection mould tools and metal forming dies, requires the accurate machining of hard or difficult to machine materials into complex and sharp internal corners[57]. Traditional toolmakers have used Electro Discharge Machining (EDM) to achieve these objectives in a cost effective manner. EDM requires electrodes to be produced in graphite or copper, of the required dimensions (minus the spark gap). These are mainly machined from solid to form a set of progression tools, as wear on both the work piece and electrode occurs during operation.

The Z-Corps process has the benefit of being able to utilise different powders to investigate the production of EDM electrodes.

4.7.2. Electro Discharge Machining

EDM is the thermal erosion process in which metal is removed by a series of recurring electrical discharges between a cutting tool acting as an electrode and a conductive workpiece, in the presence of a dielectric fluid. This discharge occurs in a voltage gap (typically 0.05 mm) between the electrode and workpiece. Heat from the discharge vaporises minute particles of workpiece material, which are then washed from the gap by the continuously flushing dielectric fluid, without applying forces to the workpiece. Very complex geometry's can be derived this way. The geometry of the cavity is obtained through the EDM tool, also known as the electrode.

4.7.2.1 Reducing lead time for electrode production

Normally, it takes quite some time to manufacture electrodes and to use these subsequently in the EDM process. By using sophisticated tool management and 3D CAD/CAM electrode machining systems this lead-time can be greatly reduced. When for example High Speed Milling techniques are combined with EDM technology, complex tools with excellent accuracy and long lifetimes can be achieved.

4.7.2.2 Characteristics of EDM Process

The benefits of the EDM process include:

- Extremely suited to producing low-wear moulds;
- High Accuracy;
- Materials of any hardness can be machined;
- Practically no geometrical limitations;
- High automated and reliable process;
- Very low surface roughness obtainable, burr free;
- The limitations of EDM include:
- Low metal removal rates compared to chip machining;
- Lead-time is needed to produce specific, consumable electrode shapes;

Potential uses of EDM

- Producing injection moulds
- Micromachining
- Engraving of moulds
- Creating cavities which cannot be manufactured with other techniques

4.7.2.3 Electro Discharge Machines

There are two main types of EDMs, Ram and Wire cut.

The Ram uses a carbon, graphite or graphite tungsten electrode, and the wire a conductive consumable copper or copper coated wire that is fed through the workpiece. Ram EDM machines are also known as diesinkers or vertical EDMs.

In Ram EDM, the electrode/tool is attached to the ram, which is connected to one pole, usually the positive pole, of a pulsed power supply. The workpiece is usually connected to the negative pole, the polarity is dependant upon the combination of work-piece and electrode material selected. The work is then positioned so that there is a gap between it and the electrode. The gap is then flooded with the dielectric fluid. Once the power supply is turned on, millions of direct current, or DC, impulses per second cross the gap, beginning the erosion process. The spark temperatures generated can range from 7,700°C to 11,500°C[58]. As the erosion continues, the electrode advances into the work while maintaining a constant gap dimension.

The electrode is fabricated with the reverse or negative image of the finished workpiece cavity. When machined using EDM, this work-piece cavity is measurably larger than the electrode. This dimensional difference is called the overcut or kerf. This kerf dimension is critical during the fabrication of the electrode.

Ram EDM machines range in size from tabletop models to large CNC units. Ram EDMs have four sub-systems:

A DC power supply to provide the electrical discharges, with controls for voltage, current, duration, duty cycle, frequency and polarity.

A dielectric system to introduce fluid into the voltage area/discharge zone and flush away work and electrode debris, this fluid is usually a hydrocarbon, silicone based oil or de-ionised water.

A consumable electrode, usually of copper, graphite or graphite tungsten

A servo system to control infeed of the electrode and provide gap maintenance.

CNC ram EDM machines generally have automatic tool change capability allowing long unattended running times, use of multiple electrodes for rough and fine metal removal, orbiting controls for cavity enlargement, and contouring capability.

4.7.3 EDM Electrode Development Via Z-Corps RP System

4.7.3.1 RP Production of EDM Electrodes

EDM electrodes are not required to be structurally strong, as the pressures exerted are not from the workpiece but from the flushing of debris with the dielectric.

The study focussed on using graphite, aluminium, copper and graphite/aluminium composite powders.

Samples of each were sought, with graphite being found to have a wide grade of particle size, with the lowest cost and highest conductivity. The investigation focuses on using this material as the major base material for electrode production.

In their pure state none of the materials, could be adhered with reasonable strength using the water-based binder supplied. A mixture of base conductive material and ceramic powder was then used to allow handleable electrodes to be produced. The mixture was selected from experimental work starting at 100% Graphite and gradually increasing the amount of ceramic to bind the composite together.

The binder solution and ceramic powder were also tested for their conductive properties. The binder solution was found to have a resistance of 173 Ω, water was found to have a resistance of 189 Ω and the ceramic powder was found to have an infinite resistance. The resistance difference between the binder and water may be due to either the composition, or more probably, due to an increase in ionic content in the binder and to a small deviation in the probe measuring distance.

Graphite Powder

All of the compositions provided smooth textured samples, with the exception of batch 5. This sample was very granular in texture and although showed low results in resistance; it could not be handled without crumbling. The strength of the compositions 1-4 were all rigid and held together under firm pressure from the resistance probes. Various ratios of graphite and graphite ceramic mixes with electrical resistances are shown in Table 4.7.3.1.

Composition	Graphite (%)	Ceramic (%)	Resistance (Ω) over 10 mm
1	20	80	∞
2	40	60	2840
3	60	40	275
4	80	20	122
5	100	0	29

Table 4.7.3.1 The Graphite Composition Electrical Resistance

Graphite/Aluminium Mix

The aluminium powder was used in conjunction with the graphite in the hope that it would allow stronger batch prototypes to be made, whilst retaining the conductivity of the part as shown in Table 4.7.3.2

Composition	Graphite (%)	Aluminium (%)	Ceramic (%)	Resistance (Ω) over 10 mm
1	40	20	40	3770
2	40	40	20	2200
3	60	20	20	444
4	60	40	0	423
5	80	20	0	36

Table 4.7.3.2. The Graphite/Aluminium Composition Electrical Resistance

The above tables shows the higher percentage of graphite in the mixture the lower the resistance for the current to flow and the higher potential for the electrode to function normally compared to traditional electrodes. The inclusion of the Aluminium powder had the effect of increasing the resistance of the electrode.

4.7.4 Dimensional Accuracy of electrodes produced

A test part as shown in Figure 4.7.5.1 was manufactured with various graphite and ceramic mix and measurements were taken with an IMS Impact Coordinate Measuring Machine (CMM) to look at mix and features versus accuracy.

It was decided to start from the highest level of graphite possible. This was to ensure that the first compositions found would be of the lowest resistance possible.

The 100% ceramic and 20% graphite – 80% ceramic mix, was also used to compare the strength and accuracy of the prototypes.

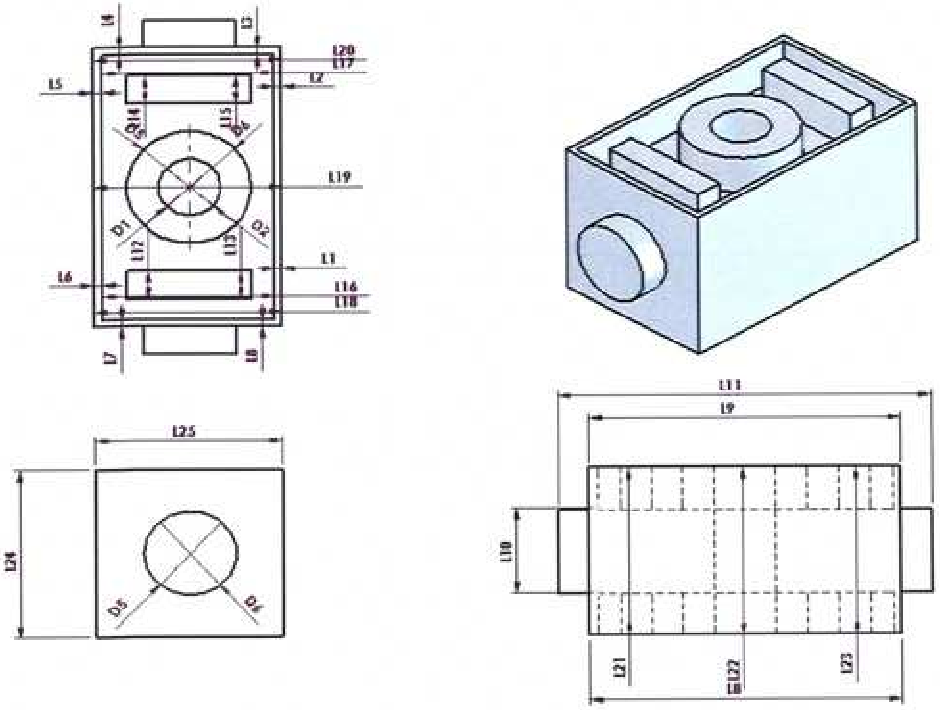


Figure 4.7.4.1 - Dimensional Accuracy test

The 3D print setting for all the prototypes was set at:

Binder saturation:	2
Layer thickness:	0.0762 mm (0.003 inches)
Core saturation:	2
Anisotropic scaling factors:	X = 1, Y = 1, Z = 1

Dimensional Test results

100% Graphite

The binder loosely held the powder together, as with the case of the test sample the binder was simply too weakly adhered to the graphite to hold together the structure. No dimensional measurements of tensile strength were obtainable for this composition.

90% Graphite – 10% Ceramic ZP100

At 90% graphite the binder appeared to have initially held the majority of the parts together, except for the tensile test parts snapping under their own weight. However, when an attempt to remove the excess powder away from the models was made, they began to crumble under the pressure of the air jet. Unfortunately again no dimensional or tensile measurements could be taken.

85% Graphite – 15% Ceramic ZP100

The binder held the composite together under the gentle pressure of the air hose, with which it was necessary to remove the loose powder from the surface. However, the binder had appeared to seep downwards as the binder was applied, thus the dimensional data could not be obtained for one side of the block. This may have been due to the binder level setting, to ensure that the parts would remain intact. However, from the sides that could be measured, the following data was obtained:

The dimensions of the parts made of 15% ceramic were all within 90.5% of the set dimensions. The dimensions in the X-Y axis had deviated from the set dimensions again by a maximum of 3.55 mm for L20, a deviation of 8.88%. The large percentage error of 90.5% was from L2, the 2 mm ledge. The Z-axis had deviated from the set dimensions by a maximum of 4.3 mm for L27, a deviation of 5.73%. The diametrical dimensions were found to large by 3.058 mm on D1, a 30.5% error on the internal dimensions, whilst the external dimensions by up to 5.945 mm on D3, a 19.82% error.

20% Graphite – 80% Ceramic ZP100

The dimensions of the parts made of 80% ceramic were all within 8% of the set dimensions. The dimensions in the X-Y axis had deviated from the set dimensions again by a maximum of 0.65 mm for L17, a deviation of 1.86%. The large percentage error of 8% was from L1, the 2 mm ledge. The Z-axis had deviated from the set dimensions by a maximum of 1.20 mm for L25, a deviation of 2.8%. The diametrical dimensions were to large by 0.38 mm on D2, a 3.8% error on the internal dimensions, whilst the external dimensions by up to 0.5 mm on D4, a 1.66% error.

100% Ceramic ZP100

The parts made using this powder were, as anticipated, the most accurate. The dimensions of the parts made of 100% ceramic were all within 3.85% of the set dimensions. The dimensions in the X-Y axis had deviated from the set dimensions again by a maximum of 0.65 mm for L17, a deviation of 1.86%. The large percentage error of 16% was from L8, the 2 mm ledge. The Z-axis had deviated from the set dimensions by a maximum of 0.49mm for L27, a deviation of 0.65%. The diametrical dimensions are out by up to 0.085 mm on D1, a 0.85% error on the internal dimensions, whilst the external dimensions by up to 0.945 mm on D3, a 1.82% error.

Summary of Dimensional test – the oversized parts can be compensated for by use of standard software Anisotropic scaling factors in X, Y and Z. The part growth in X and to a lesser degree in Y is due to seepage of the binder into the surrounding unprinted build material before the binder reacts with the build material. This seepage effect is most pronounced on thin sections as these dimensions percentage wise change the most.

Immersion Tests

The various compositions of ceramic and graphite were immersed in the EDM dielectric oil and monitored for dimensional accuracy. The electrodes could withstand up to 2 days immersion before oil impregnation begins to reduce the electrodes conductivity to a point whereby it could be considered no longer to act as an electrode, but an insulator.

Samples produced can be seen in the Figures 4.7.4.2/3/4/5 below.

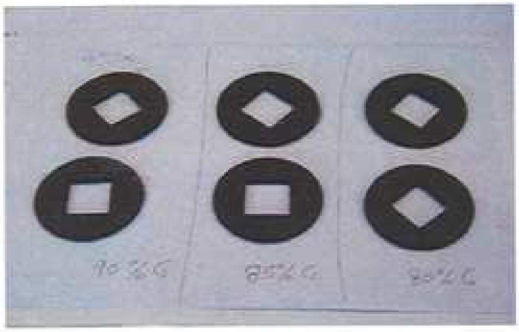


Figure 4.7.4.2: Graphite Ceramic composite tests

Figure 4.7.4.3: Test Electrode 1

Figure 4.7.4.4: "Kylie" Test Electrode 2

Figure 4.7.4.5: Copper Electrode Benchmark Part

4.7.5 EDM Test

The base of the electrode was smoothed to provide the best electrical contact possible between tool holder and tool. The electrode and tool holder resistance was found to be 120 Ω compared to 0.1 Ω for the original copper electrode. The electrode was found to withstand the flushing of electrolyte with a spark gap of 0.05 mm. The EDM was a Glevum Electronic Equipment Ltd G2093. The initial tests provided no spark and the machine advance on the ram crushed the electrode.

Altering the electrode current and voltage did create a machining effect, but due to EDM resistance coupled with the age and level of control of the EDM machine, this effect was to increase the machining time by a factor of two compared to traditional copper electrode.
Figures 4.7.5.1/2/3, show the EDM and the RP generated electrode in operation and the resultant workpiece.

Figure 4.7.5.1: Graphite Composite Electrode

Figure 4.7.5.2: Graphite Composite Electrode in operation

Figure 4.7.5.3: Results of EDM Trial

4.7.6 Conclusions of EDM Electrode Production Using 3DP Methods

This research shows that the Z-Corps process can be utilised to produce composite electrodes of graphite and ceramic capable of being used as roughing electrodes. Graphite powders cannot currently be bonded alone using the existing binder fluid.

To enable this process to provide a competitive advantage in the first stages of tool making, further research and development into the binder/powder combination is required, together with a more up to date EDM control system, in order that the erosion process can be managed more accurately.

The cost advantage of the Z-Corps process over the SLS process for metal powder binding and the range of powder material possible with the application of the innovative binders, means the process can be developed from purely a communication RP part process, to a realistic rapid tooling production process.

MATERIAL SUPPLIERS

Aluminium Powder, 30 micron 99.6%
North Derbyshire Metal Products Ltd,
Mavis SB Lea Road, Horsley Woodhouse
Derbyshire, DE7 6AZ

Graphite 50 micron (average)
James Durrans and Sons Ltd,
Phoenix Works, Thurlstone, Penistone
Sheffield, S36 9QU

4.8 Summary of the Research Into the 3DP Process

This chapter has investigated the powder based 3D printing process by first investigating the operational parameters, materials properties and accuracy. The materials properties were then improved using infiltration techniques. The resultant improved knowledge allowed the process to be applied for production of electrode discharge machining electrodes and the manufacture of direct injection mould tools.

CHAPTER FIVE: RESEARCH INTO ANALYSIS AND DEVELOPMENT OF THE ENVISONTEC DIGITAL LIGHT MANUFACTURING PROCESS

5.0 Introduction

Chapter Five investigates the newly developed Digital Light Manufacturing (DLM) rapid prototyping process. The Centre for Rapid Product Development purchased one of the first systems to be installed in the UK, specifically to undertake research work on this new low cost, high accuracy manufacturing process.

To date six papers have been published in the proceedings for international conferences refer to Appendix A for full papers. The first investigates the process capability in its current state. The second paper investigates the application for photo elastic analysis, comparing the results to physical materials data and digital analysis using finite Element analysis, the third investigates a new build monitoring system. The fourth and fifth papers investigate and optimise the build parameters for accuracy, strength and surface finish.

The following chapter investigates relationships of various process build parameters upon the build accuracy, materials properties, and surface finish and undertakes an optimisation of the build parameters for Rapid Manufactured parts. A novel build monitoring system is developed to predict build failure by monitoring the peeling action during the build process, this prevents the destruction of the silicon build base plates by attempting to cure the resin when the build part has detached from the upper glass build plate form, which is a major cause of failure and cost in the process.

The application of Finite Element analysis to DLM non-isotopic materials has been undertaken to enable the DLM manufactured components to be used for Rapid Manufacturing applications. The FEA analysis was used to establish the operating performance of components manufactured by the DLM process and their suitability for specific applications.

5.1 Investigation into the EnvisionTec PerFactory Rapid Prototyping Process for Production of Accurate and Strong Functional Parts

The PerFactory® technique was introduced by Envisiontec Ltd., Germany in 2002. This relatively new process has comparable accuracy levels with FDM and SLS processes and it builds one whole slice simultaneously, rather than a line or a point at a time. Its main advantages are low initial investment, low operating costs and high build-speed. This makes it very attractive to both small and large organisations alike.

This work deals extensively on researching the development process and the resultant mechanical properties of parts fabricated using the new Acrylate R5 based resin. The aim of this work is to establish a relationship between the desired outputs and the process parameter settings using Taguchi techniques and Statistical tools. In this case, the desired outputs are Tensile strength, Build accuracy and Surface hardness. With this knowledge in hand, RP parts can be engineered according to functional requirements.

5.2 Introduction to EnvisionTec Rapid Prototyping Process

The PerFactory® technique utilises the technology called Digital Light Processing (DLP™) developed by Texas Instruments[58]. The process is based upon a light projector working on the DLP™ technology, which polymerises a photosensitive resin layer-by-layer, resulting in a 3D part[59]. This technique also can be classed as Stereolithography (SLA), but the only difference is that a mercury lamp replaces the expensive CO_2 laser used in conventional SLA machines[60]. This is one of the main reasons that contribute to the low cost of the system. Here again, the models are built layer by layer, Figure 5.2.

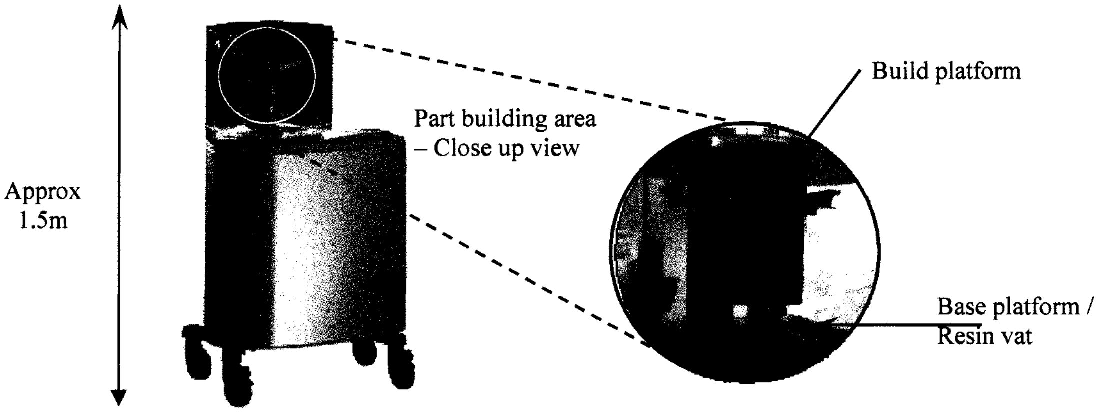


Figure 5.2 – The PerFactory machine

5.2.1 Key features of the PerFactory Process

- Build time per layer is constant throughout the process, unlike techniques like SLA, SLS and FDM where time depends on the area of the layer[61] [62]
- Economic material usage and low capital costs
- Very few moving parts and few consumable components
- Very little post processing is required, as nearly 100% curing is achieved during build
- The machine footprint is 740 mm (l) x 485 mm (w) x 1250 mm (h) and can be used in an office environment, with no need for air conditioning.

5.2.2 The PerFactory part building process

The PerFactory® technique utilises the technology called Digital Light Processing (DLP™) developed by Texas Instruments. The process uses a high-powered, precise light projector working on the DLP™ technology, to polymerise a photosensitive resin layer-by-layer. This polymerization is similar to that happening in SLA, but the laser positioning galvanic mirrors used in SLA are replaced by a DLP™ projector with a mercury lamp. The galvanic mirrors in SLA trace the exact contours of the cross section, but the PerFactory® system builds each mask in discrete Voxels, approximating the boundaries. An illustration of the PerFactory® machine is shown in Figure 5.2.2.1. The method by which the PerFactory and SLA techniques build a layer is shown in Figure 5.2.2.2.

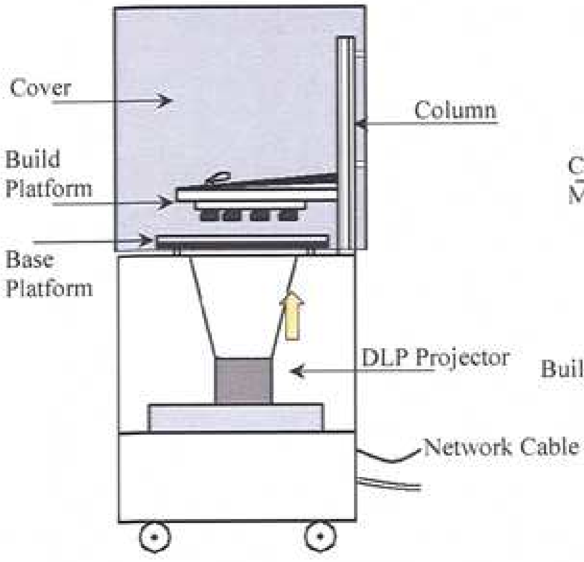


Figure 5.2.2.1 – The PerFactory® machine

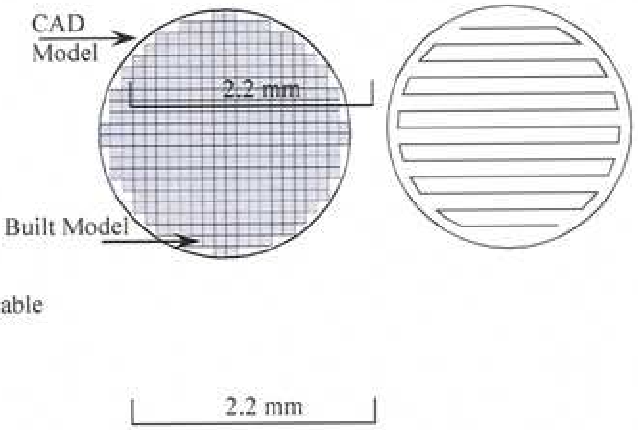


Figure 5.2.2.2 –Comparison of a layer built by the PerFactory® and SLA processes

5.2.3 Important Process Parameters & Settings

It has been experienced from previous operating experience that the following parameters would have the maximum effect on Accuracy, Strength, and Hardness. It is important to narrow down the parameters in the experimentation, so that costs and time involved can be kept to a minimum. The available process parameters and machine settings are shown in Tables 5.2.3.1/2.

Process parameters

	Parameter	Unit	Minimum	Maximum
1	Layer thickness	µm	30	100
2	Peeling velocity	µm/s	1000	3000
3	Waiting time	ms	0	2000
4	Exposure time	ms	4000	15000

Table 5.2.3.1 – DLM Process parameters

Machine settings

	Parameter	**Unit**	**Minimum**	**Maximum**
5	Work area	mm * mm	120 mm x 96 mm	190 mm x 152 mm
6	Orientation	x, y and z		

Table 5.2.3.2 – Machine settings

5.2.4 Explanation of Process parameters and Machine settings

Layer thickness: This is the thickness of the build layer. It is specified in microns and ranges from 30 to 100 microns. It is the gap between the Silicone base and the solidified layer above. Only the resin within this gap is solidified by mask projection from the DLP projector.

Peeling velocity: This is the velocity with which the build platform is peeled away from the lower platform. In effect, it is the velocity with which the newly formed and cured layer is separated from the silicone platform below it. Peeling is achieved by pivoting the silicone base plate at the front, and pulling it down away from the build plate using a stepper motor driven mechanism.

Waiting time: This has two components -

- Waiting time after peeling
- Waiting time after levelling

The user specifies individual values for the waiting time after peeling and levelling. They are independent of each other. These components are combined in our experiments and are set equal.

Exposure time: This is the time during which the bulk of the curing takes place i.e. the liquid resin is exposed to the mask layer, which results in curing. However, some curing takes place after the part building process is completed.

Work area: A small work area would result in the light being focussed in a very concentrated manner, as compared to a larger work area. This is because the size of the pixels is fixed in the projector, and the effective size falling on the resin is varied by moving the projector lens either upwards or downwards. Henceforth in this report, the term *"Pixel Size"* would be used in place of work area. A higher pixel size implies that a high work area has been used. The work area settings available on the machine are shown in Table 5.2.4. The limits of pixel size are also indicated along side the table.

	Working area, mm^2
1	120.00 x 96.00
2	128.00 x 102.40
3	140.80 x 112.64
4	153.60 x 122.88
5	160.00 x 128.00
6	166.40 x 133.12
7	179.20 x 143.36
8	185.60 x 148.48
9	190.00 x 152.00

Pixel size
0.094mm
↓
0.148m

Table 5.2.4.1 – Working area settings available

It has to be noted that the ratio between the two dimensions (aspect ratio) in all the cases is 1.25. This is an advantage in the "Design of experiments process", since maximum and minimum values can be immediately assigned to the area without being concerned about the relationship between length and breath.

5.2.4.2 Layout of the Experiments

The L18 Orthogonal Array (OA) was chosen to layout the experiments. This array can accommodate up to seven 3-level and one 2-level factors. Moreover, an interaction is inbuilt between the first two columns. Interactions between three-level columns are distributed more or less uniformly to all the other three-level columns, which permits investigation of main effects. This makes it a highly recommended array for experiments[63]. The various parameters their values to be used in the experimentation are shown in Table 5.2.4.1. The level notations (in square brackets) and their corresponding values can be seen in Table 5.2.4.2. The first and last columns have not been used since there were only six parameters.

Level	Pixel size	Peeling Vel	Waiting time	Exposure time	Orient.	Layer Thick.
1	120.00x 96.00	1000 μm/s	0 ms	4000 ms	x	0.03 mm
2	153.60 x 122.88	2000 μm/s	1000 ms	10000 ms	y	0.065 mm
3	190.00 x 152.00	3000 μm/s	2000 ms	15000 ms	z	0.1 mm

Table 5.2.4.2.1 – Parameters and levels

	1	2	3	4	5	6	7	8
Run No		Pixel Size	Peeling Vel. (μm/sec)	Waiting time (ms)	Exp Time (ms)	Orientation	Layer (mm)	
1	1	[1]120x96	[1] 1000	[1] 0	[1] 4000	[2] Y	[1] 0.030	1
2	1	[1]120x96	[2] 2000	[2] 1000	[2] 10000	[1] X	[2] 0.065	2
3	1	[1]120x96	[3] 3000	[3] 2000	[3] 15000	[3] Z	[3] 0.100	3
4	1	[2]153x122	[1] 1000	[1] 0	[2] 10000	[1] X	[3] 0.100	3
5	1	[2]153x122	[2] 2000	[2] 1000	[3] 15000	[3] Z	[1] 0.030	1
6	1	[2]153x122	[3] 3000	[3] 2000	[1] 4000	[2] Y	[2] 0.065	2
7	1	[3]190x152	[1] 1000	[2] 1000	[1] 4000	[3] Z	[2] 0.065	3
8	1	[3]190x152	[2] 2000	[3] 2000	[2] 10000	[2] Y	[3] 0.100	1
9	1	[3]190x152	[3] 3000	[1] 0	[3] 15000	[1] X	[1] 0.030	2
10	2	[1]120x96	[1] 1000	[3] 2000	[3] 15000	[1] X	[2] 0.065	1
11	2	[1]120x96	[2] 2000	[1] 0	[1] 4000	[3] Z	[3] 0.100	2
12	2	[1]120x96	[3] 3000	[2] 1000	[2] 10000	[2] Y	[1] 0.03	3
13	2	[2]153x122	[1] 1000	[2] 1000	[3] 15000	[2] Y	[3] 0.100	2
14	2	[2]153x122	[2] 2000	[3] 2000	[1] 4000	[1] X	[1] 0.030	3
15	2	[2]153x122	[3] 3000	[1] 0	[2] 10000	[3] Z	[2] 0.065	1
16	2	[3]190x152	[1] 1000	[3] 2000	[2] 10000	[3] Z	[1] 0.030	2
17	2	[3]190x152	[2] 2000	[1] 0	[3] 15000	[2] Y	[2] 0.065	3
18	2	[3]190x152	[3] 3000	[2] 1000	[1] 4000	[1] X	[3] 0.100	1

Table 5.2.4.2.2 – The run parameters table

Pixel Size is related to the build size in x and y units are in mm.

5.2.5 Experimentation and Testing

The experiments were grouped by pixel size and run in increasing order of the same. This was carried out, as it requires about an hour to adjust the pixel size settings and recalibrate the machine, while all the other parameters could be set within a matter of seconds. Runs 3, 5 and 17 failed due to process settings.

Strength and Hardness Results

The hardness and strength values obtained are shown in Figure 5.2.5.1. In order to draw comparisons, hardness values of typical engineering plastics are shown in Table 5.2.5.1. Accuracy values measured ranged from 0.04 mm to 0.62 mm, depending on the parameter combination used. Note that these values are the measured deviations from the actual specified values. The 95% confidence intervals for all the responses, as obtained from the Analysis Of Variance (ANOVA) study are specified in Table 5.2.5.2.

Material	**BARCOL Hardness**
Melamine	80
Acrylic	50
ABS	55

Table 5.2.5.1 – Hardness of some common plastics

Response	**C.I**
Hardness	± 2.19
Strength	± 1.25
Accuracy	± 0.10

Table 5.2.5.2 – Confidence intervals for responses

Figure 5.2.5.1 – Hardness & Strength values of successful runs

5.2.6 Normalised Responses

The normalised response values are shown in Figure 5.2.6. All values have been normalised against the lowest in each class. Normalised values for Accuracy and build speed have been multiplied by a suitable factor for presentation purposes. Since rapid prototyping is all about saving time, it would be a good idea to consider the build speed for a particular combination of parameters, even if they look promising in terms of part properties.

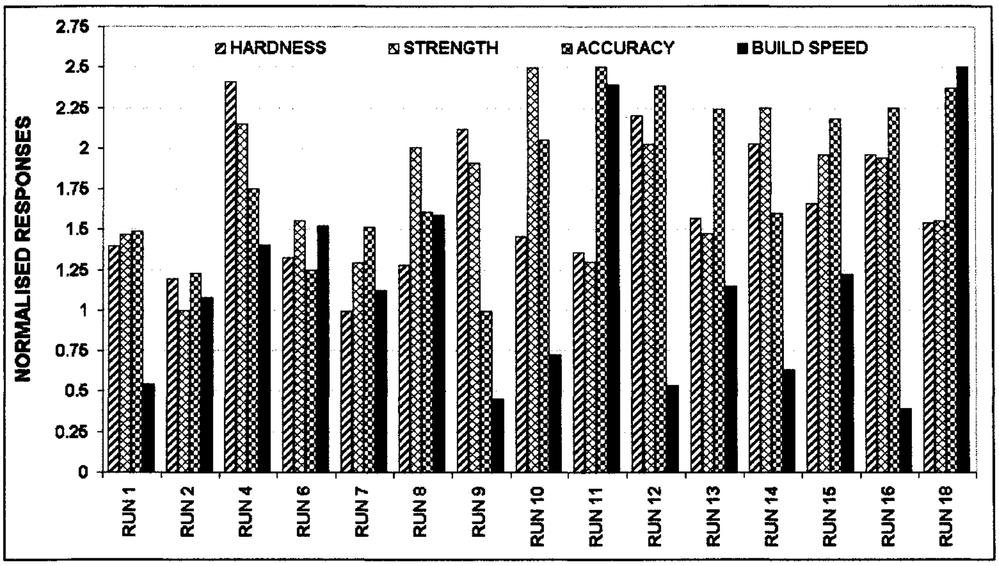


Figure 5.2.6 – Normalised response values

5.2.7 Percentage contribution of factors

As the Taguchi methodology involves only partial factorial experimentation, statistical tools are needed to establish confidence levels in the results obtained. This is done using an ANOVA, which uses the variance in results obtained to fix those confidence levels[64]. Conducting the ANOVA also provides very useful data such as percentage contribution of each parameter. The percentage contribution of each of the factors is shown in Figure 5.2.7. These factors show the effect or contribution that a particular parameter has up on the characteristic investigated. For example for strength the waiting time has the highest contribution to strength.

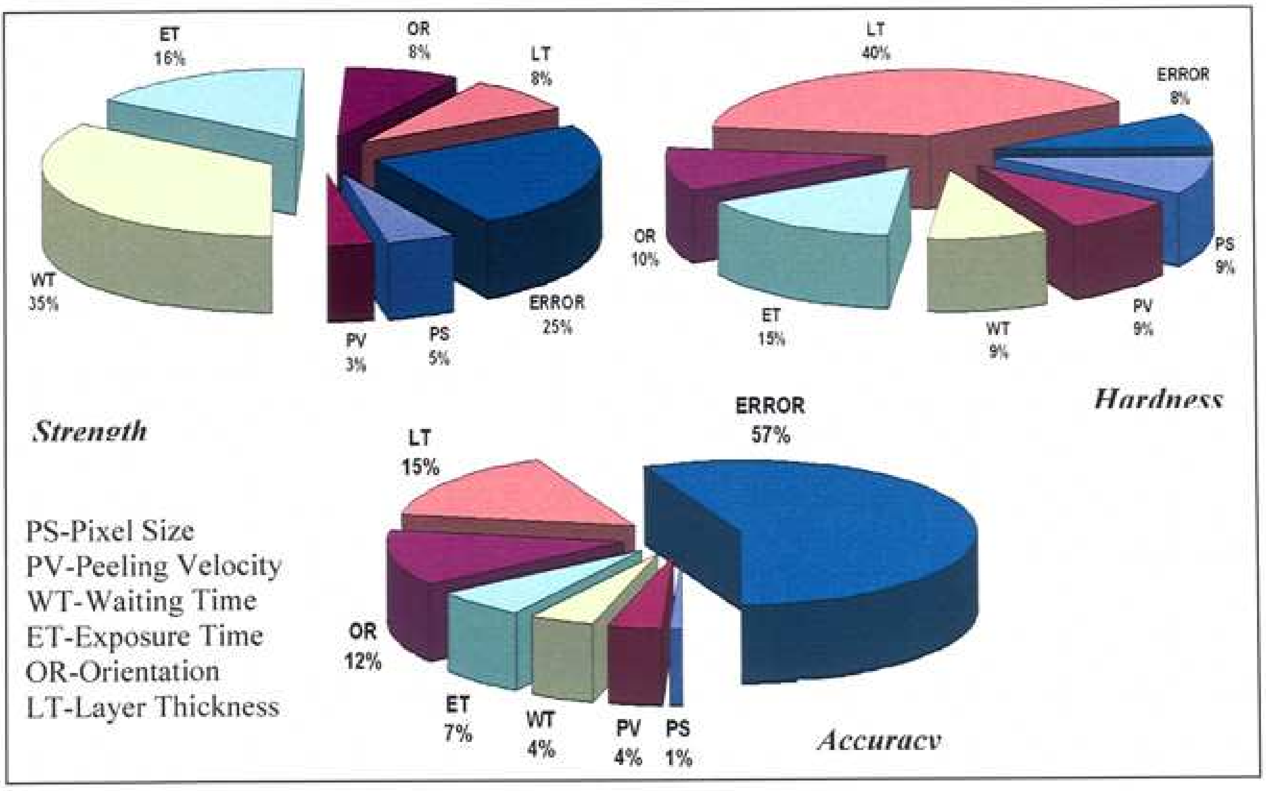


Figure 5.2.7 – Percentage contribution of factors

5.2.8 Factor effects on Response

The previous section explained the percentage contribution of all the factors on the desired response. In this section, the effect of the most important on each response is shown graphically, in Figures 5.2.8.1/2/3.

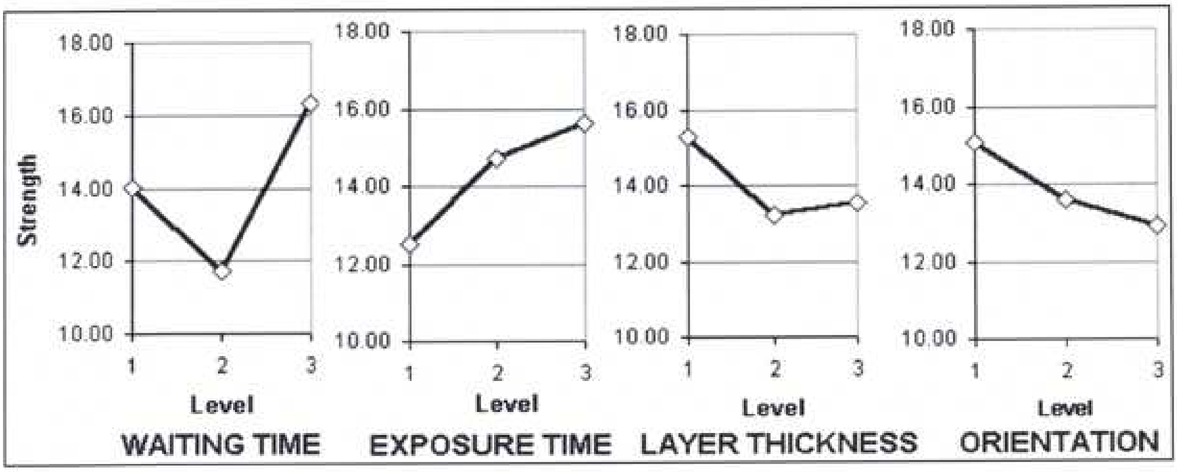


Figure 5.2.8.1 – Effect of parameters on Strength

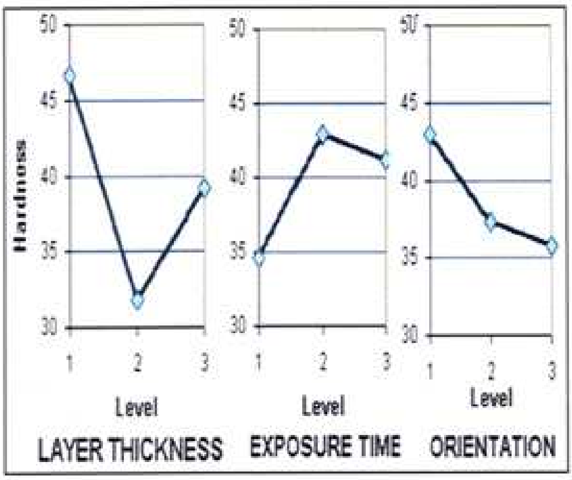


Figure 5.2.8.2 – Effect of parameters on Hardness

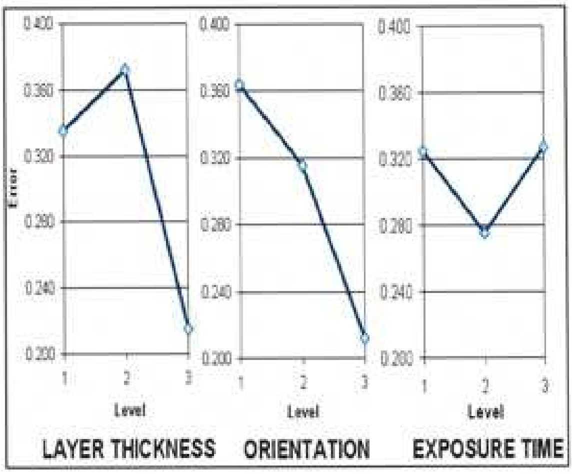


Figure 5.2.8.3 – Effect of parameters on accuracy

It can be observed from figures above that exposure time and orientation have nearly the same effect on strength, hardness and accuracy. Increasing the exposure time above 10,000 ms does not cause any significant improvement in response in all the three cases. Building along the x direction produced the best results, whereas building along the z direction produced the worst. Only in this case, accuracy is an exception, because the trend is exactly reversed, with the z direction producing the smallest error. This means that in this process, layer thickness can be more tightly controlled than x, y dimensions.

5.2.9 Interaction of Parameters

No interaction was observed between any of the parameters, for both strength and hardness. However, as far as accuracy was concerned, strong interaction was observed between the following two pairs.

- Pixel size and Layer thickness
- Orientation and Layer thickness

Hence, accuracy tests have to be run over again, with interacting factors placed in suitable columns of the array. This method would help us to discover the effect of each interaction on the response. The interacting pairs are shown in Figures 5.2.9.1/2

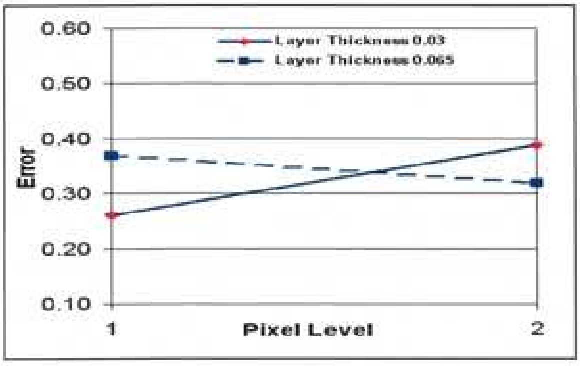


Figure 5.2.9.1 – Interaction – Pixel size and Layer thickness

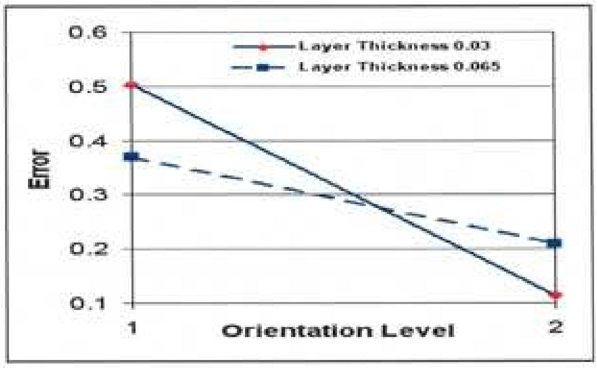


Figure 5.2.9.2 – Interaction – Orientation and Layer thickness

5.2.10 Conclusions of Surface Accuracy, Tensile Strength and Hardness Analysis

The experiments were conducted as per the selected orthogonal array and the parts were tested for strength, hardness and accuracy, and the combination of parameters for the best values of these responses were obtained. It was found that both hardness and strength increase with exposure time, but the effect peaks at 10,000 ms. Building along the x direction produced the best results for strength and hardness, the z direction producing the lowest responses. However, the trend is reversed in the case of accuracy with the z direction producing the lowest error. Furthermore, strength, hardness and accuracy improve with lower layer thickness. It has been shown that since the trends are similar for all these responses studied, an appreciable value of one can be achieved without sacrificing the others.

A thorough ANOVA test was performed on the data obtained for all the tests. The results indicated the following:

- **Layer thickness** and **Exposure time** contributed maximum towards **hardness**, while **peeling velocity** and **waiting time** contributed the **least**.
- **Waiting time** and **Exposure time** contributed the most towards **strength**, while **Peeling velocity** and **Pixel size** contributed the least. The effect of Waiting time was a totally unexpected and interesting one.
- **Layer thickness** and **Orientation** contributed the most towards a high **accuracy** value, whereas **Pixel size** and **Peeling velocity** contributed the least.
- Interaction was observed between **Pixel size** and **Layer thickness**, and **Orientation** and **Layer thickness**, in the **accuracy** tests.

5.3 Investigation into Surface Finish of Parts Built by the EnvisionTec PerFactory Rapid Prototyping Process

5.3.1 Introduction to surface finish

The PerFactory® technique from Envisiontec is unique in its method of manufacturing parts in discrete voxels, compared to the technique of smooth laser contouring implemented in the traditional SLA process. This method of approximating the contours with "Voxels" (3 dimensional pixels) has a pronounced effect on surface finish of the finished part. This work investigates the effect of pixel size, and also build angle and build direction on surface finish of parts built on the Envisiontec RP machine. A high surface finish is important because, apart from offering surfaces of high quality, it also helps to reduce post-processing time and to increase accuracy.

The influence of build angle on the surface finish of a curved face that is built using "layer by layer" prototyping is shown in Figure 3.

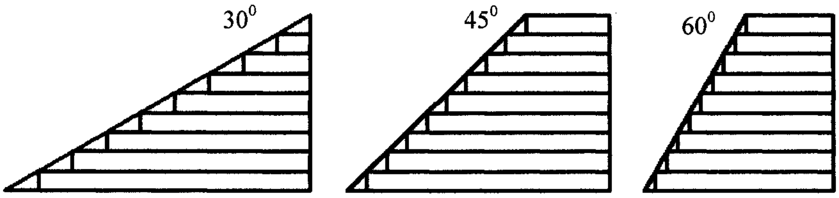


Figure 5.3.1 – Effect of build angle on surface finish

Surface finish of rapid prototyped parts is a very important quality that is desired, be it a visual or a fit/function model. Poor surface finish results in poor accuracy and appearance. Certain prototyping techniques require manual post processing to impart acceptable levels of surface finish. But this practice is not advisable, since rapid prototyping is a time compression technique, and post processing would offset the gains made. Hence, the objective should be to impart acceptable level of surface finish as the part leaves the machine. The test sample that was built for surface finish measurements is shown in Figure 3.6.5.1.

Processes involved in formation of single layer

Exposure: This is the time for which the mask layer is projected onto the resin by the DLP™ projector.

Peeling: This refers to the action during which the base platform is pulled away from the newly formed layer, by a servomechanism. Peeling is achieved by pivoting the silicone base plate at the front, and pulling it down away from the build plate using a stepper motor driven mechanism.

Waiting: This is the period of time that the base platform waits at the bottom-most point, before returning to its original position.

Levelling: This refers to the action during which the base platform returns to its original position. This happens at a constant default velocity.

The above four processes are repeated for every layer.

Additional structures:

Base Layers: The build process starts by building a base layer, which acts as a foundation for the rest of the process. Default parameters are used for the base layer.

Supports: The building of supports is the next stage in the process. The supports are built with same parameters as those used the part.

5.3.2 Surface Roughness Tests

The objective of these tests was to investigate the effect of pixel size, and also build angle and build direction on surface finish of parts built on the EnvisionTec RP machine. These terms are defined below;

Pixel size: This is the actual size of the pixels making up the mask, as projected by the DLP™ system. The smaller the build area, smaller will be the pixel size. Pixel size varies from 0.094 mm to 0.148 mm.

Build angle: This is the inclination of the face being built. In this work, all angles are measured with respect to the horizontal. Angles are marked by the symbol 'θ' in Figure 5.3.2.1.

Build direction: This is the direction in which the angular face is being built. Direction can be classified as 'Up' or 'Down' facing. It has to be noted that parts are built upside down in the PerFactory machine. In this work, all reference would be made to the direction that the angular face is oriented as it is being built on the platform.

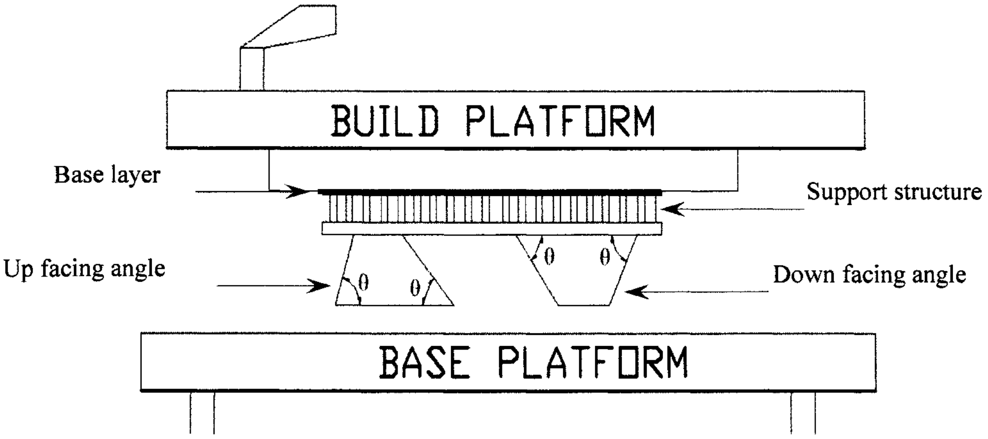
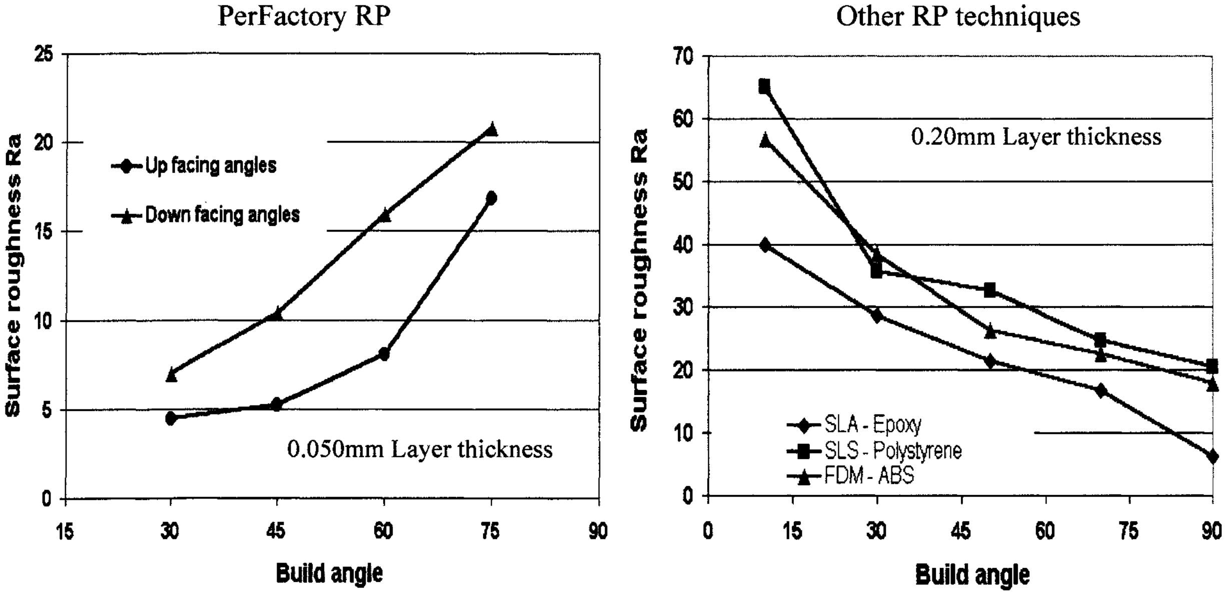


Figure 5.3.2.1 – Illustration of Up- and Down-facing angles

5.3.3 Building the surface finish test parts

Simple test parts were built with 30, 45, 60 and 75 degree slopes on them, to study how the surface finish varied with angle. The parts were built with both up and down-facing configurations of the afore-mentioned angles. They were built with a layer thickness of 0.05 mm. Example of up and down-facing angles can be seen in Figure 5.3.2.1, and Figure 3.6.5.1 shows the model of the part that was built for the study.

5.3.4 Results of the Surface Roughness test


PerFactory RP

Other RP techniques

Figure 5.3.4.1 – Effect of build angle and part surface finish Ra μm

The results of the surface finish test are graphically represented in Figure 5.3.4.1. It is observed that building in the Up facing direction consistently produced better results than in the Down direction, for the same parameters, layer thickness and build angles.

Another interesting trend can be observed when figures 5.3.4.1 are compared. It is seen that surface finish gets worse with increasing angle in the PerFactory part, whereas the trend is exactly opposite for parts built on SLA, SLS and FDM[65]. The sensitivity of surface finish to build angle, for parts built on SLA, SLS, and FDM techniques was also illustrated in Figure 5.3.4.1. The observation of this unique trend in the PerFactory technique called for further analysis of the built specimen, as it seemed that the surface finish was not influenced by layer thickness and build angle alone, but also by some other additional factor.

Micrographs of the experimental parts were made to study this behaviour further. The micrographs are shown in figure 5.3.4.2. This would also help us to understand how the steps were formed in building the angular face. It would be beneficial to define certain terms at this stage, for better understanding.

i. **Layer thickness**: This is the thickness of the build layer as specified by the user. The build platform moves upwards by this value, for each layer. It is marked by the letter "**L**" in the figure 5.3.4.3. In this experiment, a layer thickness of 0.05mm (50 microns) was used.

ii. **Step thickness**: Steps are formed when angular faces are built layer by layer. The step size is influenced by layer thickness and build angle. Step thickness has two components: Along the direction of build and perpendicular to it.

- **Thickness along the build direction**: This is always more than the layer thickness and is a multiple of it. It is indicated by the letter "**Y**" in Figure 5.3.4.4.
- **Thickness perpendicular to build direction**: It is indicated by the letter "**X**" in Figure 5.3.4.4.

Magnified views of different Up and Down facing angles

The part shown in Figure 5.3.4.2 was built using default process settings, and the various up and down facing angles were studied under the optical microscope, and micrographs obtained. All the micrographs are shown in figure 5.3.4.3/4. The solid line at the top of each image represents the build platform, and the block arrow signifies the direction in which the layers are added progressively. Figure 5.3.4.3/4 Micrographs of different build angles and directions.

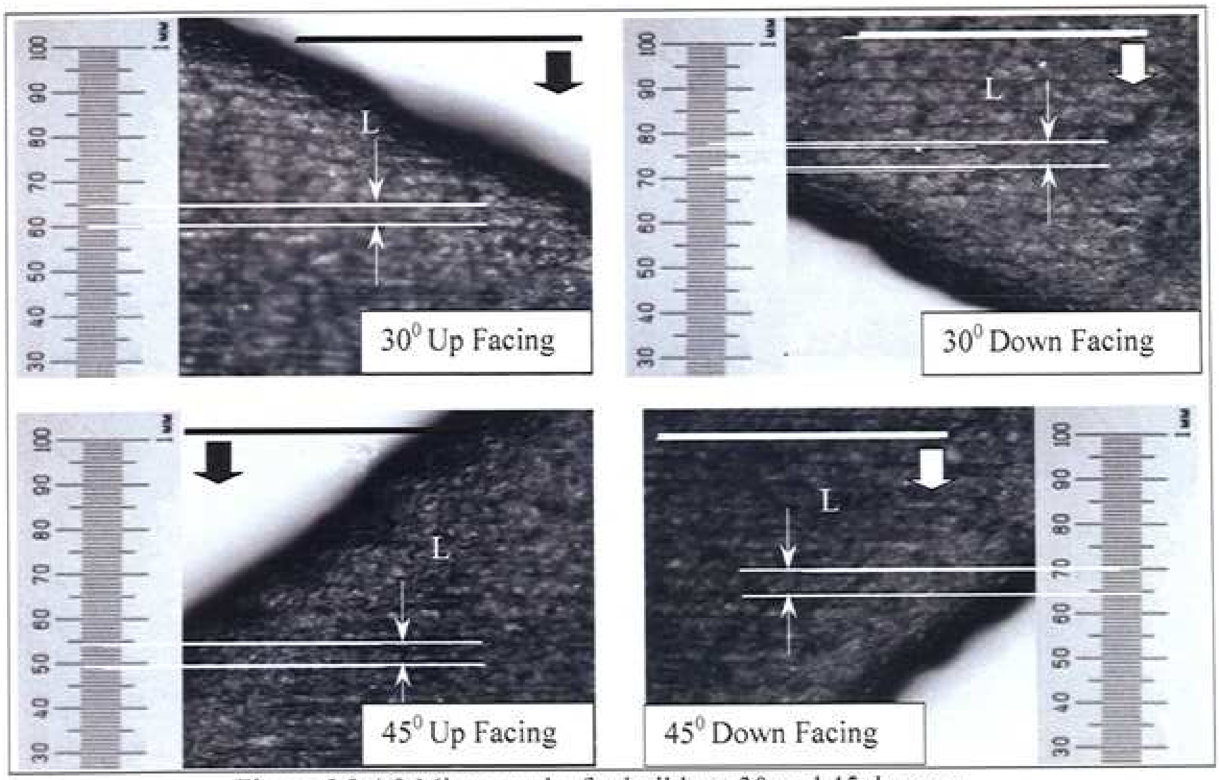


Figure 5.3.4.3 Micrographs for builds at 30 and 45 degrees

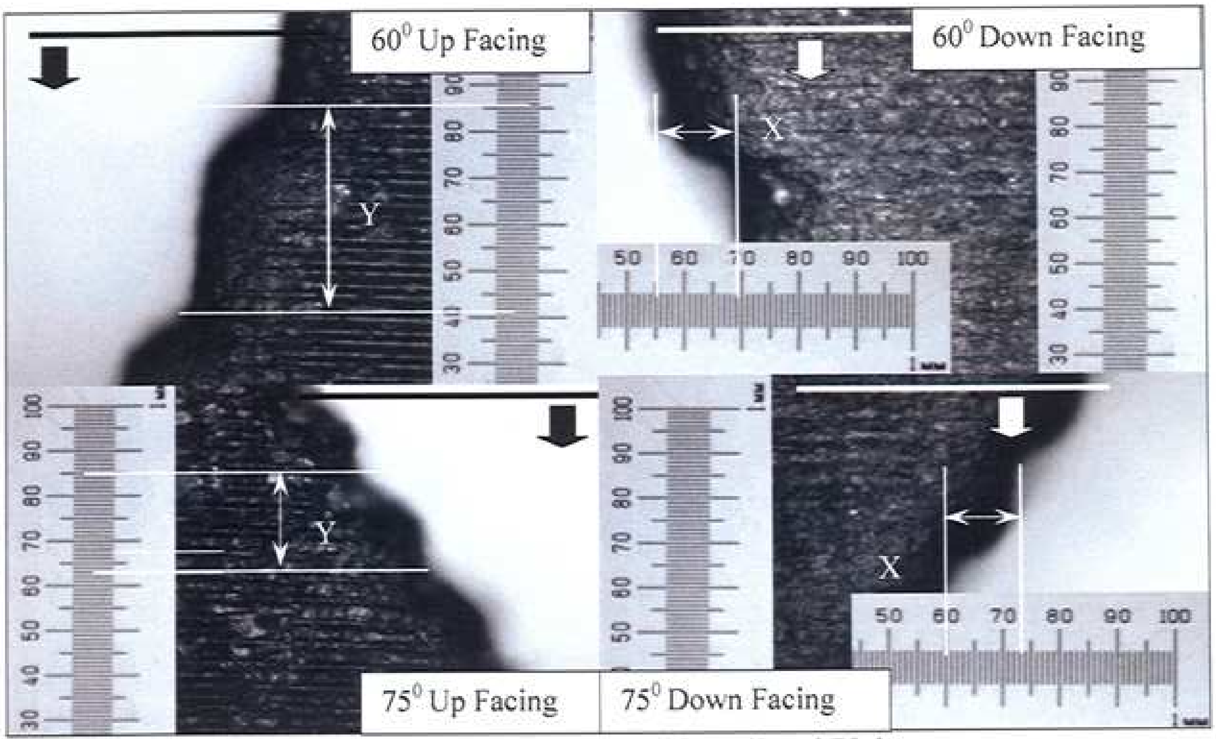


Figure 5.3.4.4 Micrographs for builds at 60 and 75 degrees

Reason for better surface finish in the 'Up' direction

From the figure 5.3.4.5/6, it can be seen that the dimension "X" closely matches with the pixel size setting used for this build, 0.15 mm. Hence it can be deduced that the trend in surface finish was caused by Pixel size. It can also be observed that the dimension "Y" increases as the angle of the face increases.

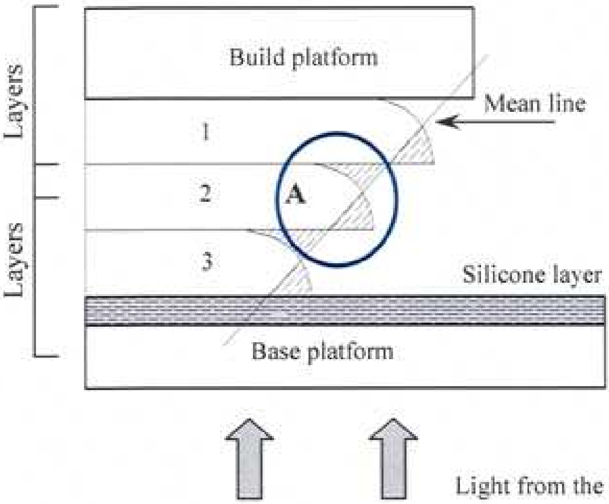


Figure 5.3.4.5 – Down facing build

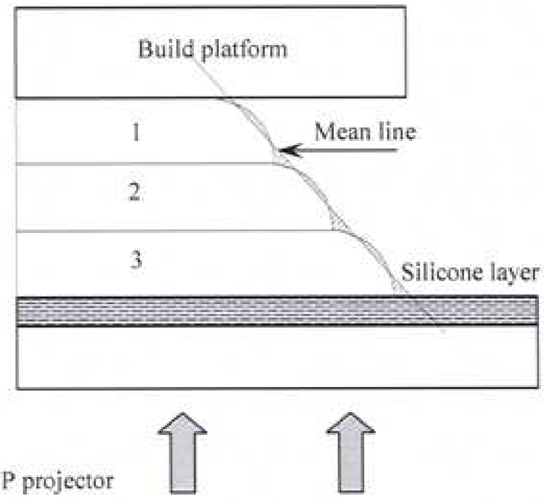


Figure 5.3.4.6 – Up facing build

The parameter 'Ra' used to express surface finish is defined as the arithmetic mean of the departures of the profile from the mean line.[66] The expression to derive Ra is as follows:

$$Ra = \frac{1}{L}\int_{0}^{L} |y(x)|\,dx$$

Effectively, it is the magnitude of the areas on either side of the mean line that dictate the Ra value – Higher the area, higher will be the value.

With information gained from the micrographs in Figure 5.3.4.3/4, the effect of build direction on surface finish are clearly illustrated in figures 5.3.4.5.6. The shaded areas on either side of the mean line for the part built in the 'down' direction are much higher than that of the 'up' direction. This explains the lower Ra values of angular faces built in the 'up' direction.

The area "A" highlighted by the circle in Figure 5.3.4.5 shows how the edges of a layer are formed in the PerFactory technique. This effect is the same for both up and down direction builds. This could be due to refraction of light at the edges of the mask, as it passes through the glass and silicone layers of the base platform.

5.3.5 Illustration of Part Building Using Voxels

Since it has been found that the Pixel size has a very pronounced effect on the step thickness and hence, surface roughness, a thorough understanding has to be gained as to how the RP part is built up using 3 Dimensional pixels (Voxels). This is illustrated clearly in Figure 5.3.5.1, along with the method of calculation of pixel size for any given work area setting.

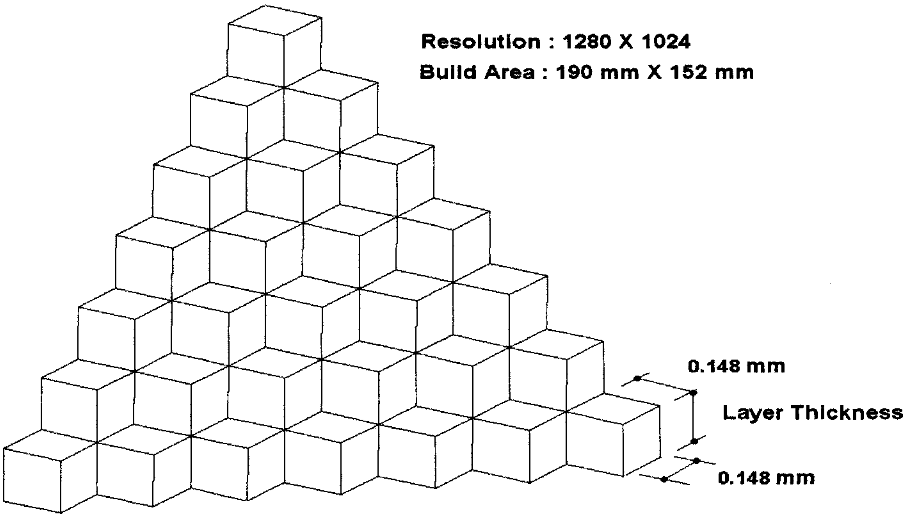


Figure 5.3.5.1 – PerFactory part building with Voxels

Calculation of Pixel size

Projector resolution = 1280×1024, therefore, total number of Pixels = 1,310,720

Work area selected = 190mm x 152mm (Maximum), therefore, total work area = 28880 mm^2

Area per pixel = 28880 / 1310720 = 0.0220 mm^2

Since a pixel is square in XY Plane, side of pixel = $\sqrt{0.0220}$ = 0.148 mm

Hence, the resolution of the machine at maximum work area setting is 0.148 mm.

Volume of a voxel for different layer thickness (at 190 x 152 Build area):

$V_{30\mu m} = .0006\ mm^3$, $V_{50\mu m} = .0010\ mm^3$, $V_{100\mu m} = .0020\ mm^3$

5.3.6 Conclusions of Surface Finish Study

The results of the surface finish study show that the roughness increases with increasing inclination with respect to the horizontal. This trend is exactly opposite to that exhibited by other established techniques like SLA, FDM and SLS. On further investigation it was found that this was caused by selection of work area settings, and therefore by the pixel size used for the build. It was also found that building in the up facing direction consistently produces better results than that of the down facing direction, for the same process parameters, layer thickness and build angle.

5.3.7 Level of Detail Tests – Filigree

The sample test piece as shown in Chapter 3 were used to assess the finest detail that could be manufactured using the DLM™ with filaments of size 3 to 0.05 mm in the three build orientations.

The samples in various build orientations are shown in Figure 5.3.7.1

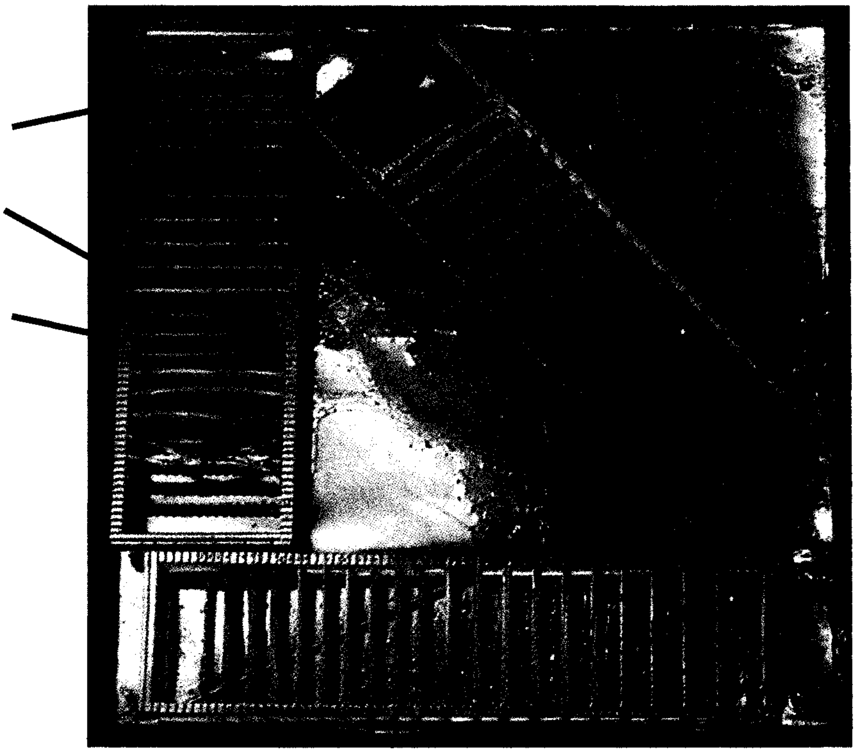


Figure 5.3.7.1 - Samples x-axis, y-axis and x-y axis

Summary: The smallest detail feature built perfectly was 0.3 mm thick rib. Features below this size are not self supporting during removal from the polymerisation bowl during build operation. The 0.1 mm rib did build in y direction, but lacks stability.

5.4 Analysis of the Application of the "Digital Light Manufacturing" Rapid Prototyping Processing for Functional Rapid Manufactured Components.

Rapid Prototyping is widely known as being able to fabricate 3D objects with complex geometries directly from accurate digital CAD data. Rapid prototyping can shorten the product development cycle and improve the design process by providing rapid and effective feedback to the designer. This section presents the findings of an investigation into the accuracy, build strength and detail of the EnvisionTec PerFactory Digital Light Processing (DLP™) based system, applied to rapid manufactured parts. The multi-directional material properties of Rapid prototyping resins can be used by Finite Element analysis to predict the functional design parameters applied to rapid manufactured components.

The results will allow designers and manufacturing engineers to access the validity of the components and the range of applications for this new evolutionary system.

5.4.1 Introduction

The move from rapid prototyping to rapid manufacture can be attributed to many factors. The major influences are:

- The development of these systems in recent years has been to improve accuracy and repeatability of components produced by understanding the interaction of the manufacturing processes.
- The advantage of new materials, for example materials with reduced shrinkage and improved inter-molecular and inter-layer bonding, has increased the range of applications and the more accurate parts can be utilised for aerospace, automotive, medical and consumer products.
- The reduction in initial investment requirements, particularly in the low cost office based "3 D Printers" has improved the economics of application of RP parts as direct manufacture of components.
- The need for lean and rapid product development to remain competitive and meet ever more demanding customer requirements.

To be able to use these new rapid prototyping processes and materials as rapid manufacturing processes, then we must first understand the capabilities and limitations of each and every process and materials used, so the correct process and material can be matched to the application.

In the past, studies such as the "Implementation of Product Design by the Introduction of Rapid Manufacturing", EPSRC GR/R13517/01[67], have focused upon the Stereolithography SLA and Selective Laser Sintering SLS processes. More recent work undertaken at Loughborough University by Richard Hague et-al has concentrated on the recent advanced materials developed for the SLA process[68].

This research work complements this study by adding to the knowledge base of materials data for the DLM process and will allow designers to design for this new low cost process compared to traditional laser based Sterolithography process.

In the first instance, the materials properties of the Acrylate resin used in the DLM process will be investigated, and secondly, using this materials data allowed designers to assess their designs using Finite Element Analysis techniques, and finally, will validate the analysis with case studies.

5.4.2 Test Sample Preparation

The test samples were manufactured in the three major axis,
The part can be built in any of the six orientations x, y and z, as shown in Figure 5.4.2.1/2
The orientation is chosen considering the following factors:

- Geometry of the part
- Surface finish requirements
- Areas to be supported
  (Faces in contact with the support end up with a rougher finish)

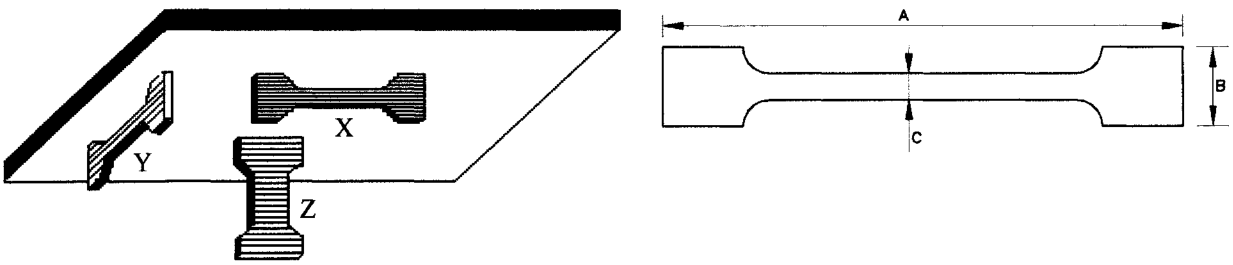


Figure 5.4.2.1 : Different build orientations and Test specimen

5.4.2.1 Build Parameters

The build parameters set have been derived from previous part optimisation studies in sections 5.2 and 5.3, Table 5.4.2.1 shows the build parameters utilised to produce the specimens with Acrylate R5 resin.

Parameter	**Value**
Separation Distance μm	3000
Positioning Velocity msec	1000
Separation Velocity msec	1000
Exposure Time msec	7000
Work area mm	152 * 120
Layer thickness μm	50

Table 5.4.2.1 : Build parameters

The samples were manufactured in the **x** – y, **x** – z, **y** – z, **y** - x, **z** – x and **z** – y where the bold axis indicated the major axis of length for the sample.

5.4.2.2 The Materials Testing and Results

Testing Procedure

Tensile strength tests on the specimens were conducted on the Instron 3382 materials test machine, the results for each axis over a sample of 12 parts averaged are shown in Table 5.4.2.2

Direction	Young's modulus MPa	Poisson's Ratio	Tensile Strength MPa	Percentage Strength %
X - Y	690.5	0.35	25.84	131
Y - X	562.3	0.38	22.09	112
X - Z	848.6	0.39	25.90	132
Y - Z	925.5	0.39	24.60	125
Z - X	774.5	0.37	19.67	100
Z - Y	1054.0	0.38	27.58	140

Table 5.4.2.2 : Results of tensile test in 6 planes

A matrix was then produced to apply the corresponding Young's modulus, Poisson's ratio and Tensile Strength to each of the test components under investigation; this proposed that the component was analysed as if it were in each of the six orientations. Therefore each finite element analysis was repeated for the six build orientations figure 5.4.3.3 to evaluate the best orientation for the production component.

5.4.3 Application of FEA to Non-Isotropic Structures

5.4.3.1 Application of FEA to Non-Isotropic Structures

The following Non-Isotropic components were considered. The restraints and loading for part 1 shock strut, figure 5.4.3.1.1/2 as both tensile and compressive load, part 2 as a tensional load held at the larger bore and loaded through the pin hole.

Other parts analysed included a garage door opening bracket and a tensile test piece, however these will not be shown here.

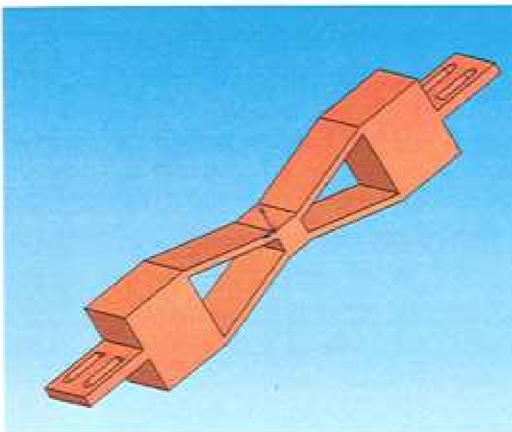


Figure 5.4.3.1.1 - Part 1 Shock Strut

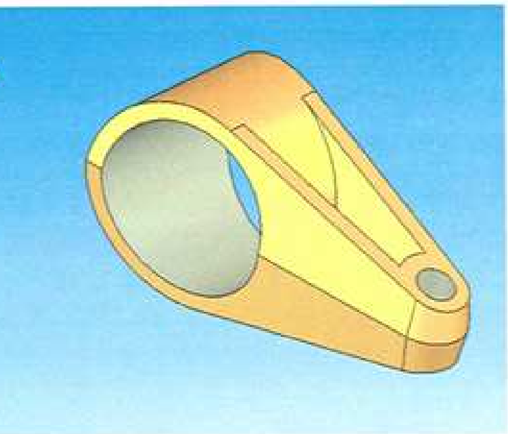


Figure 5.4.3.2.2 - Part 2 Rocker Arm

The loadings of 15,000 N where applied the analysis load values shown in Table 3 reflect the test carried out on the shock strut, Part 1, these where then repeated for the subsequent parts.

5.4.3.2 Case Studies of Rapid Manufacture

The Case studies were undertaken to apply the material properties to real components not just tensile sample pieces.

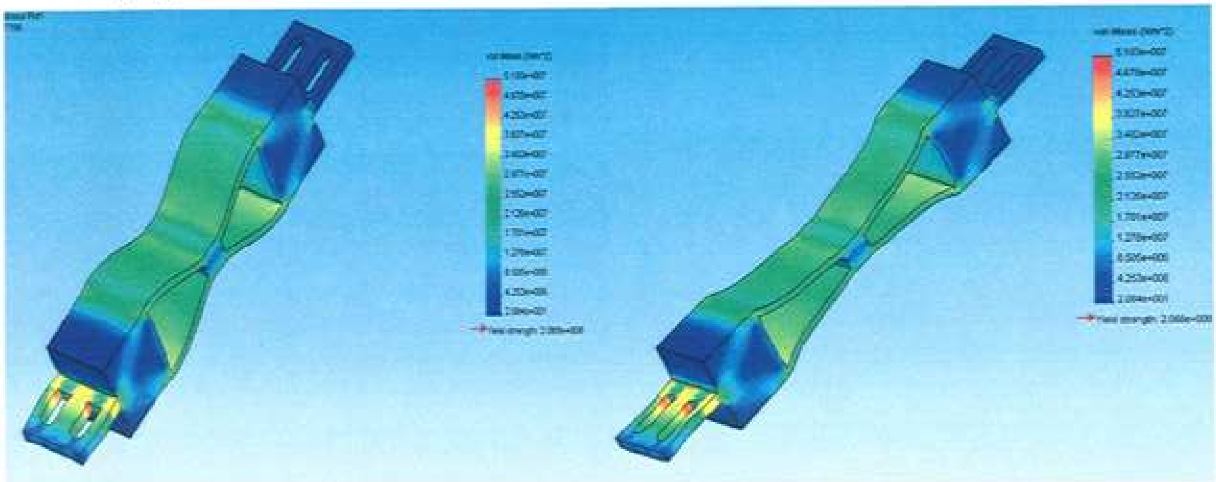


Figure 5.4.3.2 - FEA analysis Part 1 in compression FEA analysis Part 1 in tension

The FEA analysis can be seen for Part 1 and 2 in figures 5.4.3.2. The tabulated analysis results are shown in Table 5.4.3.2 shows the verification of the analysis for the Von Misses Stress and displacement for the build directions indicated in Figure 5.4.2.3.

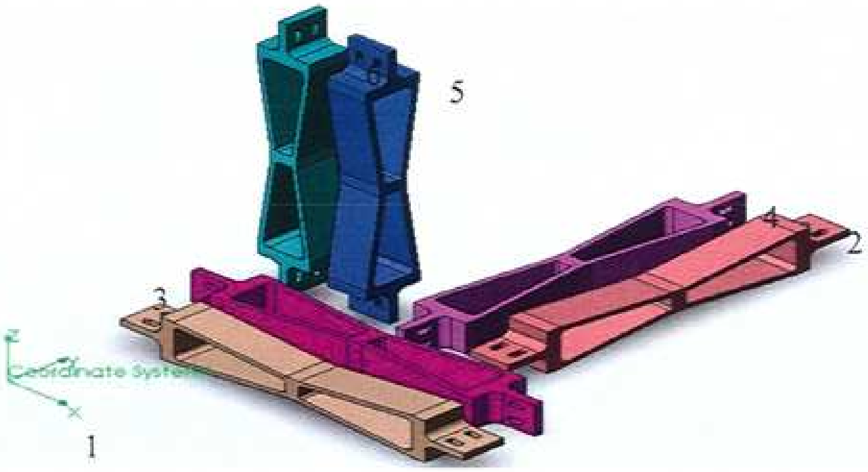


Figure 5.4.3.3 - Build Layout in 6 planes

Test/ Major Plane	1 X – Y	2 Y - X	3 X - Z	4 Y - Z	5 Z - X	6 Z - Y
Max stress MPa	15.65	15.04	14.60	14.21	13.97	13.51
Displacement mm	0.823	0.849	0.698	0.624	0.645	0.553
Factor of Safety (F.O.S)	1.7	1.7	1.8	1.8	1.9	1.9
% Stress reduction	100	104	107	109	111	114

Table 5.4.3.2: Results for Part 1 in six possible orientations

The results shown in Table 5.4.3.2 indicate that least stress and therefore the highest Factor of Safety was in the build Z - Y direction, the least deformation and strain was also found to be in the Z - Y direction.

An improvement in load carrying capacity of 14% can be achieved by selecting the correct build orientation. This is due to the improved bonding due to further resin curing in the Z depth as predicted from the ANOVA analysis undertaken in section 5.2.7 and 5.2.8

The best orientation compared to the best build speed is shown in Figure 5.4.3.4

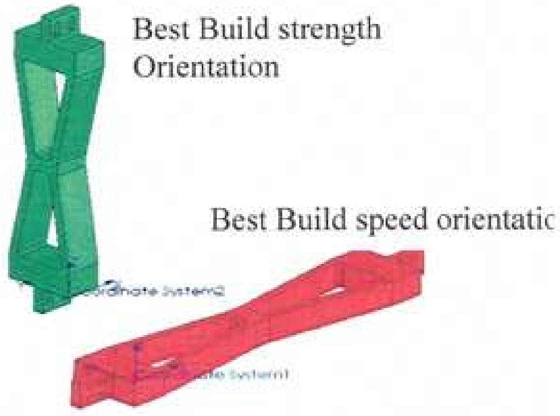


Figure 5.4.3.4 Build speed and build strength orientation

5.4.4 Conclusions of Rapid Manufactured parts from DLM process

Extensive build orientation testing of the materials properties has been undertaken to establish key materials properties for each of the possible build orientation. These results have been incorporated into the FEA analysis for several parts.

This section has shown how physical prototypes manufactured from the PerFactory process can be analysed taking into account the different unique directional materials properties that many RP processes inherently possess.

The example part chosen showed the best orientation for build for strength to be orientation 6 in the Z - Y plane, this is also the best orientation for deflection and strain.

The sample part is a simple tensile component with a single load scenario, it is envisaged that a more complex component under multi-directional restraints and loading would be more difficult to predict. Research work by Jayanth Majhi in the USA are currently investigating build optimisation for build parameters such has speed, support requirements, stair step effect[69]. Future work will focus on the application of artificial intelligent methods such as Neural Networks, to predict the best build orientation (to include inclined planes) to build the component to achieve the best results.

5.5 Rapid Manufacturing of Polymer Injection Mould Tool Inserts for Prototype Tooling Production

Product design is a multi-criteria decision process with the complexity of selecting the optimum between functionality, cost, reliability, manufacturability and many other conflicting criteria.
The only true way to really know how a component will perform under real world conditions is to manufacture it, in the production intent materials, using production tooling. However, this is not only costly but it can take several months to produce the tooling to produce the part.
Computer modelling, analysis and simulations such as 3D Computer Aided design, Finite Element Analysis, Flow Analysis etc can reduce the test programmes, but there is still a requirement for prototype parts to test under various load and climatic scenarios.
This section will present the application of Rapid prototyping processes to produce direct soft (polymer) materials for prototype production tooling.

5.5.1 Introduction to Rapid Tooling with the DLM Process

Productivity, short product lifetime and cost savings have become the main concerns of industries worldwide. Industries increasingly need to develop and manufacture new products more cost effectively in shorter lead times. The problems of product design and the production of prototypes are significant obstacles to the launch of new products because design iterations add time to the product development process, and prototypes are required to confirm the design and customer requirements.

This research section focuses on mould design and the use of the Envisiontec Digital Light Manufacturing (DLM) process machine to produce injection mould tooling to manufacture simple and aesthetic 3D plastic parts.

The investigation looked at the manufacture of a simple part first to establish build parameters, post manufacturing settings were applicable. The results then being utilised to manufacture an aesthetic 3D component based upon the Northumbria University's paper clip logo, this was used to validate the process. To verify the design of the mould tooling, Moldflow Plastics Adviser^{TM} software package was used to predict the quality of the plastic product. It was also used to analyse the best gate location of the injection sprue, pressure, flow analysis, and temperature in the injection moulding process.

The original definition of Rapid Tooling (RT) was "A 3D CAD driven process that generates tooling inserts in a layer by layer process for the production of components in end use materials[70]. RT is a natural extension of rapid prototyping. It originated from the need to assess rapid prototyping models in terms of their performance[71], it has introduced a new generation of tool making techniques, and has defined as a technique to produce low volume metal and plastic products from the rapid prototyping process. Rapid tooling is a process that allows a tool for injection moulding or die casting to be manufactured quickly and efficiently. It is the ability to build prototype tools directly as opposed to prototype products directly from 3D CAD models resulting in compressed time to market solutions. RT offers a high potential for a faster response to market needs, creating a new competitive edge. In addition, the rapid tooling process provides higher quantities of models in a wider variety of materials. The purpose of rapid tooling is not the manufacture of final parts, but the preparation of the means to manufacture final parts[72].

Injection moulding is one of the most common processing methods for polymers. The injection moulding process is a complex process that involves a series of sequential process steps. The different phases of the injection moulding process include the mould filling phase, the packing phase, the holding phase, the cooling phase, and part ejection. Solid plastic is melted, and the melt is injected into the mould under high pressure (usually between 10 and 100 MPa).

5.5.1.1 Important process parameters & settings for RT production

It has been learnt from previous operating experience that the parameters and settings in Table 5.5.1 would have the maximum effect on Accuracy, Strength, and Hardness. It is important to narrow down the parameters in.the experimentation, so that costs and time involved can be kept a minimum.

	Parameter	Unit	Minimum	Maximum
1	Layer thickness	μm	30	100
2	Peeling velocity	μm/s	1000	3000
3	Waiting time	ms	0	2000
4	Exposure time	ms	4000	15000
5	Work area	mm^2	120mm x 96mm	190mm x 152mm

Table 5.5.1: Process parameters

5.5.2 Research Methodology into Rapid Tooling

The aim of this research is an investigation into the application of DLM machine for sample plastic part production. The method for this investigation can be divided into six stages.

1. Concept generation and 3D CAD model
2. Using rapid prototyping for part checking
3. Using Moldflow for injection mould analysis
4. Create mould tool design from 3D CAD
5. Using DLM machine to build mould tool
6. Injection moulding trials

Stages 1 to 3 were undertaken to design, accurately manufacture and validate the test mould tooling for the sample parts and the desired design component as shown in Figure 5.5.2.1.

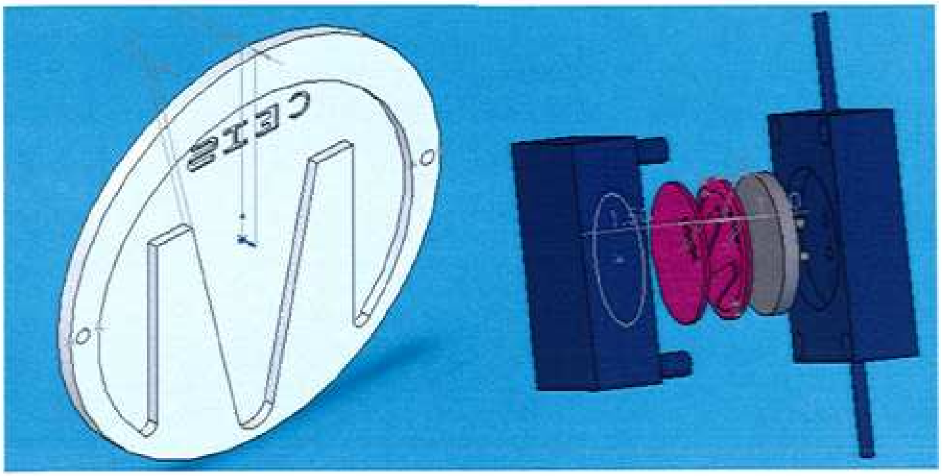


Figure 5.5.2.1 - 3D design of logo paper clip design showing both sides of insert and mould tool assembly

The finished parts of the rapid prototyping process were then measured by digital vernier calliper, to identify any errors in build accuracy.

Plastic flow analysis involves an investigation of best gate location, flow analysis, confidence of fill, quality prediction of the parts.

The Mould tools were then designed to fit the Manimould process and the bolster manufactured to support the 3DP inserts as per Figure 5.5.2.1

5.5.3 Results and Analysis of Rapid Tooling

The parts produced were tested as described below for accuracy and surface finish

Accuracy testing:

The main object of the project is to test how accurate the mould part is with that of the prototype, the mould exactly fits and can be easily separated with the prototype without using excessive force, the accuracy of the final mould part was 98% and the 2% of error can be compensated for at the design stage, that is the mould part tends to shrink after cooling due to the changes in the mechanical properties.

The following figure 5.5.4.1 shows a manufactured component and Table 5.5.4.1 shows the tabulated values for accuracy for the mould and the prototype.

Figure 5.5.3.1: Finished product

Prototype dimensions	Mould dimensions
Thickness of prototype (2mm)	Thickness of the mould (2.056mm)
Radius of the prototype (43.50 mm)	Radius of the mould (43.55)
Radius of concentric circle 8.24 & 6.18 mm	Radius of concentric circle 8.28 & 6.21 mm

Table 5.5.3.1: Accuracy test for mould part

The accuracy of the mould tends to vary with injection pressure and temperature, the precision of the mould can be increased only when the temperature of the molten polymer is maintained between 200~220 ^{0}C if the temperature is increased above 220^{0}C the prototype of methacrelate tends to fail due to fractures and tearing.

Surface Finish testing:

The surface finish is one aspect of a product's perception in the competitive world. To satisfy customers and make the product more attractive and feel good, it normally requires a good surface finish.

The Surface finish parameter Ra is the universally recognised and most used international parameter of roughness. It is the arithmetic means of the absolute departures of the roughness profile from the mean line figure 5.5.4.2 and results shown in Table 5.5.4.2 for five samples produced.

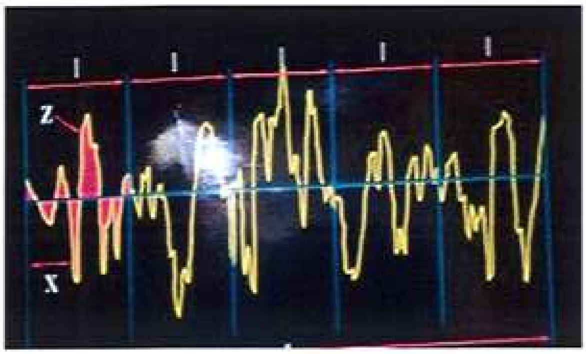


Figure 5.5.3.2: Example of surface Ra value

No of Specimen	Ra value Average (5 readings)
1	1.22μm
2	1.08μm
3	1.09μm
4	1.96μm
5	0.98μm
Average Ra value =	1.266μm

Table 5.5.3.2: Average Ra values for five specimens produced

5.5.4 Discussion of Rapid Tooling Investigation

The main areas investigated for making a die were as follows:

- Can the die withstand high temperature?
- Can the die be reused for making multiple models?
- Can the pattern and the die be separated easily?
- Can we get the accuracy that we required, when we use the die?
- Will the product have the smooth surface finish, when compared to the metal die finish?
- Can it withstand the pressure that is used when the molten metal is injected into the die?

Defects of the products, such as warpage, shrinkage, sink marks, and residual stress, are caused by many factors during the production process. These defects influence the quality and accuracy of the products. The most important factor is the dimensional stability for the minimum warpage of thin shell plastic parts. Reducing warpage is one of the top priorities to improve the quality of injection-moulded parts.

The Injection temperature: The temperature should be maintained between 210~220^{0}C, above this temperature, it resulted in the rupture of the die and collapse of the product as shown below.

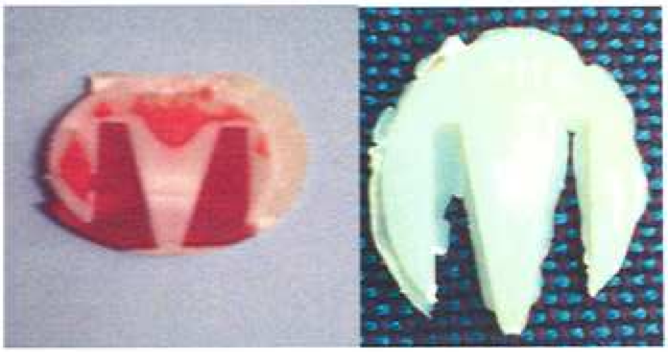


Figure 5.5.4.1. Deformed mould & die due to high temperature and injection pressures

The pressure: The pressure should not exceed a maximum found to be 80 MPa, if exceeded the die may rupture and tends to split off (press fit) resulting in the damage of the product.

Accuracy of the mould: The accuracy of the mould mainly relies on the accuracy of the RP build. The accurate build of die results in a perfect mould.

Surface roughness: To obtain a smooth surfaced finish product, the prototype mould tool requires a smooth surface finish; this can be obtained easily by using Envisiontec because this method doesn't require post machine operations on the die.

All the restrictions detailed above regarding temperature and pressure are due to the thermal and mechanical properties of the methacrylate resin used. When the resin is raised above 220^{0}C, the polymeric bonds begin to loosen which causes rupture and collapse of die along with product. Therefore the usefulness of the die totally depends on the properties such as toughness, melting point, compressive strength, etc. of resin used for making the die.

5.5.5 Conclusions of Rapid Tooling Investigation

One application of the PerFactory DLM system is in the manufacture of moulds for the polymer Injection Moulding process.
A mould for Injection moulding machine was manufactured with the PerFactory DLM machine by rapid prototyping technique (layer by layer).

- The die can be used up to an injection temperature of 220^{0}C. If it is used above this temperature as shown in Figure 5.5.5.1 it begins to tear due to the loosening of polymeric bonds.
- The die injection pressure should not exceed the pressure 80 MPa.
- The accuracy of die and product is quite impressive. The quality of product depends on surface finish of die. Here the product obtained is of good quality which provides a good surface finish up on the product.

In this study, it was found that plastic parts manufactured from a DLM mould are acceptable, but still need post processing to improve the accuracy and quality. The DLM rapid prototyping technology can be used as a mould tool to produce plastic parts. However, this manufacturing technique is currently not suitable for complex geometry or delicate products. This technology is more suitable for a simple product or parts, which do not require high accuracy.

5.6 Development of a Build Monitoring System for the EnvisionTec PerFactory Rapid Prototyping Process

5.6.1 Introduction to DLM build monitoring

The EnvisionTec PerFactory® technique fabricates the part through layer-by-layer polymerisation of a photosensitive resin. It is unique in its method of part building, using discrete elements rather than smooth laser contouring implemented in the traditional SLA process. The build platform moves upwards as layers are added and the part is built upside down. Presently, there is no feedback system to warn the user if build failure has occurred. Continuing the build process after the part has failed, leads to time wastage, resin degradation and possible destruction of the base platform. A system for monitoring if part build failure has occurred is developed and tested in this work. Build failure can be predicted by studying the signature characteristics of base platform displacement during the peeling process. An illustration of the PerFactory machine is shown in Figure 5.6.1.1

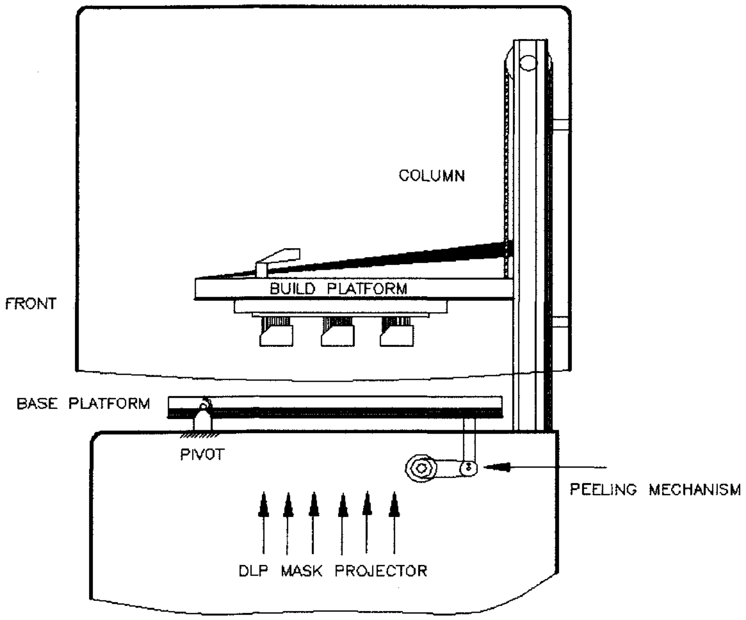


Figure 5.6.1.1 – Illustration of the part build area of the PerFactory machine

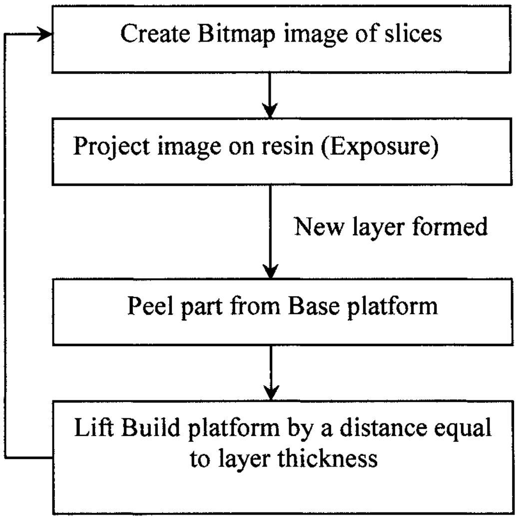


Figure 5.6.1.2 : The part building process

5.6.2 The process of building a single layer

1. Exposure: This is the time for which the mask layer is projected onto the resin by the DLM projector. The bulk of the curing takes place at this stage.

2. Peeling: This refers to the action during which the base platform is pulled away from the newly formed layer, by a servo mechanism. Peeling is achieved by pivoting the silicone base plate at the front, and pulling it down away from the build plate using a stepper motor driven mechanism.

3. Waiting: This is the period of time that the base platform waits at the bottom-most point, before returning to its original position.

4. Levelling: This refers to the action during which the base platform returns to its original position. This happens at a constant default velocity.

The above four processes are repeated for every layer, refer to Figure 5.6.1.2

5.6.3 Build Monitoring and Failure Detection System

At present, no feedback system is available to warn the user or to stop the process if failure has occurred during the build. Part build failure can happen due to one or more of the following reasons:

- Incorrectly set process parameters
- Inappropriate support structure
- Deterioration of Silicone coating on Base platform
- Large flat structure in XY plane
- Lamp power fluctuation due to ageing of bulb

Effects of build failure

The following are the losses incurred due to build failure:

- Time and resin wastage – causing probable increase in development time
- Deterioration of resin quality
- Deterioration of Silicone coating on base

5.6.4 Working principle of the Build monitoring system

A build monitoring system was designed based on the fact that the platform drive belt is subjected to forces during peeling, due to which it stretches for a while before reaching a steady state. This causes the platform to have a variation in velocity during the peeling process. This variation is proportional to the peeling forces encountered when the newly polymerised layer separates from the Silicone base. Part build failure can be detected if the platform moves with a constant velocity, indicating that it is not encountering any peeling forces.

5.6.4.1 Instrumentation used

Transducer: Linear variable resistance type, coupled to the cantilever arm at rear of the base platform. This is driven by a dc power source and outputs to an oscilloscope.

Digital Oscilloscope: This equipment displays the change in voltage with respect to time, on an LCD screen. The display can be frozen at required points and printed out.

Printer: The printer is coupled with the oscilloscope, and the shape of the printed Displacement - Time curve indicates whether the build is going on successfully or has failed.

5.6.4.2 Schematic of the Build Monitoring System

A schematic representation of the build monitoring system developed at Northumbria University is shown in Figure 5.6.4.1, a close-up of the belt drive system is also shown.

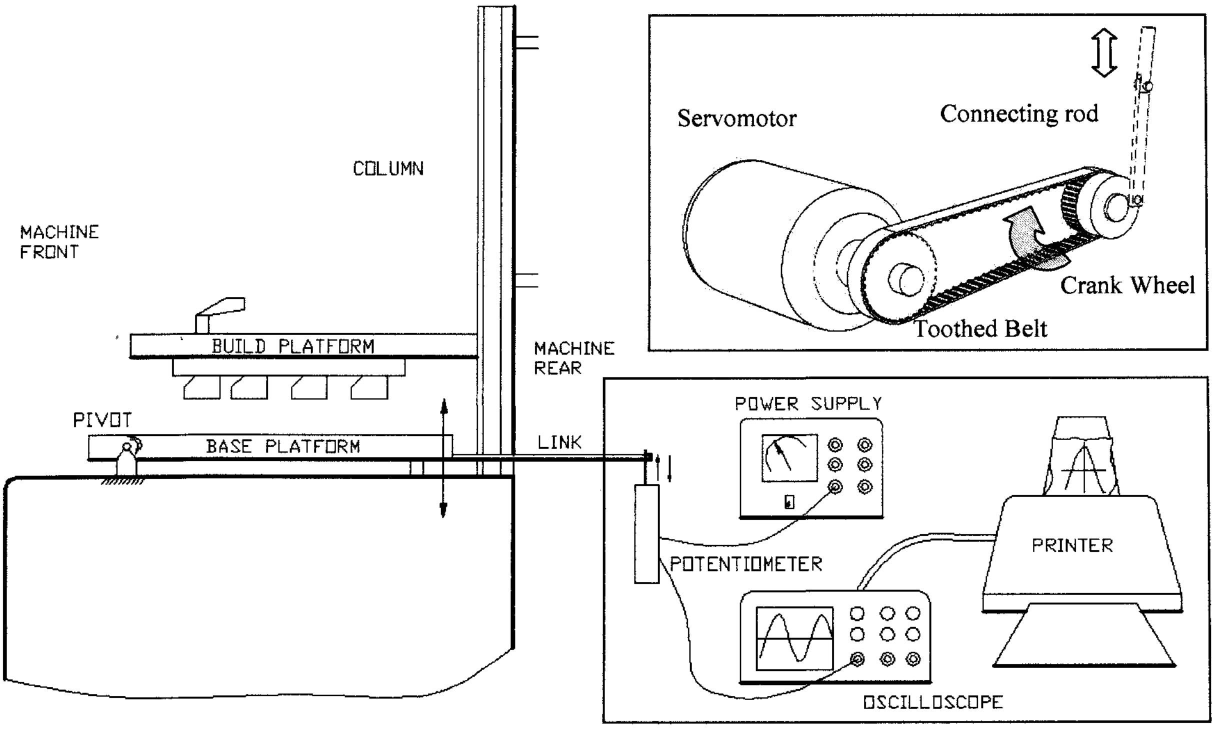


Figure 5.6.4.1 – The Build monitoring system

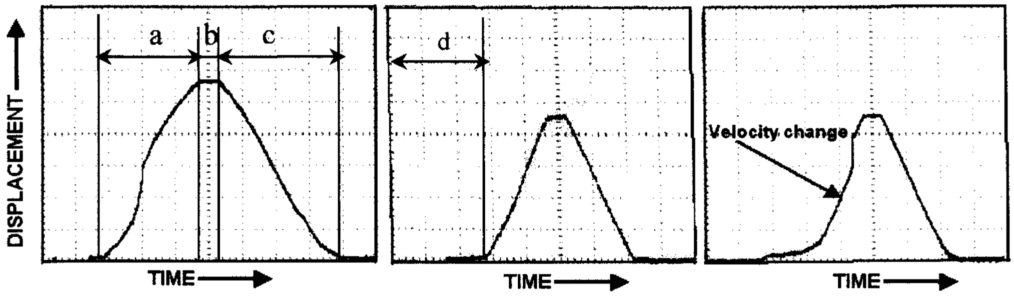
The system operation;

- The link transfers the motion of the base platform to the transducer and also serves to amplify the displacement of the platform during peeling.
- The output voltage of the transducer is processed by the oscilloscope, to show a graph against time.
- The plot can be printed by a printer interfaced directly with the oscilloscope.

Types of layers built during the entire build cycle

Base Layers

The build process starts by building a base layer, which acts as a foundation for the rest of the process. Default parameters are used for the base layer. The displacement of the base platform is at a maximum during building of the base layer. Considerable peeling forces are encountered at this stage, as is indicated by the velocity drop in the section labelled 'a' in 5.6.4.2 – Base Layers.



BASE LAYERS **SUPPORTS** **PART**

a – Displacement during Peeling

b – Waiting time after peeling

c - Displacement during Levelling

d – Exposure time

Figure 5.6.4.2 – Build characteristics graph

Supports

The building of supports is the next stage in the process. The supports are built on the same parameters as that of the part. We can see from Figure 5.6.4.2 - Supports, that peeling forces encountered at this stage are very small compared to that during the part build stage.

Part build

This stage, in which the part is built, takes the bulk of the total build time. Here, the magnitude of peeling forces depends on many process parameters, as well as cross-section of the layer being peeled away. The change in velocity due to peeling force can be clearly seen in 5.6.4.2 – Part.

5.6.5 Investigation of the working of the system

All the instruments were connected as shown in figure 5.6.4.2, and the oscilloscope readings were studied continuously, as the part was being built. The graphs were printed at intervals of 0.3 mm part build height. Figure 5.6.5.1 shows the test part that was built for this experimentation. The steps are provided to study the sensitivity of the system at different build cross sections.

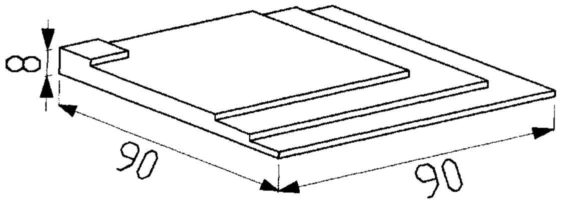


Figure 5.6.5.1 – Sample part used for testing the system

The Displacement – Time graphs obtained at selected intervals during the part building stage, for a successful and a failed part are shown in Figure 5.6.5.2. The part geometry and all process and machine parameters are similar in both cases. It has to be noted that the graphs have been plotted during build of the main part, after the supports have been completed.

It can be clearly seen from the figure that the peeling forces encountered during successful build causes a reduction in velocity. But in the case of a failed part, the peeling happens at a constant velocity, indicating that there is no peeling force encountered. This means that the part has failed. The peeling and levelling velocities are equal in this case, but they need not be so every time. These experiments were repeated five times in order to test the consistency of the results.

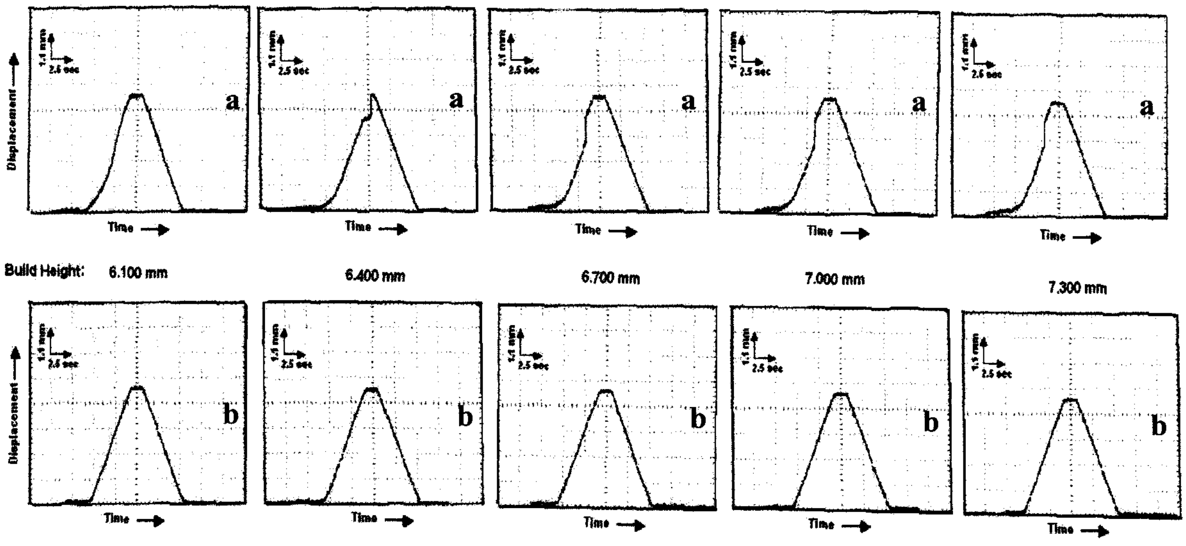


Figure 5.6.5.2 – Displacement vs. Time graphs for Successful (a) and Failed (b) parts

5.6.6 Development of a build-monitoring algorithm

Logic of this algorithm

This algorithm works by measuring the slope (displacement / time) at five different sections along the curve representing peeling. The measurements are started after the base and support layers are built. The peeling curve of a failed part would have the slopes of all the five points equal. A counter is activated in this case. These slope measurements are made every 0.3 mm of part height. The build process is aborted if failures are recorded five consecutive times, that is, when the counter reaches five in as many measurements. The different sections of the algorithm are listed below:

1 – Resets counter for new build

2 – Calculation of slope for first segment in the peeling characteristics graph

3 – Comparison of five consecutive slope readings. If the difference between slopes is within 25% of each other, they are considered to be equal, and a counter is incremented.

4 – The process is aborted or an alarm is sounded if the counter reaches five.

An algorithm was developed, that could be incorporated into the PerFactory software, and is shown in Figure 5.6.6. It is designed to abort the process if it senses that build failure has occurred.

Limitations of this system

This failure detection system has a few limitations and they are listed below. They can be attributed to the hardware as well as to the algorithm.

- Initial build failure occurring at the base or support layers cannot be detected by this system
- It is not sensitive at very small layer cross sectional areas. This is due to the resolution of the transducer. This fact can be observed from figure 5.6.6.2, where no change in velocity can be seen in the peeling curve of the graph.

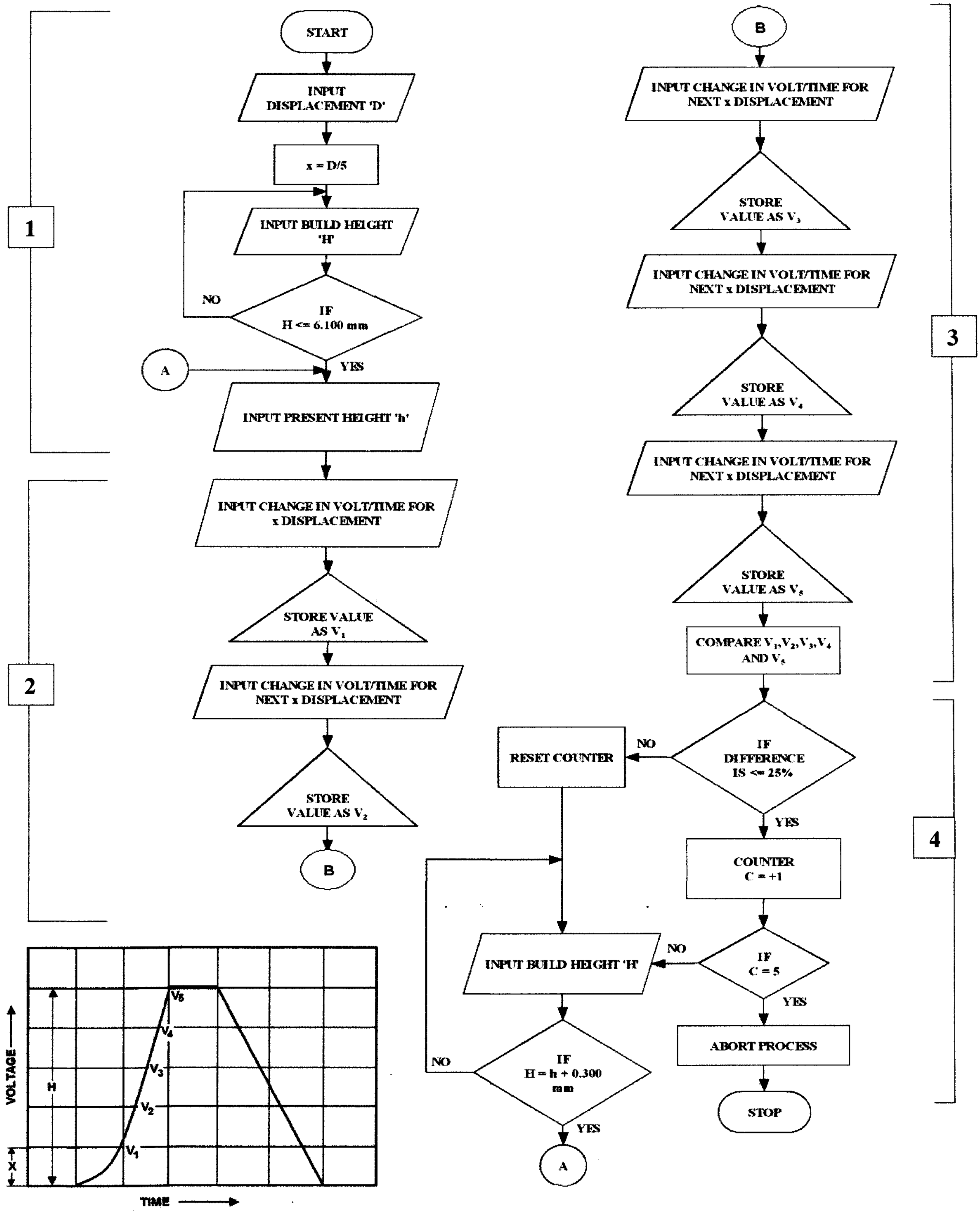


Figure 5.6.6 – The failure detection algorithm

5.6.7 Conclusions and Future Work for Build Analysis

A concept for build monitoring was developed and tested successfully. The user can identify if build failure has occurred, from the signature characteristics of the output graph during peeling action. The algorithm developed could be implemented into the PerFactory software, and along with the displacement transducer and oscilloscope, could be programmed to automatically stop the build if it detects build failure.

This algorithm has to be implemented into the PerFactory software in such a way that it acquires information like build height, support height etc. and also aborts the building if it senses that failure has occurred. Work also has to be conducted on improving the sensitivity and repeatability of the system. Use of an LVDT (Linear Variable Differential Transformer) would help to record even minute changes in velocity, which is typical during build of parts with very small cross sections.

Progressing from this stage, work has to be conducted in the following areas:

- Implementation of the build-monitoring algorithm into the PerFactory® software.
- Use of more accurate transducers like LVDT to enable detection of build failure even in very small models, thereby widening the working envelope of the system.
- Improvement of sensitivity and repeatability of monitoring system.
- Identification of a relationship between the mask white area and peeling force.
- Development of build platform surface for better adhesion to the base layer.

5.7 Summary of the Research into the Digital Light Manufacturing Process

This chapter has investigated the digital light manufacturing system, it has investigated and optimised the build parameters in relation to accuracy, part strength and surface finish. The interaction of key build parameters has been established. The application of these improved operating parameters have been applied to a rapid manufactured case study, verified by the application of Finite element analysis and physical testing. The application of the DLM for the manufacture of rapid tooling for injection polymer moulding has been completed. Furthermore a build monitoring system has been proposed and developed.

In total seven refereed research papers have been presented at three international conferences with in the UK and Europe, with a further 2 more abstracts awaiting acceptance at a further conference.

CHAPTER SIX: CASE STUDIES UNDERTAKEN

6.0 Application of Research

This chapter focuses upon the application of the research findings for real life commercial products. Several of the products are now sold world wide from the UK, USA to Japan. The products shown and analysed in this chapter would not have been achievable without the application of the research as reported in chapters four and five. The projects have been drawn from a wide range of the Authors applications to highlight the range of applications for digital product development, Rapid Prototyping, Rapid tooling and Rapid manufacturing.

Prior to 1996 the North East of England had only very limited access to RP technologies and lacked the experience of using these emerging technologies. The CRPD was set up in 1996 to assist small to medium sized companies leverage the benefits that when correctly applied can provide companies with significant benefits in their product development processes. Several of the companies assisted know use RP and RT as part of their ever day process for example Black and Decker, Elmwood Sensors and ASL Automotive.

6.1 Case Study : ASL Automotive Junction Box

ASL SYSTEMS LTD - Based at Gateshead Riverside Industrial Estate, the company manufactures electrical cable harnessing and control solutions for the automotive industry.

6.1.1 The Problem

For many years ASL had been buying in connector boxes (sometimes from their competitors), adding their own patented components and then selling on to their customers. An opportunity to win a large £1.2 m order lasting two years, meant they had to re-assess their working practices to achieve economies of scale and production. They needed a solution quickly, i.e. a design within two weeks. Figure 6.1.1

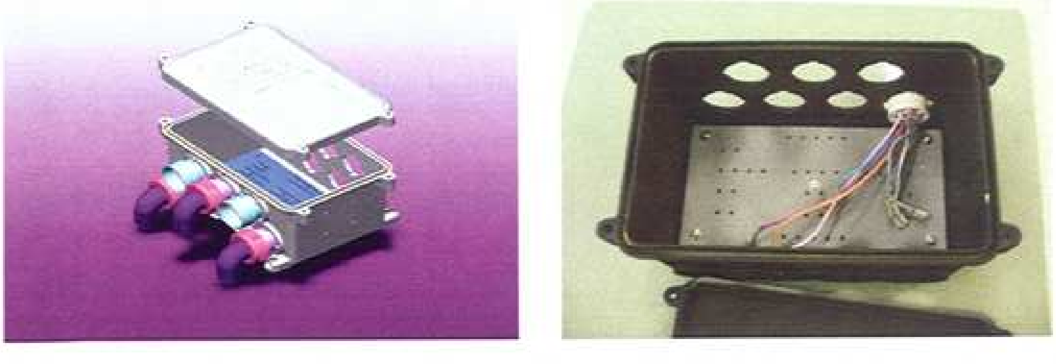


Figure 6.1.1 - ASL Control Box CAD Rendered Image and SLA Prototype for trade Show

6.1.2 The Approach

Initial meeting -

- Contract agreement – 3 days.
- Design specification drawn up with ASL Engineers and operatives.
- Concept design of box, fittings, circuit board and connectors.
- Detailed design and rapid prototype concept model created – 2 weeks.
- Virtual reality model generated for promotional meeting.
- ASL are one of the last three contenders for a £1.2m bid – 1 week.
- Prototype model produced for NEC exhibition and toolmakers' evaluation – 1 week.
- **£1.2m order won.**
- 3D models sent to toolmakers in UK and China (20+ parts).
- First off models produced and reviewed at ASL – 12 weeks.
- Minor modifications made to design to assist installation.
- Production – 3 weeks.

6.1.3 The Benefits

- 100 Jobs safeguarded
- Increase in turnover
- Market penetration

"The University engineers based at PDTCC have done a great job, I only wish we had approached them earlier." Reg Hardy, MD, ASL Systems.

6.2 Case Study : A1 Wall Ties Ltd

Based at Wallsend in Newcastle, this is a small engineering company who provide remedial work to the industrial and residential construction industry. One particular product requiring external assistance was for the design and prototype production of remedial wall ties for the building market.

6.2.1 The Problem

The major problem the company faced was in the slow speed of installation of the existing remedial wall ties. Remedial wall ties replace failing existing wall ties that where inserted during original building construction. The function of a wall tie is to hold the two layers of brickwork together in a cavity wall. However after a period of time these have been found to be corroded and failing and need to be replaced.

6.2.2 The Assistance

The initial contact with the company was through one of the network of companies already assisted by the centre. The centre assisted in securing further development funding via Knowledge House at Northumbria University.

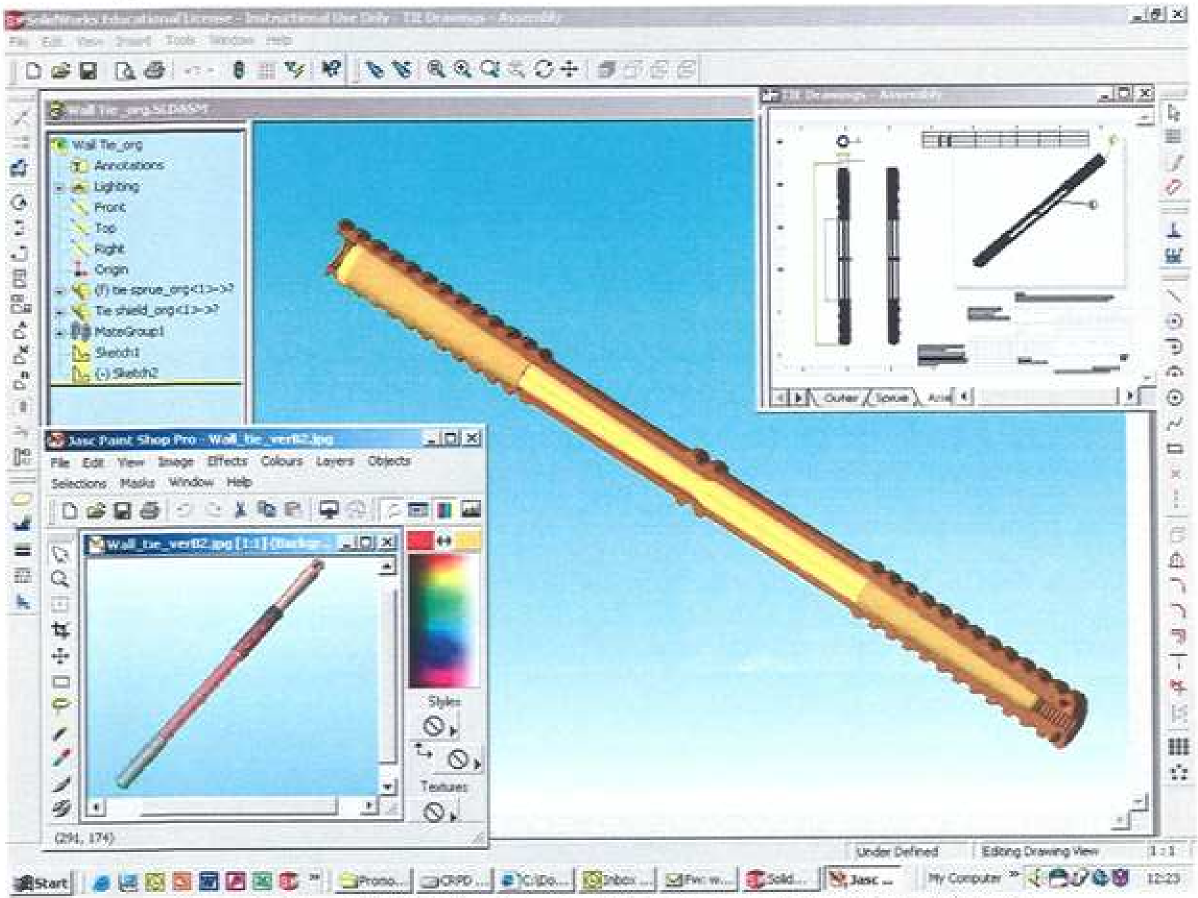


Figure 6.2.1 - Wall tie drawing, central sprue and detail required for grip

6.2.3 The Approach

In depth meetings into the nature of intended product operation, installation and materials research resulted in the unique patented design shown.

A Rapid prototype of the assembly was manufactured to test the design Figure 6.2.1.

To ensure compliance with building regulations prototype injection moulding tools were then manufactured and samples tested using the University's extensive test equipment.

Plans are being developed to further assist the company to manufacture production for cavity tooling, produce and package the product.

6.2.4 The Benefits

New product with sales in excess of 1 million assemblies per annum.

"Without the technical assistance, know-how and expertise of the staff at the Centre for Rapid Product Development, the new wall tie design could not have been achieved in the time required; the help provided resolved this problem." June Whitfield, MD, A1 Wall Tiles Ltd

6.3 Salamander Pumps Ltd - Pressure Shower Development

This product development was a spin out from a Knowledge Transfer Partnership (KTP) scheme and the Regional CAE project undertaken in 2006. The design brief expanded as the project developed, from initially Reverse Engineering their pump impellers to improve the static pressure characteristics, to a completely new series of shower units with their OEM Triton Showers. The thrust of the design was the marriage between wireless controllers, PIC control, mechanical design and thermodynamics to develop a new product range. Initial designs were developed and the use of in-house DLM and sourced SLA and SLS components allowed Salamander test engineers to;

1. Check that the CAD design was correct (i.e. tread was counter-clockwise on the model)
2. Ensure the units worked to specification within their operating range
3. Optimise the flow paths and position of key temperature sensors in the flow path, before the commitment to several hundreds of thousands of pounds in tooling, Figure 6.3.1

The results of this project is the direct employment of 4 additional staff within the company on that production line alone, therefore the revenue back into the regional economy is estimated at £200,000 per annum.

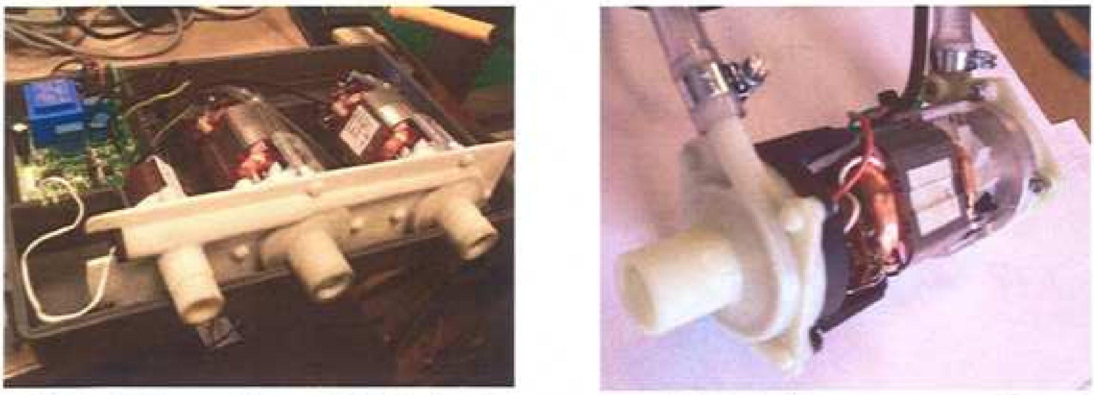


Figure 6.3.1 - SLS manufactured LP Hydroplane on test and SLA built new pump configuration

6.4 Projects Past and Present

The following projects have been undertaken by the Author during the period of research and have applied some of the techniques discussed in this research work, on a project by project basis.

To aid understanding of the application of Rapid prototyping, Rapid tooling and direct manufacture techniques, each project will be briefly discussed alongside the application, the benefits and the problems encountered.

6.4.1 Elmwood Sensors

Humidity and temperature sensor

Initial use of LOM part to check size, fit and access for design. Elmwood developed the electronics for inclusion into SLA produced prototypes for initial engine trials for VW and Skoda models, Figure 6.4.1

Rapid manufactured parts have been used on the first 100 Mini's, the name badge was rapid manufactured until the production parts were available.

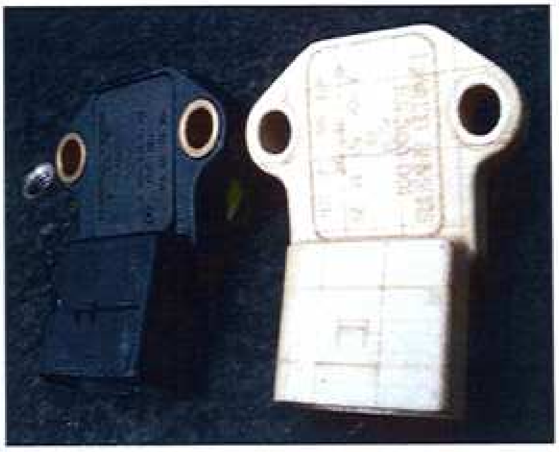


Figure 6.4.1 End product and LOM prototype

6.4.2 Charles Taylor Foundry

Gas turbine inlet manifold, Figure 6.4.2

Actual Size over 2 m high and weighs approximately 10 tons.

The Z-Corps 3DP part used for shop floor visualisation, also an aid to the production of casting patterns and to explain areas of concern, when undertaking casting analysis and subsequent client supplier meetings.

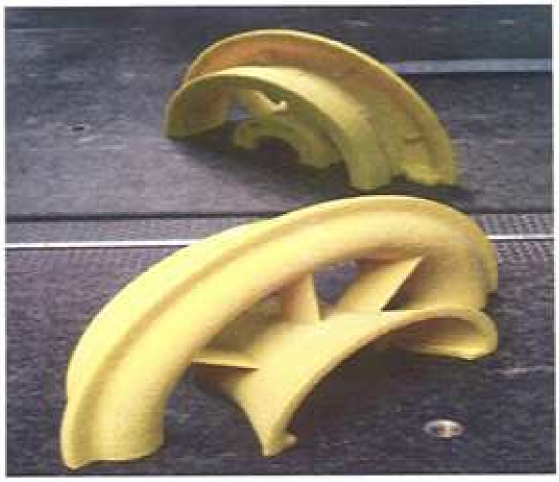


Figure 6.4.2 - 3DP Gas turbine inlet manifold

6.4.3 VisiTech Ltd

Dual Port Camera Adapter

This prototype helped to explain the components that were developed by the Author in this industrial Design and Manufacture project. The finished product is now available world wide for application upon medical microscopes for the detection and observation of abnormal cells.

The prototype shown Figure 6.4.3 is a combination of LOM parts in the lens and camera ports and 3DP parts for the main body and lens holder.

The prototypes assisted in discussions with the client and manufacturers especially where tight tolerances and mating surfaces were required.

Figure 6.4.3 - Visitech Dual Port Adapter

6.4.4 HandiLock

Key turn disability aid, Figure 6.4.4

Figure 6.4.4 - HandiLock Range of turning knobs

The 3DP parts of different turning concepts were assessed to ascertain the best shape and size for this product before commitment to tooling. The whole product was prototypes for discussions with the client and manufactures of the castings. Several design modifications where undertaken as a result of these meetings reduce cost of 20% achieved.

6.4.5 Durham University

Wind Tunnel Gas turbine blade trials, Figure 6.4.5

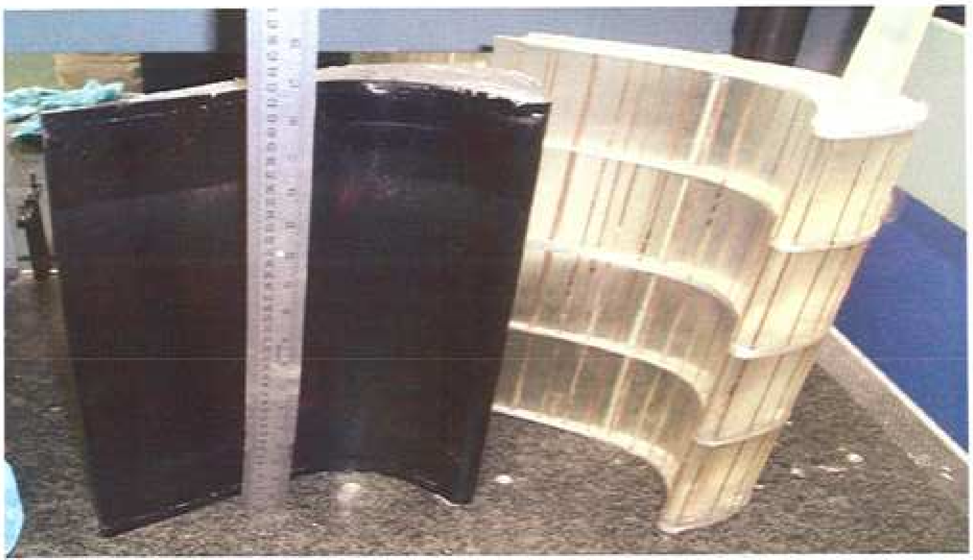


Figure 6.4.5 - Master for Vacuum casting and Clear Taped blade

Durham University required a set of six solid (plus one tapped) wind tunnel test blades manufactured from CFD surface data for scaled up testing and evaluation.

A Master was designed a with the tapping points running con-formally 2 mm below the surface, with connections to the outer wall at predefined intervals. However the SLA master required considerable additional work in ensuring the 0.25 mm holes were clear and attached to the inner tubes. A decree of shrinkage occurred in the Vacuum casting process due to the large volume of material poured and the exothermic process involved.

The components withstood the pressures and the application of the flow visualisation dies and oils successfully.

6.4.6 Novelty Light Switch

3DP Vacuum forming mould tool, Figure 6.4.6

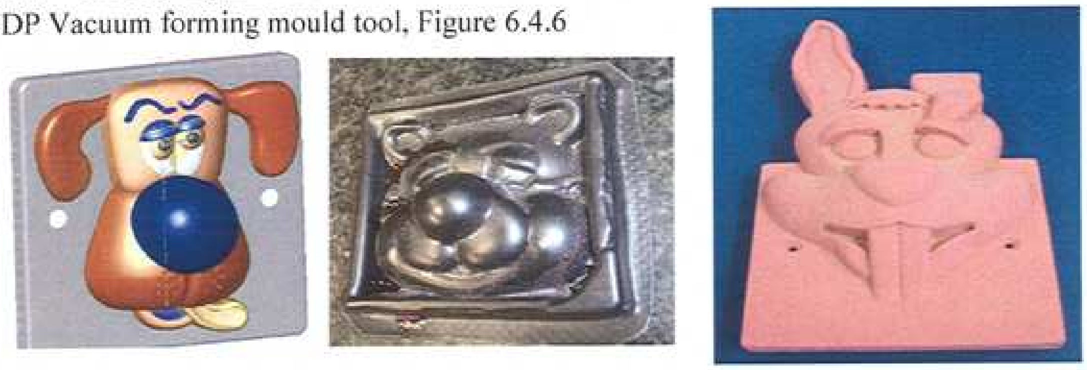


Figure 6.4.6 Teddy bear light switch Vacuum formed and Rabbit 3DP part

The clay model was reverse engineered into a CAD model for visualisation and rendering. The prototype was used to help the inventor assess his product ideas.

6.4.7 Tommy Hannigan Mobile Phone Holder

Mobile Phone Holder, Figure 6.4.7

The Author was involved with this project after the original designers failed to design a manufacturable product. The Author took the original IGES Data and designed new components and revised the existing design. Prototypes were used extensively to ensure the design functioned as required and enabled detail design and manufacturing discussions to take place with non technical clients and for focus group work to evolve the product. The product was tooled for injection moulding at a cost of £65,000 and several thousand units produced and sold UK wide.

Figure 6.4.7 - SLA RP of Holder with phone and CAD design rendered

6.4.8 Invision - Lithographic display panel

Animated Advertising Display unit, Figure 6.4.8

A print company approached the CRPD with a design brief to develop a advertising display panel using Lithographic images. The process works by having 3 or more pictures that are split up into sequential small horizontal bars i.e. Picture 1 strip, picture 2 strip followed by picture 3 strip and the next strip from picture 1 and so on. In front of the paper is a horizontal lens that focuses on a single strip, the paper is moved up a strip width via a cam mechanism driven by a clock motor.

Use of RP mainly SLA for production of the masters then the application of Vacuum forming to manufacture a sample quantity (10 off). However the power available and the static build up of the paper coupled with a rival product caused this project to fail before entry into the market place.

Figure 6.4.8 - Invision CAD Model and Vacuum cast of base stand

6.4.9 LOM Machine upgrade

In the past, the LOM RP machine has exhibited poor cutting quality and accuracy. The laser is guided around the perimeter of the cut layer via a roller driven plotter mechanism. This mechanism is roller bearing based, the Y axis being replaced with a manufacturer's upgrade to a linear bearing. Figure 6.4.9.1

Figure 6.4.9.1 - LOM Laser guide (plotter), Y axis linear bearing and X axis old roller bearing

The investigation into the X axis revealed a similar upgrade was required for this axis, as no manufacturer's upgrade was available, a new design was proposed using linear bearings.

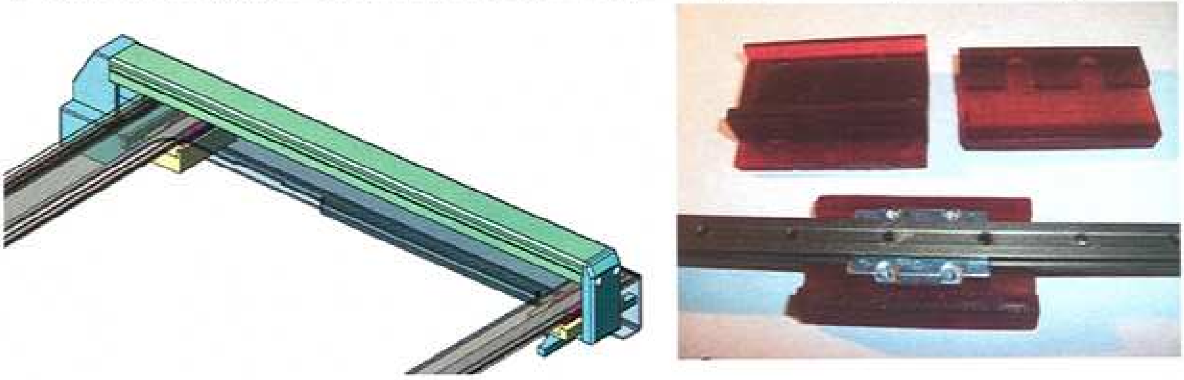


Figure 6.4.9.2 – CAD Design and Direct Manufactured parts awaiting assembly

The design was modelled in solidworks and animated to develop the concept, using the existing carriage and drive train. The final design required the manufacture of two components to replace the x axis carriage supports.

The components were manufactured using the DLM process in two hours and fitted to the carriage and linear bearing as shown in Figure 6.4.9.2

6.5 Summary of Case Studies

Of the twelve case studies highlighted above, the most appropriate to show how the application of different rapid prototype processes has impacted upon both the product and also the company is the very successful Salamander project. This project used RP in the early stages to assist in the design iteration process and then later to assist in the verification of the operating principles. The early testing revealed the requirement for an additional solenoid valve for sealing off the outlet pipe in addition to the two control valves for hot and cold flow for the HP unit. Also the position of the temperature probe was critical to control the motor speed and hence outlet temperature in the LP unit with several iterations required before the optimum position was found.

An exhibition quality product was manufactured using SLA technology to help promote the product at trade shows. The OEM manufactured in-house more RP for tooling and to resolve design for manufacture issues.

Rapid Tooling has been used on the several products using traditional vacuum casting techniques for both the Display panel and the Durham blade projects, the largest tool was for a child car seat produced from the LOM process as shown in figure 6.5

Rapid manufactured parts using the DLM have been applied to the design of a new LOM "X" axis linear bearing.

Figure 6.5 - Thermoformed child car safety seat from LOM mould tool

CHAPTER SEVEN: DISCUSSION,

7.1 Context of Resarch

The Rapid prototyping industry has matured quickly in the last decade, from being a new little understood "fad" that was unable to manufacture components accurately or reliably in engineering materials, to a key tool for companies engaged in new product development or manufacturing.

The application of RP techniques has allowed companies to revolutionise their product development process and methods of manufacture, resulting in more complex products being launched with reduced lead times, higher functionality and quality. The further development of these processes as highlighted by this research has allowed the application of these techniques to have a significant impact not only upon the product development process but the products themselves.

The unique ability to directly print the digital 3D CAD design has allowed new and innovative products to be added to a company portfolio producing mass product customerisation. This parametric product portfolio directly impacts on previously held views of "Design it once, make many" or "One product fits all" philosophy previously exhibited by the post industrial revolution mentality. Good business is all about allowing the customer to exercise their own choice. In the past a company's view of the market place was "dozens of markets of millions" and nowadays it would be "millions of markets of dozens". It is this expansion into mass niche product development that will be a driver for ever more efficient manufacturing processes such as Rapid Prototyping or Rapid Manufacture as it is becoming more widely referred to.

The new capabilities of the RP industry allows designers and companies to develop products previously thought to be un-manufacturable due to materials, processing, complexity, form, etc. They are currently being applied to high value products such as hearing aids. However as the processes and materials develop, the application will migrate down the value chain.

The powder based 3D printing process with inherent build speed and lack of support requirement has clear advantages over its competitors. The addition, realistic colour 3D printing makes this an ideal process for concept and exhibition type product development. This research has extended the boundaries of this process into direct manufactured components, and direct and indirect tooling applications.

The more recent research into the Digital Light Manufacturing DLM process has focused on this relatively new technique. The research has investigated how the process parameters interact with the parameters required for production of functional parts i.e. rapid manufactured parts. The process parameters have been optimised for part strength, detail, accuracy and surface finish. The application of these non-isotropic materials has been developed with the application of Finite Element stress analysis and physical testing to predict the working life of a product in the field. The application of the DLM for tooling for polymer injection moulding has also been investigated.

The research reported here, has involved interaction with the RP industry and has led to the improvement of their processes. The setting-up costs of the RP processes considered was in the region of £20-40 k.

The results of this industry led research, has been implemented into over twelve case studies documented in this thesis described in Chapter Six. The results of these new products has seen the launch of eight commercial products and an increase in turn over for the companies assisted of over £3 million and also increased employment within the North East region.

This research has been developed from the time compression technologies applied to new product development, enabling new high quality products to be brought to market in shorter lead times with greater efficiency. In Chapter One, the research methodology was defined by the author and reveals the goals and scope of the research work being undertaken, in line with the PhD initial research proposal. The research was progressed as shown by the Gantt chart to target to achieve its aims and objectives.

A number of Rapid Prototyping and Rapid tooling technologies were reviewed in Chapter Two and set the scene of the currently the available main stream technologies and their applications. This also provides background knowledge and research into the technologies of Rapid Prototyping, Rapid Tooling and the application of these methods to Rapid Manufacturing.

The Z-Corps powder based 3D Printing process was investigated in Chapter Four. This shows the author's research work to-date in the development of the 3D printing process from a low cost low accuracy process into a capable rapid manufacturing process. The contribution to knowledge and the uniqueness of the author's research leads on three fronts; process development, materials development and novel application of the technology.

Chapter Four, covers the investigation of the powder based 3D printing process by first investigating the operational parameters, materials properties and accuracy. The process materials properties were then improved using infiltration techniques. The resultant improved knowledge allowed the process to be applied for production of electrode discharge machining electrodes and the manufacture of direct injection mould tools.

This section of the investigation was undertaken in the first halve of the research project and resulted in eight published papers in refereed conference proceedings and journal publications.

The second process to be investigated was the EnvisionTec Acralyte resin based PerFactory process. This area of research is documented in Chapter Five which reveals the research undertaken for the development of the recently developed Digital Light manufacturing process. This process was less well developed compared to the 3D printing development process, and consequently offered more scope for investigation.

Chapter Five, covers the investigation of the digital light manufacturing system parameters and led to an optimised system in relation to accuracy, part strength and surface finish. The interaction of key build parameters has been established. The application of these improved operating parameters, have been applied to a rapid manufactured case study, verified by the application of Finite element analysis and physical testing. The application of the DLM for the manufacture of rapid tooling for injection polymer moulding has been completed. Furthermore a build monitoring system has been proposed and developed.

In total seven refereed research papers investigating the DLM process have been presented at three international conferences with-in the UK and Europe, with a further 2 more abstracts awaiting acceptance at a further conference.

7.2 Research Discussion

7.2.1 Process and Materials Characterisation

The processes have been investigated to understand how they operate, and then they have been systematically researched to improve performance of the both the process and products manufactured. Taguchi techniques have been used to set up and perform a structured test program to provide understanding of the relationships between process parameters such as cure time, peeling velocity, peel height, waiting time, etc and the components manufactured accuracy, strength, hardness and surface finish. The application of experimental analysis allowed these interactions to be analysed, understood and presented.

The experimental analysis can be summarised for each process below;

Powder Based 3D Printing process

- The accuracy of the process has been improved by experimental analysis to optimise the process parameters. The accuracy has been improved by 2% using anisotropic build parameters in the x, y and z directions of 1.0073, 1.0013 and 1.0025.
- The part strength of the final component material has been improved by 25% by infiltrating it with an Araldite and PVA mixture.

Resin Based digital light Manufacturing process

- The DLM process has been characterised and the build parameters optimised for part strength, accuracy, hardness and surface finish using experimental analysis
- The ANOVA test results indicate the following:
    - Layer thickness and exposure time contributed maximum towards hardness, while peeling velocity and waiting time contributed the least.
    - Waiting time and exposure time contributed the most towards strength, while peeling velocity and pixel size contributed the least.
    - Layer thickness and orientation contributed the most towards high accuracy, whereas pixel size and peeling velocity contributed the least.

7.2.2 Finite Element Analysis

To be able to apply Finite element Analysis to components manufactured from any process requires that the material properties need first to be determined. This was achieved by first using the optimised values from the experimental analysis with build samples in the 6 planes of build to provide the non-isotropic values for the material properties. The finite element method then showed that the optimum build direction for strength was found to be in the ZY plane. This data enabled the DLM components to have part strength increase of 14%. . This was then verified using computer simulations and physical testing as presented in section 5.4.

7.2.3 Application of the Processes

A build monitoring system to reduce material wastage and damage to the build plate form has been developed for the DLM system.

The development of the optimised processes, have been applied to the following key manufacturing processes;

Powder Based 3D Printing process

- Manufacture of tooling for thermoforming applications.
- Manufacture of concept parts using polymer injection moulding process.
- Production of electrodes for electro-discharge machining has been achieved using 85% Carbon and 15% ceramic found to be the best mixture.

Resin Based digital light Manufacturing process

- Isotropic properties of DLM materials have been established. The development of the process for direct tooling applications and injection moulding parameters determined.
- A process has been developed for the manufacture of direct tools for polymer injection moulding. Also the Injection moulding operating parameters have been determined.

The research presented has developed a strand of the many strands required for the goal of a Flexible Rapid Manufacturing Systems to be achieved that will enable designers and manufactures to develop new and innovative mass customised products economically.

7.3 Research Impacts

7.3.1 The Application of the process

The 3DP system although not the cheapest in the sub £20k systems, has the quickest build times and one of the lowest part production costs. This when coupled with limited post production processing due to its self supporting build characteristic makes it ideal for concept and design office based operation. The development of new and more accurate processes and materials has allowed the parts to be utilised for components other than proof of concept and shape parts. Figure 4.7.5.1 shows an application of this research developed by the author for production of thermoforming tools, polymer injection tools and production of EDM electrodes.

The DLP system is competing in the £30k region, its major direct competitors are the ObJets and 3D Systems resin based 3DP systems. The traditional Laser based SLA systems cannot compete on price due to the cost of the lasers systems, but do offer greater build accuracy, size and range of materials. However they are currently over 3 times the price of the EnvisionTec DLM system, Section 5.4.3 shows a typical application of the improved process developed from this research work. Isotropic properties of DLM materials have been established. The development of the process for direct tooling applications and injection moulding parameters determined.

7.3.2 Commercial Success of Projects

The application of the research findings have been applied to new product development in a wide range of applications. Chapter Six, utilises the application of case studies, 12 in total, highlighting how the author has applied the findings from this research, to real life product development applications. The result of these projects and industrial collaboration with industry has directly resulted in over £3 million of investment, 20 new jobs created and 125 jobs safe guarded in the North East region.

This is a significant contribution to the local and national economy directly attributable to the Application of "Time Compression Technologies" such as Digital Product Design, Rapid Prototyping and Rapid Manufacturing, allowing the North East region to compete in a global knowledge market based economy.

7.3.3 Concept and Exhibition Prototype Manufacture

The application of the DLM system on the ASL Ltd project documented in section 6.1 coupled with digital product animation, enabled the company to win a £2 million order from Volvo. The connector box shown in Figure 6.1.1 shows a later SLA manufactured part after proof of concept and assembly issues had been resolved using the Z-Corps 3DP prototype connector junction box.

7.3.4 The Niche Product Development or Mass Customerisation

Both processes have been optimised to increase components properties in terms of strength hardness and accuracy. These components now can be increasing used for manufacture of one-off niche market products.

An example of the application of the 3DP is the novelty light switches prototypes using reverse engineering and the 3DP process shown in Figure 6.4.6 and also the LOM Laser guide project described in section 6.4.9. An example application of the DLM system was described in section 6.3.1 for the Salamander Ltd project: initial trials were undertaken using the DLM manufactured components with the company and their client Triton Showers.

7.3.5 Dissemination of research – Impact upon the North East region

The research work has been disseminated within Northumbria University to both under and post graduate students, via lectures, research seminars and case study materials. The research has been disseminated externally by published papers presented at international conferences, exhibitions and company based seminars.

CHAPTER EIGHT: CONCLUSIONS AND FURTHER WORK

8.1 Conclusions

This report full fills the report requirement by the Author for an award of PhD

- **Research Methodology**

  The Author has developed a methodology for the assessment and optimisation of RP processes, as referenced in Chapters 4 and 5 and can be concluded for the;

- **Investigation in to the Powder Based 3D Printing process**
  - The accuracy of the process has been improved by experimental analysis to optimise the process parameters. The accuracy has been improved by 2% using anisotropic build parameters in x, y and z directions of 1.0073, 1.0013 and 1.0025.
  - The 3DP process has been analysed materials properties with the part strength improved by 25% when infiltrated with an Araldite and PVA mixture.
  - The process has been developed for
    - tooling for thermoforming applications
    - manufacture of concept parts using polymer injection moulding process
    - Production of electrodes for electro-discharge machining has been achieved using 85% Carbon and 15% ceramic found to be the best mixture.

- **Investiagtion in to the Resin Based Digital Light Manufacturing process**
  - The DLM process has been characterised and the build parameters optimised for part strength, accuracy, hardness and surface finish using experimental analysis
  - The ANOVA test results indicate the following:
    - Layer thickness and exposure time contributed maximum towards hardness, while peeling velocity and waiting time contributed the least.
    - Waiting time and Exposure time contributed the most towards strength, while peeling velocity and Pixel size contributed the least.
    - Layer thickness and Orientation contributed the most towards high accuracy, whereas Pixel size and Peeling velocity contributed the least.
  - Isotropic properties of DLM materials have been established. The optimum build direction for strength is in the ZY plane

  - The application of finite element techniques to allow DLM components to be used for end use products with a increase of part strength of 14%.
  - The development of the process for direct tooling applications and injection moulding parameters determined.
  - The development of a build monitoring system to reduce material wastage and damage to the build plate form.

- **Research Impacts**
  - The research has been applied to the 3DP and DLM processes to produced enhanced final end use products as referenced in Chapter 6.
  - The research presented has developed a strand of the many strands required for the goal of a Flexible Rapid Manufacturing Systems to be achieved that will enable designers and manufactures to develop new and innovative mass customised products economically.
  - Two Journal Papers and twenty six refereed conference papers have been published and presented at international conferences.
  - The application of this research and collaboration with industry and RP manufacturers has resulted in over eight commercially available products.
    - One of these products, “two pint” re-useable plastic bear glass has now sold over 1 million units,
    - One automotive project assisted in the winning of a £2 million order for ASL Systems Ltd,
    - Another high value medical imaging product is sold world wide by VisiTec International ltd.
    - £3 million of investment in manufacturing capacity, 20 new jobs created and 125 jobs safe guarded in the North East region are directly attributed to the Authors research for his MSc and PhD

8.2 Uniqueness of Research

The uniqueness of the research for each process is:

- The 3D powder based printing process:
    - Characterisation of the process and materials.
    - Development of the application of 3DP parts for mould tools for both vacuum forming and injection moulding.
    - Development of materials for the manufacture of carbon electrodes for Electro discharge machining.
    - Development of the 3DP process for Flexible Rapid Manufacturing Applications

- The Digital Light Manufacturing process;
    - Characterisation of the process and the effects of the build parameters on strength, accuracy and surface finish.
    - The application of DLM for direct or rapid manufactured components.
    - The development of process for Rapid Tooling applications.
    - The development of a new build monitoring system.

- The application of this research for the development of several commercial products.

8.3 Further Work

Over the period of this project several research topics have been investigated, however several more have gained prominence and require further investigation. The scope for further research includes;

- Foaming of DLM resins for manufacture of porous light structures for medical applications.
- Development of a DLM test rig, to enable testing of new materials developments such as the new ceramic Nanotechnology resins released September 2006 by EnvisionTec.
- Development of new materials for the build structure for the DLM process, for example the basement requires development to allow longer and more dependable life spans.
- Analytical analysis of DLM process for improvement of the build performance in particular the peeling action after each layer,
- Dissemination of research outputs to industrial and academic community
    - 4 papers to be published.

References

1 Dickens P M, “Rapid Prototyping the Ultimate in Automation?, Assembly Automation”, Vol 14 No 2, 1994, pp. 10-13.

2 Burns M, Howison J, Digital Manufacturing – “Napster Fabbing: Internet delivery of physical products”, Rapid Prototyping Journal, Vol 7 No 4, 2001, pp. 194-196.

3 Kochan, A, “Rapid Prototyping helps Renault F1 Team UK improve championship prospects”, Assembly Automation, Vol 23 No 4, 2003, pp. 336-339.Burns, M, “Automated Fabrication – Improving Productivity in Manufacturing”, PTR Prentice-Hall, Englewood Cliffs, NJ, 1993.

4 Meeting Minutes at House of Hardy, 22nd August, 2006

5 Stan Davis, “Future Perfect”, Addison-Wesley, Reading, MA, 1997

6 Marianna Sigala, “Mass customisation implementation models and customer value in mobile phone services” Managing Service Quality, Vol 16 No 4, 2006, pp. 395-420

7 Hart, C Taylor, JR, “Value creation through MC, Achieving competitive advantage through mass customisation”, paper presented at University of Michigan Business School Seminar, 1996

8 Hague R, Mansour S, Saleh N, ”Design opportunities with rapid Manufacturing” Assembly Automation , Vol 23 No 4, 2003, pp. 346-356

9 Chua CK, The SH, Gay, RKL, “Rapid Prototyping Versus Virtual prototyping in product Design and Manufacture”, Int Journal Advanced Manufacturing technology, Vol 15, 1999, pp. 597-603

10 Burns, M, “Automated Fabrication – Improving Productivity in Manufacturing”, PTR Prentice-Hall, Englewood Cliffs, NJ, 1993.

11 Wolhers T, “State of the Rapid Prototyping Industry, Journal for Strategic Direction”, Vol 20 No 1, 2004, pp 27-29.

12 Rapid Prototyping Report (1999), “Selective laser sintered parts used directly in spacecraft production”, Rapid Prototyping Report, Vol 9 No 11, 1999.

13 http://home.att.net/~edgrenda/pow/pow9.htm, accessed 06/06/2007

14 http://home.att.net/~castleisland/home.htm, accessed 06/06/2007

15 Time Compression Technologies Magazine (Europe), “Rapid Manufacturing – Using additive manufacturing processes for production”, Time Compression Technologies Magazine (Europe), Vol 8 No 4, Aug 2000, pp. 53-61.

16 Upcraft S, Fletcher R, “The rapid Prototyping Technologies”, Assembly Automation, Vol 23 No 4, 2003 pp. 318-330.

17 Wai, HW, “RP in Art and Conceptual Design”, Rapid Prototyping Journal, Vol 7 No 4, 2001, pp. 217-219.

18 Ng P, Lee PS, et al. “Prosthetic sockets fabricated using rapid prototyping technology”, Rapid Prototyping Journal, Vol 8 No 1, 2002, pp. 53-59.

19 Rosen DW, Chen Y et al.”The rapid tooling testbed: a distributed design-for-manufacturing system””, Rapid Prototyping Journal, Vol 9 No 3, 2003, p. 122-132.

20 Colton J, Blair B, “Expermental Study of Post-build cure of stereolithography polymers for injection moulds”, Rapid Prototyping Journal, Vol 5 No 2, 1999, pp. 72-81.

21 Chuk N, Thomson V, “A comparision of Rapid Prototyping techniques used for wind tunnel model fabrication”, Rapid Prototyping Journal, Vol 7 No 4, 1998, pp.185-196.

22 http://home.att.net/~castleisland/, accessed 09/10/2006

23 Jacobs P, "Sterolithography and Other RP&M Technologies", ASME Press, 1996.

24 Pham DT, Gault RS, "A comparison of Rapid prototyping Technologies", Int Journal of Machine Tools and manufacturine, Vol 38, 1998, pp.1257-1287.

25 Park J, Tari M, et al. "Characterisation of the Laminated Object Manufacturing (LOM) process", Rapid Prototyping Journal, Vol 6 No 1, 2000, pp.36-49.

26 Bellini, A, Guceri A, "Mechanical characterisation of Parts Fabricated using Fused Deposition Modelling", Rapid Prototyping Journal, Vol 9 No 4, 2003, pp.252-264.

27 www.warwick.ac.uk/atc/rpt/Techniques/3dprinting.htm, accessed 20/06/07

28 Hackney P M, Pancholi K P, "Analysis of the application of the Z-Corps 3D-printing system for rapid tooling for plastic injection moulded components", 5th National Conference on Rapid Prototyping, Rapid Tooling and Rapid Manufacturing, Buckinghamshire Chilterns University College, High Wycombe, UK, 2004.

29 http://www.mcp-group.co.uk/rpt/SLM.pdf, accessed 12th July 2006.

30 Hackney PM , Sarwar M, et al. "Getting started in Rapid Prototyping", Flexible Automation & Manufacturing Conference, Teesside University, Teesside, July 1997.

31 Hackney PM , "A Study of Build Accuracy of the Z-Corps 3D Printing Technique and Related Seepage Control", 4th National Conference on Rapid Prototyping, Rapid Tooling and Rapid Manufacturing, Buckinghamshire Chilterns University College, High Wycombe, UK, June 2003.

32 Hackney P M, Sarwar M, "Development of Time Compression Techniques to Assist SMEs with Product Competitiveness", Flexible Automation & Manufacturing Conference, Dublin City University, Dublin, July 2001.

33 Sreenathbabu A, K.P. Karunakaran, "Hybrid adaptive layer manufacturing: An Intelligent art of direct metal rapid tooling process", Robotics and Computer-Integrated Manufacturing ,Volume 22, Issue 2, April 2006, Pages 113-123

34 Hackney P M, Pancholi K P, "The Application of the Z-Corps 3D-Printing System for the Manufacture of Rapid Tooling inserts, for the Production Polymer Injection Moulded Parts", 2004 Time Compression Technologies Conference, Birmingham UK, November 2004.

35 Segal JI, Campbell RI, "A review of Research into the effects of Rapid Tooling on Part properties", Rapid Prototyping Journal, Vol 7 No 2, 2001, pp. 90-98.

36 Hackney P M, Sarwar M, et al. "Spin Casting of Metal parts directly from RP masters", Flexible Automation & Manufacturing Conference, Teesside University, Teesside, July 1997.

37 P Dickens, R Hague, T Wohlers, "Methods of Rapid Tooling Worldwide", Moldaking Technology, Feature Articule, 2007, accessed 25/06/2007

38 Hague R, Mansour S, et al."Design Opportunities with Rapid Manufacturing", Assembly Automation, Volume 23 No 4, 2003, pp. 346-356.

39 P M Hackney, M Sarwar, and J Van Bedaf, "Reverse Engineering – Speeds up manufacture of thermoforming tools", Flexible Automation & Manufacturing Conference 05, University of Deusto, Bilbao, July 2005

40 Hemrick JG, Starr TL, et al. "Release behaviour for powder injection moulding in Sterolithography moulds", Rapid Prototyping Journal, Vol 7 No 2, 2001, pp.115-121.

41 Barcol Number conversion chart, www.barcol-impressor.com/download/impressorinst.pdf, accessed 20/06/2007

42 "A manufacturer's guide to maximising the productivity Gains of finite Element Analysis", Cosmos white paper, accessed 01/02/2006

43 D. Kochan, "Solid Freeform Manufacturing", Manufacturing Research and Technology, Vol 19 Amsterdam, Elsevier, 1993.

44 S. H. Choi and S Amavedeam, "Modelling and Optimisation of Rapid Prototyping", Computers in Industry, Vol 47, 2002, pp.39-53.

45 J. G. Zhou and D. Hersovici, "Parameter Tuning and Optimisation for SLA", Rapid Prototyping Manufacturing Process, Int Conf Manufacturing Automation, Vol 2, 1997.

46 P. M. Hackney, "The Development of 3D Printing Techniques for "Concept Modellers" to Competitive Rapid Prototyping Systems", 3rd Conference on Rapid Prototyping, Rapid Tooling & Rapid Manufacturing, CDRM, Buckinghamshire University, UK, 2002.

47 H. J. Jee and E. Sachs, "A Visual Simulation Technique for 3D Printing", Advances in Engineering Software, 2000, pp. 97–106.

48 X. Yan and P. Gu, "A Review of RP Technologies and Systems", Journal Computer Aided Design, Vol 28, 1996, pp. 307–318,

49 M. A. Wilson, "Analytical Approach to Water Absorption Based In Situ Test Procedure for Concrete", Proceedings Institute of Mechanical Engineers, Vol 217, 2002. Part L

50 P. M. Hackney, "Production of Electro Discharge Machining Electrodes from the Z-Corps 3D Printing Process", Time Compression Technologies, 2002, Manchester, UK, 2002.

51 J. R. Philip, "Theory of Infiltration", Adv. In Hydrosci, Vol 5, 1969, pp 215–296,

52 W. H. Green and G. A. Ampt, "Studies on Soil Physics Part 1: The Flow of Air and Water Through Soils.", Journal Agriculatural Science, 1911, Vol 4, pp.1-24

53 "Z-Corps Installation and Maintainance Pulication", Z-Corporation Ltd, September 2000.

54 Wenbin Hong, Yong Tsui Lee, Haiqing Gong: "Thermal analysis of layer formation in a stepless rapid prototyping process", Applied Thermal Engineering, Vol 24, Issues 2-3, February 2004, pp.255-268

55 Michele Lanzetta, Emanuel Sachs: "Improved surface finish in 3D printing using bimodal powder distribution", Rapid Prototyping Journal, Vol 9 number 3, 2003, pp.157-166,

56 R. Aluru, M. Keefe, S. Advani, "Simulation of Injection Moulding into Rapid Prototype Moulds", Rapid Prototyping Journal, Volume 7, Number 1, 2001, pp. 42-5 1

57 http://am12.eng.rpi.edu/GMPWEB/PDF/EDM.pdf, accessed 21/01/2002

58 www.dlp.com, – Homepage of Texas Instruments Ltd, USA, accessed 25/01/2000.

59 www.envisiontec.de, – Homepage of Envisiontec Ltd., Germany, accessed 06/02/2005.

60 Hackney PM, Pancholi KP, "Analysis of the Envisiontec Perfactory System for Rapid Production of Components and Validation Using Finite Element and Photo-elastic Analysis", Fifth National Conference on Rapid Prototyping, Rapid tooling and Rapid Manufacture, 2004

61 Gibson I, Shi D, "Material Properties And Fabrication Parameters In Selective Laser Sintering Process", Rapid Prototyping Journal, Vol. 3, No. 4, 1997, pp. 129–136.

62 Agarwala et al, "Structural Quality of Parts Processed by Fused Deposition", Rapid Prototyping Journal, Vol. 2, No. 4, 1996, pp. 4–19.

63 Roy Ranjith K, "A Primer on the Taguchi Method", Van Nostrand Reinhold Publications, New York, 1990. ISBN 0-442-23729-4

64 www.itl.nist.gov/div898/handbook, - e Handbook: Engineering Statistics, NIST, accessed 15/01/2005

65 Upcraft S, Fletcher R, "The Rapid Prototyping Technologies", Assembly Automation, vol. 23, No. 4, 2003, pp. 318–330.

66 Users' manual for Taylor Hobson Talysurf Surtronic 3+, Rank Taylor Hobson Ltd., England, 1993.

67 R Hague, S Mansour et al, "Design Opportunities with Rapid Manufacturing", Assembly Automation, Vol 23, No 4, 2003, pp 346 – 356

68 R Hague, S Mansour, N saleh, R Haris, "Materials Analysis of Sterolithography resins for use in Rapid Manufacturing", Journal of Materials Science, Volume 37, 2004, pp. 2457 - 2464

69 J Majhi, R Janardan, et-al, "Multi-criteria geometric optimisation problems in Layer Manufacture", Proceedings of the fourteenth annual symposium on Computational geometry, Minneapolis, United States, 1998, pp.19–28, ISBN:0-89791-973-4

70 "Rapid Tooling", http://www.atirapid.com/tech/te_rapidtool.html, accessed 20/06/2007

71 A. Rosochowski, A. Matuszak, "Rapid tooling: the state of the art", Journal of Materials Processing Technology 106, 2000, pp. 191-198

72 N. P. Karapatis, J.-P.S. van Griethuysen, et al, "Direct Rapid Tooling", Rapid Prototyping Journal, Volume 4, Number 2, 1998, pp. 77-89.

Appendix - Highlighted Research Papers Published

Refereed Journal Papers

1. P M Hackney, M Sarwar
"An Evaluation of Rapid Prototyping "Concept Modelling" Techniques for New Product Development", International Journal of Manufacturing, Product and Process Development Incorporating Computer Integrated Manufacturing System Volume 20 issue 2, 2004, ISSN: 0736-5845.

Refereed Conference Papers Published

2. P M Hackney, M Sarwar
"Operating Characteristics of the Z-Corps 3D Printing Process",
Hackney P. M., Sarwar M.,
National Conference on Materials Research (NCMR 01) University of Cardiff - September 2001,

3. P M Hackney
"The Development of 3D Printing Techniques for "Concept Modellers" to Competitive Rapid Prototyping Systems"
3rd National Conference on Rapid Design, Prototyping and Manufacturing, Buckinghamshire Chilterns University College, High Wycombe, UK, June 2002

4. P M Hackney
"Production of Roughing Electro Discharge Machining Electrodes from the Z-Corps 3D Printing Process"
2002 Time Compression Technologies Conference, Manchester, UK, October 2002, Manchester

5. P M Hackney
"A Study of Build Accuracy of the Z-Corps 3D Printing Technique and Related Seepage Control"
4th National Conference on Rapid Design, Prototyping and Manufacturing, Buckinghamshire Chilterns University College, High Wycombe, UK, June 2003

6. P M Hackney, M Sarwar
"A Comparison of "Concept Modeling" Techniques for Rapid Prototyping"
Flexible Automation & Manufacturing Conference 03, University of South Florida, June 2003

7. P M Hackney
"Analysis of the EnvisionTec PerFactory Rapid Prototyping System"
2003 Time Compression Technologies Conference, Birmingham UK, November 2003

8. P M Hackney, K P Pancholi
"Application Of The Z-Corps 3d Printing Processes For Medical Bone Replacement Implants"

5th National Conference on Rapid Design, Prototyping and Manufacturing, Buckinghamshire Chilterns University College, High Wycombe, UK, June 2004

9. P M Hackney, K P Pancholi
"Analysis of the EnvisionTec PerFactory System for Rapid Production of Components and Validation Utilising FEA and Photo elastic Analysis."
5th National Conference on Rapid Design, Prototyping and Manufacturing, Buckinghamshire Chilterns University College, High Wycombe, UK, June 2004

10. P M Hackney, K P Pancholi
"Analysis of the application of the Z-Corps 3D-printing system for rapid tooling for plastic injection moulded components"
5th National Conference on Rapid Design, Prototyping and Manufacturing, Buckinghamshire Chilterns University College, High Wycombe, UK, June 2004

11. P M Hackney, L C Channap
"Development Of Systems To Increase The Green Part Strength Of The 3d Printed Z-Corps Manufactured Parts By Infiltration Processes To Improve Their Range Of Application"
5th National Conference on Rapid Design, Prototyping and Manufacturing, Buckinghamshire Chilterns University College, High Wycombe, UK, June 2004

12. P M Hackney, K P Pancholi
"The Application of the Z-Corps 3D-Printing System for the Manufacture of Rapid Tooling inserts, for the Production Polymer Injection Moulded Parts."
2004 Time Compression Technologies Conference, Birmingham UK, September 2004

13. P M Hackney, G K Chinnaswamy, A C Arulraj, B T Nair
"Investigation into Surface Finish of Parts Built by the EnvisionTec PerFactory® Rapid Prototyping Process"
6th National Conference on Rapid Design, Prototyping and Manufacturing, Buckinghamshire Chilterns University College, High Wycombe, UK, June 2005

14. P M Hackney, B T Nair, A C Arulraj, G K Chinnaswamy
"Development of a Build Monitoring System for the EnvisionTec PerFactory® Rapid Prototyping Process"
6th National Conference on Rapid Design, Prototyping and Manufacturing, Buckinghamshire Chilterns University College, High Wycombe, UK, June 2005

15. P M Hackney, A C Arulraj, G K Chinnaswamy, B T Nair,
"Investigation into the EnvisionTec PerFactory® Rapid Prototyping Process for Production of Accurate and Strong Functional Parts"
6th National Conference on Rapid Design, Prototyping and Manufacturing, Buckinghamshire Chilterns University College, High Wycombe, UK, June 2005

16. P M Hackney, M Sarwar
"Rapid Manufacturing of Polymer Injection Mould Tool Inserts for Prototype Tooling Production"
Flexible Automation & Manufacturing Conference 06, University of Limerick, Ireland, June 2006

17. P M Hackney
"Analysis of the application of the "digital light processing" rapid prototyping process for functional rapid manufactured components."
7th National Conference on Rapid Design, Prototyping and Manufacturing, Buckinghamshire Chilterns University College, High Wycombe, UK, June 2006

International Conferences committee membership

1. Time Compression Technologies Conference
2. National Conference on National Conference on Rapid Design, Prototyping and Manufacturing

International Conferences Attended

1. Flexible Automation & Manufacturing Conference, Teesside University, Teesside, July 1997
2. Time Compression Technologies Conference, Gayden, UK, October 1996, Warwick
3. Flexible Automation & Manufacturing Conference, Dublin City University, Dublin, July 2001
4. 3rd National Conference on Rapid Design, Prototyping and Manufacturing, Buckinghamshire Chilterns University College, High Wycombe, UK, June 2002
5. 2002 Time Compression Technologies Conference, Manchester, UK, October 2002, Manchester
6. 4th National Conference on Rapid Design, Prototyping and Manufacturing, Buckinghamshire Chilterns University College, High Wycombe, UK, June 2003
7. 2002 Time Compression Technologies Conference, Manchester, UK, October 2002, Manchester
8. 2003 Time Compression Technologies Conference, Birmingham UK, November 2003
9. 5th National Conference on Rapid Design, Prototyping and Manufacturing, Buckinghamshire Chilterns University College, High Wycombe, UK, June 2004
10. 2004 Time Compression Technologies Conference, Birmingham UK, November 2004
11. Flexible Automation & Manufacturing Conference 2005 , Bilbo University, Spain, July 2005
12. 6th National Conference on Rapid Design, Prototyping and Manufacturing, Buckinghamshire Chilterns University College, High Wycombe, UK, June 2005
13. 2005 Northumbria University Research Seminar, Newcastle upon Tyne, UK, Sept 2005
14. Flexible Automation & Manufacturing Conference 2006 , Limerick University, Ireland, June 2006
15. 7th National Conference on Rapid Design, Prototyping and Manufacturing, Buckinghamshire Chilterns University College, High Wycombe, UK, June 2006
16. 8th National Conference on Rapid Design, Prototyping and Manufacturing, Buckinghamshire Chilterns University College, High Wycombe, UK, June 2007

JOURNAL PAPER

An Evaluation of Rapid Prototyping "Concept Modelling" Techniques for New Product Development

P M Hackney M Sarwar

Centre for Rapid Product Development, School of Engineering, University of Northumbria at Newcastle, UK.

ABSTRACT

Rapid Prototyping systems use layer technology to build physical prototypes directly from 3D Computer Aided Design (CAD) data. This provides the opportunity to design more complex parts and assemblies which cannot be made by existing technologies [1]. This paper reviews the emerging technology of low cost 3D printing techniques initially used for "concept modelling", to prove design intent and visualisation of these complex designs, but now being applied to end usage applications.

Concept modellers such as 3D System's ThermoJet, Z-Corp's 3D Printer, ObJet's Quanda, Stratasys' Dimension and EnvisionTec's PerFactory will be examined. A case study is used to show how these low cost systems can substantially reduce new product development time by their utilisation as production processes.

1.0 INTRODUCTION

1.1 Rapid Prototyping (RP) is a range of technologies which describe a process capable of creating complex physical parts directly from 3D digital CAD data [2]. There are now several commercial processes available, all of which work on much the same principle, ie layer manufacture, whereby the 3D digital part is sliced into many very thin layers that are then formed subsequently on top of one another to form the finished component or assembly. The use of RP is becoming more widespread as 3D CAD as a design tool is being used by small to medium sized enterprises (SMEs) to design and manufacture new products [3]. The advantages of RP over traditional CAM based tools are both time and cost of manufacture, ensuring the designer can hold a part designed yesterday in his/her hand today.

1.2 At the moment the RP industry is split into two distinct areas:

- High cost, high precision systems - SLA, SLS, FDM, LOM,
- Low cost (<£50k) "concept modellers" - 3D "Ink Jet" Systems
    - 3DSystems ThermoJet,
    - ObJet's Inkjet System
    - Z-Corps 3D Printer.
  - Other concept modelling systems
    - Stratasys FDM Dimension
    - Envision PerFactory

The high cost RP machines are predominantly situated in bureau companies with a range of machines to enable them to serve all their customer needs. The low cost RP machines are predominantly being installed in design houses and large OEMs to enable design verification and to serve as a communication tool [4]. Wohlers Associates estimates that 3D Systems, Stratasys, Z Corps, ObJet Geometries and EnvisionTec sold a combined total of 656 3D printers in 2002, compared to 490 in 2001. This is an increase of 33.9%. This jump compares to a decline of 4.3% in 2001. Growth of 3D printers in 2002 is an interesting topic of discussion, especially considering that sales of other RP systems grew by only 2.1%. 3D printers have grown to represent 25.8% of all RP systems installed worldwide [5]. This paper will review the current concept modelling processes and benchmark these processes. The paper will also investigate the application of the Z-Corps ZP400 3D Printer, and illustrate, via case studies, the use of the ZP400 RP process.

2.0 THE BENEFITS OF CONCEPT MODELLING TECHNIQUES

2.1 The principle of the "concept modellers" is that the parts are produced to a low accuracy of normally $\mp$ 0.5 mm, low part strength <15 *MPa*, with limited engineering part utilisation. The benefits include:

low system purchase and operating costs, low part costs, load and go capability, and fast prototype part production.

However these "Concept parts" have been successfully used in several projects as parts, sacrificial patterns or tools for production of working components. A good example is the Z-Corps 3D printer binder cartridge head cap shown in Figure 1. This component is actually produced on the same machine that made itself. The ThermoJet uses a type of investment casting wax, and is now being used regularly in the production of aluminium and steel parts via the investment casting process without expensive new processes or process modifications at the foundry.

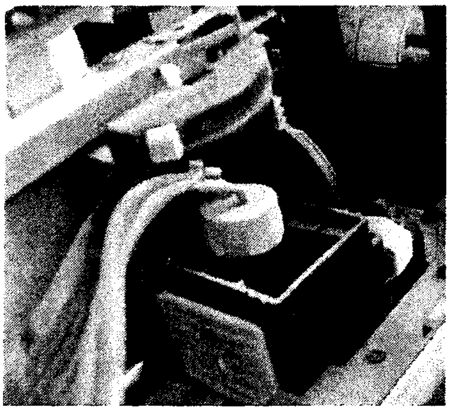


Figure 1: Z-Corps 3D Printer, Print head Cap

2.2 *RAPID PROTOTYPE SYSTEM SELECTION*

The selection of an appropriate, reliable RP system is an impossible task to fulfill to cover every prototyping requirement of a company. As most products comprise many different parts, which by their nature are manufactured from a range of materials due to the design intent. The selection of an RP system is a trade-off between total use of bureau services 100% to 0%, ie total production of all RP parts "in-house".

Several RP systems can produce parts in a small variety of base materials. This is limited by the system process chosen and the amount of research effort that has been expended into the development of specific process dependant materials and process accuracy.

An analysis of typical parts requirements for a company is essential before even considering purchasing an RP system or systems. The key factors to consider are end part final material, part function, part size, accuracy, details, cost, security and speed, Figure 2 represents some of the decision branches that need to be followed when selecting an RP system.

Concept design is where the design is fully fluid and several concepts/ideas are being developed at the same time, as the optimum solution is not yet defined.

Concept modelling systems have been developed to provide designers with fast feedback on their work, and in order for this to be possible, the manufacture of RP parts for concept must be physically close to point of use. The parts need to reflect the intent of the designer in the form of shape and occasionally texture. They must also be quick and inexpensive in order that experimentation can occur freely.

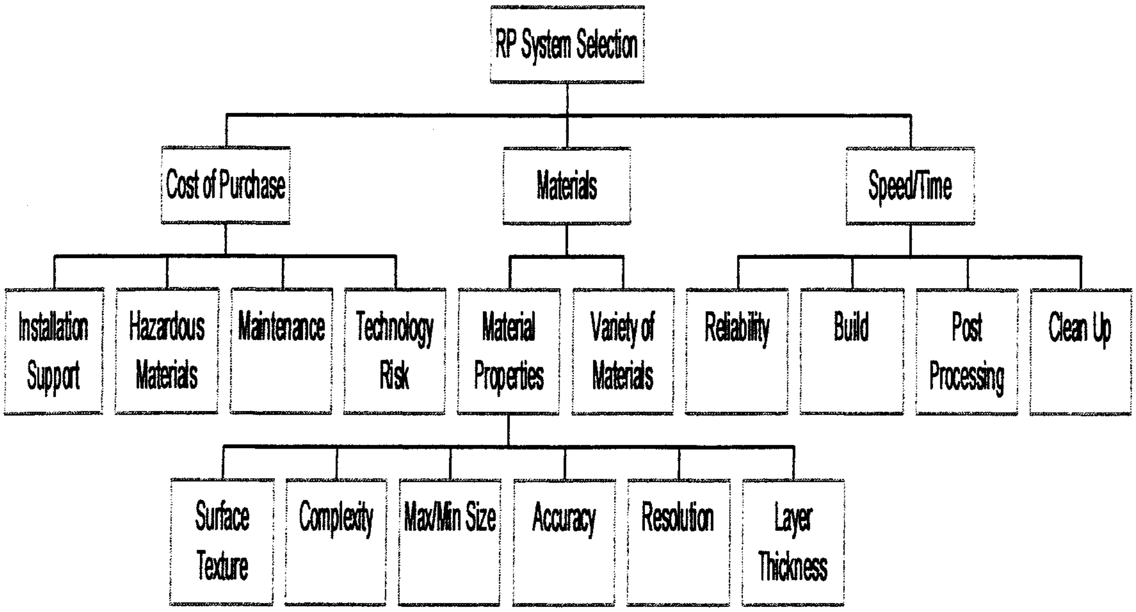


Figure 2: RP Selection Framework

3.0 REVIEW OF CONCEPT MODELLING PROCESS

3.1. 3D Systems ThermoJet system

The MJM ThermoJet system [6] uses a print head to spray droplets of molten wax build material (also used as support material). The print resolution is 300 x 400 x 600 dpi (x, y, z). The process operates by first slicing the 3D CAD data into layers, these layers are then printed onto the layer below with several passes of the head required to deposit the full width of the component, Figures 3a and 3b.

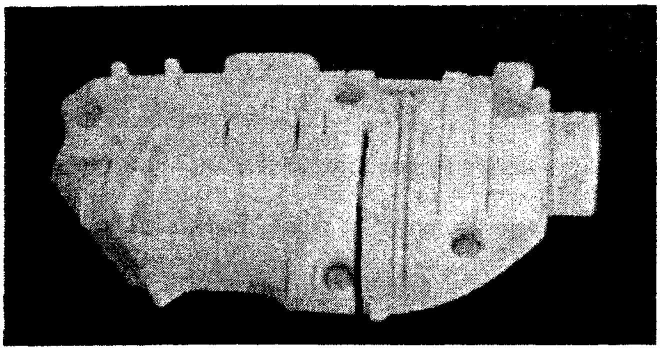


Figure 3a: Part from ThermoJet Process

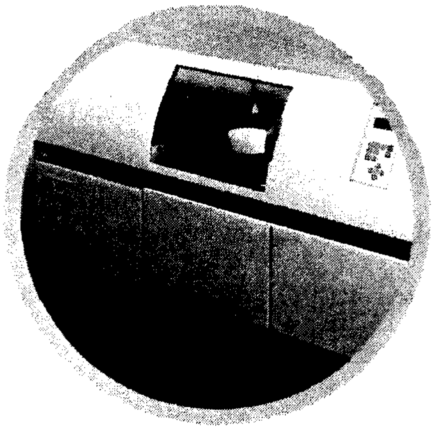


Figure 3b: ThermoJet Machine
(Courtesy of 3D Systems Ltd)

A support framework is required for the underside of the components and any overhangs unconnected to lower regions of the model. The support removal is facilitated with the parts first being refrigerated to embrittle the support structure, this is one limiting factor of this process. Upper facing surfaces are capable of excellent surface finish detail, but underside surfaces are poor and the requirement for support removal means that wall thickness is limited.

Benefits	**Drawbacks**
Excellent for productive of investment casting waxes	Support material removal
Excellent upper surface definition	Brittle parts
Parts easily joinable via melting	Poor underside surface finish

Excellent upper surface finish	Not suitable for thin walled parts
Choice of two materials – ThermoJet™ 2000, 88	Reliability problems reported
Able to smooth models with heat gun or hot knife	
Supported by 3D Systems (largest RP machine manufacturer)	

3.2. OBJET'S INKJET SYSTEM

The ObJet system [7] was developed in Israel and uses similar resins to the SLA processes, i.e. it uses UV sensitive photopolymer. The process comprises the inkjet head traversing the build area, and where the part is solid, fine droplets of model material are deposited simultaneously with the support structure for future layers, Figures 4a and 4b. The resin is deposited with a print resolution of 600 x 300 dpi (x, y). A UV lamp situated above the build platform cures the resin droplets. The head has a y deposition width of 60 mm, thereby several strips of resin are laid for wider parts. The build platform lowers by one layer thickness (20 microns) and the process repeated. The parts are cleaned and the support structure removed by a combination of hand and water jet washing.

A second generation of ObJet machines have been released with fullcure™ materials with 16 μm resolution with eight print heads.

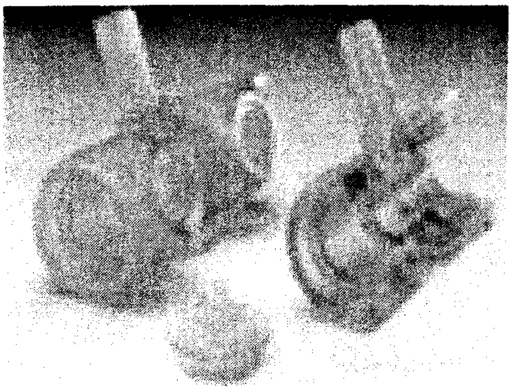


Figure 4a: Part from ObJet Process

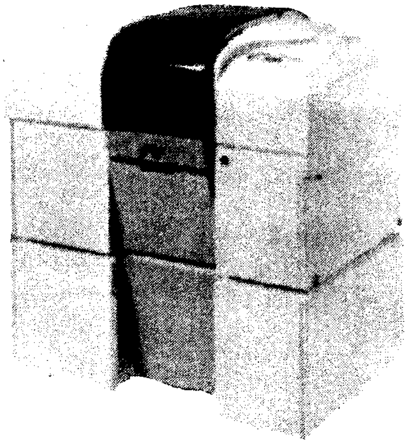


Figure 4b: ObJet Machine
(courtesy of ObJet Technology Ltd)

Benefits	**Drawbacks**
Material strength	Technology still under development – reliability, accuracy
Speed/width of build strip	New start-up Company
Similar to SLA resins	
Finest layer resolution (layer step) and print resolution (DPI)	
Form and fit testable	
Vacuum castable	
Two machine variants	
Large research and development budget	

Machines: ObJet Quadra Tempo, ObJet Quadra, Eden 330

3.3. *Z-Corps 3D Printer*

The 3D printer is available in three machines. The basic build process is the laying down a layer of powder (ceramic or starch based) 0.1 to 0.25 mm thick. The model is sliced and the solid sections printed via "Canon InkJet cartridge" in the y axis, the carriage increments (similar to paper feed) in the x axis and another strip of binder is deposited. The parts are formed in the build chamber that drops by one layer thickness as more material is deposited [8] and bound above it, Figures 5a and 5b.

The machine is capable of building several layers per minute. As the powder supports the part no support structure is required therefore allowing complex parts to be built. The binder can be coloured with a dye allowing coloured parts to be generated, for example the results of a Finite Element Analysis. The surface finish on the underside is poorer than the topside due to seepage of the binder into the surrounding material [9].

A secondgeneration machine has recently been released based on a HP print head system, increase in accuracy and utilisation of Z-cast material for investment casting mould production

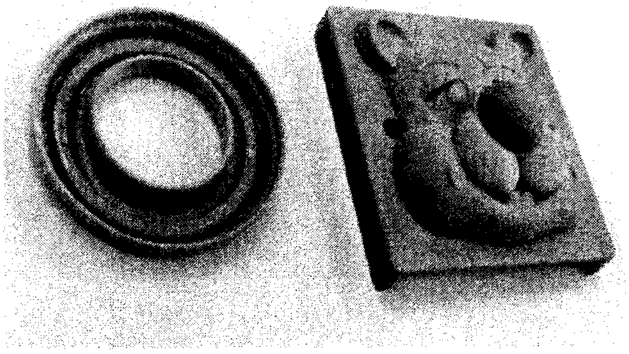


Figure 5a: Parts from 3D Printing Process

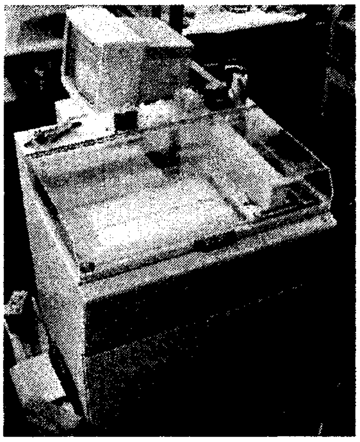


Figure 5b: Z-Corps ZP400 Machine

Benefits	**Drawbacks**
Fastest build speed	Least accurate of concept modellers
No support structure	Underside surface finish - poor
Complex parts, thin walled parts	Poor strength
Build materials :	Limited fit and function usage

starch - rubberising, investment castable
plaster ceramic - detail, definition strength
zircon - investment casting

New large build volume machine (largest of concept modellers)

Colour capable, Easy clean

Alternative powders – metallic, conductive

Machines ZP400, ZP406, ZP810

3.4. *Stratasys – FDM System*

Fused Deposition Modeller – Dimension – this is a re-packaged FDM 2000 system that uses ABS or wax filaments that are heated and extruded to form the part and support structure in the same way as the more accurate high end FDM machines [10]. The part is built on a foam base, and support structure and base removed by hand, Figures 6a and 6b.

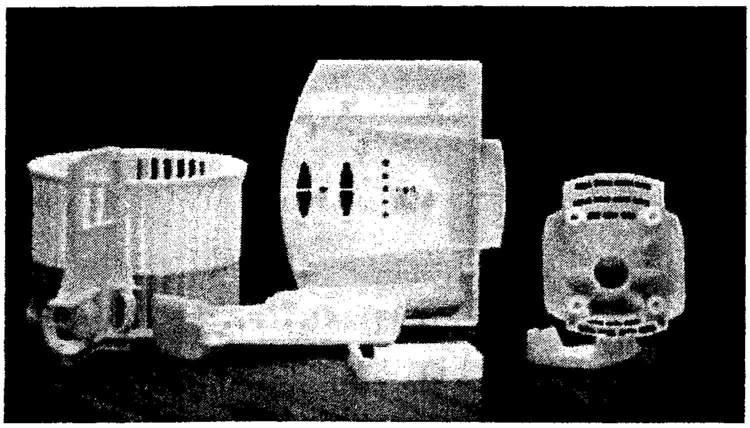


Figure 6a: FDM Dimension parts and Machine

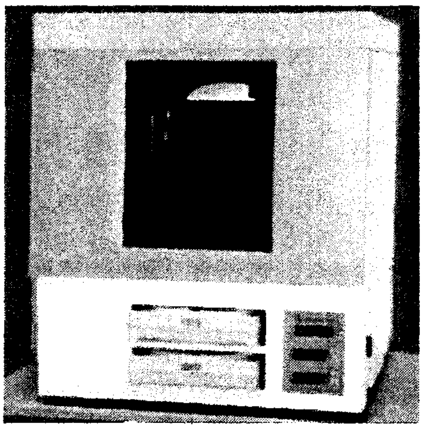


Figure 6b: FDM Dimension Machine
(Courtesy of Stratasys Ltd)

Benefits	**Drawbacks**
Material	Slow
Material strength	Expensive materials
Flexible hinges	Surface finish
Water proof	Finishing
Mature Technology	
Inexpensive - £23k	

3.5. *ENVISIONTEC - PERFACTORY*

Personal Factory – this is a new commercial process that uses similar technology to SLA in that light sensitive resins are set where the solid part is required.

The process is that of Stereolithography (SLA) machine in reverse, in that it builds the part from the bottom of the vat of photosensitive liquid and not from the top as in the SLA process. In place of an expensive laser, the Perfactory system uses visible light to set the resin [11].

The vat has a glass base, through which light is directed to set the layer of liquid resin above. The build platform tilts to peel the part from the glass and then lifts and squeezes a new layer of resin between the part and the glass, and a new layer is exposed, Figures 7a and 7b.

The light is projected onto the glass via an array of 1.25 million mirrors, each electronically controlled to shine a pixel of light upwards, or to deflect away from the build area. This Digital Light Processing (DLP) is the heart of the new technology (used in large screen projectors), and sets a layer in one process therefore saving valuable time. [11]

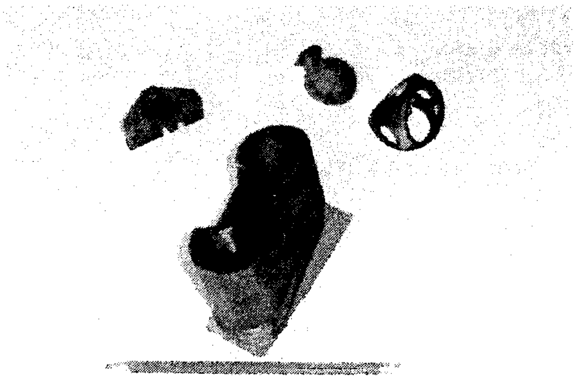


Figure 7a: PerFactory

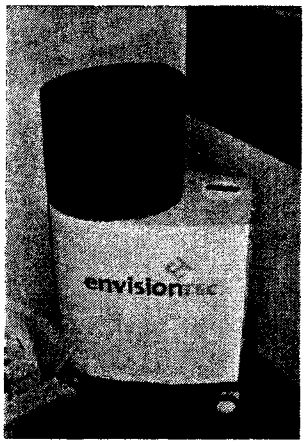


Figure 7b: PerFactory Machine

Benefits	**Drawbacks**
Materials similar to SLA	New Process
Accuracy	Materials and process in early stage of development
Speed	
Inexpensive - £34k	

4.0 BENCHMARKING OF CONCEPT MODELLERS

4.1. The systems considered in section 4 have been benchmarked in Table 2. The processes are based on different technologies, therefore direct comparison of one to another is not possible. For example, the FDM machine has a vector manoeuvring system. Table 2 will assist companies in following their own specific decision path as per Figure 2, to ensure optimum process selection for their own individual requirements.

4.2.

RESOLUTION	Manufacturers' quoted accuracy – dots per inch or per mm of material laid down
ACCURACY	Relative from test work, observation and manufacturers' information 0 – lowest, 10 – highest relative to 3D systems SLA Viper System
DURABILITY	Relative to handling after post processing 0 – lowest, 10 – highest relative to 3D systems selective Laser Sintering process with 30% GF Nylon
SPEED	Time from receipt of STL file to part in hand, 0 – slowest, 10 – fastest, relative to Z-Corps ZP40x 3D printer
TYPICAL COSTS	Based on machine purchase price, speed of build, part build operation and material cost
COST	Includes installation, training and start up materials

Table 1: Justification for Table 2

4.3.

When relative criteria is used between 1 and 10 this is from user feedback and part inspection. (1 – lowest, 10 – highest.)

	3D Systems ThermoJet MJM System	Z-Corps 3D Printer ZP400/ZP406/ZP810	ObJet's InkJet Printer Quadra/Quadra Tempo/Eden 330	FDM Dimension	Envision PerFactory
Build Size (mm)	250 x 190 x 200	250 x 200 x 200/ 500 x 600 x 400	270 x 300 x 200	203 x 203 x 305	75 x 56 x 50 mini 255 x 191 x 250 std
Material	Thermoplastic wax	Starch, ceramic	Photopolymer	ABS	Photopolymer
Resolution (x, y, z) dpi/mm	300 x 400 x 600/ 0.08 x 0.065 x 0.04	300 x 300 x 360/0.08 x 0.08 x 0.07	600 x 300 x 1270/ 0.04 x 0.08 x 0.02	0.178mm(2)	0.07 x 0.07 x 0.03 min 0.25 x 0.25 x 0.5 std
Accuracy Relative (1-10)	5	4	6	6	7
Office Environment	Yes	Yes	Yes	Yes	Yes
No of build materials	Build material only	Power and Binder	Two – build & support photo-polymers	Build material only	Build material only
Support requirements	Yes	No	Yes	Yes	Yes
Date of Introduction	1998	1998/2000/2001	2000	2002	2003
Colour	Single neutral, grey black	Any single, colour upgrade/colour/colour	Amber (SLA colour)	White	Red
Durability Relative (1-10)	Brittle – wax 2	Brittle – plaster 2, Infiltrated 6	Good 7	Excellent 8	Average 5
Support removal	Yes – Refrigerated	No	Yes – Waterjet	Yes	Yes
Speed (1-10)	4	0	7	1	7
Material Recyclable	No	Ceramic – Yes, Starch – Limited	No	No	Yes
Medical models usage	Yes	No	Yes	No	Yes
Investment casting	Yes	Starch only – limited application	No	No	Yes
Bureau usage (UK)	Yes	No – In house	Yes	No	Not Yet
File type	STL	STL	STL	STL	STL/CLI
Support/Equipment	Fridge, technician	De-powdering unit, autowaxer (supplied)	Water jet washer	None	None
Typical costs per part (min costs may apply)	£20	£5 ceramic £10 starch	£30	£20	£15
Detail upper surface	Excellent	Good	Good	Good	Excellent
Detail lower surface	Poor – where supports removed	Average – Mottled underside	Good	Poor	Good
Expected Materials development	Improved strength thermoplastics	Metals, ceramics, carbons	Increased as per SLA process	None	Very Good
Cost	£36k	£37k	£46k	£23k	£34k
Maintenance (pa)	£5k	£3k	£6k	£4k	£3k
Start up Cost	£1.3k	£1.5k	£5k	£2k	£2k

Table 2: Benchmarking of Concept Modellers

5.0 CASE STUDY OF APPLICATION OF LOW COST CONCEPT RP MODELLERS FOR PROTOTYPE PRODUCTION

A local company approached the Centre for Rapid Production Development based at Northumbria University, after encountering problems with a new product they were developing. The function of the product was to produce the recess for electrical wall sockets, in a plaster/breeze block/brick wall. The product fits onto industrial impact hammer drills (with the drill action turned off); the component consists of a square plate with symmetrically arranged teeth in the shape of daggers, debris is allowed to fall between the teeth and out of the rear of the tool. The hole is produced by first drilling a location hole for the socket, the hole cutter is then located by this hole with a tapered extension, the cutter is aligned to the wall and 30 seconds of impacts occur. A furrow is then produced in the masonry, the tool is rotated 90 degrees and a further 30 seconds of impacts occur. The processes of furrow making and dislodging the brittle masonry in this pattern, rapidly makes the hole of the required size and depth even in very hard engineering bricks.

The problem the company was experiencing was that the hard brittle tool steel (D2) were found to be cracking and fracturing after limited usage (30 seconds). The company had been through the lengthy and costly process of design modifications, tooling modifications, wax pattern production and investment casting using traditional techniques several times. This cycle took typically 13 weeks from failure to new design concept, CAD design, tooling, casting and production of working prototypes. The public and their OEM's were losing faith in their product and their capabilities. To solve the problem, the CRPD and The CADCAM Centre worked together to redesign the cutter to reduce weight and critical stress concentrations by 40%. The FEA analysis however could not fully simulate the high-speed impacts and resonance, therefore physical prototypes were required as shown in Figures 8 - 10. Several sacrificial patterns were produced on the Z-Corps printer within the CRPD and successfully cast at a commercial investment casting foundry, which eliminated the tooling and wax production stages, therefore cutting 5 weeks off a 6 week process to get to the trial stage. The company now had D2 tool steel prototypes on test within a week of a new design being finalised and sent for RP production at 25%

of the cost previously paid. These sacrificial patterns are now being made using the ThermoJet process at the Digital Factory, Bishop Auckland College, UK, as this process is more tuned to investment casting than the Z-Corps process.

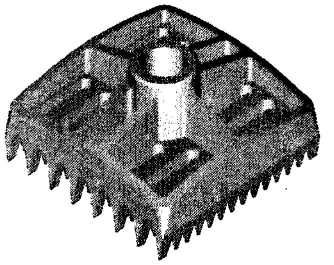


Figure 8: 3D model of design of square hole

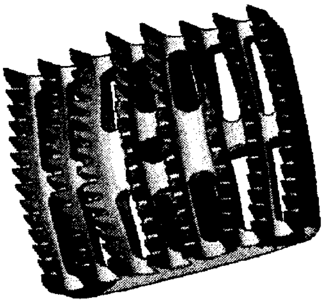


Figure 9: FEA Analysis

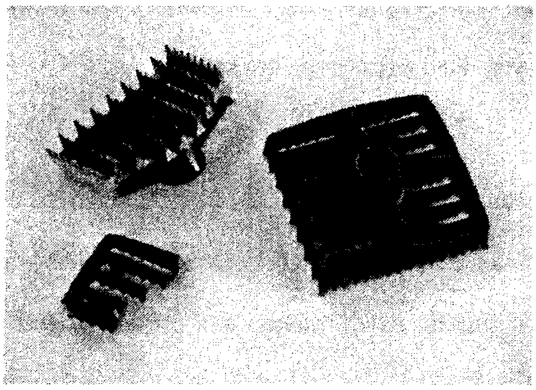


Figure 10: Original Casting and failed castings *(courtesy of Cleveland Engineering Ltd)*

6.0 CONCLUSIONS

The advent of mid range 3D CAD solutions capable of being used by Engineers as design tools, not just 3D modellers, has resulted in a requirement for rapid prototyping. Concept modellers as described in this paper can fulfil some of the design, test and evaluation requirements found in the product development process. The choice of which system is dependent on the end use of the parts produced. The ObJet process produces the most accurate and durable parts, the Z-Corps 3DP process the quickest, and the EnvisionTec process the most complex parts. The ThermoJet process is the most suitable for investment casting and excellent upper surface detail. The FDM Dimension produces the most usable parts due to the ABS mind material, but is the slowest process.

The PerFactory produces parts quickly with the material development along the SLA route this could replace some SLA processes.

The cost advantage of concept modellers discussed in this paper over traditional RP processes allows companies to create models as the design process progresses, allowing increased communication and participation of all stakeholders in the product development process.

7.0 ACKNOWLEDGEMENTS

The author would like to thank Government Office North East for providing the ERDF funding to support this project, together with the CRPD core team, Professor M Sarwar, Mr D Bell and Ms F Ward.

REFERENCES

[1] Innovations, State of the Rapid Prototyping Industry, *Strategic Direction*, Vol 20 No 1 2004, p 27 – 29.

[2] P M. Hackney & M. Sarwar, *Development of Time Compression Techniques to Assist SMEs with Product Competitiveness*, FAIM Conference 2001, Dublin.

[3] P. M. Hackney & M. Sarwar, *Operating Characteristics of the Z-Corps 3D Printing Process*, NCMR Conference 2001, Cardiff University.

[4] P M Hackney, M Sarwar, S Hogarth, *Getting Started in Rapid Prototyping,* Flexible Automation & Manufacturing Conference, Teesside University, Teesside, July 1997

[5] Wohlers Report 2003, Rapid Prototyping, Tooling and Manfufacture, State of the Industry, Annual Worldwide Progress Report. http://wohlersassociates.com

[6] 3D Systems Website: www.3Dsystems.com (accessed 04/02/02)

[7] ObJet Technology Website: www.2Objet.com (accessed 06/02/02)

[8] ZCorporation Ltd Website: www.Zcorporation.com (accessed 21/01/02)

[9] P M Hackney, *A Study of Build Accuracy of the Z-Corps 3D Printing Technique and Related Seepage Control*, 4th National Conference on Rapid Prototyping, Rapid Tooling and Rapid Manufacturing, Buckinghamshire Chilterns University College, High Wycombe, June 2003

[10] STRATASYS Website: www.stratasys.com (accessed 21/03/03)

[11] Perfactory – EnvisionTec Website: www.envision.com (accessed 21/03/03)

Operating Characteristics of the Z-Corps 3D Printing Process

P M Hackney, M Sarwar
School of Engineering, University of Northumbria at Newcastle, Ellison Building, NEWCASTLE UPON TYNE, NE1 8ST

SYNOPSIS

Rapid Prototyping processes such as Stereolithography (SLA), Selective Laser Sintering (SLS) and Fused Deposition Modelling (FDA) have developed over the last decade into accurate manufacturing tools. This has positively assisted companies to develop innovative new products and hence improve competitiveness.

Although the above processes have proved to be successful they have rarely been implemented within companies owing to their large initial cost and operating requirements.

The introduction of new low cost "concept" modellers such as the Z-Corps 3D printer and the 3D System ThermoJet printer has produced a step change in rapid prototyping activity.

This paper investigates the operating performance associated with the Z-Corps 3D printer and should prove useful to the potential users of this new technology and design engineers.

1 INTRODUCTION

Rapid Prototyping has taken enormous steps since its launch in 1987 with the Steriolithography process; today there are over 30 commercially available processes. The accuracy and the material properties have also evolved, with systems now able to produce accurate parts in realistic engineering materials.

These developing systems have split into two sectors: high cost, high accuracy systems such as SLA, FDM, SLS, LOM, etc, and low cost, low accuracy "concept modellers" such as 3D Systems, ThermoJet, and Z-Corps 3D printer. The high accuracy systems have a capital/cost greater than £200k and are predominantly found in bureaux, and the low accuracy systems have a capital cost under £40k and are found in design centrix companies.

The Centre for Rapid Product Development (CRPD) recently purchased a Z-Corps 3D Printer to assist its design function and this paper outlines the findings of investigations into its production capability.

2 Z-CORPS 3D PRINTER

The office compatible Z402 System claims to be the world's fastest rapid prototyping system[1] for the creation of 3D models directly from 3D CAD files. The 3D model is sliced into sections 0.1 mm to 0.3 mm thick. The machine consists of a feed chamber, a build chamber (z travel), powder spreader and a binder print head (x, y travel). The build platform drops the build depth and the feed piston travels up a corresponding amount. Powder is spread across at the required thickness to fill the build chamber. The print head (ex canon bubble jet)[2] then prints the layer with the binder solution (ZP09), the outer shell has a higher binder density than the internal section, providing a hard shell and softer internal structure.

Build Speed:	25 mm per hour – ceramic 50 mm per hour – starch
Build Size:	200 x 250 x 200 mm (8 x 10 x 8 inches)
Machine Size:	740 x 910 x 1070 mm
Weight:	136 Kg
Support Equipment:	Depowder Unit Autowaxer
Recyclability:	Starch – 2 to 3 times only Ceramic – several times
Post Production:	Wax infiltration strengthens parts by filling voids with a paraffin wax at 60^0C, this also improves the surface finish.
Siconnect 900:	Strengthens the exterior shell only, by a drip infiltration method.
Elastomer:	Starch materials only, used to create rubberised components such as Bellows and seals.

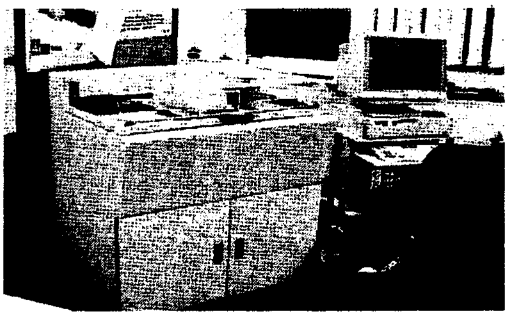


Fig. 1. Z402 Rapid Prototyping Machine

3 ZP402 MATERIAL CHARACTERISTICS

X-Ray Defraction (XRD) is a technique to characterise materials. This technique takes advantage of coherent scattering of x-rays by polycrystalline materials to obtain structural information. This technique is used to characterise the ZP402 build materials.

3.1 ZP11 – Starch Based

Starch is the common name given to white granular powder that is odourless and tasteless. A complex carbohydrate ($C_6H_{10}O_5$), is abundant in cereal plants, also a significant amount of sucrose (sugar) ($C_{12}H_{22}O_{11}$) was found.

This material is water-soluble and the effect of heating above 180^0C results in the material becoming liquid.

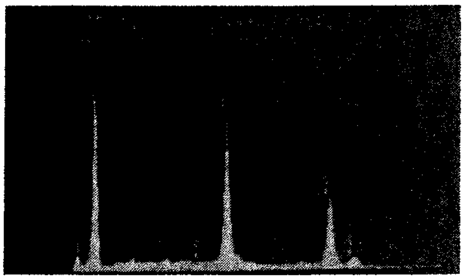


Fig. 2. XRD Analysis ZP11 Starch Based Powder

3.2 ZP100 – Ceramic Based

XRD revealed calcium sulphate ($C_aS_{04}ZH_20$), also called "Gypsum". It is very common in dried salt pans and sedimentary rocks such as limestone. The material is in hemi-hydrate form (C_uS_{04} ½ H_20) such as Plaster of Paris. This sets rapidly (10-20 minutes) by recrystallising with water. A significant amount of calcium (C_a) was also found.

4 MATERIAL STRUCTURE

A Scanning Electron Microscope and Optical Microscope were used to reveal the structures of the build samples before and after wax infiltration when studies. Figs 3, 4, 5, 6. The starch based build material clearly has an open "candy floss" fibrous structure which latter tests revealed had lower hardness and strength. The ceramic build material is closer grained and this is reflected in the better part finish and strength.

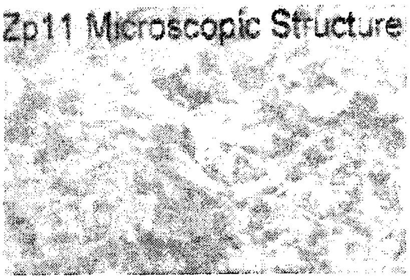


Fig. 3. ZP11 Microscopic Structure

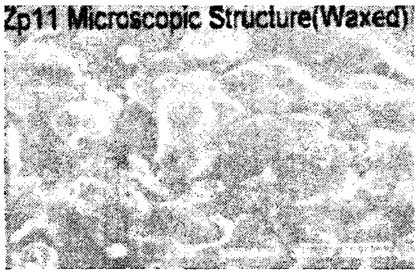


Fig. 4. ZP11 Microscopic Structure (Waxed)

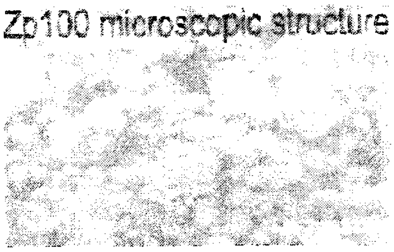


Fig. 5. ZP100 Microscopic Structure

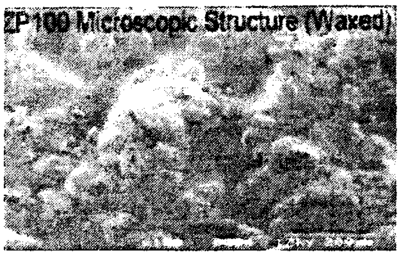


Fig. 6. ZP100 Microscopic Structure (Waxed)

5 MATERIAL HARDNESS

Due to build characteristics parts were tested on all sides. Fig 7.

ZP11 Starch Based – The base was found to be the softest and the top hardest. The average hardness was 27 Vickers, with the highest 29 and lowest 25.

ZP100 Ceramic Based – The results were found to be similar to ZP11 in that the top layer was harder. However the ceramic material is 180% harder overall.

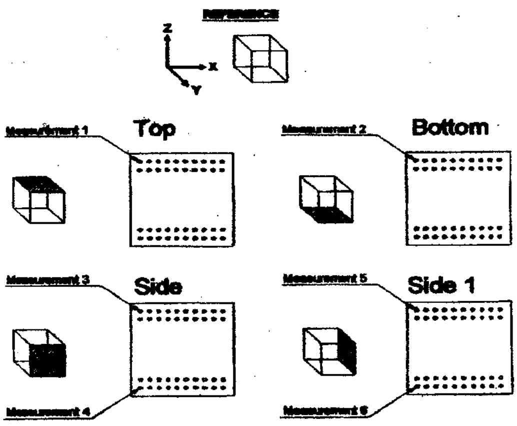


Fig. 7. Hardness Measurement

6 STRESS ANALYSIS

Test specimens were produced and Finite Element Analysis carried out to assess the theoretical stress versus actual failure mode. The orientation of the part on the build platform was investigated and the results are shown in

Fig 8. This revealed that the highest strength is in either direction, in the x-y plane, and weakest is vertically across the build. The binder concentration was varied from the prescribed values and a variance of 15% can be obtained in part strength.

The binder concentration was varied from the prescribed values and a variance of 15% can be obtained in part strength.

ZP11 – Starch Based.	75N on an 8 x 4 mm section.
ZP100 – Ceramic Based	112N on an 8 x 4mm section.

This shows that the ZP100 is 150% stronger than the starch. It was also found that wax infiltration doubled the above values.

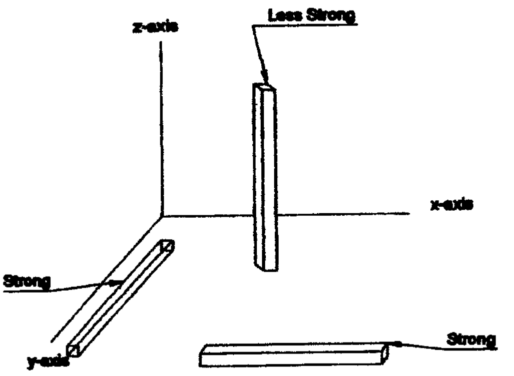


Fig. 8. Build Orientation effect on part strength

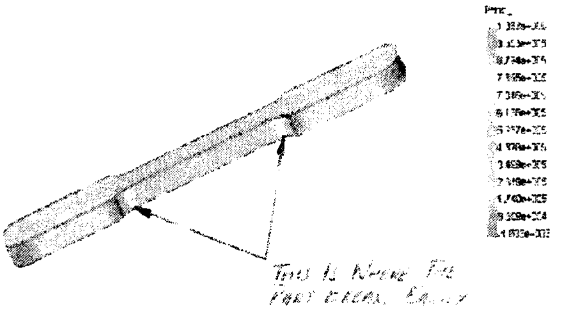


Fig. 9. FEA Test Specimen

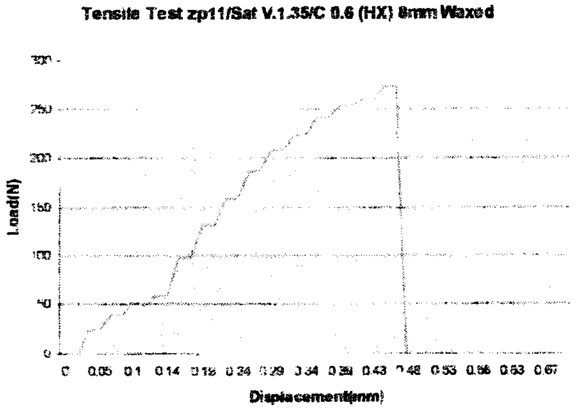


Fig. 10. Tensile Test Results

7 ACCURACY ANALYSIS

Fifteen test parts were built in three phases, in four quadrants of the bed. The build binder core and shell saturation and layer thickness was also varied. This comprised over 200 tests with both ceramic and starch based materials. The conclusions are as follows:

ZP11 Starch Based

- Parts built consistently 0.7% to 2% smaller, an Anistopic scaling factor of 1.0073, 1.0013 and 1.0025 in x, y, and z axis.
- Build time directly proportional to binder and core saturation.
- Wax infiltration reduces part size by 2%.
- Raw parts absorb moisture and should be sealed to maintain accuracy.

- Build location, particularly with contaminated build material effects parts' geometric shape and accuracy.

ZP100 Ceramic Based

- Binder print area spreads outwards from print area causing the cylinder inner diameter to become too small, whilst its outer diameter is too large, therefore no single scale factor can be used.
- Greatest error in 2 direction.
- Parts repeatable in x, y, but not z axis.
- Wax infiltration has negligible effect on accuracy.
- Anistropic scale factor of 0.998 in x and y axis required for accurate parts dependent on cross-section area.
- Parts need to be left to harden in the machine for several hours to allow removal.

8 CASE STUDY: ELECTRICAL SOCKET, SQUARE HOLE CUTTER

A local company approached the CRPD after encountering problems with a new product they were developing. The function of the product was to produce the recess for electrical wall sockets, in a plaster/breeze block/brick wall.

The product fits onto industrial impact hammer drills (with the drill action turned off); the component consists of a square plate with symmetrically arranged teeth in the shape of daggers, debris is allowed to fall between the teeth and out of the rear of the tool. The hole is produced by first drilling a location hole for the socket, the hole cutter is then located by this hole with a tapered extension, the cutter is aligned to the wall and 30 seconds of impacts occur. A furrow is then produced in the masonry, the tool is rotated 90 degrees and a further 30 seconds of impacts occur. The processes of furrow making and dislodging the brittle masonry in this pattern, rapidly makes the hole of the required size and depth even in very hard engineering bricks.

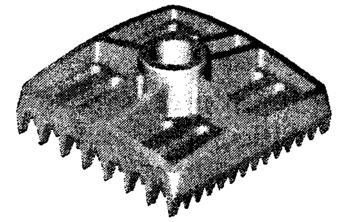


Fig. 11. 3D Model of Design of Square hole

The problem the company was experiencing was that the hard brittle tools steel (D2) were found to be cracking and fracturing after limited usage. The company had been through the lengthy and costly process of design modifications, tooling modifications, wax pattern production and investment casting using traditional techniques several times. This cycle took typically 13 weeks from failure to new design, CAD design, tooling, casting and production of working prototypes. The public and their OEM's were losing faith in their product and their capabilities. To solve the problem, the CRPD and The CADCAM Centre worked together to redesign the cutter to reduce weight and critical stress concentrations by 40%. The FEA analysis however could not fully simulate the high-speed impacts and resonance, therefore physical prototypes were required, Figs 11, 12, 13,14.

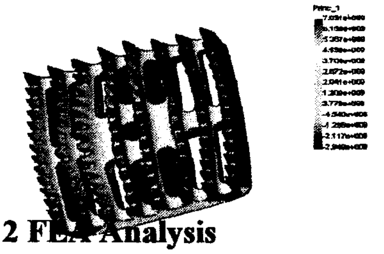


Fig 12 FEA Analysis

Several sacrificial patterns were produced on the Z-Corps printer within the CRPD and successfully cast at a commercial investment casting foundry, which eliminated the tooling and wax production stages, therefore cutting 5 weeks off a 6 week process to get to the trial stage. The company now had D2 tool steel prototypes on test within a week of a new design being finalised and sent for RP production at 25% of the cost previously paid. These sacrificial patterns are now being made using the ThermoJet process at the Digital Factory, Bishop Auckland College, as this process is more tuned to investment casting than the Z-Corps process.

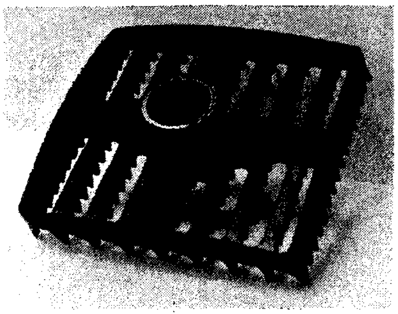


Fig. 13. Original Casting
(Courtesy of Cleveland Engineering Ltd)

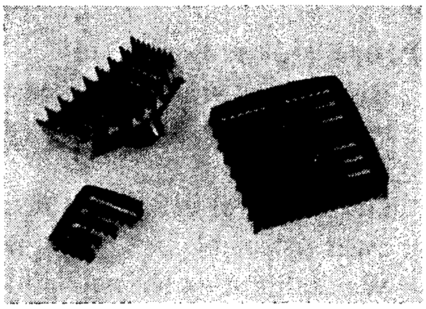


Fig. 14. Original Casting and failed castings

9 CONCLUSIONS

The aim of this paper was to characterise the Z-Corps 3D Printer. The findings can be summarised as follows:

- ZP11 Starch based build material used only when investment casting or rubberising equipment.
- ZP100 ceramic-based build material is superior to starch based materials in resolution, strength, hardness and accuracy.

The correct materials have proved that 3D concept modellers can produce 3D parts. However this process has the capability to use other materials, such as aluminium powders and casting sands to produce parts and cast patterns.

It is believed that 70% of all rapid prototyped models[3] are used as a communication tool, and in this, concept modellers fulfil this requirement at a lower capital and revenue cost, within the range of large and medium sized companies.

10 ACKNOWLEDGEMENTS

The authors would like to thank Government Office North East for providing the ERDF funding to support this project, together with the CPRD core team, Dr T J Bond, Mr D Bell and Mrs F Todd.

11 REFERENCES

1. Z-Corps Publicity Brochure, January 2000.
2. Z-Corps Installation and Maintainance Pulication, Z-Corporation Ltd, September 2000.
3. Wohlers, Terry T. Wohlers Report 2001, Wohlers Associates, Inc., Spring 2001

The Development of 3D Printing Techniques for "Concept Modellers" to Competitive Rapid Prototyping Systems

P M HACKNEY
Centre for Rapid Product Development, School of Engineering, University of Northumbria at Newcastle, UK, phil.hackney@unn.ac.uk

ABSTRACT

The rubicon has been crossed and we have moved from traditional high capital, maintenance and material costs associated with traditional rapid prototyping techniques such as SLA, FDM and SLS processes to low capital, low maintenance and low material costs of the so called "concept modellers". This paper will focus on the new 3D printing techniques and their industrial and tooling applications, together with the possibilities of new materials which are now becoming justifiable to large and medium sized enterprises as well as large OEM companies. Concept modellers such as 3D System's ThermoJet and Z-Corp's 3D Printer will be examined, together with Objet's new 3D UV Reactive Resin Printer. New materials developments undertaken by researchers at Northumbria University into both the materials and accuracy of the Z-Corps process will also be presented.

KEYWORDS Rapid Prototyping, Concept Rapid Prototyping, 3D Printers, Benchmarking

1 INTRODUCTION

Rapid Prototyping (RP) is a range of technologies which describe a process capable of creating complex physical parts directly from 3D digital CAD data [1]. There are now several commercial processes available, all of which work on much the same principle, ie layer manufacture, whereby the 3D digital part is sliced into many very thin layers that are then formed subsequently on top of one another to form the finished component or assembly. The use of RP is becoming more widespread as 3D CAD as a design tool is being used by small to medium sized enterprises (SMEs) to design and manufacture new products [2]. The advantages of RP over traditional CAM based tools are both time and cost of manufacture, ensuring the designer can hold a part designed yesterday in his/her hand today.

At the moment the RP industry is split into two distinct areas:

- High cost, high precision systems – SLA, SLS, FDM, LOM,
- Low cost (<£50k) "concept modellers" – 3D "Ink Jet" Systems - 3DSystems ThermoJet, Objet's Inkjet System and Z-Corps 3D Printer.

The high cost RP machines are predominantly situated in bureau companies with a range of machines to enable them to serve all their customer needs. The low cost RP machines are predominantly being installed in design houses and large OEMs to enable design verification and to serve as a communication tool. This paper will review the current concept modelling processes and benchmark these processes. The paper will also investigate the application of the Z-Corps ZP400 3D Printer, and illustrate, via case studies, the use of the ZP400 RP process.

2 THE BENEFITS OF CONCEPT MODELLING TECHNIQUES

The principle of the "concept modellers" is that the parts are produced to a low accuracy of normally ∓ 0.5 mm, low part strength <15 *MPa*, with limited engineering part utilisation. The benefits include:

- Low system purchase and operating costs
- Low part costs
- Load and go capability

However these "Concept parts" have been successfully used in several projects as either parts, sacrificial patterns or tools for production of working components. A good example is the Z-Corps 3D printer binder cartridge head cap shown in figure 1. This component is actually produced on the same machine that made itself. The ThermoJet uses a type of investment casting wax, and is now being used regularly in the production of aluminium and steel parts via the investment casting process without expensive new processes or process modifications at the foundry.

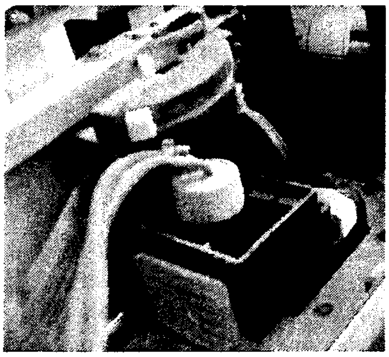


Figure 1: Z-Corps 3D Printer, Print head Cap

3 REVIEW OF CONCEPT MODELLING PROCESS

3.1 3D Systems ThermoJet system

The MJM ThermoJet system [3] uses a print head to spray droplets of molten wax build material (also used as support material). The print resolution is 300 x 400 x 600 dpi (x, y, z). The process operates by first slicing the 3D CAD data into layers, these layers are then printed onto the layer below with several passes of the head required to deposit the full width of the component.

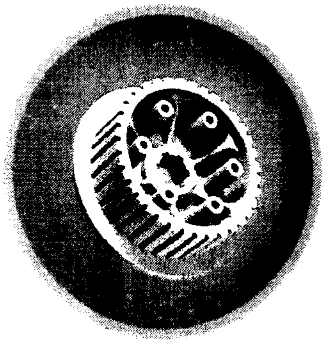


Figure 2a: Part from ThermoJet Process

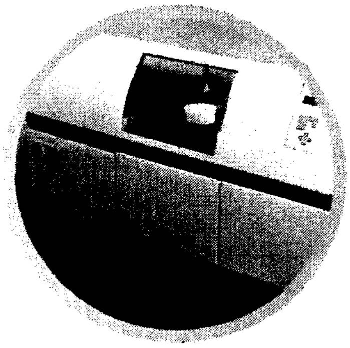


Figure 2b: ThermoJet Machine

A support framework is required for the underside of the components and any overhangs unconnected to lower regions of the model. The support removal is facilitated with the parts first being refrigerated to embrittle the support structure. This is one limiting factor of this process. Upper facing surfaces are capable of excellent detail, but underside surfaces are poor and the requirement for support removal means that wall thickness is limited.

- **Benefits**
  Excellent for investment casting waxes
  Excellent upper surface definition
  Easily joinable via melting
  Choice of two materials – ThermoJet^{TM} 2000, 88
  Able to smooth models with heat gun or hot knife
  Supported by 3D Systems (largest RP machine manufacturer)

- **Drawbacks**
  Support material removal
  Brittle parts
  Poor underside surface finish
  Not suitable for thin walled parts

3.2 Objet's inkjet system

The Objet system [4] was developed in Israel and uses similar resins to the SLA processes, i.e. it uses UV sensitive photopolymer. The process comprises the inkjet head traversing the build area, and where the part is solid, fine droplets of model material are deposited simultaneously with the support structure for future layers. The resin is deposited with a print resolution of 600 x 300 dpi (x, y). A UV lamp situated above the build platform cures the resin droplets. The head has a y deposition width of 60 mm, thereby several strips of resin are laid for wider parts. The build platform lowers by one layer thickness (20 microns) and the process repeated. The parts are cleaned and the support structure removed by a combination of hand and water jet washing.

Figure 3a: Part from Objet Process

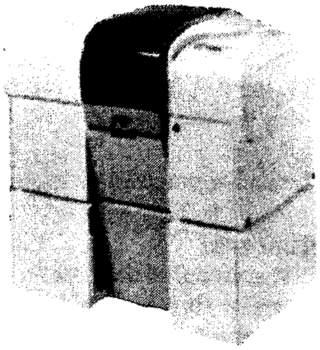


Figure 3b: Objet Machine

- **Benefits**
  Material strength
  Speed/width of build strip
  Similar to SLA resins
  Finest layer resolution and print resolution
  Form and fit testable
  Vacuum castable
  Two machine variants
  Large research and development budget

- **Drawbacks**
  Technology still under development – reliability, accuracy
  New start-up company

- **Machines:** Object Quadra Tempo, Object Quadra

3.3 Z-Corps 3D printer

The 3D printer is available in three machines. The basic build process is the laying down a layer of powder (ceramic or starch based) 0.1 to 0.25 mm thick. The model is sliced and the solid sections printed via "Canon InkJet cartridge" in the y axis, the carriage increments (similar to paper feed) in the x axis and another strip of binder is deposited. The parts are formed in the build chamber that drops by one layer thickness as more material is deposited and bound above it.

The machine is capable of building several layers per minute. As the powder supports the part no support structure is required therefore allowing complex parts to be built. The binder can be coloured with a dye allowing coloured parts to be generated, for example the results of a Finite Element Analysis. The surface finish on the underside is poorer than the topside due to seepage of the binder into the surrounding material.

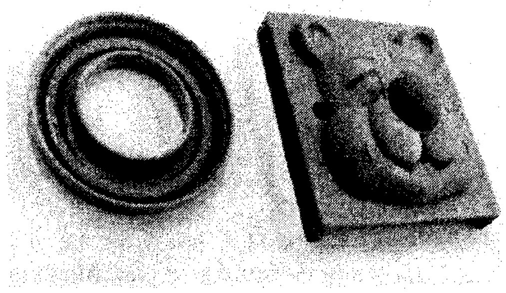


Figure 4a: Parts from 3D Printing Process

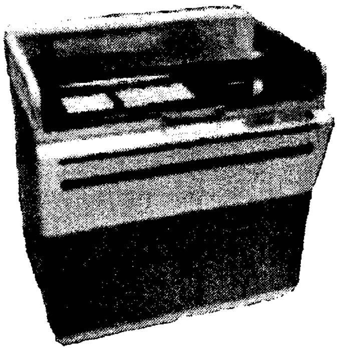


Figure 4b: Z-Corps ZP400 Machine

- **Benefits**
  Fastest build speed
  No support structure
  Complex parts, thin walled parts
  Two materials - starch - rubberising, investment castable
  - ceramic – detail, definition strength
  New large build volume machine (largest of concept modellers)
  Colour capable
  Easy clean
  Alternative powders – metallic, conductive

- **Drawbacks**
  Least accurate of concept modellers
  Underside surface finish – poor
  Poor strength
  Limited fit and function usage

- **Machines** ZP400, ZP406, ZP810

3.4 Stratasys – FDM system

A new low cost fused deposition modeller (FDM) is due to be launched soon. However, to date little technical data is available to review/benchmark this machine.

4 BENCHMARKING OF CONCEPT MODELLERS

When relative criteria is used between 1 and 10 this is from user feedback and part inspection.
(1 – lowest, 10 – highest.)

	3D Systems ThermoJet MJM System	Z-Corps 3D Printer ZP400/ZP406/ZP810	Objet's InkJet Printer Quadra/Quadra Tempo
Build Size (mm)	250 x 190 x 200	250 x 200 x 200/ 500 x 600 x 400	270 x 300 x 200
Material	Thermoplastic wax	Starch, ceramic	Photopolymer
Resolution (x, y, z) dpi/mm	300 x 400 x 600/ 0.08 x 0.065 x 0.04	300 x 300 x 360/0.08 x 0.08 x 0.07	600 x 300 x 1270/ 0.04 x 0.08 x 0.02
Accuracy Relative (1-10)	5	4	7
Office Environment	Yes	Yes	Yes
No of build materials	Build material only	Power and Binder	Two – build & support photo-polymers
Support requirements	Yes	No	Yes
Date of Introduction	1998	1998/2000/2001	2000
Colour	Single neutral, grey black	Any single, colour upgrade/colour/colour	Amber (SLA colour)
Durability Relative (1-10)	Brittle – wax 2	Brittle – plaster 2, Infiltrated 6	Excellent 8
Support removal	Yes – Refrigerated	No	Yes – Waterjet
Speed (1-10)	4	8	7
Material Recyclable	No	Ceramic – Yes, Starch – Limited	No
Medical models usage	Yes	No	Yes
Investment casting	Yes	Starch only – limited application	No
Bureau usage (UK)	Yes	No – In house	Yes
File type	STL	STL	STL
Support/Equipment	Fridge, technician	De-powdering unit, autowaxer (supplied)	Water jet washer
Typical costs per part (min costs may apply)	£20	£5 ceramic £10 starch	£30
Detail upper surface	Excellent	Good	Good
Detail lower surface	Poor – where supports removed	Average – Mottled underside	Good
Materials development expected	Improved strength thermoplastics	Metals, ceramics, carbons	Increased as per SLA process
Cost	£36k	£37k	£46k
Maintenance (per annum)	£5k	£3k	£6k
Start up Cost	£1.3k	£1.5k	£5k

Table 1: Benchmarking of Concept Modellers

5 ANALYSIS OF Z-CORPS 3D PRINTING PROCESS AND MATERIALS

A series of investigations at the Centre for Rapid Product Development, Northumbria University, were undertaken to characterise the Z-Corps 3D printing process.

5.1 Accuracy analysis

Fifteen test parts were built in three phases, in four quadrants of the bed. The build binder core and shell saturation and layer thickness was also varied. This comprised over 200 tests with both ceramic and starch based materials. The conclusions are as follows:

ZP11 Starch Based

- Parts built consistently 0.7% to 2% smaller, an Anisotropic scaling factor of 1.0073, 1.0013 and 1.0025 in x, y, and z axis.
- Build time directly proportional to binder and core saturation.
- Wax infiltration reduces part size by 2%.
- Raw parts absorb moisture and should be sealed to maintain accuracy.
- Build location, particularly with contaminated build material affects parts' geometric shape and accuracy.

ZP100 Ceramic Based

- Binder print area spreads outwards from print area causing the cylinder inner diameter to become too small, whilst its outer diameter is too large, therefore no single scale factor can be used.
- Greatest error in z direction.
- Parts repeatable in x, y, but not z axis.
- Wax infiltration has negligible effect on accuracy.
- Anisotropic scale factor of 0.998 in x and y axis required for accurate parts dependent on cross-section area.
- Parts need to be left to harden in the machine for several hours to allow removal.

5.2 Material hardness

Due to build characteristics parts were tested on all sides as shown in figure 5. ZP11 Starch Based – The base was found to be the softest and the top hardest. The average hardness was 27 Vickers, with the highest 29 and lowest 25. ZP100 Ceramic Based – The results were found to be similar to ZP11 in that the top layer was harder. However the ceramic material is 180% harder overall.

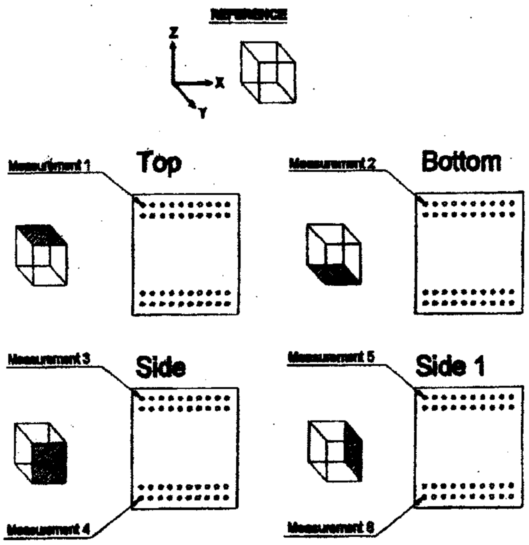


Figure 5: Hardness Measurement

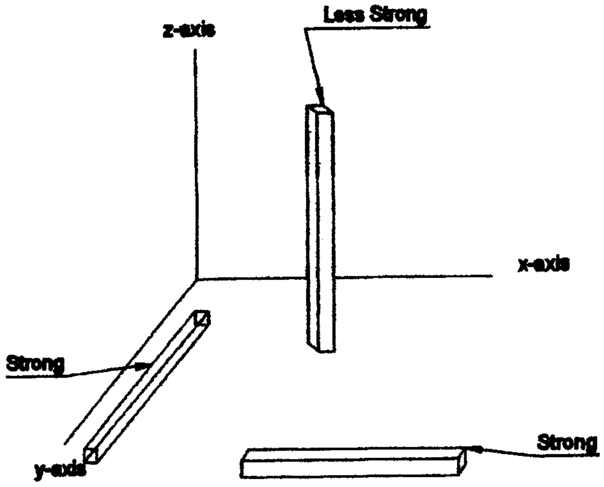


Figure 6: Build Orientation effect on part strength

5.3 Build strength analysis

A set of British Standard tensile test specimens were produced and Finite Element Analysis carried out to assess the theoretical stress versus actual failure mode. The orientation of the part on the build platform was investigated and the results are shown in Fig 6. This revealed that the highest strength is in either direction, in the x-y plane, and weakest is vertically across the build. The binder concentration was varied from the prescribed values and a variance of 15% can be obtained in part strength. The binder concentration was varied from the prescribed values and a variance of 15% can be obtained in part strength.

ZP11 – Starch Based. 75N on an 8 x 4 mm section.
ZP100 – Ceramic Based 112N on an 8 x 4mm section.

This shows that the ZP100 is 150% stronger than the starch. It was also found that wax infiltration doubled the above values.

5.4 ZP402 material characteristics

X-Ray Diffraction (XRD) is a technique used to characterise materials. This technique takes advantage of coherent scattering of x-rays by polycrystalline materials to obtain structural information. This technique is used to characterise the ZP402 build materials.

ZP11 – Starch Based

Starch is the common name given to white granular powder that is odourless and tasteless. A complex carbohydrate ($C_6H_{10}O_5$), is abundant in cereal plants, also a significant amount of sucrose (sugar) ($C_{12}H_{22}O_{11}$) was found.

This material is water-soluble and the effect of heating above 180^0C results in the material becoming liquid.

ZP100 – Ceramic Based

XRD revealed calcium sulphate (C_aSO_4 $2H_2O$), also called “Gypsum”. It is very common in dried salt pans and sedimentary rocks such as limestone. The material is in semi-hydrate form $(CaSO4)_2$ H_20 such as Plaster of Paris. This sets rapidly (10-20 minutes) by recrystallising with water. A significant amount of calcium Ca was also found.

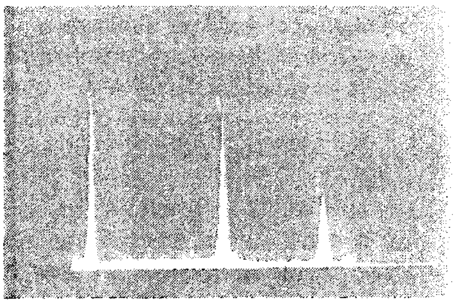


Figure 7: XRD Analysis ZP11 Starch Based Powder

5.5 Material structure

A Scanning Electron Microscope and Optical Microscope were used to reveal the structures of the build samples before and after wax infiltration when studies. Figs 8, 9, 10, 11. The starch based build material clearly has an open “candy floss” fibrous structure which latter tests revealed had lower hardness and strength. The ceramic build material is closer grained and this is reflected in the better part finish and strength.

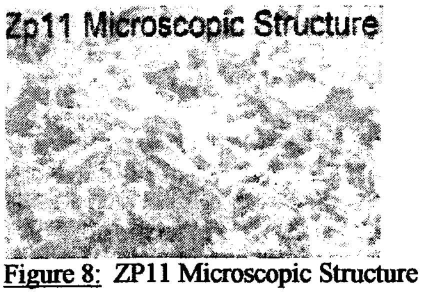


Figure 8: ZP11 Microscopic Structure

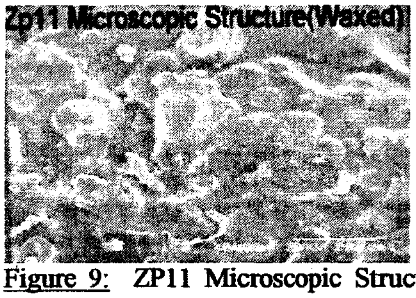


Figure 9: ZP11 Microscopic Structure (Waxed)

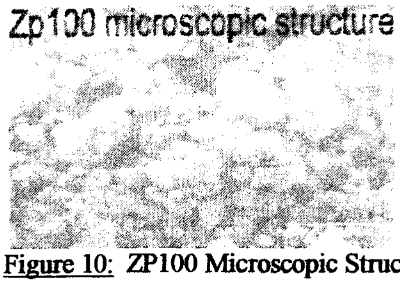


Figure 10: ZP100 Microscopic Structure

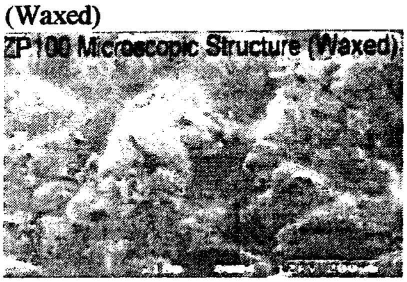


Figure 11: ZP100 Microscopic Structure (Waxed)

6. CASE STUDY

A local company approached the CRPD after encountering problems with a new product they were developing. The function of the product was to produce the recess for electrical wall sockets, in a plaster/breeze block/brick wall. The product fits onto industrial impact hammer drills (with the drill action turned off); the component consists of a square plate with symmetrically arranged teeth in the shape of daggers, debris is allowed to fall between the teeth and out of the rear of the tool. The hole is produced by first drilling a location hole for the socket, the hole cutter is then located by this hole with a tapered extension, the cutter is aligned to the wall and 30 seconds of impacts occur. A furrow is then produced in the masonry, the tool is rotated 90 degrees and a further 30 seconds of impacts occur. The processes of furrow making and dislodging the brittle masonry in this pattern, rapidly makes the hole of the required size and depth even in very hard engineering bricks.

The problem the company was experiencing was that the hard brittle tool steel (D2) were found to be cracking and fracturing after limited usage. The company had been through the lengthy and costly process of design modifications, tooling modifications, wax pattern production and investment casting using traditional techniques several times. This cycle took typically 13 weeks from failure to new design, CAD design, tooling, casting and production of working prototypes. The public and their OEM's were losing faith in their product and their capabilities. To solve the problem, the CRPD and The CADCAM Centre worked together to redesign the cutter to reduce weight and critical stress concentrations by 40%. The FEA analysis however could not fully simulate the high-speed impacts and resonance, therefore physical prototypes were required as shown in figures 12 to 14. Several sacrificial patterns were produced on the Z-Corps printer within the CRPD and successfully cast at a commercial investment casting foundry, which eliminated the tooling and wax production stages, therefore cutting 5 weeks off a 6 week process to get to the trial stage. The company now had D2 tool steel prototypes on test within a week of a new design being finalised and sent for RP production at 25% of the cost previously paid. These sacrificial patterns are now being made using the ThermoJet process at the Digital Factory, Bishop Auckland College, as this process is more tuned to investment casting than the Z-Corps process.

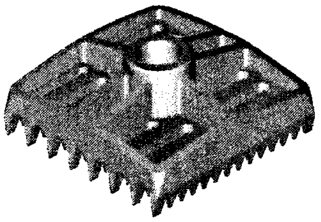


Figure 12: 3D model of design of square hole

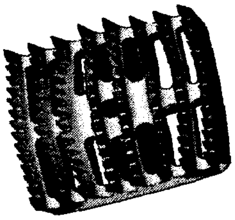


Figure 13: FEA Analysis

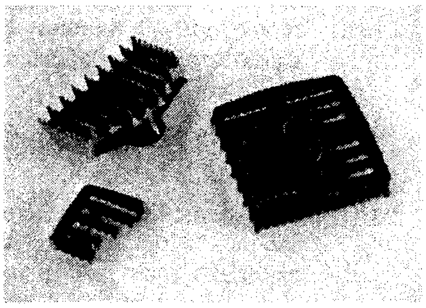


Figure 14: Original Casting and failed castings *(courtesy of Cleveland Engineering Ltd)*

7. CONCLUSIONS

The advent of mid range 3D CAD solutions capable of being used by Engineers as design tools, not just 3D modellers, has resulted in a requirement for rapid prototyping. Concept modellers as described in this paper can fulfil some of the design, test and evolution requirements found in the product development process. The choice of which system is dependent on the end use of the parts produced. The Objet process produces the most accurate and durable parts, the Z-Corps 3DP process the quickest and most complex parts, and the ThermoJet the most suitable for investment casting and excellent upper surface detail. The cost advantage of concept modellers over traditional RP processes allows companies to create models as the design progresses, allowing increased communication and participation of all stakeholders in the product development process.

Acknowledgements

The author would like to thank Government Office North East for providing the ERDF funding to support this project, together with the CRPD core team, Professor M Sarwar, Dr T J Bond, Mr D Bell and Mrs F Todd.

References

1. P M. Hackney & M. Sarwar, *Development of Time Compression Techniques to Assist SMEs with Product Competitiveness*, FAIM Conference 2001, Dublin.
2. P. M. Hackney & M. Sarwar, *Operating Characteristics of the Z-Corps 3D Printing Process*, NCMR Conference 2001, Cardiff University.
3. 3D Systems Website: www.3Dsystems.com (accessed 04/02/02)
4. Objet Technology Website: www.2Objet.com (accessed 06/02/02)
5. ZCorporation Ltd Website: www.Zcorporation.com (accessed 21/01/02)

Production of Roughing Electro Discharge Machining Electrodes from the Z-Corps 3D Printing Process

Author: P M Hackney, School of Engineering, Northumbria University, Ellison Building, Newcastle upon Tyne, NE1 8ST, United Kingdom

ABSTRACT

In the manufacture of complex components and hard tooling for plastic injection mouldings, Electro Discharge Machining (EDM) techniques are often used, to achieve the geometry and accuracy required for the designed component.

Traditional techniques require the CNC machining of a set of electrodes from copper or graphite blocks for each stage of the manufacturing process, this takes time out of the tooling production process, (typical 75% of actual 4-12 weeks process is actual manufacturing time). Therefore any progress in the production of EDM electrodes would shorten lead times and reduce the need for soft tooling.

Several attempts to fabricate EDM electrodes from rapid prototyping and rapid tooling techniques have been attempted, with limited success, mainly electro plating of conductive coatings on stereolithography parts. The major problems being coating adhesion, thickness and life of the coatings and substrate.

This paper investigates the use of the Z-Corps 3D printing process to produce roughing electrodes using composite graphite powers as the build material in place of the traditional build materials of ceramic and starch materials. It highlights the problems encountered in producing accurate, conductive robust electrodes for the EDM process.

1. INTRODUCTION

The production of plastic injection mould tools and metal forming dies, requires the accurate machining of hard or difficult to machine materials into complex and sharp internal corners[1]. Traditional toolmakers have used Electro Discharge Machining (EDM) to achieve these objectives in a cost effective manner. EDM requires electrodes to be produced in graphite or copper, of the required dimensions (minus the spark gap). These are mainly machined from solid to form a set of progression tools, as wear on both the workpiece and electrode occurs during operation.

The Product Development – Time Compression Centre has been conducting research into methodologies to reduce the lead times for mould and die tool production.

This paper reveals the ongoing research work undertaken into the production of roughing electrodes utilising the Z-Corps 3D printing process.

The Z-Corps 3D printing process traditionally uses starch or ceramic powders to produce concept physical parts directly from 3D digital data via a layer based additive process, often referred to a Rapid Prototyping (RP).

Rapid Prototyping (RP) is a range of technologies, which describe a process capable of creating complex physical parts directly from 3D digital CAD data[2]. There are now several commercial processes available, all of which work on much the same principle, ie layer manufacture, whereby the 3D digital part is sliced into many very thin layers that are then formed subsequently on top of one another to form the finished component or assembly. The use of RP is becoming widespread as a 3D CAD design tool, it is being used by Small to Medium Sized Enterprises (SMEs) to design and manufacture new products[3]. The advantages of RP over traditional CAM based tools are both time and cost of manufacture, ensuring the designer can hold a part designed yesterday in his/her hand today.

At the moment the RP industry is split into two distinct areas:

• High cost, high precision systems	-	SLA, SLS, FDM, LOM
• Low cost (<£50k) "concept modellers"	-	3D "Ink Jet" Systems – 3D Systems Thermojet Objet's Inkjet System, and Z-Corps 3D Printer Stratysys - Dimensions

The Z-Corps process has the benefit of being able to utilise different powders to investigate the production of EDM electrodes.

The Z-Corps process is considered to be a concept modeller[4], lacking in accuracy and repeatability as a production machine. However, it can be utilised for roughing electrodes, roughing electrodes are used in the first stage of EDM, while finishing electrodes are being manufactured in parallel to the roughing operation.

2. ELECTRO DISCHARGE MACHINING

EDM is the thermal erosion process in which metal is removed by a series of recurring electrical discharges between a cutting tool acting as an electrode and a conductive workpiece, in the presence of a dielectric fluid. This discharge occurs in a voltage gap (typically 0.05 mm) between the electrode and workpiece. Heat from the discharge vaporises minute particles of workpiece material, which are then wash from the gap by the continuously flushing dielectric fluid, without applying forces to the workpiece. Very complex geometry's can be derived this way. The geometry of the cavity is obtained through the EDM tool, also known as the electrode.

2.1 Reducing lead time

Normally, it takes quite some time to manufacture electrodes and to use these subsequently in the EDM process. By using sophisticated tool management and 3D CAD/CAM electrode machining systems this lead-time can be greatly reduced. When for example High Speed Milling techniques are combined with EDM technology, complex tools with excellent accuracy and long lifetimes can be achieved.

2.2 Characteristics of EDM Process

The benefits of the EDM process include:
- Extremely suited for producing low-wear moulds,
- High Accuracy's,
- Materials of any hardness can be machined,
- Practically no geometrical limitations,
- High automated and reliable process,
- Very low surface roughness obtainable, burr free.

The limitations of EDM include:
- Low metal removal rates compared to chip machining
- Lead-time is needed to produce specific, consumable electrode shapes

2.3 Potential uses of EDM

Producing injection moulds
Micromachining
Engraving of moulds
Creating cavities which cannot be manufactured with other techniques

2.4 Electro Discharge Machining

There are two main types of EDMs, Ram and Wire cut.
The ram uses a carbon, graphite or graphite tungsten electrode, and the wire a conductive consumable copper or copper coated wire that is fed through the workpiece. Ram EDM machines are also known as diesinkers or vertical EDMs.

In Ram EDM, the electrode/tool is attached to the ram, which is connected to one pole, usually the positive pole, of a pulsed power supply. The workpiece is usually connected to the negative pole, the polarity is dependant upon the combination of work-piece and electrode material selected. The work is then positioned so that there is a gap between it and the electrode. The gap is then flooded with the dielectric fluid. Once the power supply is turned on, millions of direct current, or DC, impulses per second cross the gap, beginning the erosion process. The spark temperatures generated can range from 7,700°C to 11,500°C[1]. As the erosion continues, the electrode advances into the work while maintaining a constant gap dimension.

The electrode is fabricated with the reverse or negative image of the finished workpiece cavity. When machined using EDM, this work-piece cavity is measurably larger than the electrode. This dimensional difference is called the overcut or kerf. This kerf dimension is critical during the fabrication of the electrode.

Ram EDM machines range in size from tabletop models to large CNC units. Ram EDMs have four sub-systems:

- A DC power supply to provide the electrical discharges, with controls for voltage, current, duration, duty cycle, frequency and polarity.
- A dielectric system to introduce fluid into the voltage area/discharge zone and flush away work and electrode debris, this fluid is usually a hydrocarbon, silicone based oil or de-ionised water.
- A consumable electrode, usually of copper, graphite or graphite tungsten
- A servo system to control infeed of the electrode and provide gap maintenance.

CNC ram EDM machines generally have automatic tool change capability allowing long unattended running times, use of multiple electrodes for rough and fine metal removal, orbiting controls for cavity enlargement, and contouring capability.

3. Z-CORPS 3D PRINTER

The 3D printer is available in three machine variants, Figure 1b. The basic build process is the laying down a layer of powder (ceramic or starch based) 0.1 to 0.25 mm thick. The model is sliced and the solid sections printed via "Canon InkJet cartridge" in the y-axis, the carriage increments (similar to paper feed) in the x-axis and another strip of binder is deposited. The parts are formed in the build chamber that drops by one layer thickness as more material is deposited and bound above it.

The machine is capable of building several layers per minute. As the powder supports the part no support structure is required therefore allowing complex parts to be built, Figure 1a. The binder can be coloured with a dye allowing coloured parts to be generated, for example the results of a Finite Element Analysis. The surface finish on the underside is poorer than the topside due to seepage of the binder into the surrounding material.

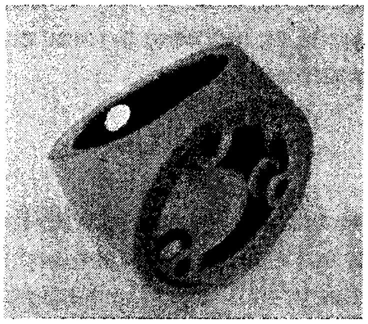


Figure 1a: Part from 3D Printing Process
"Odd Leg" Courtesy of CW Taylors Ltd

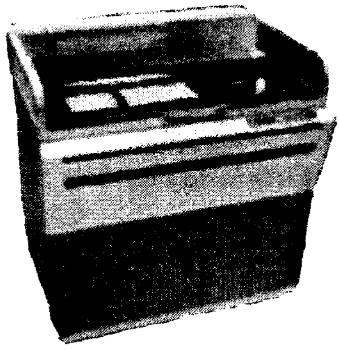


Figure 1b: Z-Corps ZP400 Machine

- **Benefits**
  Fastest build speed of all RP processes
  No support structure required
  Complex parts, thin walled parts
  Two materials - starch - rubberising, investment castable
  - ceramic - detail, definition strength
  New large build volume machine (largest of concept modellers)
  Colour capable
  Easy clean
  Alternative powders – metallic, conductive

- **Drawbacks**
  Least accurate of concept modellers
  Underside surface finish – poor
  Poor strength
  Limited fit and function usage

- **Machines** ZP400, ZP406, ZP810

4. EDM ELECTRODE DEVELOPMENT VIA Z-CORPS RP SYSTEM

4.1 RP Production of EDM Electrodes

EDM electrodes are not required to be structurally strong, as the pressures exerted are not from the workpiece but from the flushing of debris with the dielectric.
The study focussed on using graphite, aluminium, copper and graphite/aluminium composite powders.
Samples of each were sought, with graphite being found to have a wide grade of particle size, with the lowest cost and highest conductivity. The investigation focuses on using this material as the major base material for electrode production.

None of the materials, in their pure state, could be adhered with reasonable strength using the water-based binder supplied. A mixture of base conductive material and ceramic powder was then used to allow handleable electrodes to the produced.

The binder solution and ceramic powder were also tested for their conductive properties. The conductivity results were as follows:

The binder solution was found to have a resistance of 173 Ω, water was found to have a resistance of 189 Ω and the ceramic powder was found to have an infinite resistance. The resistance difference between the binder and water may be due to either the composition, however most probably due to an increase in ionic content in the binder and to a small deviation in the probe measuring distance.

4.2 Graphite Powder

All of the compositions provided smooth textured samples, with the exception of batch 5. This sample was very granular in texture and although showed low results in resistance; it could not be handled without crumbling. The strength of the compositions 1-4 were all rigid and held together under firm pressure from the resistance probes. Various ratios of graphite and graphite ceramic mixes with electrical resistances are shown in Table 1.

Composition	Graphite (%)	Ceramic (%)	Resistance (Ω) over 10 mm
1	20	80	∞
2	40	60	2840
3	60	40	275
4	80	20	122
5	100	0	29

Table 1. The Graphite Composition Results

4.3 Graphite/Aluminium Mix

The aluminium powder was used in conjunction with the graphite in the hope that it would allow stronger batch prototypes to be made, whilst retaining the conductivity of the part as shown in Table 2.

Composition	Graphite (%)	Aluminium (%)	Ceramic (%)	Resistance (Ω) over 10 mm
1	40	20	40	3770
2	40	40	20	2200
3	60	20	20	444
4	60	40	0	423
5	80	20	0	36

Table 2. The Graphite/Aluminium Composition Results

4.4 Dimensional Accuracy

A test part as shown in Figure 2 manufactured with various graphite and ceramic mix and measurements taken with an IMS Impact Coordinate Measuring Machine (CMM) to look at mix and features versus accuracy.

It was decided to start from the highest level of graphite as possible. This was to ensure that the first

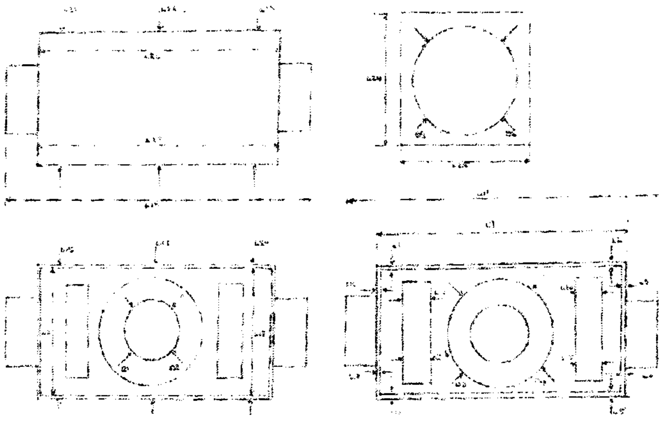


Figure 2: Dimensional Accuracy test part

compositions found would be of the lowest resistance possible. The 100% ceramic and 20% graphite – 80% ceramic mix were also used to compare the strength and accuracy of the prototypes.

The 3D print setting for all the prototypes was set at:

Binder saturation:	2	Layer thickness:	0.0762 mm (0.003 inches)
Core saturation:	2	Anisotropic scaling factors:	X = 1, Y = 1, Z = 1

4.5 The Dimensional Test

100% Graphite
The binder loosely held the powder together, as with the case of the test sample the binder was simply too weakly adhered to the graphite to hold together the structure. No dimensional measurements of tensile strength were obtainable for this composition.

90% Graphite – 10% Ceramic
At 90% graphite the binder appeared to have initially held the majority of the parts together, except for the tensile test parts snapping under their own weight. However, when an attempt to remove the excess powder away from the models was made, they began to crumble under the pressure of the air jet. Unfortunately again no dimensional or tensile measurements could be taken.

85% Graphite – 15% Ceramic
The binder held the composite together under the gentle pressure of the air hose, with which it was necessary to remove the loose powder from the surface. However, the binder had appeared to seep, downwards as the binder was applied, thus the dimensional data could not be obtained for one side of the block. This may have been due to the binder level setting, to ensure that the parts would remain intact. However, from the sides that could be measured, the following data was obtained:

The dimensions of the parts made of 15% ceramic were all within 90.5% of the set dimensions. The dimensions in the X-Y axis had deviated from the set dimensions again by a maximum of 3.55 mm for L20, a deviation of 8.88%. The large percentage error of 90.5% was from L2, the 2 mm ledge. The Z-axis had deviated from the set dimensions by a maximum of 4.3 mm for L27, a deviation of 5.73%. The diametrical dimensions are out by up to 3.058 mm on D1, a 30.5% error on the internal dimensions, whilst the external dimensions by up to 5.945 mm on D3, a 19.82% error.

20% Graphite – 80% Ceramic
The dimensions of the parts made of 80% ceramic were all within 8% of the set dimensions. The dimensions in the X-Y axis had deviated from the set dimensions again by a maximum of 0.65 mm for L17, a deviation of 1.86%. The large percentage error of 8% was from L1, the 2 mm ledge. The Z-axis had deviated from the set dimensions by a maximum of 1.20 mm for L25, a deviation of 2.8%. The diametrical dimensions are out by up to 0.38 mm on D2, a 3.8% error on the internal dimensions, whilst the external dimensions by up to 0.5 mm on D4, a 1.66% error.

100% Ceramic
The parts made using this powder were, as anticipated, the most accurate. The dimensions of the parts made of 100% ceramic were all within 3.85% of the set dimensions. The dimensions in the X-Y axis had deviated from the set dimensions again by a maximum of 0.65 mm for L17, a deviation of 1.86%. The large percentage error of 16% was from L8, the 2 mm ledge. The Z-axis had deviated from the set dimensions by a maximum of 0.49mm for L27, a deviation of 0.65%. The diametrical

dimensions are out by up to 0.085 mm on D1, a 0.85% error on the internal dimensions, whilst the external dimensions by up to 0.945 mm on D3, a 1.82 error.

Summary or Dimensional test – the oversized parts can be compensated for by use of standard software Anisotropic scaling factors in X, Y and Z. The part growth in X and to a lesser degree in Y is due to seepage of the binder into the surrounding unprinted build material before the binder reacts with the build material. This seepage effect is most pronounced on thin sections as these dimensions percentage wise change the most.

4.6 Immersion Tests

The various compositions of ceramic and graphite were immersed in the EDM dielectric oil and monitored for dimensional accuracy. The electrodes could withstand up to 2 days immersion before oil impregnation begins to reduce the electrodes conductivity to a point whereby it could be considered no longer to act as an electrode, but an insulator.
Samples produced can be seen in the Figures 3, 4, 5 and 6 below.

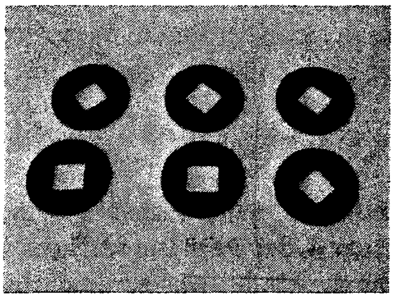


Figure 3: Graphite Ceramic composite tests

Figure 4: Test Electrode 1

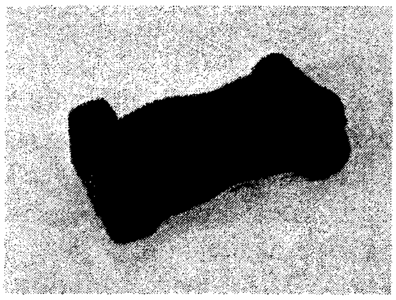


Figure 5: "Kylie" Test Electrode 2

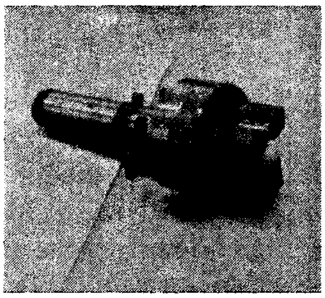


Figure 6: Copper Electrode Benchmark Part

4.7 EDM Test

The base of the electrode was smoothed to provide the best electrical contact possible between tool holder and tool. The electrode and tool holder resistance was found to be 120 Ω compared to 0.1 Ω for the original copper electrode. The electrode was found to withstand the flushing of electrolyte with a spark gap of 0.05 mm. The EDM was a Glevum Electronic Equipment Ltd G2093. The initial tests provided no spark and the machine advance on the ram crushed the electrode.

Altering the electrode current and voltage did create a machining effect, but due to the age and level of control this effect was to increase the machining time by a factor of two compared to traditional copper electrode.

Figures 7, 8 and 9, show the EDM and the RP generated electrode in operation and the resultant workpiece.

Figure 7: Graphite Composite Electrode

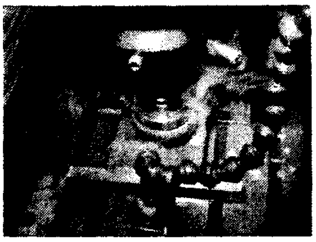


Figure 8: Graphite Composite Electrode in operation

Figure 9: Results of EDM Trial

5. CONCLUSIONS

Research at the Product Development – Time Compression Centre shows that the Z-Corps process can be utilised to produce composite electrodes of graphite and ceramic capable of being used as roughing electrodes. Graphite powders cannot currently be bonded alone using the existing binder fluid.

To enable this process to provide a competitive advantage in the first stages of tool making, further research and development into the binder/powder combination is required, together with a more up to date EDM control system, in order that the erosion process can be managed more accurately.

The cost advantage of the Z-Corps process (£22k) over the SLS process for metal powder binding and the range of powder material possible with the application of the innovative binders, means the process can be developed from purely a communication RP part process, to a realistic rapid tooling production process.

6. ACKNOWLEDGEMENTS

The author would like to thank Government Office North East for providing the ERDF funding to support this project, together with the PD-TCC core team, Professor M Sarwar, Dr T J Bond, Mr D Bell and Ms S B Todd.

7. REFERENCES

1. http://am12.eng.rpi.edu/GMPWEB/PDF/EDM.pdf
2. P M Hackney and M Sarwar, Development of Time Compression Techniques to Assist SMEs with Product Competitiveness, FAIM Conference 2001, Dublin
3. P M Hackney and M Sarwar, Operating Characteristics of the Z-Corps 3D Printing Process, NCMR Conference 2001, Cardiff University
4. Zcorporation Ltd Website: www.Zcorporation.com (accessed 21/01/02)

MATERIAL SUPPLIERS

Aluminium Powder, 30 micron 99.6%
North Derbyshire Metal Products Ltd,
Mavis SB Lea Road, Horsley Woodhouse
Derbyshire, DE7 6AZ

Graphite 50 micron
James Durrans and Sons Ltd,
Phoenix Works, Thurlstone, Penistone
Sheffield, S36 9QU

A Study of Build Accuracy of the Z-Corps 3D Printing Technique and Related Seepage Control

P M HACKNEY
Centre for Rapid Product Development, School of Engineering & Technology,
Northumbria University, UK
Phil.Hackney@unn.ac.uk

ABSTRACT.

Rapid Prototyping techniques can create physical parts directly from accurate, desired shape, 3D models, which are typical untoleranced desired size. As with all manufacturing processes there will be a deviation from desired size due to manufacturing parameters dependant upon process and operating conditions.

This paper describes the Z-Corps powder-based 3D printing technique. The 3D printing process will be analysed so that the key operating parameters and mechanisms can, in the first instance, be understood, and thereafter be controlled in order to improve part accuracy.

Keywords: 3D Printing, Rapid Prototyping, Dimensional Accuracy, Bleed Compensation.

1. INTRODUCTION

Rapid Prototyping (RP) refers to a group of technologies for the fabrication of physical objects directly from accurate digital 3D Computer Aided Design (CAD) data [1].

The designer normally models the desired component true size without any tolerances. The process of placing manufacturing tolerance is normally carried out during the detailed design stage, via annotation of the technical drawing. These tolerance attributes will define whether the part will be accepted or rejected. An alternative approach is to place an attribute on a 3D model dimension for later use within the technical drawing.

All data translation mechanisms (IGES, DXF, STEP and STL) strip out these annotations from the 3D model as they only define geometry. It is a requirement of the manufacturing process to manufacture the part to the required geometry accurately.

The use of RP produced parts is restricted by three major parameters – part accuracy, part strength, and part definition;

- Part accuracy is a function of the process and the interaction with the build materials, and this paper aims to further understand the interactive relationship of the two applied to the Z-Corps 3D printing process,
- Part strength is related to the build material or materials and the intermolecular bonds produced during the process,
- Part definition is a combination of resolution of the process and the manufacturing process constraints, i.e. green strength, support requirements etc.

Over the last decade there has been significant advancement within the RP field in the above parameters, particularly in the area of Stereolithography (SLA) process whereby both process and material improvements have led to the acceptance of parts as functional prototypes and Rapid Manufactured (RM) parts [2] [3].

3D Printing refers to a range of techniques characterised by the method of delivering build material or build adhesive via a series of nozzles that are translated across the build platform.

An earlier process, Ballistic Particle Manufacture (BPM) used two heads, one for the build material and one for the support material, and a levelling machining operation was performed between layers to increase accuracy. Although this process built small accurate parts, it was slow and unreliable.

A development of the BPM process was incorporated by 3D Systems into their Actua Multi-Jet System or ThermoJet™ using wax as the build material and support material without the machining stage. They are now widely used for investment casting, but they have limited strength for prototype use. This uses 300 jets to deposit wax over the build area.

The ObJet System uses a similar two head system to the BPM system with a build material of Ultra Violet (UV) sensitive resin and support resin that is set at the end of each layer by a UV lamp in one step. Problems with accuracy and part strength still remain with this system, but material and process improvements have optimised the process.

The Z Corps 3D printer is available in four machine versions. The basic build process is the laying down of a layer of powder (ceramic or starch based) 0.1 to 0.25 mm thick. The model is sliced and the solid sections printed via "Hewlett Packard print heads" in the *y*-axis, the carriage increments (similar to paper feed) in the *x*-axis and another strip of binder is deposited. The parts are formed in the build chamber that drops by one layer thickness as more material is deposited and bound above it. The machine is capable of building several layers per minute. As the powder supports the part, no support structure is required therefore allowing complex parts to be built. The binder can be coloured with a dye allowing coloured parts to be generated, for example the results of a Finite Element Analysis. The surface finish on the underside is poorer than the topside due to seepage of the binder into the surrounding material (see figure 1).

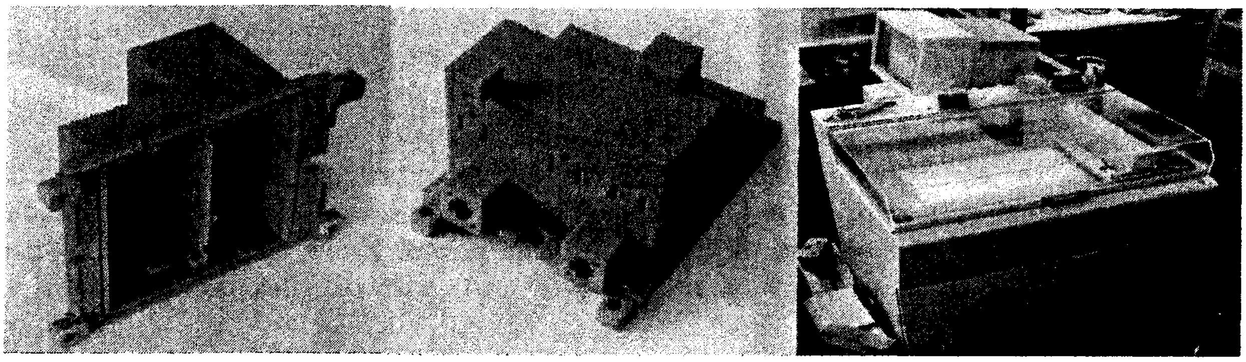


Figure 1: Example Parts and picture of Z-Corps Machine

- **Benefits**
  Fastest build speed, No support structure
  Complex parts, thin walled parts,
  Two materials:
    - Starch - rubberising, investment castable
    - Ceramic - detail, definition strength
  Colour capable, Easy clean
  New large build volume machine ZP810 (largest of concept modellers)

- **Drawbacks**
  Least accurate of concept modellers
  Underside surface finish – poor
  Poor strength
  Limited fit and function usage

Alternative powders – metallic, conductive
Machines: **ZP310, ZP406, ZP810, (ZP402** Now replaced by ZP310)

A benchmark of 3D printing systems revealed the various application areas for these concept-modelling processes [4]. Namely: ThermoJet for investment casting, ObJet most accurate and strongest, and Z-Corps cheapest and fastest.

2. Z-CORPS 3D PRINTING PROCESS

2.1 The build process

The system software first converts a three-dimensional design built using 3D CAD (saved in STL format) into thousands of cross-sections or slices that can be between 0.07 – 0.25 mm thick. The three-dimensional printer then prints these cross-sections one after another from the bottom of the design to the top.

Inside the printer there are two pistons. The feed piston is filled with powder, the part is constructed within the build piston volume and a roller transfers the material from the feed piston to the build piston.

To begin the 3D printing process, the system first spreads a layer of ZP series powder in the same thickness as the cross section to be printed. The binder cartridge then applies a water based binder solution to the powder, causing the powder particles to bind to one another and to the printed cross-section one level below. The feed piston comes up and the build piston drops one layer thickness and the roller transfers one layer of material between the pistons. The system then spreads a new layer of powder and repeats the process, and in a short time the entire part is printed.

The system employs several techniques to quickly build great parts. First, binder solution is applied in a higher concentration around the edges of the part, creating a strong shell around the exterior of the part. Within parts, the printer builds an infrastructure by printing strong scaffolding within part walls with a higher concentration of binder solution (See figure 2). The remaining interior areas are printed with a lower saturation, which gives them stability, but prevents over saturation, which can lead to part distortion.

After printing, the part is removed from the powder bed, de-powdered and dried. The part can then be infiltrated with wax, epoxy, or other materials to increase strength and durability. Because the powder layers support the structures being printed above, the system prints parts without support structures of any kind and can print parts with complex geometries that are impossible for other processes.

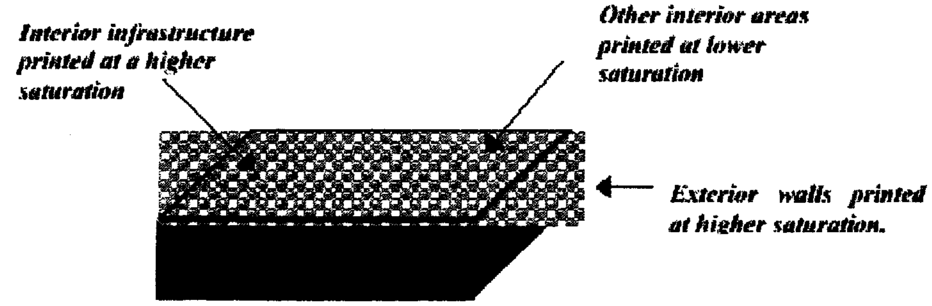


Figure 2: Representation of the Z402 Shelling and Infrastructure Features.

3. RAPID PROTOTYPING ACCURACY

3.1 Positional accuracy of drop deposition

Accuracy is evaluated as dimensional error, form error and surface roughness of manufactured parts [5]. A large number of parameters limit the ability of RP systems to create parts as accurate as the CAD designs they are based upon. The major errors are:

- Mathematical errors due to forced approximation of part surfaces in the standard file input. These STL errors can be reduced by control of tolerancing and angle parameters during triangulation of CAD data,
- Process related errors affect the shape and definition of the part in *x-y* plane due to positioning errors due to head translation, and in the *z*-axis due to registration of different layers,
- Material related errors are related to shrinkage, distortion during and post manufacture, infiltration absorption during part processing and bleed or seepage of binder during production,
- Mathematical errors can be corrected using finer tolerances and more powerful algorithms to process the input data.

Process related errors as described by Jee & Sachs ignore the practicalities of the 3D printing process, i.e. set print head resolution and linear axis of the print head and print head translation mechanisms [6].

3.2 Printing accuracy

Printing accuracy of the 3DP machine will also have to be considered as a contributor to the accuracy and conformity of a printed physical part from a designed CAD model. It is defined as the maximum deviation of a binder drop position from the numerical fabrication code along the three orthogonal printing directions as follows:

E_{fx}: maximum deviation error of drop placement along the fast *y*-axis.
E_{sx}: maximum deviation error of drop placement along the slow *x*-axis.
E_{zx}: maximum deviation error of drop placement along the *z*-axis.

The ability to reproduce fine surface textures relies heavily on the machine's accuracy. This accuracy depends on the errors introduced in the system by each component of the machine. The final combination of the machine errors, including the controller errors, can be made within an error budget. Manufacturing rules must reflect this printing accuracy to explain discrepancy in geometry between a designed CAD model and the physical part to be manufactured by 3DP process.

3.3 Printing style

Two different visually simulated models in accord with different printing styles of 3DP are possible in the CAD tool implemented using the proposed method. Binary deflection printing (BDP), for example, is a printing style in which the lines of drop placements are parallel to the printing direction as illustrated in (Figure 3). Proportional deflection printing (PDP), on the contrary, is a different printing style in which the lines of drop placements follow the edge contour of the 2D layered CAD data, which provides smoother edges in the shape of a fabricated complex part.

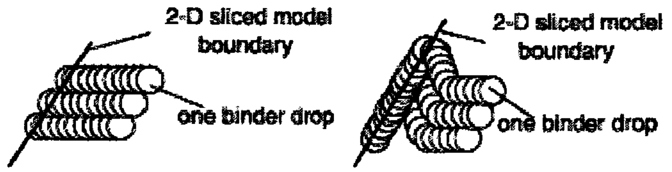


Figure 3: Two printing styles of 3DP process – BDP (right) and PDP (left).

For example, the positive feature size along the fast axis is equals to $M_{pf}(=m_{pf}R_{fx}+D_p\pm\lambda_{pf}E_{fx})$, algebraic sum of drop placement primitive size D_p, total increment size of binder drops $m_{pf}R_{fx}$ and printing accuracy along the same axis $\pm\lambda_{pf}E_{fx}$ as illustrated in Figure 4.

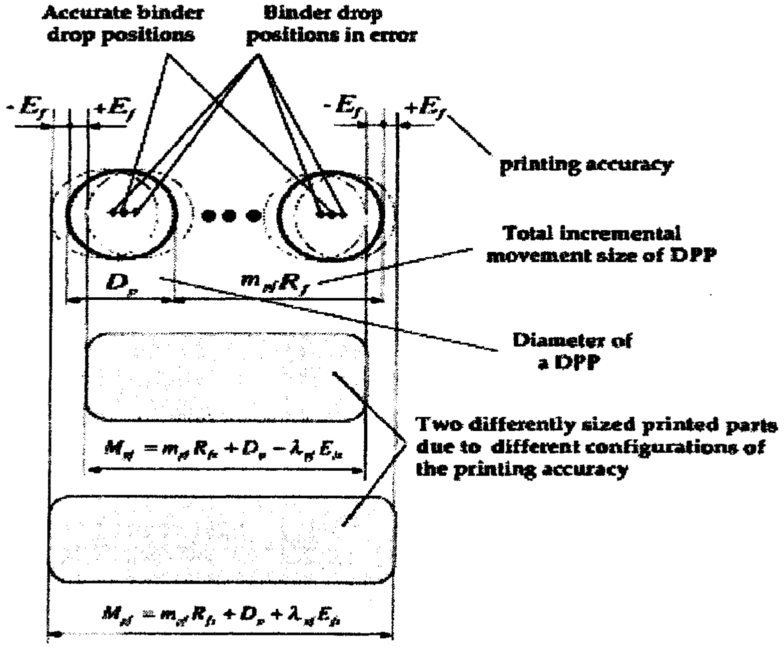


Figure 4: Printing accuracy for a positive feature in 2D layers.

4. MATERIAL RELATED ERRORS

4.1 Material data

The bonding of the powder to form a layer and bond to the layer below is critical for part strength, and this is controlled by the build shell and core saturation parameters.

The Z-Corps printer can use two major build materials, a starch based powder for speed and a plaster based powder for strength and resolution. The plaster-based powder was investigated, as this is the most commonly used material for the Z-Corps machine.

Plasters are manufactured from gypsum and anhydit. Gypsum is a fairly soft rock containing calcium sulphate, and the rock is crushed and semi-dried to form hemi-hydrate plaster, also known as plaster of paris.

When water is added to the plaster the water of crystallisation reforms to convert the plaster into gypsum. The growth and interlocking of crystals is the setting action of the plaster. Plasters can have retarders to reduce the speed of crystallisation.

$$C_a\,O + H_2O \rightarrow C_a\,(OH_2)$$

Setting – water dries and carbon dioxide is reabsorbed into the atmosphere – carbonation.

$$C_a\,CO_3$$

Absorption of the water in the surrounding and non-part designated areas means that the parts are built with a loss of accuracy and definition. This is of particular note with materials having low sorptivity similar to graphite/ceramic composite used for EDM electrode manufacture [7][8].

4.2 Mathematical background to sorptivity

One-dimensional capillary absorption is described by the non-linear diffusion equation [9] [10],

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left[D(\theta)\frac{\partial\theta}{\partial x}\right] \qquad (1)$$

Where θ is the water content and $D\theta$ is the unsaturated hydraulic diffusivity. This equation has a solution of the form,

$$x(\theta,t) = \phi(\partial)\sqrt{t} \qquad (2)$$

where Φ is the Boltzmann variable $xt^{-1/2}$. The total amount of water absorbed is,

$$i(t) = t^{1/2}\int_{\theta 0}^{\theta s}\phi d\theta = St^{1/2} \qquad (3)$$

where S is the sorptivity. Note that the sorptivity is dependent on the initial and final water contents of the material, θ_0 *and* θ_s.

The sorptivity is established as the most useful parameter to describe the water absorption properties of porous media and defines the ability of a material to absorb and transmit water by capillarity [10]. In plaster the sorptivity is sensitive to variation in composition such as calcium content and water/gypsum ratio as well as to differences in density and compaction [11,12]. As shown by equation (3) the sorptivity is also dependent on the water content of the material and decreases systematically with increasing (uniform) initial water content [12]. It is therefore important to know the water content of the material at the time of measurement.

The procedure of measuring the sorptivity has been standardised [10, 11, 12]. The most straightforward method of determining the sorptivity of any porous solid is to measure the increase in mass of the specimen during capillary absorption of water using one-dimensional absorption geometry. The specimen must be of constant cross-sectional area parallel to the absorbing surface, most conveniently in the form of a rectangular or cylindrical prism. Most materials are sufficiently fine pored, so that any effects of gravity on short-term capillary absorption may be neglected and the sorptivity may be measured in a simple vertical capillary rise experiment. After drying to constant mass (and therefore zero initial water content), the sample is placed on supports in a tray of water so that the lower surface of the solid is a few millimetres below the water surface. The sample is weighed at intervals (typically at $t = 1, 4, 9, 16$, and 25 min), with each weighing operation being completed as quickly as possible and without stopping the clock. The sorptivity is determined from the gradient of the straight line [equation (3)] obtained by plotting the cumulative absorbed volume of water per unit area, i against $t^{1/2}$. One-dimensional absorption is the only geometry to exhibit this linear absorption behaviour with $t^{1/2}$.

During *in situ* testing, it is clearly not possible to determine the sorptivity using the simple laboratory experiment described above, and various surface caps or drilled holes are used to hold sources of water in absorption experiments. In some cases relatively small hydrostatic pressures are applied to the water source. It is therefore useful to note the relationship defining the variation in sorptivity with pressure,

$$S(h) = \left[S_0^2 + 2hK_e f\right]^{1/2} \qquad (4)$$

where $S(h)$ is the sorptivity under an applied hydrostatic pressure head h, S_0 is the sorptivity without applied pressure and K_e is the effective hydraulic conductivity of the solid. For most cementitious materials, capillary forces are dominant for all but the largest hydrostatic heads and small pressures have a negligible effect on the measured sorptivity.

Geometry of the drop deposition layer and surrounding part affects the seepage to the surrounding area as per Figure 5.

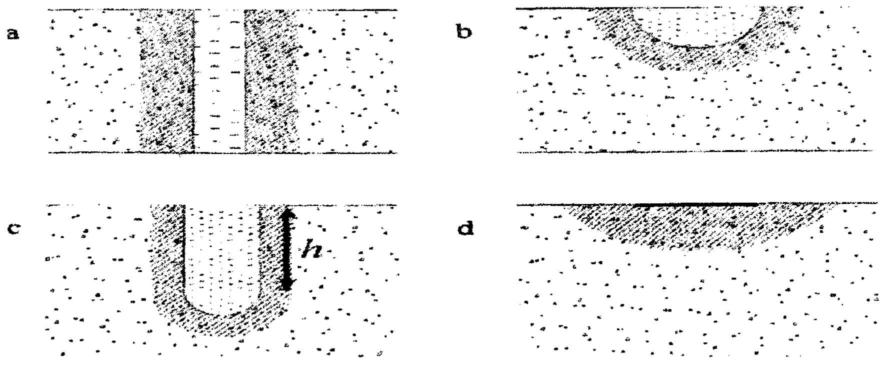


Figure 5: Absorption geometries: (a) cylindrical source (with sealed end); (b) hemispherical source: (c) drilled hole with hemispherical end; (d) plane circular source. The shaded area in each case represents the wetted region

4.3 Bleed or seepage compensation

Bleed compensation comprises offsetting the print area inwards from the desired part size to compensate for the seepage into the surrounding material, refer to (Figure 6). The offset can be set as bleed compensation as a scale factor inside and outside of the shell profiles. Typical values of 1.05 in x-axis and y-axis and 1.03 for the z-axis, but these are part geometry dependant.

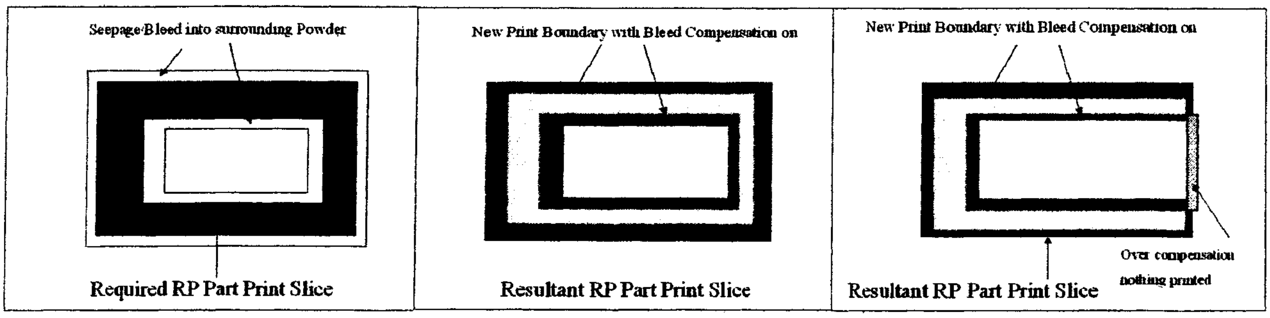


Figure 6: Bleed compensation applied to 3D printing process

However, for thin walled parts this thinning of the print area leaves undesirable non-printed areas and as described above, the bleed is geometry and part orientation (gravity) dependant (figure 6).

5. CONCLUSIONS

The Z-Corps 3D printing process is one of the least accurate RP processes commercially available to date. However for speed of production and lack of part finishing (support removal) there is little to compare it to.

This paper has shown the major causes of dimensional errors to be positional and material errors.

Positional errors can be compensated for within build software when machines are calibrated, in much the same way as when a new print head is fitted to a conventional printer to realign the unit. Material errors are much more complex than initially thought, and simple single bleed or seepage compensation will not remove them, although they can be improved.

This paper has shown the seepage errors to be geometry controlled in three dimensions, therefore bleed/seepage compensation must look forward and backward at 3D build geometry to define the value of offset to build accurate parts.

6. ACKNOWLEDGEMENTS

The author would like to thank GONE for providing the ERDF funding to support this project, together with the PD-TCC core team, Professor M Sarwar, Dr T J Bond, and Ms S B Todd.

REFERENCES

1. D. Kochan, *Solid Freeform Manufacturing*, Manufacturing Research and Technology, Vol 19 Amsterdam, Elsevier, 1993.
2. S. H. Choi and Amavedeam. S., *Modelling and Optimisation of Rapid Prototyping*, Computers in Industry, Vol 47, 2002, pg 39-53.
3. J. G. Zhou and D. Hersovici, *Parameter Tuning and Optimisation for SLA, Rapid Prototyping Manufacturing Process,* Int Conf Manufacturing Automation 1997, Vol 2.
4. P. M. Hackney, *The Development of 3D Printing Techniques for "Concept Modellers" to Competitive Rapid Prototyping Systems,* 3rd Conference on Rapid Prototyping, Rapid Tooling & Rapid Manufacturing, CDRM, Buckinghamshire University, UK, 2002.
5. X. Yan and P. Gu, *A Review of RP Technologies and Systems*, Journal Computer Aided Design, Vol 28, pg 307 – 318, 1996.
6. H. J. Jee and E. Sachs, *A Visual Simulation Technique for 3D Printing,* Advances in Engineering Software, 2000, Pg 97 – 1006.
7. P. M. Hackney, *Production of Electro Discharge Machining Electrodes from the Z-Corps 3D Printing Process*, Time Compression Technologies, 2002, Manchester, UK, 2002.
8. M. A. Wilson, *Analytical Approach to Water Absorption Based In Situ Test Procedure for Concrete*, Proceedings Institute of Mechanical Engineers, Vol 217, Part L, 2002.
9. J. R. Philip, *Theory of Infiltration,* Adv. In Hydrosci, Vol 5, pg 215 – 296, 1969.
10. W. H. Green and G. A. Ampt, *Studies on Soil Physics Part 1: The Flow of Air and Water Through Soils.*, Journal Agriculatural Science, Vol 4, pgs 1-24 1911.
11. R. J. Gummerson, C. Hall and W. D. Hoff, *Water Movement in Porous Brick and Other Masonry Materials,* Building and Environment, Vol 15, pg 101-108, 1980.
12. C. Hall and K. M. Tse, *Water Movement in Porous Building Materials 7: The Sorptivity of Mortars,* Building and Environment, Vol 21, pgs 113 – 118, 1986.
13. C. Hall and M. H. R. Yau, *Water Movement in Porous Building Materials 9: The Water Absorption and Sorptivity of Concretes,* Building and Environment, Vol 22, 1987.

A Comparison of "Concept Modelling" Techniques for Rapid Prototyping

P M Hackney M Sarwar

Centre for Rapid Product Development, School of Engineering, University of Northumbria at Newcastle, UK.

ABSTRACT

Rapid Prototyping systems use layer technology to build physical prototypes directly from 3D Computer Aided Design (CAD) data. This provides the opportunity to design more complex parts and assemblies which cannot be made by existing technologies. This paper reviews the emerging technology of low cost 3D printing techniques initially used for "concept modelling", to prove design intent and visualisation of these complex designs.

Concept modellers such as 3D System's ThermoJet and Z-Corp's 3D Printer will be examined, together with ObJet's and PerFactory new 3D UV Reactive Resin systems.

1. INTRODUCTION

Rapid Prototyping (RP) is a range of technologies which describe a process capable of creating complex physical parts directly from 3D digital CAD data [1]. There are now several commercial processes available, all of which work on much the same principle, ie layer manufacture, whereby the 3D digital part is sliced into many very thin layers that are then formed subsequently on top of one another to form the finished component or assembly. The use of RP is becoming more widespread as 3D CAD as a design tool is being used by small to medium sized enterprises (SMEs) to design and manufacture new products [2]. The advantages of RP over traditional CAM based tools are both time and cost of manufacture, ensuring the designer can hold a part designed yesterday in his/her hand today.

At the moment the RP industry is split into two distinct areas:

- High cost, high precision systems - SLA, SLS, FDM, LOM,
- Low cost (<£50k) "concept modellers" - 3D "Ink Jet" Systems
    - 3DSystems ThermoJet,
    - ObJet's Inkjet System
    - Z-Corps 3D Printer.
  - Other concept modelling systems
    - Stratasys FDM Dimension
    - Envision PerFactory

The high cost RP machines are predominantly situated in bureau companies with a range of machines to enable them to serve all their customer needs. The low cost RP machines are predominantly being installed in design houses and large OEMs to enable design verification and to serve as a communication tool. This paper will review the current concept modelling processes and benchmark these processes. The paper will also investigate the application of the Z-Corps ZP400 3D Printer, and illustrate, via case studies, the use of the ZP400 RP process.

2. THE BENEFITS OF CONCEPT MODELLING TECHNIQUES

The principle of the "concept modellers" is that the parts are produced to a low accuracy of normally ∓ 0.5 mm, low part strength <15 *MPa*, with limited engineering part utilisation. The benefits include: low system purchase and operating costs, low part costs, load and go capability

However these "Concept parts" have been successfully used in several projects as parts, sacrificial patterns or tools for production of working components. A good example is the Z-Corps 3D printer binder cartridge head cap shown in figure 1. This component is actually produced on the same machine that made itself. The ThermoJet uses a type of investment casting wax, and is now being used regularly in the production of aluminium and steel parts via the investment casting process without expensive new processes or process modifications at the foundry.

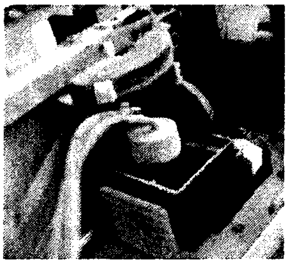


Figure 1: Z-Corps 3D Printer, Print head Cap

3. REVIEW OF CONCEPT MODELLING PROCESS

3.1. 3D SYSTEMS THERMOJECT SYSTEM

The MJM ThermoJet system [3] uses a print head to spray droplets of molten wax build material (also used as support material). The print resolution is 300 x 400 x 600 dpi (x, y, z). The process operates by first slicing the 3D CAD data into layers, these layers are then printed onto the layer below with several passes of the head required to deposit the full width of the component.

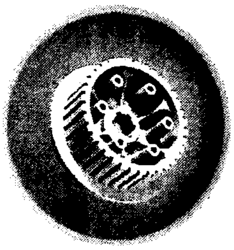


Figure 2a: Partfrom ThermoJet Process

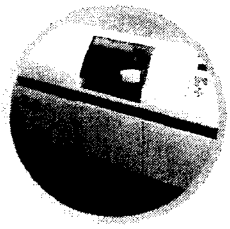


Figure 2b: ThermoJet Machine

A support framework is required for the underside of the components and any overhangs unconnected to lower regions of the model. The support removal is facilitated with the parts first being refrigerated to embrittle the support structure. This is one limiting factor of this process. Upper facing surfaces are capable of excellent detail, but underside surfaces are poor and the requirement for support removal means that wall thickness is limited.

Benefits
Excellent for investment casting waxes
Excellent upper surface definition
Easily joinable via melting
Choice of two materials – ThermoJet™ 2000, 88
Able to smooth models with heat gun or hot knife
Supported by 3D Systems (largest RP machine manufacturer)

Drawbacks
Support material removal
Brittle parts
Poor underside surface finish
Not suitable for thin walled parts

3.2. OBJET'S INKJET SYSTEM

The Objet system [4] was developed in Israel and uses similar resins to the SLA processes, i.e. it uses UV sensitive photopolymer. The process comprises the inkjet head traversing the build area, and where the part is solid, fine droplets of model material are deposited simultaneously with the support structure for future layers. The resin is deposited with a print resolution of 600 x 300 dpi (x, y). A UV lamp situated above the build platform cures the resin droplets. The head has a y deposition width of 60 mm, thereby several strips of resin are laid for wider parts. The build platform lowers by one layer thickness (20 microns) and the process repeated. The parts are cleaned and the support structure removed by a combination of hand and water jet washing.

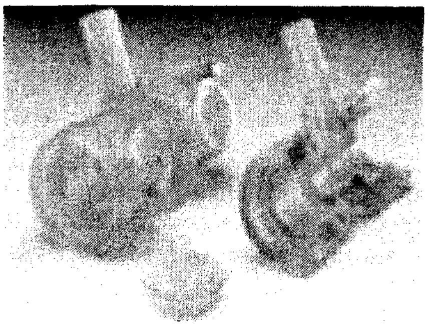


Figure 3a: Part from ObJet Process

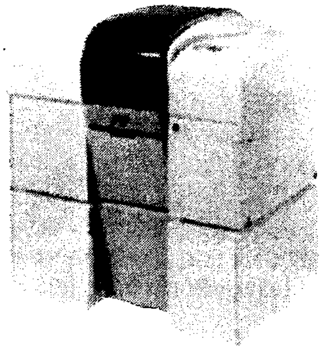


Figure 3b: ObJet Machine

Benefits
Material strength
Speed/width of build strip
Similar to SLA resins
Finest layer resolution and print resolution
Form and fit testable
Vacuum castable
Two machine variants
Large research and development budget

Drawbacks
Technology still under development – reliability, accuracy
New start-up company

Machines: Objet Quadra Tempo, Objet Quadra

3.3. *Z-CORPS 3D PRINTER*

The 3D printer is available in three machines. The basic build process is the laying down a layer of powder (ceramic or starch based) 0.1 to 0.25 mm thick. The model is sliced and the solid sections printed via "Canon InkJet cartridge" in the y axis, the carriage increments (similar to paper feed) in the x axis and another strip of binder is deposited. The parts are formed in the build chamber that drops by one layer thickness as more material is deposited and bound above it.

The machine is capable of building several layers per minute. As the powder supports the part no support structure is required therefore allowing complex parts to be built. The binder can be coloured with a dye allowing coloured parts to be generated, for example the results of a Finite Element Analysis. The surface finish on the underside is poorer than the topside due to seepage of the binder into the surrounding material.

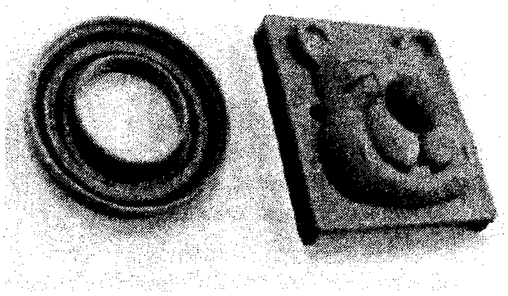


Figure 4a: Parts from 3D Printing Process

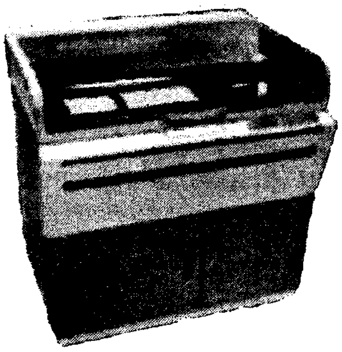


Figure 4b: Z-Corps ZP400 Machine

Benefits

Fastest build speed
No support structure
Complex parts, thin walled parts
Two materials :
    starch - rubberising, investment castable
    ceramic - detail, definition strength
New large build volume machine (largest of concept modellers)
Colour capable, Easy clean
Alternative powders – metallic, conductive
Machines ZP400, ZP406, ZP810

Drawbacks

Least accurate of concept modellers
Underside surface finish – poor
Poor strength
Limited fit and function usage

3.4. *STRATASYS – FDM SYSTEM*

Fused Deposition Modeller – Dimension – this is a re-packaged FDM 2000 system that uses ABS or wax filaments that are heated and extruded to form the part and support structure in the same way as the more accurate high end FDM machines [6, 7].

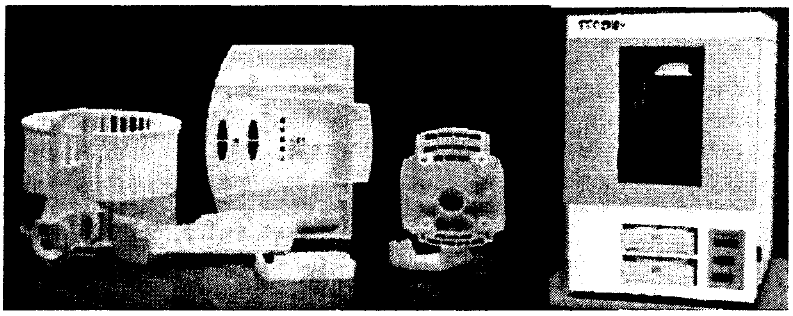


Figure 5: FDM Dimension parts and Machine

Benefits –

Material
Material strength
Flexible hinges
Water proof
Mature Technology
Inexpensive - £23k

Drawbacks –

Slow
Materials expensive
Surface finish
Finishing
Support removal

3.5. *ENVISIONTEC - PERFACTORY*

Personal Factory – this is a new commercial process that uses similar technology to SLA in that light sensitive resins are set where the solid part is required.

The process is that of Stereolithography (SLA) machine in reverse, in that it builds the part from the bottom of the vat of photosensitive liquid and not from the top as in the SLA process. In place of an expensive laser, the Perfactory system uses visible light to set the resin [7].

The vat has a glass base, through which light is directed to set the layer of liquid resin above. The build platform tilts to peel the part from the glass and then lifts and squeezes a new layer of resin between the part and the glass, and a new layer is exposed.

The light is projected onto the glass via an array of 75,000 mirrors, each electronically controlled to shine a pixel of light upwards, or to deflect away from the build area. This Digital Light Processing (DLP) is the heart of the new technology (used in large screen projectors), and sets a layer in one process therefore saving valuable time.

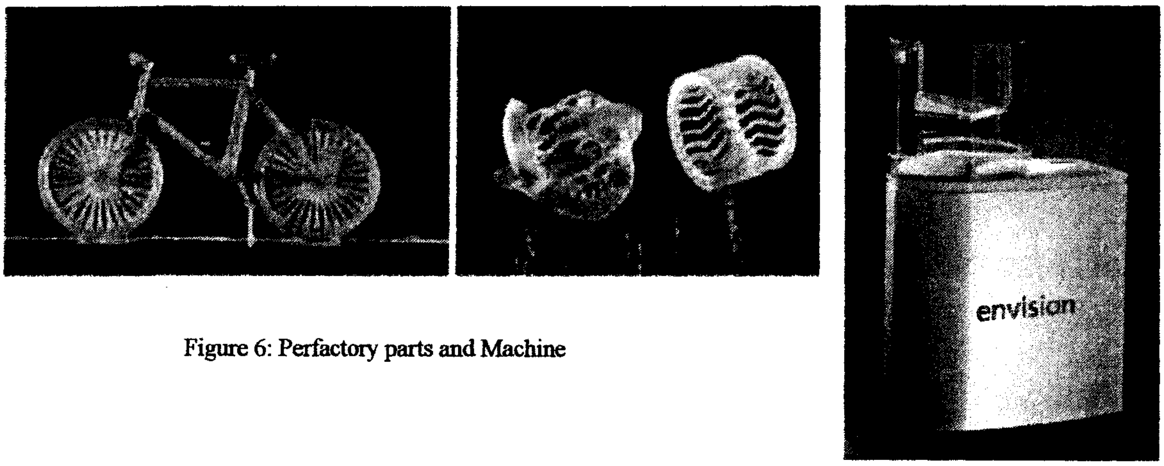


Figure 6: Perfactory parts and Machine

Benefits – Materials similar to SLA
Accuracy
speed
Inexpensive - £34k

Drawbacks – New Process
Materials and process in early stage of development

4. BENCHMARKING OF CONCEPT MODELLERS

When relative criteria is used between 1 and 10 this is from user feedback and part inspection. (1 – lowest, 10 – highest.)

	3D Systems ThermoJet MJM System	Z-Corps 3D Printer ZP400/ZP406/ZP810	ObJet's InkJet Printer Quadra/Quadra Tempo	FDM Dimension	Envision PerFactory
Build Size (mm)	250 x 190 x 200	250 x 200 x 200/ 500 x 600 x 400	270 x 300 x 200	203 x 203 x 305	75 x 56 x 50 mini 255 x 191 x 250 std
Material	Thermoplastic wax	Starch, ceramic	Photopolymer	ABS	Photopolymer
Resolution (x, y, z) dpi/mm	300 x 400 x 600/ 0.08 x 0.065 x 0.04	300 x 300 x 360/0.08 x 0.08 x 0.07	600 x 300 x 1270/ 0.04 x 0.08 x 0.02	0.178mm(2)	0.07 x 0.07 x 0.03 min 0.25 x 0.25 x 0.5 std
Accuracy Relative (1-10)	5	4	7	6	7
Office Environment	Yes	Yes	Yes	Yes	Yes
No of build materials	Build material only	Power and Binder	Two – build & support photo-polymers	Build material only	Build material only
Support requirements	Yes	No	Yes	Yes	Yes
Date of Introduction	1998	1998/2000/2001	2000	2002	2003
Colour	Single neutral, grey black	Any single, colour upgrade/colour/colour	Amber (SLA colour)	White	Red
Durability Relative (1-10)	Brittle – wax 2	Brittle – plaster 2, Infiltrated 6	Good 7	Excellent 8	Average 5
Support removal	Yes – Refrigerated	No	Yes – Waterjet	Yes	Yes
Speed (1-10)	4	8	7	1	7
Material Recyclable	No	Ceramic – Yes, Starch – Limited	No	No	Yes
Medical models usage	Yes	No	Yes	No	Yes
Investment casting	Yes	Starch only – limited application	No	No	Yes
Bureau usage (UK)	Yes	No – In house	Yes	No	Not Yet
File type	STL	STL	STL	STL	STL/CLI
Support/Equipment	Fridge, technician	De-powdering unit, autowaxer (supplied)	Water jet washer	None	None
Typical costs per part (min costs may apply)	£20	£5 ceramic £10 starch	£30	£20	£15
Detail upper surface	Excellent	Good	Good	Good	Excellent
Detail lower surface	Poor – where supports removed	Average – Mottled underside	Good	Poor	Good
Materials development expected	Improved strength thermoplastics	Metals, ceramics, carbons	Increased as per SLA process	None	Very Good
Cost	£36k	£37k	£46k	£23k	£34k
Maintenance (per annum)	£5k	£3k	£6k	£4k	£3k
Start up Cost	£1.3k	£1.5k	£5k	£2k	£2k

Table 1: Benchmarking of Concept Modellers

5. CASE STUDY

A local company approached the CRPD after encountering problems with a new product they were developing. The function of the product was to produce the recess for electrical wall sockets, in a plaster/breeze block/brick wall. The product fits onto industrial impact hammer drills (with the drill action turned off); the component consists of a square plate with symmetrically arranged teeth in the shape of daggers, debris is allowed to fall between the teeth and out of the rear of the tool. The hole is produced by first drilling a location hole for the socket, the hole cutter is then located by this hole with a tapered extension, the cutter is aligned to the wall and 30 seconds of impacts occur. A furrow is then produced in the masonry, the tool is rotated 90 degrees and a further 30 seconds of impacts occur. The processes of furrow making and dislodging the brittle masonry in this pattern, rapidly makes the hole of the required size and depth even in very hard engineering bricks.

The problem the company was experiencing was that the hard brittle tool steel (D2) were found to be cracking and fracturing after limited usage. The company had been through the lengthy and costly process of design modifications, tooling modifications, wax pattern production and investment casting using traditional techniques several times. This cycle took typically 13 weeks from failure to new design, CAD design, tooling, casting and production of working prototypes. The public and their OEM's were losing faith in their product and their capabilities. To solve the problem, the CRPD and The CADCAM Centre worked together to redesign the cutter to reduce weight and critical stress concentrations by 40%. The FEA analysis however could not fully simulate the high-speed impacts and resonance, therefore physical prototypes were required as shown in figures 7 - 9. Several sacrificial patterns were produced on the Z-Corps printer within the CRPD and successfully cast at a commercial investment casting foundry, which eliminated the tooling and wax production stages, therefore cutting 5 weeks off a 6 week process to get to the trial stage. The company now had D2 tool steel prototypes on test within a week of a new design being finalised and sent for RP production at 25% of the cost previously paid. These sacrificial patterns are now being made using the ThermoJet process at the Digital Factory, Bishop Auckland College, UK, as this process is more tuned to investment casting than the Z-Corps process.

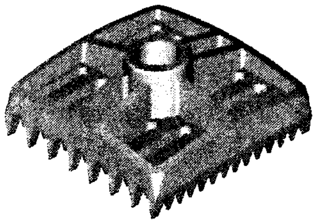


Figure 7: 3D model of design of square hole

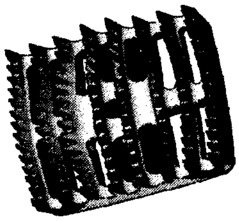


Figure 8: FEA Analysis

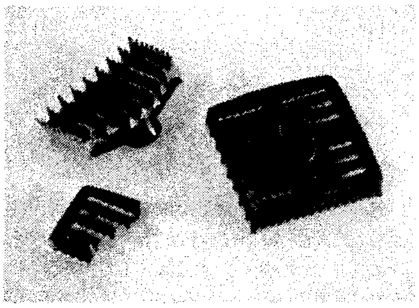


Figure9: Original Casting and failed castings *(courtesy of Cleveland Engineering Ltd)*

6. CONCLUSIONS

The advent of mid range 3D CAD solutions capable of being used by Engineers as design tools, not just 3D modellers, has resulted in a requirement for rapid prototyping. Concept modellers as described in this paper can fulfil some of the design, test and evolution requirements found in the product development process. The choice of which system is dependent on the end use of the parts produced. The Objet process produces the most accurate and durable parts, the Z-Corps 3DP process the quickest and most complex parts, and the ThermoJet the most suitable for investment casting and excellent upper surface detail.

The FDM Dimension produces the most usable parts due to the ABS mind material, but is the slowest process.

The PerFactory produces parts quickly with the material development along the SLA route this could replace some SLA processes.

The cost advantage of concept modellers over traditional RP processes allows companies to create models as the design progresses, allowing increased communication and participation of all stakeholders in the product development process.

7. ACKNOWLEDGEMENTS

The author would like to thank Government Office North East for providing the ERDF funding to support this project, together with the CRPD core team, Professor M Sarwar, Dr T J Bond, Mr D Bell and Ms F Todd.

REFERENCES

[1] P M. Hackney & M. Sarwar, *Development of Time Compression Techniques to Assist SMEs with Product Competitiveness*, FAIM Conference 2001, Dublin.

[2] P. M. Hackney & M. Sarwar, *Operating Characteristics of the Z-Corps 3D Printing Process*, NCMR Conference 2001, Cardiff University.

[3] 3D Systems Website: www.3Dsystems.com (accessed 04/02/02)

[4] ObJet Technology Website: www.2Objet.com (accessed 06/02/02)

[5] ZCorporation Ltd Website: www.Zcorporation.com (accessed 21/01/02)

[6] STRATYSIS Website: www.Stratysis.com (accessed 21/03/03)

[7] Perfactory – Envision Website: www.envision.com (accessed 21/03/03)

ANALYSIS OF THE BUILD QUALITY OF THE "DIGITAL LIGHT PROCESSING" RAPID PROTOTYPING PROCESS

P M Hackney, Northumbria University, School of Engineering & Technology

ABSTRACT

Rapid Prototyping is widely known as being able to fabricate 3D objects with complex geometries directly from accurate digital CAD data. Rapid prototyping can shorten the product development cycle and improve the design process by providing rapid and effective feedback to the designer. This paper presents the findings of an investigation into the accuracy, build strength and detail of the EnvisionTec PerFactory™ Digital Light Processing (DLP™) based system. The results will allow designers and manufacturing engineers to access the validity of the components and the range of applications for this new evolutionary system.

Key Words: Rapid Prototyping, Digital Light Processing, Accuracy

1.0 INTRODUCTION

Rapid Prototyping (RP) technologies use a layer by layer fabrication principle employing computer controlled laser, powder, print or photopolymer, together with a combination of other materials and techniques [1]. The ability to turn 3D digital Computer Aided Design (CAD) data, or other 3D data, into a physical artefact has enabled companies to reduce product development time cycles, and hence is a major factor in time compression technologies. These RP techniques complement more traditional manufacturing techniques such as CNC machining for prototype production. Several RP processes can produce functional and semi-functional components and assemblies, and can also be used as masters or patterns for tooling.

The use of RP is becoming more widespread as 3D CAD as a design tool is being used by small to medium sized enterprises (SMEs) to design and manufacture new products[2]. The advantages of RP over traditional CAM based tools are both time and cost of manufacture, ensuring the designer can hold a part designed yesterday in his/her hand today. At the moment the RP industry is split into two distinct areas:

- High cost, high precision systems - SLA, SLS, FDM, LOM,
- Low cost (<£50k) "concept modellers" - 3D "Ink Jet" Systems
    - 3DSystems ThermoJet,
    - ObJet's Inkjet System
    - Z-Corps 3D Printer
  - Other concept modelling systems
    - Stratasys FDM Dimension
    - EnvisionTec DLP™ PerFactory

The high cost RP machines are predominantly situated in bureau companies with a range of machines to enable them to serve all their customer needs. The low cost RP machines are predominantly being installed in design houses and large OEMs to enable design verification and to serve as a communication tool. This paper will review the current concept modelling EnvisionTec DLP™ processes and benchmark these processes.

The principle of the "concept modellers" is that the parts are produced to a low accuracy of normally ∓0.5 mm, low part strength <15 *MPa*, with limited engineering part utilisation. The benefits include: low system purchase and operating costs, low part costs, load and go capability, and fast prototype part production.

However these "Concept parts" have been used successfully in several projects as parts, sacrificial patterns or tools for production of working components. A good example is the Z-Corps 3D printer binder cartridge head cap shown in Figure 1. This component is actually produced on the same machine that made itself. The ThermoJet uses a type of investment casting wax, and is now being used regularly in the production of aluminium and steel parts via the investment casting process without expensive new processes or process modifications at the foundry.

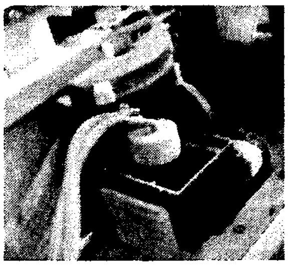


Figure 1: Z-Corps 3D Printer, Printer Head Cap

The use of RP produced parts is restricted by three major parameters – part accuracy, part strength, and definition:

- Part accuracy is a function of the process and the interaction with the build materials, and this paper aims to further understand the interactive relationship of the two applied to the DLP™ process.
- Part strength is related to the build material or materials and the intermolecular bonds produced during the process.
- Part definition is a combination of resolution of the process and the manufacturing process constraints, i.e. green strength, support requirements etc.

Over the last decade there has been significant advancement within the RP field in the above parameters, particularly in the area of Stereolithography (SLA) process whereby both process and material improvements have led to the acceptance of parts as functional prototypes and Rapid Manufactured (RM) parts [3] [4].

3D Printing refers to a range of techniques characterised by the method of delivering build material or build adhesive via a series of nozzles that are translated across the build platform. An earlier process, Ballistic Particle Manufacture (BPM) used two heads, one for the build material and one for the support material, and a levelling machining operation was performed between layers to increase accuracy. Although this process built small accurate parts, it was slow and unreliable.

A development of the BPM process was incorporated by 3D Systems into their Actua Multi-Jet System or ThermoJet™ using wax as the build material and support material without the machining stage. They are now widely used for investment casting, but they have limited strength for prototype use. This uses 96 jets to deposit wax over the build area.

The ObJet System uses a similar two head system to the BPM system with a build material of Ultra Violet (UV) sensitive resin and support resin that is set at the end of each layer by a UV lamp in one step. Problems with accuracy and part strength still remain with this system, but material and process improvements have optimised the process with the new FullCure™ resins and ObJet Multihead Eden machines.

2.0 DIGITAL LIGHT PROCESSING MANUFACTURING

2.1 Traditional Stereolithography

In the Stereolithography (SL) process, a light beam is used to scan the surface of the photo-polymer according to the sliced data, and solidify a thin layer. Most machines use a UV laser beam to solidify the photo-polymer. He-Cd, argon or semi-conductor excited lasers are popular UV laser sources used in the SL process. There are several commercialised SL systems, which could also use visible-light laser as the light source.[5]

2.1.1 Photo-Polymer

In SL technology, photochemistry plays a very important role. A highly precise SL machine may not be able to produce a high accuracy model if the photo-polymer has a shrinkage problem. The properties of the photo-polymer are, therefore, very important.

2.1.2 UV Argon Laser

Ionizing atoms using electric discharge and promoting them into highly excited energy levels emit UV light emitted when the atoms fall to a lower energy state. Ionisation of

Argon requires high-density excitation energy; therefore a large current is applied onto a very thin tube to increase the current density. Due to the low efficiency, most of the UV Argon laser units are large and require water-cooling. This would make an Argon laser-based SL machine very bulky.

2.1.3 Acoustic Optical Modulator (AOM)

Since the Argon laser cannot be turned on and off frequently, the laser beam must be switched on and off by some equipment such as a shutter. However, the ordinary mechanical shutter speed is not high enough for scanning a laser beam. An acoustic optical modulator is used to control the switching of the beam.

2.1.4 Galvano-Mirrors

Although an AOM can switch the laser beam on and off immediately, the inertia of the mirrors would cause delay of movement and hence positioning accuracy. High positioning accuracy and high scanning speed are, therefore, required for the galvano-mirrors. The 'laser-on' and 'laser-off' timing parameter must be set to adjust the delay to achieve high positioning accuracy.

2.1.5 The cost and maintenance of the laser system for SLA process is a high proportion of the machine costs.

2.2 Digital Light Processing Manufacturing

EnvisionTec founded in 1999 in Marl, Germany, for the development, production and promotion of computer assisted model making for industry and bio-medical fields. Two basic versions of DLP™ PerFactory system (Personal Factory) are commercially available. One for the manufacture of industrial components, "standard system", 190 x 152 x 230 mm build size, and a "mini system" 77 x 61 x 230 mm build size for 3D high accuracy/intricate objects for example in the jewellery industry. Both systems retail at 50,000 Euros and compete alongside ObJet, Z-Corps, ThermoJet and FDM Dimension processes.

3.0 BUILD PROCESS

The PerFactory system, like other commercial RP systems builds in layers directly from sliced STL triangle files. The data is cut into layers transferred to the machine to generate the slice via a DLP™ technique.

The projection unit for the machine is located under the polymerisation bowl, which means the projection of the layer occurs through a silicon coated transparent contact window. The build platform is lowered to the build z-height above the polymerisation bowl, and the DLP™ unit switches to display the required slice, and a light is shone onto the DLP™ chip. The acrylate material is micro photo hardened by the light source. The part is peeled from the polymerisation bowl, raised, and then re-set ready for the next z-layer.

3.1 System Components

- UV Screen Cover
- Build Platform
- Polymerisation Bowl
- Build Material Vat
- Focussing Lenses (2 off)
- Digital Light Processing Chip or Digital Mirror Device™ DMD™ of Texas Instruments SXGA

Figure 2: Perfactory Standard System

3.2 System Specification

Resolution of picture unit – a Digital Mirror Device™ by Texas Instruments – at this time the SXGA (1280 x 1024 pixel equilent to 1.3 million mirrors) chip is used. Build up time by using standard material about 36 mm/hour at 100 µm layer thickness. Two system models are available for different build accuracy and areas:

System variant	PERFACTORY® Standard SXGA I Zoom	PERFACTORY® Mini SXGA I Multi Lens	
Resolution	SXGA - 1280 x 1024 Pixel	SXGA - 1280 x 1024 Pixel	
Build envelope XYZ	190 x 152 x 230 mm to 120 x 96 x 230 mm	Lens f=60 mm 77 x 61 x 230 mm	Lens f=85 mm 41 x 33 x 230 mm
Pixel size XY	148 µm Pixel to 93 µm Pixel	60 µm Pixel	32µm Pixel
Layer thickness Z	50 µm to 150 µm	25 µm to 50 µm	

The standard material is orange, translucent acrylate, biocompatible and almost ashless burn outable (0.8% ash).

4.0 DLP™ SYSTEM TEST PROCEDURE

The intention of the tests was not to optimise parameters, but to run as per manufacturers' pre-set parameters on an EnvisionTec DLP™ PerFactory "standard" machine.

4.1 Repeatability

No process can be accurate if it is not repeatable. This test required the same parts to be built several times (10), and the variance between builds assessed for x, y, z build orientations.

4.2 Part Strength

Tensile test specimens were manufactured using Acrylate resin with a build increment of 0.1 mm as per Figure 3a and 3b.

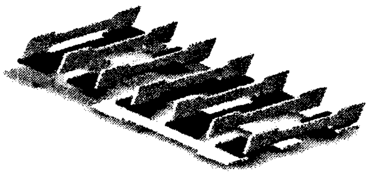


Figure 3a: Orientations and Build Positions

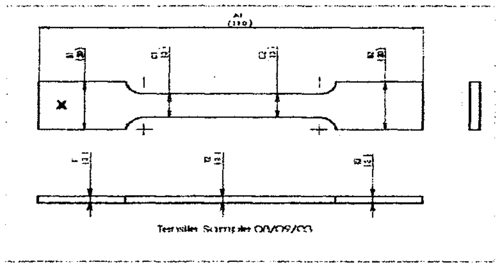


Figure 3b: Dimensional checks

Figure 3a and 3b shows orientations and build positions after x, y, and z for various build platform positions, they were tested on a Neme tensile test machine for various build orientations and build positions.

4.3 Dimensional Accuracy

The test piece as shown in Figure 4a and 4b was designed to allow the measurement of multiple build axis to be assessed, coupled with part location within the build platform in a single part. Accuracy measurements were undertaken with an International Metrology System (IMS) Impact™ Coordinate Measuring Machine (CMM) – accuracy of 3 µm.

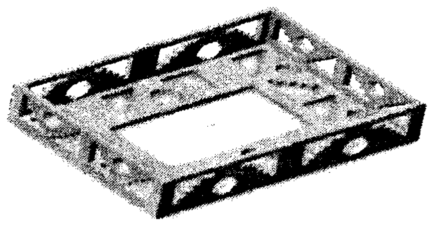


Figure 4a: Accuracy Test Pieces

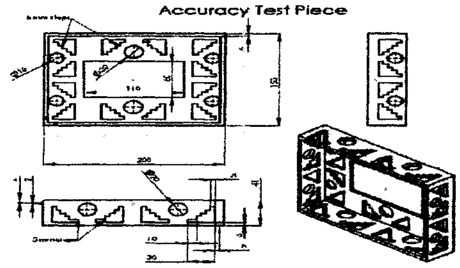


Figure 4b: Dimensional checks

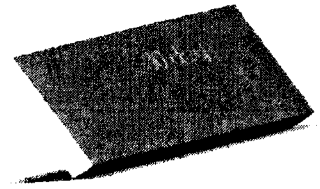
4.4 Surface Flatness

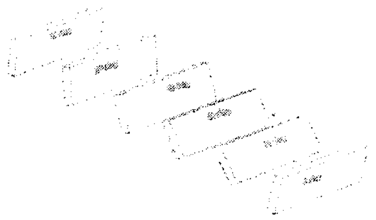
The test pieces shown in Figure 3a and 3b were evaluated for surface flatness before tensile testing using the IMS Impact CMM along the full length of each specimen.

4.5 Surface Roughness

The test pieces shown in Figure 5a were evaluated at angle of inclination of 5°, to 45° and 90°, to assess the stair stepping effect found with all RP systems. Measurements were taken using a Taylor Hobson Surftronic 3t machine, measuring Ra volume.

4.6 Build





Detail Tests – Filigree

The sample test piece as shown in Figure 6a and 6b was used to assess the finest detail that could be manufactured using the DLP™ with filaments of 3 to 0.05 mm in the three build orientations.

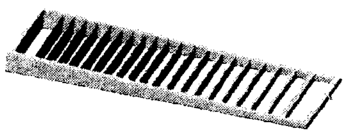


Figure 6a: Filigree Test Piece

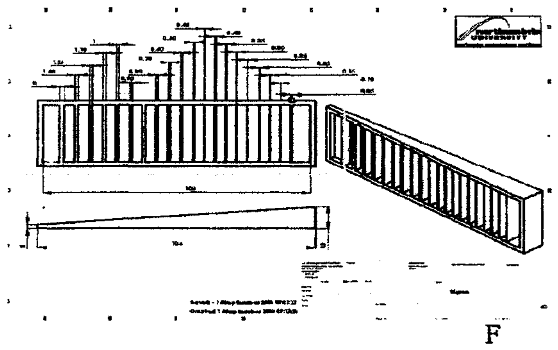


Figure6b: Dimensional checks

5.0 DLP™ TEST RESULTS

The test results are summarised below:

5.1 Repeatability

The parts built had a standard deviation, minimum and maximum error axis as shown in Table 1.

	Std Dev mm	Min Error %	Max Error %
X	0.243	-1.318	-0.855
Y	0.148	-0.909	-0.555
Z	0.194	-0.718	0.127

Table 1: Repeatability

Summary: The repeatability tests show a good degree of reliability of the process. These tests were performed on two different machines over a period of 8 weeks with different settings, operators and resins. The errors in to provide repeatable results can be improved with calibration and operational knowledge of the process.

Dimensions are also shown in Figure 1. Arrows show the directions in which prototypes have been made. Ten specimens were taken for each direction group to perform tensile test on Insitron Tensile Testing Machine.

2.2 Tensile testing

The fragile specimens are clamped in deep knurled jaw to prevent it from slipping. Clamping force kept to minimum to prevent specimen from breaking before test starts. The utmost care has been taken in applying clamping force on test specimen, because greater the clamping force, more pre-stressed the components is. Pre-stressed specimen tends to fail early during tensile testing. Data for each tensile force versus strain was plotted and stress calculated along with young's modulus. Tensile test settings can be seen from Table 2

1.	Speed of crosshead	5 mm/min
2.	Load Cell configuration	5 kN max.
3.	Load Unit	kN
4.	Max. Displacement	5 mm
5.	Time unit	Second
6.	Tension Test	Y

Table 2. Tensile Test Data

2.3 Photo-Elastic Testing

Prototype was mounted on acrylic base plate to give bottom support. To make support rigid, another support was also provided in the middle of the acrylic plate. The supported prototype loaded by means of tightening the screw in middle. Load was applied in middle of specimen to observe fringe contour of stress, Figure 2. The set up is designed to quantify the load applied on test piece. It has been set up in such a way that spring balance was pre-stressed to 5.5 N, when no stress fringes are observed on the test piece. After applying the load, spring balance reading quantified the amount of load applied to the specimen.

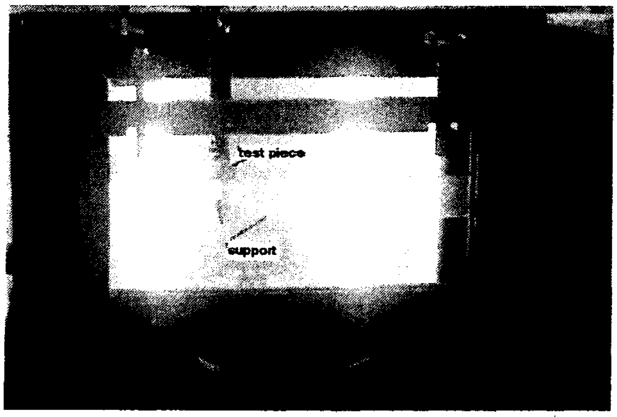


Figure 2. Photo-elastic test setup

Strain gauges were mounted on specimens to quantify the strain and thereby load, but it only provides the value in one particular axis, and hence load acting on one particular axis can be observed, which does not satisfy our aim of quantification of load applied in Y direction.

After taking the reading on spring balance, fringe photographs were taken to calculate the fringe.

2.4 Finite Element Analysis

All data were recorded for tensile test were used to model material in COSMOS software. Values are fed into directional property option of material and material was named as Perfactory.

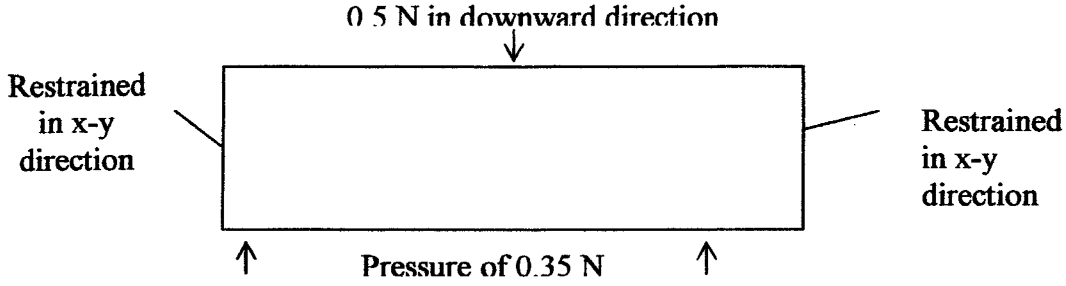


Figure 3. Finite Element loading scenario

As shown in figure, problem has been set up to imitate same condition as it was in photo-elastic test method. So, we can compare the results of photo elastic test with FEA.

3. Results

Reasons for comparing FEA with photo elastic analysis:

Since data from tensile test is fed into software, the results of FEA will be tensile test data dependent. If same data is used to validate the results, that will be duplication of data. Hence, to validate the results of FEA, different set of stress results were obtained through photo elasticity.

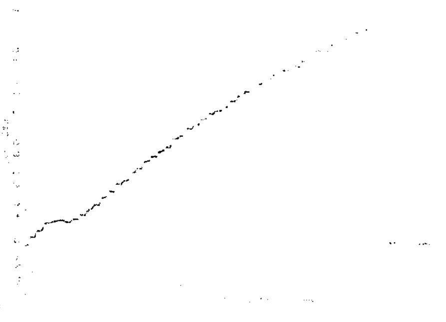
Tensile Test Results of test specimen in Y-direction								
Tensile Test Results Of Test Specimen In X-direction								
Load In KN	**Length**	**Width**	**Notch width**	**Thick**	**Area**	**Stress**		**Average**
1.21	86.21	13.73	12.43	3.77	51.7621	23376.	N/m^2	21005.
Tensile Test Results Of Test Specimen In Y-direction								
Load In KN	**Length**	**Width**	**Notch width**	**Thick**	**Area**	**Stress**		
1.15	86.32	14.78	13.43	3.84	56.7552	20262.	N/m^2	21869.
Tensile Test Results Of Test Specimen In Z-direction								
Load In KN	**Length**	**Width**	**Notch Width**	**Thick**	**Area**	**Stress**		
10.4	94.05	14.93	13.43	7.53	112.42	92507.	N/m^2	92479.

5.2 Tensile Tests

Tensile results are shown in Table 2.

	Average Tensile Stress MPa	Min Tensile Stress MPa	Max Tensile Stress MPs	Std Dev MPa
X	13.397	8.76	15.893	3.181
Y	20.693	16.197	27.1	3.710
Z	13.792	6.633	16.403	3.650

Table 2: Tensile Tests



Graph 1: Tesile Test result Y sample

Summary: The strength in x and z is similar, however the strain in z is double that in x and y showing the interlocking bond between layers has a degree of elasticity. The reason for the high y direction strength is unknown, however these samples were from a different build and could reflect the different properties of new and older resins. Brittle failure as can be seen in Graph1.

5.3 Dimensional Accuracy

Table 3 shows the results for dimensional accuracy in X, Y, Z:

X	A1	B1	B2	C1	C2	T1	T2	T3
Average	108.700	19.843	19.823	10.060	10.033	2.735	3.163	2.928
StDEV	0.243	0.059	0.154	0.067	0.090	0.274	0.035	0.293
Desired Dim	110.000	20.000	20.000	10.000	10.000	3.000	3.000	3.000
Dev	1.300	0.157	0.178	-0.060	-0.032	0.265	-0.163	0.072
ųm Error/mm	11.818	7.875	8.875	-6.000	-3.250	88.333	-54.444	24.167
av error %	1.182	0.787	0.888	-0.600	-0.325	8.833	-5.444	2.417
Min err %	-1.318	-1.100	-1.600	0.000	-0.500	-16.667	4.333	-16.333
Max Err %	-0.855	-0.450	-0.150	1.400	1.600	3.333	6.667	4.667

Y	A1	B1	B2	C1	C2	T1	T2	T3
Average	109.213	19.920	19.996	10.041	10.037	3.051	3.150	3.133
StDEV	0.148	0.056	0.137	0.125	0.108	0.159	0.053	0.057
Desired Dim	110.000	20.000	20.000	10.000	10.000	3.000	3.000	3.000
Dev	0.787	0.080	0.004	-0.041	-0.037	-0.051	-0.150	-0.133
ųm Error/mm	7.156	4.000	0.214	-4.143	-3.714	-17.143	-50.000	-44.286
av error %	0.716	0.400	0.021	-0.414	-0.371	-1.714	-5.000	-4.429
Min err %	-0.909	-0.800	-0.750	-0.700	-0.700	-5.333	3.000	1.667
Max Err %	-0.555	-0.100	0.750	2.800	2.600	6.667	7.333	7.333

Z	A1	B1	B2	C1	C2	T1	T2	T3
Average	109.806	20.041	20.092	10.144	10.124	3.049	3.029	3.054
StDEV	0.266	0.131	0.053	0.221	0.070	0.062	0.043	0.065
Desired Dim	110.000	20.000	20.000	10.000	10.000	3.000	3.000	3.000
Dev	0.194	-0.041	-0.092	-0.144	-0.124	-0.049	-0.029	-0.054
ųm Error/mm	1.760	-2.036	-4.607	-14.429	-12.429	-16.429	-9.762	-17.857
av error %	0.176	-0.204	-0.461	-1.443	-1.243	-1.643	-0.976	-1.786
Min err %	-0.718	-0.950	0.050	0.300	0.400	-1.667	-0.667	-0.333
Max Err %	0.127	1.450	1.000	9.000	2.700	4.667	3.667	8.333

Table 3: Dimensional Test Results

Summary: Maximum error of 0.19 mm similar in all planes. The percentage error for smaller dimensions is higher than for larger dimensions as would be expected.

5.4 Surface Flatness

The surface flatness results are shown in Table 4 where performed on the thin tensile test pieces shown in Figure 3a.

	Deviation mm
X	1.065
Y	0.956
Z	0.060

Table 4: Surface Flatness

Summary: The thin 3mm width samples shown, curl due to shrinkage in the x and y planes during plane change. This is over a 100mm length test piece. The z direction is virtually flat. A new release of resin is due to be released in October 2003 with significantly less shrinkage characteristics which will improve this problem.

5.5 Surface Roughness

Surface Roughness Ra

	0 deg top	0 deg Bot	5 deg top	5 deg Bot	10 deg top	10 deg Bot
Average Ra	0.475	3.325	23.300	25.950	27.050	23.350
Std Dev	0.096	0.096	1.183	1.136	1.063	0.985

	20 deg top	20 deg Bot	30 deg top	30 deg Bot	40 deg top	40 deg Bot	45 deg top	45 deg Bot
Average Ra	24.550	16.750	24.800	18.500	21.800	14.450	21.200	14.250
Std Dev	0.252	0.100	1.689	0.600	1.166	0.870	0.432	1.482

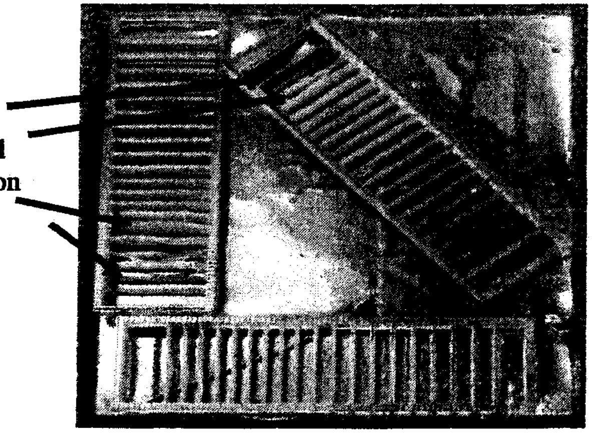
Table 5: Surface Roughness

Summary: The top of each sample, from 20° to 45°, showed a lower value of surface roughness to the lower side. This is due to the curing by the light through the thickness of the build layer being defined by the polymerisation both on the top side providing a well defined step, and through the resin curing to various depth on the liquid side.

The vertical and horizontal build planes showed excellent surface finish, showing good light mask alignment and controlled vertical curing of the resin.

5.6 Build Detail – Filigree

The samples in various build orientations are shown in Figure 8



Failed to build required section

Figure 8x: Samples x-axis, y-axis and xy axis

Summary: The smallest detail feature built perfectly was 0.3 mm thick rib. Features below this size are not self supporting during removal from the polymerisation bowl during build operation. The 0.1 mm rib did build in y direction, but lacks stability.

6.0 CONCLUSIONS

This study was not intended to be a full investigation into the EnvisionTec Perfactory Standard System, but an "out of the box" analysis of the key characteristics of the parts built from it. No calibration other than standard machine setup has been undertaken to improve results.

The results of the tests revealed the following:

Repeatability:	Yes, within 0.2mm for x, y and z planes.
Strength:	Fair – brittle failure at a stress of 14 MPa, z strain twice, x and y strains.
Dimensional Accuracy:	Majority of error less than 1% of desired dimension, improving with the size of the sample.
Surface Flatness:	Excellent in z, but due to large shrinkage of resin during curing with current materials, poor in x and y for thin sections.
Surface Roughness:	Excellent horizontal and vertical build directions up to Ra of 27 at 10% inclination with better underneath surface.
Detail:	The system can reliably manufacture thin walled features up to 0.05mm thick.

The above results are an indication of performance of the PerFactory System during the period of testing. Improvements have been made to the set-up, operation calibration, and materials used. The process can only improve with iminant release of the new build resin.

7.0 ACKNOWLEDGEMENTS

The author would like to thank Government Office North East for providing the ERDF funding to support this project, together with the CRPD core team: Professor M Sarwar and Ms SB Ward. In addition the author would like to thank Envisiontec GmbH Ltd for providing use of a test machine while awaiting delivery and training of a system at Northumbria University.

REFERENCES

[1] P. F. Jacoby, *Rapid Prototyping and Manufacturing – Fundamentals of Stereolithography,* McGraw Hill, New York, 1992, ISBN:

[2] P. M. Hackney & M. Sarwar, *Operating Characteristics of the Z-Corps 3D Printing Process*, NCMR Conference 2001, Cardiff University.

[3] S. H. Choi and Amavedeam. S., *Modelling and Optimisation of Rapid Prototyping,* Computers in Industry, Vol 47, 2002, pg 39-53.

[4] J. G. Zhou and D. Hersovici, Parameter Tuning and Optimisation for SLA, Rapid Prototyping Manufacturing Process, International Conference on Manufacturing Automation, 1997, Vol 2.

[5] R C Luo, J H Tzou and W Z Lee, The Development of LCD Panel Display Based RP system for Advanced Manufacturing, International Conference on Robitics and Automation, April 2000, San Francisco.

Application of the Z-Corps 3D Printing Processes using Novel Material to Manufacture Bio-Scaffold for Bone Replacement.

P M HACKNEY, K P PANCHOLI
Centre for Rapid Product Development, Northumbria University, UK
Phil.Hackney@unn.ac.uk, Katen.Pancholi@unn.ac.uk

ABSTRACT

Tissue engineering promises new bone replacement in area of large defects due to traumatised, damaged or lost bone. One of the bone formation strategies is to construct bio-scaffold, which allows bone reformation, once it is surgically placed in bone-defect. Current issues with manufacturing and designing bio-scaffolds are mechanical strength along with biocompatibility, osteoinductiveness (which allows induction of bone cells), osteoconductiveness (conducive to cell attachment) of materials of the bio-scaffold. This paper explores the combination of biomaterials to form bio-scaffold using 3D printing rapid prototyping method. Using novel medical application of synthetic Hydroxyapatite with sol (hydrolyzed ethyl silicate) to form 3 dimensional prototypes, the possibility of bio-scaffold manufacturing for hard tissue engineering is studied. Sintered 3D printed prototypes are assessed for densification (pore size) and strength using bi-axial stress methodology. Osteoinductiveness and osteoconductiveness of both materials with strong binding tendency of sol-gel seemed more promising in bio-scaffold manufacturing for bone tissue engineering. Conventional 3D printing methodology and materials are identified to make bio-scaffold structures. Relationships with temperature and catalyst concentration are studied to use these as basic principle for modification of the 3D printing process.

Keywords: Bone tissue engineering, bio-scaffold, 3D printing, sol, ceramics, and porosity.

1. INTRODUCTION

Regeneration of hard bony tissue in a shape similar to bone defect in a patient is the main function of the scaffolds structure (1). The shape of bone defect can be generated by using same shape of scaffold made up of materials facilitating growth of new bone tissues. The ideal designed scaffold should have the same geometry as the bone defect, and equivalent young's modulus to bone A structure with interconnected pores to facilitate growth of tissue or osteogenic stem cell delivery for faster integration of surrounding tissues(2,3). The main concern in design of bio-scaffold is of combination of materials having similar material properties as the host tissue as has been described in 'Wolff's Law'-"With the changing stress or strain imposed, bone will remodel itself to maintain stress level within". In total hip replacement, bone resorption in the femur nearby leads to aseptic loosening of the prosthesis (4),(5). In order to avoid this kind of mechanical stress level concentrations in the implant, an implant should be of similar modulus. The study of loss factor due to collagen damage (tan δ) and viscoelastic property (E') of bone suggested that viscoelastic property(E') remains around 9.5 GPa to 11.1 GPa, while loss factor changes with dry and wet condition of bone from 0.14 to 0.43 x 10^{-1}.(6)

Bio-scaffold is one of the important strategies of bone formation among stem cell and gene therapy, bio mimetic and smart material but it has yet to yield functional use. Bio scaffold should ideally be of similar shape as bone, biocompatible, osteoinductive, osteoconductive. There have been various materials and processes has been tried to produce ideal bio scaffold but its process ability into three dimensional complex structures has remained a critical issue considering biocompatible-osteoinductive materials available.

The challenge lies in adapting Rapid-Prototyping (RP) processes for use of various biomaterials. Today available RP techniques require either high power laser or material which is toxic for human or unsuitable for print head. The 3 D Printing process owing to its non-involvement with high power, toxic material or thermal treatment, is considered to be potential technology for designing and fabricating bio-scaffold. However, low strength and suitability of the print head for various types of material binder, is key in achieving successful bio-scaffold design. Use of gelatine, starch and bio-degradable materials in the 3D printing process has been reported with water as binder, though salt leaching technique is required to produce interconnected porosity in the prototype, which can be caused by gelatine and starch, which melts on interaction with water to give a dense structure. Many materials and composites of natural material like corn-starch, starch/ethylene vinyl alcohol and starch/cellulose acetate and their respective composites with Hydroxyapatite (HA), corn starch, gelatine, dextran with water as binder have been explored for 3D prototyping technique. Various other technologies of manufacturing bio-scaffolds like fibre bonding, solvent casting and leaching, membrane lamination, melt moulding and gases foaming exist. The drawbacks of these systems are use of highly toxic solvents, long fabrication process, labour intensive work, thin substrate, irregular pore connectivity or irregular geometries and repeatability of shape(7).

2. MATERIALS

In recent years, ceramics, glasses and glass ceramics are used in the medical field, which are termed as 'bio ceramics' and are accepted as viable biomaterials for tissue engineering. Biocompatibility is result of chemical composition of material, which contains ions commonly found in the physiological environment like Ca^+, Mg^+, Na^+ etc. Amongst all bioceramics, Hydroxyaptite, ceramic of β-tricalcium phosphate phosphate finds many applications due to the composite of HA and collagen found in human bone.

Experimental and research reveal a binder-powder combination to achieve a moduli of 10 GPa with reduced toughness and long elastic range. Several polymer-HA composites have been employed either using natural or synthetic occurring polymer. The obvious requirement of strong, stiff hybrid composite should have strong bond between particles of inorganic ceramic matrix besides densification of particles. To compensate low volume fraction resulted from shrinkage of silane bond in Sol, the component is sintered at different temperature.

Sol has been taken as binder for inorganic HA matrix. Sol is prepared in conjunction with Imperial college (Materials Department). Either acid can produce inorganic sol or alkali catalyzed hydrolysis of silicon or metal alkoxides.
Ha (sintered grade) powder procured from Plasma Biotal ltd. UK. of 1 micron particle size.

3. EXPERIMENTAL

3.1 Sol Preparation: 98% Tetra ethyl orthosilicate (TEOS, 2L 13,190-3) Aldrich Chemicals Ltd., was added to deionised water with nitric acid 2 N of a roughly equal amount and stirred for an hour. Calcium nitrate hydrate has been added to leave it for an hour; this sol was used as binder by adding more water to make surface tension and viscosity in line with the binder supplied by Z-Corp. 3D printing machine. This is a prerequisite for making any binder suitable for the print head, to print without any problems.

3.2 Temp. Vs Gelation Time: Since binder is being used in a thermal inkjet printing head, the binder is subjected to 60-70°C temperature; the relationship between temperature and sol has been studied thoroughly. Ceramic Petri dish preheated up to 70°C for an hour and then 5 ml of sol drop is placed and studied for Gelation time.

3.3 Particle Sizing and Spread: Particle size of obtained HA was quite small for the spreading of its layers in defect free manner. In order to achieve defect free layers, HA powder was sprayed with sol to make agglomerates, which, in turn, were ground sieved to get bi-modal distribution of 1 micron to 50 micron particles sizes. This powder particle size improved the surface finish and particle density in component made by 3D printing.

3.4 Printing: The Z-Corp 3D printing machine ZP–402, HA powder is fed on to the feed platform by compacting it with hand compactor. Binder surface tension and viscosity is found to be in line with 40% ethanol and 60% sol. To avoid further heating up of the binder solution, it is directly fed in to the print head with a gravity feed system instead of pumping it through solenoid pump available in 3D printing machine. However, initially fine powder was sticking to the nozzle outlet of printing head to block it, but on adjustment of height between head and powder substrate it started printing up to certain layers. Though the binder chemistry or printing head technology still needs to be refined to print continuously without any problem.

3.5 Infiltration: During printing binder concentration was found to be enough to hold particles of HA powder together only. To strengthen printed components further, they were dipped into sol for 3 minutes to make sure that sol was infiltrated throughout the depth of components.

3.6 Drying: Infiltrated components are immediately placed in airtight box to dry it slowly and retain moisture in while drying. This will ensure that silane bonding between two particles will not be pre-stressed to become quite brittle. These boxes are stored at room temperature of 20 to 23°C for 36 hours. After 36 hours, boxes are opened and components were found to be reasonably dry and strong.

3.4 Sintering: Dried components were kept in an open environment for 12 hours to remove any moisture left. These components were sintered in over for 1 hour at different temperature from 900°C, 1000°C, 1100°C and 1150 °C. They were then oven cooled to bring them to room temperature.

4. RESULTS

4.1 XRD (X-Ray Diffraction) of Printed Component, HA Powder, Gelled Silica.

XRD results obtained on Siemens Diffraktometer 5000. The presence of Calcium silicate in the sintered printed components is proof of the ionic bond between calcium ion of HA and Silicate of sol. Primarily the strength of the component is attributed to chemical bonding between calcium and silicate besides polymerization of Sol Figures 1, 2, 3.

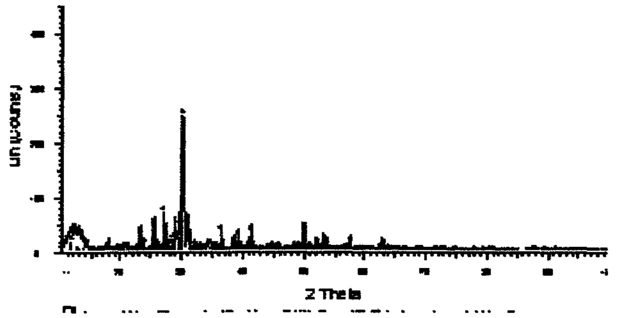


Figure 1. Sintered prototype showing peaks of Calcium silicate.

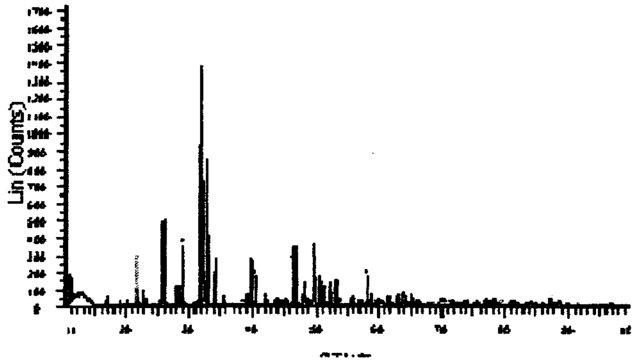


Figure 2. Sintered Sol at 900°C showing Coesite SiO_2 Cristoballite and silicate.

4.2 Scanning Electron Microscope (SEM) Analysis

Prototypes are sintered at 900°C for an hour, then slowly cooled to room temperature. These sintered prototypes were found to be harder than un-sintered prototype. However, the SEM, found there is little difference between them, except sintered small particles of HA having diffused to become a denser structure, excess silica binder also disappeared in sintered sample Figure 3. This phenomenon caused shrinkage in the silica bond and thus in the prototype as well. Table 1. shows the overall dimensions change due to shrinkage.

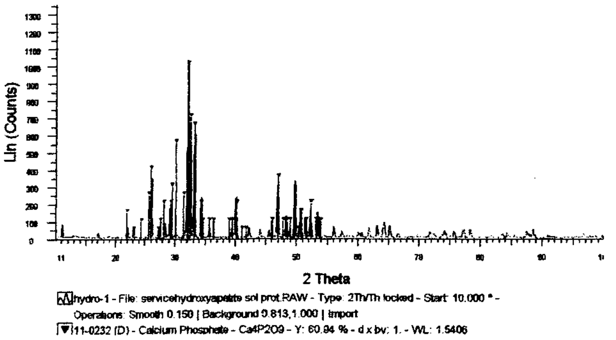


Figure 3. Sinter Pure HA powder showing Calcium phosphate peaks.

	% overall Shrinkage	% wt of silica binder
Sample 1	7.55	4.2
Sample 2	8.01	4.9
Sample 3	8.55	5.3
Sample 4	9.12	6.2

Table 1. Shrinkage of component at different silica binder percentage.

The SEM element analysis of sintered sample shows a significant amount of Carbon, which could be the reason of burning the organic portion in binder Figure 4.

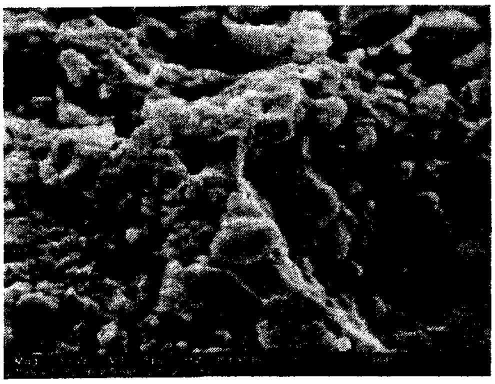


Figure 4a. SEM of un-sintered prototype

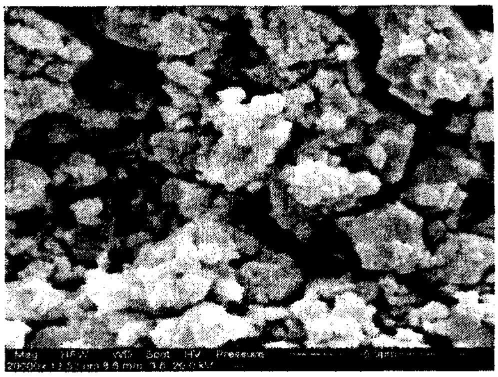


Figure 4b. SEM of sintered prototype

4.3 Mechanical Strength with Respect of Percentage of Sol.

Determining the strength of the component has been considered with utmost care. Beforehand, the layer thickness, saturation level and other factors had been set to optimum for the best result. Figure 5.

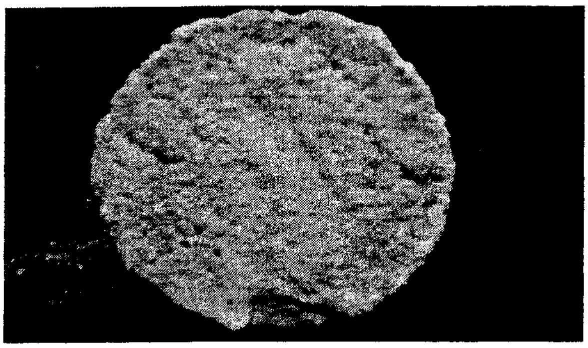


Figure 5. Produced Prototype

	E GPa	Strength MPa
Sample 1	1.02	72
Sample 2	1.04	69
Sample 3	1.34	85
Sample 4	1.52	89

Table 2. Young modulus of bio-scaffold

Layer thickness and binder saturation level is an important factor in deciding component strength, as dispersion throughout the layer improves the strength and quality of the prototype(8). For this experiment, layer thickness was kept at 0.1 mm and 1.8/0.8 saturation for the shell/core ratio. The utmost care must be taken in drying the prototype to avoid cracking, however 2 out of 5 components were found to be cracked due to pre stressed silicon bond.

4.4 Gelation Timing :

No.	Material Temperture at 100 C	Time for complete Gelation	Gelation starting time
1	100% sol	4 mins 45 sec	4 mins
2	90% sol and 10% ethanol	8 mins	5 mins
3	80% sol and 20% ethanol	9mins 20 sec	5mins 40 secs
4	70% sol and 30% ethanol	11mins	6mins 20 secs
5	60% sol and 40% ethanol	12mins 30 secs	7mins 40 secs
6	100% sol with calcium nitrate hydrate	6 mins 30 secs	4 min 20 secs

Table 3. Gelation Time

4.5 Particle Size:

Particle size of powder substrate is an important factor to produce a good surface finish and strong component. In the 3D printing process of ZP-402 machine, powder is spread from feed platform to the build platform by means of a roller moving in raster motion. If particle sizes are uniform and less than 20 microns, the spread layer quality is quite low, as seen in figure 6a, 6b.

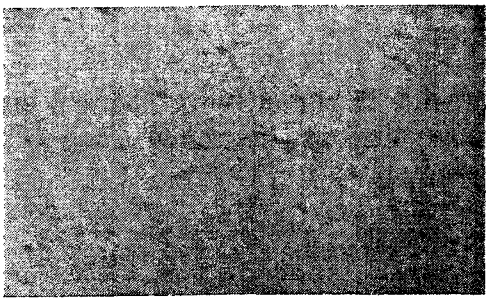


Figure 6a. Improved Spread

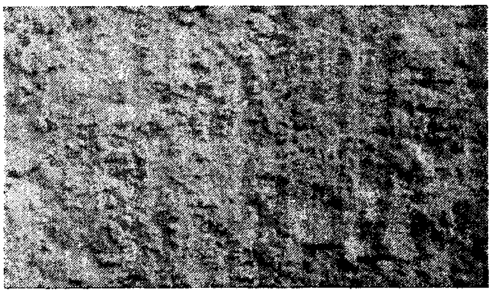


Figure 6b. Rough spread on ZP-402

As seen in figure 6a the uniform size of 1 micron is spread with rough texture of the layer but it improved when powder sized 1 to 50 micron (mean 25 microns) was used. This phenomenon could be attributed to settling of finer particles between the voids of coarse particles. This also improves dispersion of binder between the substrate to a great extent.

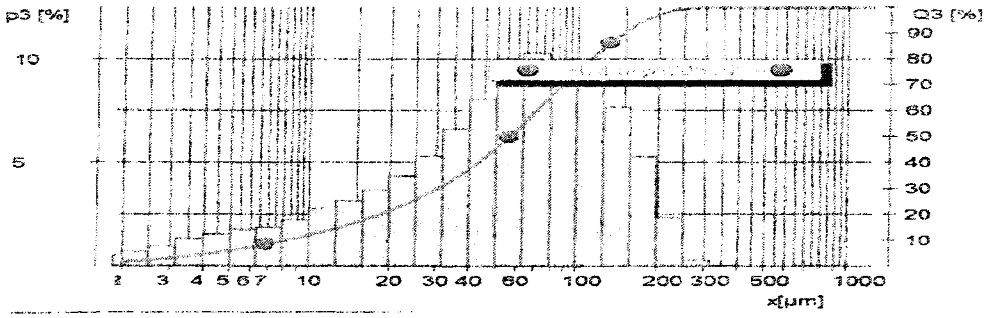


Figure 7. Particle size distribution in given sample

4.6 Surface tension and viscosity

The thermal inkjet is a disposable inkjet print head, which has been replaced by a plastic cylindrical reservoir with a certain height to maintain pressure to force binder ink to pass through the filter and reach the chamber. A droplet of binder was propelled from the nozzle when electric heat causes vapour bubble to be formed by ink.(9). Orifice dimension and firing signal profile influence droplet frequency volume and velocity.(10). The mass and velocity of the droplet are a function of the physical properties of ink i.e. surface tension, viscosity and chemical composition(11).

In general the drop on demand (DoD) system uses nozzle opening size of 60 micron for Z-402 print head. An upper limit of droplet production rate of 12 kHz is suggested. However droplet frequency and volume significantly affects the surface quality of the print head component as bigger droplet and high frequency tends to make trench in loose powder substrate(12).

Even spreading of binder in loose particles is also an important factor in binding subsequent printed lines. Overlapping of two subsequent printed lines is also desirable for stronger components, as it will limit the formation of weak zones produced due to entrapment of loose unbound powder between two subsequent printed lines. Viscosity more than 20 MPa and particle size of powder less than 20 microns prevents absorption and spreading of binder ink. Ink surface tension is kept around 30 mNm^{-1} to make sure a bubble is formed within the print head chamber. To overcome the temperature(13) dependence of viscosity and subsequent bubble formation complication water based colloidal silica has been used.

For finding the ideal viscosity of binder to facilitate spraying of binder using Thermal ink-jet technology, various viscosity measured as Table 4. below. Viscosity measured using U tube viscometer in minute and seconds.

No.	Different Concentration	Viscosity
1	50% sol 50% Ethanol	5 minutes 01 seconds
2	50% water 50% sol	5 minutes 25 seconds
3	75% water 25% sol	2 minutes 40 seconds
4	Z-corp. binder	1 minutes 33 seconds
5	Water	1 minutes 28 seconds
6	10% sol 90% water	1 minutes 49 seconds
7	5% sol 95% water	1 minutes 39 seconds

Table 4. Viscosity of binder at different concentration

To make the viscosity the same as Z-Corp binder, 5% sol concentration was used, and this was enough to give handleable green strength to the part. These parts are then infiltrated with sol to increase part strength.

from the work of Fromm's, it has been argued that surface tension is critical for maintenance of droplets. Thus the ratio of Reynolds number to Webber' number is given by:

$$\frac{\mathrm{Re}}{We} = \frac{(\gamma\rho a)}{\eta}$$

Where, a is the orifice diameter γ, ρ and η represent the density surface tension and viscosity of the binder ink.

Drop resolution is dependent on dispersion and total free surface energy of the substrate (14). When free surface energy is greater than dispersion, then the ceramic tends to displace around the drop of binder but reducing the viscosity of the binder and thus increasing dispersion can control this.

5. CONCLUSIONS

For successful 3D printing with powder and binder, following care must be taken:

- Viscosity of binder should be in range of 1 minute 25 seconds to 1 minute 38 seconds. However, dispersion and proper mixing of binder with base material should be maintained. Any settling down of high-density liquid could lead to unsuccessful spraying.

- Surface Tension also found to be critical item for bubble formation. Best value is 25 mN/m.

- Particle size is also important for the purpose as it decides good powder spread with dense structure for component strength. Following particle size is found to be best possible for getting good component, however, for particular experiment, some 50-micron size particles were increased by 10% to get porosity in component.

- Sintering of HA improves the strength of component till it is sintered up to 1160^{0}C but if component is sintered above 1160°C, it looses it strength due to breaking or weakening of silane bonds. However, improvement in densification of HA prototype is observed.

- Porosity is not affected by densification to a great extent, which prevents function of prototype as bio-scaffold material.

- Layer thickness for each layer can be varied with absorption of the binder in the powder. High viscosity and very fine size powder of 1 to 5 micron size is the worst case of binder absorption, while 200 micron with low viscosity like water disperses in the x and y direction to such an extent, it reduces accuracy by up to 5%. Bio compatibility and in-vitro experiment also can be carried out but since both the powder and sol are bio compatible, bio compatibility should not be the problem.

REFERENCES

(1) K H Tan, C K Chua, K.F. Leong, C.M.Cheah, P. Cheang, M.S.Abu Bakar, S. W. Cha, Biomaterials, 24 (2003) 3115 - 3123
(2) R.O.C. Oreffo and J.T.Triffitt, Bone Vol. 25, No.2 Supplement August 1999: 5S-9S
(3) R.A.J. Rose and Richard O.C. Oreffo, Biochemical and Biophysical Research Communications 292, 1-7 (2002) Elsevier Science (USA)
(4) Min Wang, Biomaterials, 24 (2003) 2133 – 2151, Elsevier –Science Direct.
(5) Julian R Jones, Larry L Hench, Current Opinion in Solid State & Materials Science xxx (2003) xxx-xxx Article in press.
(6) Junro Yamashita, Xiaoe Li, Benjamin R. Furman, H.Ralph Rawls, Xiaodu Wang, C. Mauli Agrwal, 2001 John Wiley & sons Inc., J Biomed Mater Res (Appl Biomater) 63: 31 -36, 2002
(7) Material Science and Engineering, C 20 (2002) 49 – 56, C.X.M Lam, X.M.Mo, S.H.Teoh, D.W. Hutchmacher.
(8) Albert Y.L.Yao and Y.C.Tseng, Rapid Prototyping Journal Volume 8, Number 3 2002, 180 -189
(9) M. Ediresinghe , J.R.G Evans, B.Y.Tay International material research In Proof. 2003
(10) H.P.le, J.imaging Sci. Tech, 1998, 42,49-62
(11) W.J. Lloyd, H.H.Taub, In. output hardcopy devices, R.C. Durbeck and S.Sherr, Eds,Academic press, incorparted boston usa 1988, 311-370
(12) Paul Calvert, John O'Kelly, Chad Souvignier Materials Science and Engineering C6 (1998) 167 - 174
(13) K.F.Leong, K K S Phua, CK Chua, Z H Du and K O M Teo , HO4600 IMechE 2001, Proc Instn Mech Engrs Vol 215 Part H.
(14) B.Y.tay, M.J.edhiresinghee, J.mater.res,2001 16, 373-384

Analysis of the EnvisionTec PerFactory System for Rapid Production of Components and Validation Utilising Finite Element and Photo-elastic Analysis.

P M HACKNEY, K P PANCHOLI
Centre for Rapid Product Development, Northumbria University, UK
Phil.Hackney@unn.ac.uk, Katen.Pancholi@unn.ac.uk

ABSTRACT:

The PerFactory prototyping machine manufactured by EnvisionTec GMBH uses the photo polymerisation principle. Unlike SLA, it uses light instead of high cost laser, which makes it commercially attractive. The strength of material is major issue while exploring possible direct use of prototypes as component. This paper attempts to set-up and validate Finite Element Analysis (FEA) work in 'COSMOS' software for prototyping process. This can be used later on for stress analysis of other prototypes made using the PerFactory process. Material data were obtained by tensile tests of specimens considering its directional properties relating to interlayer adhesion. Results of FEA were validated against photo-elastic analysis and physical test of various shaped prototypes.

Keywords: PerFactory Digital Light Machine system, Accuracy and Material properties, FEA, Photo-elastic analysis

1. INTRODUCTION:

Photopolymerizable composite resins are used worldwide as well established restorative systems [1]. Despite successful inventions of adhesive systems, the problem with adhesion of photo polymerized resin has remained unanswered due to photo polymerization shrinkage during curing. It is observed that rapid prototypes made using photo polymerization process has limited strength and accuracy .The rapid prototype has got directional stress property due to interbonding of layers [2]. Interbonded layers makes prototype more elastic in one particular direction. The process itself and method of polymerization is quite complex to understand and is not covered in this paper.

The use of Rapid prototype has penetrated small and medium sized company to assist in the design and manufacture new products [3]. Several attempts have been made to use prototype processes to manufacture direct tool, components or implants in medical use [4] [5]. Considering its potential use as component rather than prototype for Rapid manufacturing application, its strength and relation of strength with process parameters are investigated in this paper.

To investigate the strength and its relation with parameters, photo-elastic stress analysis has been employed to calculate maximum stress in a component, when loaded by certain load. Photo-elastic stress analysis is quick and useful method to analyse where component is transparent.

Photo elastic method to study photo polymerization shrinkage was used by Clause-Peter Ernst – Meyer-Klocker-Brita. Fiedler-Schulte[6] applied photo elastic in determining fracture toughness of fiber-reinforced model composite materials to observe micromechanical interdependence between the local fibre/matrix load transfer and crack propagation in the matrix starting from the location of fibre failure[7]. In order to find out micromechanical properties, composite are stretched with a testing device, when placed under microscope to observe crack propagation and stress contour associated at different time step can be observed. This novel method shows the usefulness of photo-elasticity in analysing stress induced dynamically. Unlike strain gauge stress measurement method, it does not depend on placement of transducer, associate wiring and its need to be static.

According to principle of photo elasticity, When elastically deformed, the optical properties of a photo elastic specimen become Anisotropic. Using a special optical system and polarized light, the stress distribution within the specimen may be deduced from interference fringes that are produced. These fringes within the four photo elastic specimens, indicate how the stress concentration. Distribution changes with notch geometry for an axial tensile Stress.
The main equation of the photo elastic analysis is as follows:

$$2\tau_m = \sigma_1 - \sigma_2 = \frac{s}{h} m \tag{1}$$

Where, τ_m = Main shear stress, σ_1, σ_2 are the principal stresses, h is the thickness of the specimen, s is the photo-elastic constant, n is the briefringerence number.

Many transparent non-crystalline materials that are optically isotropic when free of stress become optically anisotropic and display characteristics similar to crystals when they are stressed.

The stress optic law:
Maxwell noted that the changes in the indices of refraction were linearly proportional to the loads and thus to stresses or strains for a linearly elastic materials. The relationships can be expressed in the equation form as:

$$n_1 - n_0 = c_1\sigma_1 + c_2(\sigma_2 + \sigma_3) \tag{2}$$

$$n_2 - n_0 = c_1\sigma_2 + c_2(\sigma_3 + \sigma_1) \tag{3}$$

$$n_3 - n_0 = c_1\sigma 3 + c_2(\sigma_1 + \sigma_2) \tag{4}$$

Where,
σ_1, σ_2, σ_3 = principal stresses at point,
n_0 = index of refraction of material is unstressed state,
n_1, n_2, n_3 = principal indices of refraction which coincide with the principal stress directions,
c_1, c2 = constants known as stress optic coefficients.

The above three equation can be simplified to,

$$\sigma_1 - \sigma_2 = \frac{Nf_\sigma}{h}, \text{ Where } N = \nabla/2\pi,\ f_\sigma = \lambda/c \qquad (5)$$

If we get $\sigma_1 - \sigma_2$, we can calculate maximum shear stress and stress as well by using

$$\tau_{max} = (\sigma_1 - \sigma_2) = N f_\sigma/2h \text{ and } \sigma 1 = N f_\sigma/h - p \qquad (6)$$

2. EXPERIMENTAL PROCEDURE

2.1 Sample Production

Tensile specimens were prepared by the PerFactory process, using 0.1 mm layer thickness, the material was Penta Erythritoltri/tetra acrylate, 1,1,1 Trihydroxy methylpropyl – triacrylate. The values for PerFactory building parameters for prototype manufacturing are tabulated in Table 1.

PerFactory Machine	Date:		
Parameter Build Name:			
Parameters	Base	Build	Units
Layers	10	10	
Thickness	0.1	0.1	µ mm
Exposure Time	22,000	15,000	µs
Positioning Velocity	800	2500	m/s
Separation Velocity	6000	6000	m/s
Waiting Time (upper turning)	2000	1000	µs
Waiting Time (lower turning)	2000	1000	µs
No. of solid base plate	5		

Table 1. PerFactory Build Setting.

Specimens are prepared in different orientations, Figure 1,

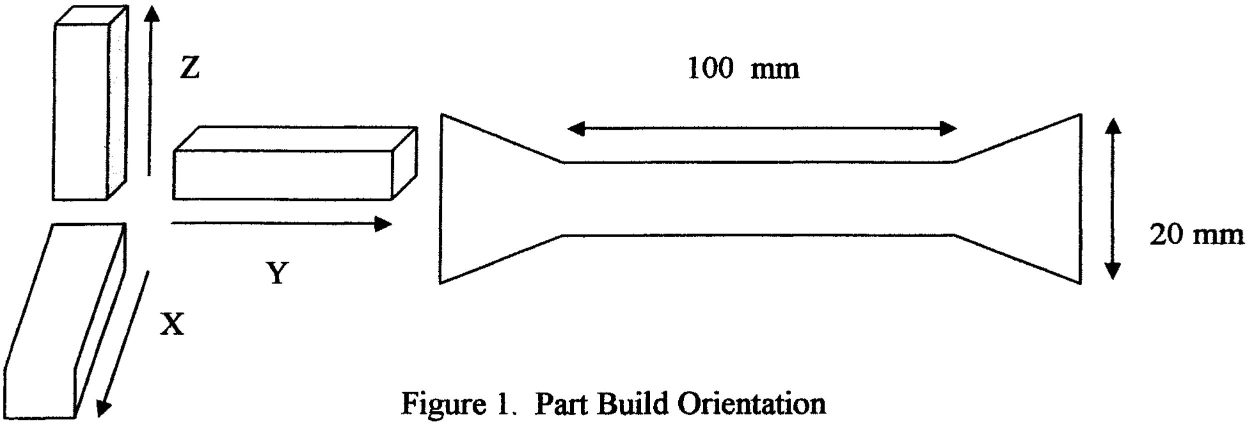
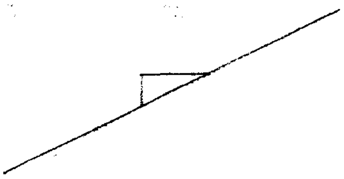


Figure 1. Part Build Orientation

Table 3. Tensile test results

Value in x-direction are higher than x and y direction. That is observed because of interlayer bonding between to layers.



$$E = \frac{\Delta \sigma}{\Delta \varepsilon}$$

$$= \frac{32}{15} = 2.183 \ KN/mm^2$$

$$= 2133000000 \ N/mm^2$$

$$= 2.13 \times 10^9 \ Pa$$

$$V = 0.24$$

Figure 5. Young's' Modulus Calculation

This data has been taken was the input for the material data in COSMOS WORK to analyze the specimen.

Calculations for photo-elasticity:

$$\sigma_1 - \sigma_2 = \frac{Nf_\sigma}{h} \qquad 7$$

Now, f_σ = 574.5 for this material and N= fringe order, h= thickness of prototype

As it can be seen in picture that on right hand side bottom, the fringe is numbered 4 and hence fringe order is ¼,

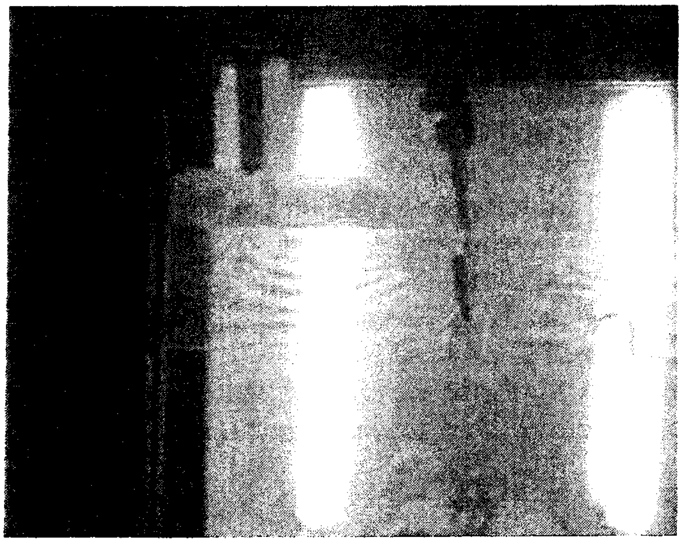


Figure 4. Photo-Elastic Specimen

$$\sigma_1 \text{ or } \sigma_2 = 1 \times 534.5/3.77 \times 4$$
$$= 35.44 \times 1000$$
$$= 35{,}440 \text{ N/m}^2$$

Thus maximum Stress on plate is 38,090 N/m^2

4. CONCLUSIONS

Comparison: The maximum stress achieved in plate was found to be

Max. Stress Achieved by Photo Elastic method	Max. Stress achieved by FEA
35,440 N/m^2	39,182.5 N/m^2
It shows that FEA results are in agreement with photo-elastic practical results, which validates the material data obtained from tensile test.	

The research revealed that little difference in values of maximum stress between physical and digital testing, hence, data obtained for the PerFactory material can be used rapid manufactured products.

5. REFERENCES.

[1] Stansbury J W, Curing Dental Resins And Composites By Photo Polymerization. J Eshtet Dent 2000:12:300-8

[2] Analysis Of The Build Quality Of The "Digital Light Processing" Rapid Prototyping Process. P.M.Hackney, Northumbria University, School Of Engineering & Technology.

[3] P. M. Hackney & M. Sarwar, Operating Characteristics Of The Z-Corps 3 D Printing Process, NCMR Conference 2001, Cardiff University.

[4] A Review Of The Manufacture Of Below-Knee Prosthetic Sockets Using Rapid Prototyping Technologies. N S Herbert, The National Conference On Rapid Prototyping And Manufacturing.

[5] Rapid Manufacture Of Burn Resistant Ti Components Using Direct Laser Fabrication (DLF), R Sharman, S Wu, M H Loretto And W Voice.

[6] Determination Of Polymerization Shrinkage Stress By Means Of A Photo Elastic Investigation, Clause-Peter Ernst, Gerrit R Meyer, Kerstin Klocker, Brita Willerhue, Dental Material (2003) Accepted In 28 April 2003.

[7] Photo-Elastic Analysis Of Fibre Reinforced Model Composite Materials, B Fiedler & K Schutle, Composite Science And Technology 57(1997) 859 – 867, 1997, Elsevier Science Limited.

The Application of the Z-Corps 3D-Printing System for the manufacture of Rapid Tooling inserts, for the Production Polymer Injection Moulded Parts.

P M HACKNEY
Northumbria University, UK
Phil.Hackney@unn.ac.uk

ABSTRACT.

This paper investigates the utilisation of Z-Corps low cost 3D printing process to produce direct polymer injection moulding tool inserts for fast low, cost aesthetic components.

Rapid Tooling using rapid prototyping methods such as SLAs' AIM and SLSs' Rapid steel has been used to produce plastic injection mould tools.

The application of 3D printing utilising plaster based materials and hardeners for direct injection moulding is investigated. The investigation focuses upon the feasibility, repeatability, accuracy and moulding process.

The application is to create low cost aesthetic parts in durable engineering polymers directly in hours rather than weeks.

Keywords: Rapid Tooling, 3D printing, Plastic Injection moulding

1. INTRODUCTION

The focus on productivity, short product lifetime, and cost savings has become one of the main concerns of industries worldwide. Industries need to develop and manufacture new products more cost effectively in shorter lead times. The problems of product design and the production of prototypes are significant obstacles to the launch of new products because design iterations add time to the product development process, and prototypes are used to confirm the design and customer requirements. A prototype is a duplicate version of an end product.

To this end, the 3D Computer Aided Design (3DCAD) and various Rapid Prototyping (RP) techniques have been developed to produce physical prototypes in an effort to reduce time to market [1]. Rapid prototyping was once considered as a technology for only the industries such as automotive and aerospace, but it is becoming more commonplace in the government, military, academic institutions, business machines, consumer products, and medical industries[2]. Rapid Prototyping is a technology used for building physical models of a component and prototype parts directly from 3D computer aided design data. The technology is able to produce a part or an object of moderately complex geometry. Also, rapid prototyping facilitates the early detection and correction of design flaws.

The slowest and most expensive step in the manufacturing process is tooling. Since moulds and dies often have complex geometries and require high quality, they are traditionally made by CNC machining, i.e. lathe, milling, grinding, electro-discharge machining (EDM), or by hand all of which are time consuming [3]. Rapid tooling is a natural progression from RP that can build prototype tools directly from CAD models. It is able to reduce lead times and costs for low volume tooling and prototype tooling. At present, rapid tooling has been developing robust

technologies to be used for manufacturing processes such as vacuum forming, die casting, injection moulding, etc. There are many different rapid tooling processes available for producing injection moulded prototype parts, e.g. SLA Aim tooling, SLS tooling RapidSteel, epoxy tooling, Keltool and other processes.
The research focuses up on mould design and also the use of the Z-Corp machine to produce injection mould tooling to manufacture simple 3D and aesthetic 3D plastic parts. The low cost Z-Corp printing machine is able to produce physical prototypes quickly, easily and inexpensively from 3D CAD data.

The investigation looks at the manufacture of a simple part first to establish which infiltrates and manufacturing settings are applicable. The results then being utilised to manufacture an aesthetic 3D component based upon both Northumbria University's logo and the Gateshead Millennium Bridge, this was used to validate the process. To verify the design of the mould tooling, Moldflow Plastics Adviser^{TM} software package was used to predict the quality of the plastic product, also used to analyse the best gate location of the injection sprue, pressure, flow analysis, and temperature in the injection moulding process.

The original definition of Rapid Tooling was "A 3D CAD driven process that generates tooling inserts in a layer by layer process for the production of components in end use materials [4]. Rapid tooling (RT) is a natural extension of rapid prototyping. It originated from the need to assess rapid prototyping models in terms of their performance [5]. It was introduced as a new generation of tool making techniques, and was defined as a technique to produce low volume metal and plastic products from the rapid prototyping process. Rapid tooling is a process that allows a tool for injection moulding and die casting operations to be manufactured quickly and efficiently. It is the ability to build prototype tools directly as opposed to prototype products directly from 3DCAD models resulting in compressed time to market solutions. RT offers a high potential for a faster response to market needs, creating a new competitive edge. In addition, the rapid tooling process provides higher quantities of models in a wider variety of materials. The purpose of rapid tooling is not the manufacture of final parts, but the preparation of the means to manufacture final parts [6].

Rapid tooling can be divided into two methods, which are indirect and direct. The indirect process is a method that requires a pattern, typically produced from a rapid prototyping system, to create the tooling inserts. The direct method produces the inserts from a rapid prototyping system without an intermediate process.

Indirect rapid tooling is a method that uses rapid prototyping master patterns to create moulds or dies. This method can be used for production of both plastic and metal, for example, injection, vacuum casting, blow moulding, extrusion, sand casting, investment casting, sheet metal forming, etc. Indirect rapid tooling can be divided into soft tooling and hard tooling.

Soft tooling can be obtained via replication from a positive pattern or master. The alternative definition is based on the rigidity and durability of the tooling [5]. It is possible to define soft tooling by the method and material of manufacturing, such as silicone, epoxy, wax, low melting alloys, etc.

Hard tooling is often referred to as that made from hardened tool steels processes such as Keltool Tooling, Cast Metal Tooling and Electroformed Tooling.

Direct rapid tooling is aimed at the realization of production tooling directly from CAD data files, with the smallest possible number of operations [6].

- Direct AIM: A technique from 3D systems in which stereolithography produced cores and cavities are used, with traditional metal moulds for injection moulding of high and low density polyethylene, polystyrene, polypropylene and ABS plastic [7]. Tools can be produced within 2 to 5 days with good accuracy.
- LENS/Laser Generating: Sandia developed Laser Engineered Net Shaping; LENS involves blowing powder into a molten pool, a laser beam melts the top layer of the part in areas where material is to be added. Powder metal is injected into the molten pool, which then solidifies. Layer after layer is added until the part is complete [7]. This technique offers fully dense parts, since the metal is melted, not merely sintered. There are varieties of metals including stainless steel, tool steel, titanium carbide cements, etc.

- SLS/DTM/RapidSteel: DTM sells a steel powder; coated with a thermoplastic binder. A product is built by melting the thermoplastic with a 50W laser [8]. DTM process is used to produce a metal mould for injection moulding. RapidSteel can also be used for pressure die casting of metals.

Why use the Z-Corp 3DP process – the Z-Corp 3DP has one of the highest build rates of any rapid prototyping machine, it allows users to produce three-dimensional conceptual models of any complexity directly from CAD data, quickly and inexpensively [9]. The technique creates models by printing a binder onto individual thin layers of powder. An ink jet printer head lays binder solution to a controlled thickness of material such as starch powder, plaster, ceramic, etc, representing a slice through the 3D computer model of the part.

The main disadvantage of the system is poor accuracy of parts built. The accuracy of the system depends on the material that is used and is affected by binder seepage, shrinkage, and geometry. In addition, the models produced are not particularly strong in tension especially without infiltrates, but compressive strength is high. The surface quality of prototypes from the 3DP process is not high, a smoother surface can only be obtained by post processing.

Injection moulding is one of the most common processing methods for polymers. The injection moulding process is a complex process that involves a series of sequential process steps. The different phases of the injection moulding process include the mould filling phase, the packing phase, the holding phase, the cooling phase, and part ejection. Solid plastic is melted, and the melt is injected into the mould under high pressure (usually between 10 and 34.5 MPa) [10].

2. RESEARCH METHODOLOGY

2.1 Research Goal

The goal of this research is an investigation into the use of Z-Corp 3D printer machine for sample plastic production. The method for this investigation can be divided into five stages.

1. Concept generation and 3D CAD model
2. Using rapid prototyping for part checking
3. Using Moldflow for injection mould analysis
4. Create mould tool design from 3D CAD
5. Using Z-Corp machine to build mould tool

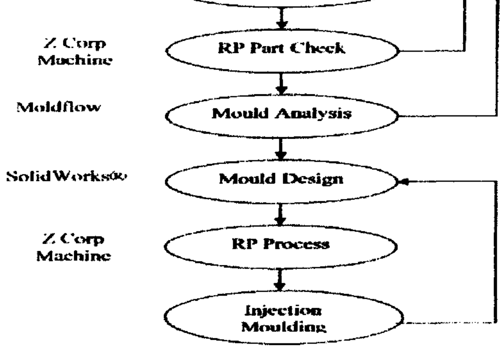


Figure 1: Research Methodology

Stages 1 to 3 were undertaken to design, accurately manufacture and validate the test mould tooling for the sample parts and the desired design component as per Figure 2. Two infiltrates, cyanoacrylate and paraffin wax, were investigated.

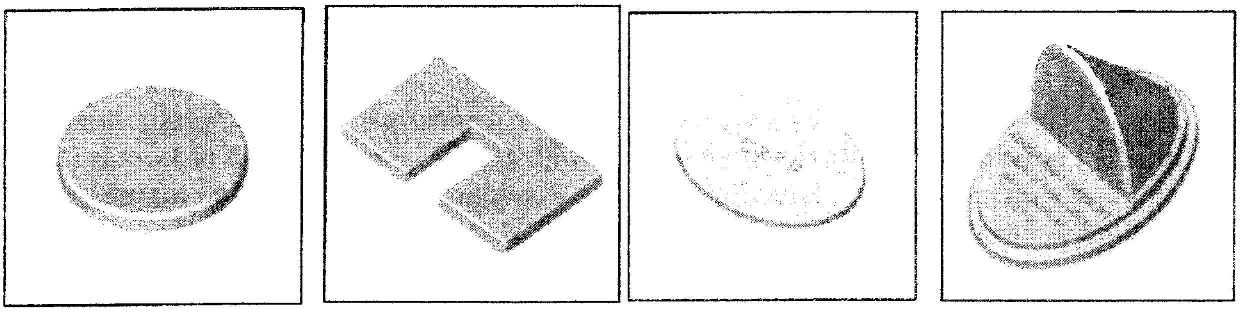


Figure 2: 3D design of cylinder, U shape and ellipse test pieces and Millennium Bridge.

The finished parts of the rapid prototyping process were then measured by digital vernier calliper, to identify any errors in build accuracy. From the measurements, the parts built from 3DP process were bigger than the original 3DCAD model dimensions by 1.63%. To solve this problem the anisotropic scaling factor was changed from 100% to 98.37%.

Plastic flow analysis involves an investigation of best gate location, flow analysis, confidence of fill, quality prediction of the parts as per Figure 3.

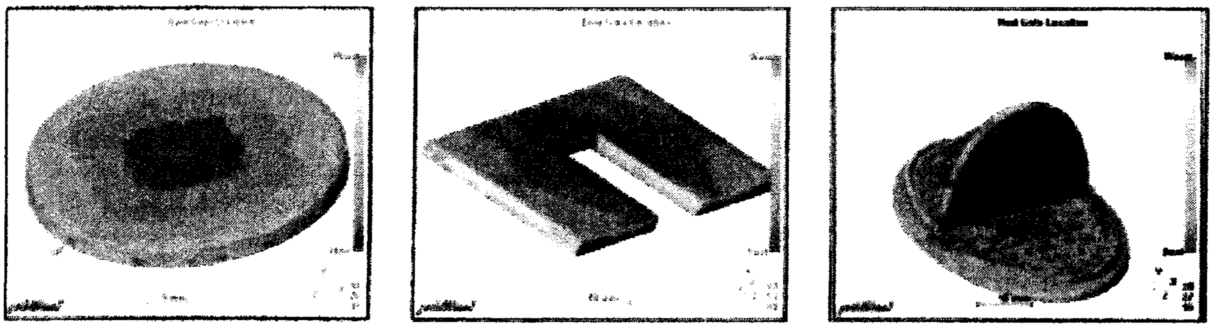


Figure 3: The best gate location analysis, Circular model, U shape and Millennium Bridge

The Mould tools were then designed to fit the manimould process and the bolster manufactured to support the 3DP inserts as per Figure 4.

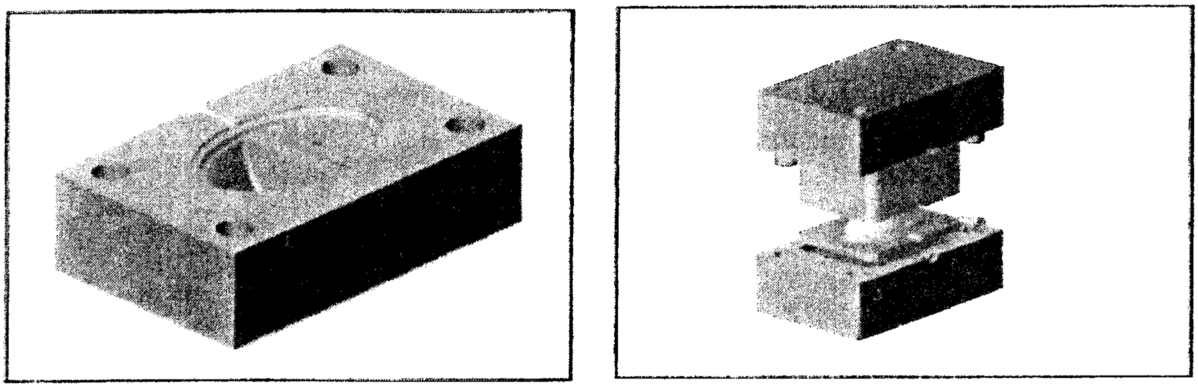


Figure 4: Mould tool design of mould (female) and total tooling for Millennium Bridge

2.2 Mould Tool Production

The material used to create the mould tool is plaster-based powder ZP100. The setting of the Z402 machine is shown as follows:

- The build layer thickness 0.1 mm
- Binder shell saturation value 2
- Binder core saturation value 1
- Anisotropic scaling factor 99.63% for X, Y, and Z-axis

The wax infiltration was undertaken by using the ZW4 autowaxer, the part was preheated for 30 minutes, 5 second dip, and 15 minutes post heated. The cyanoacrylate penetration was undertaken by dripping the material onto the moulds. Figure 5 shows the sample of mould produced by the Z-Corp printer.

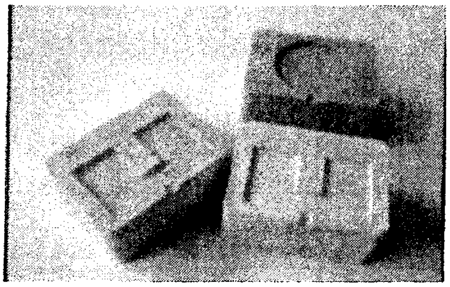


Figure 5: Mould tool produced by 3DP U shape and Cylinder (female)

2.3 Injection Moulding

In this experimental test, the injection-moulding machine used to produce the plastic product is "Plunger injection machine" Manimould. The temperature at barrel was set at 200^{0}C and the temperature at barrel head was set at 180^{0}C. The thermoplastic used polystyrene with a melt temperature of approximately 200^{0}C.

The melt is forced into the mould through the injection nozzle of the injection unit. This operation is known as the shot rate. This shot rate can also refer to the pressure of the process. In this research, shot rate and various pressures are controlled in order to know the suitable shot rate and pressure for the Z-Corp mould tools.

From the injection nozzle, the material passes through the sprue bush of the mould. It is then distributed to the cavities. When the cooling period has elapsed, the mould is opened and the finished parts are ejected.

The experimental test can be separated into two sections, which are:

1. Z-Corp mould tools with cyanoacrylate (ZR10) infiltration
2. Z-Corp mould tools with paraffin low melt wax infiltration

The different features of the Z-Corp mould block (Circular, U shape, Ellipse, and Gateshead Millennium Bridge) are tested with the different shot rate and various pressures. The shot rate used in this research can be divided into 2 shots, 1 shot, 3/4 shot, 3/5 shot, and 1/2 shot. Various pressures are used to force the melt material into the Z-Corp mould. The temperature is set in the range of 180^{0}C to 200^{0}C.

3. RESULTS AND ANALYSIS

3.1 Z-Corp Mould Tools with Cyanoacrylate ZP10 Infiltration

Z-Corp mould tools used in this experimental test had improved surface quality and strength by using cyanoacrylate (ZP 10) or super glue infiltration. The tests covered the quality of the finished part, and impact of the injection moulding conditions against the mould tools. The injection moulding results were divided into the ranges of F (part Failed), n/f (filled short part), A (Acceptable), and S (Satisfactory). The tests were divided into the four types of model parts to be manufactured, only the simple cylinder and bridge designs evaluated in this paper.

1. Test 1: Cylinder Model

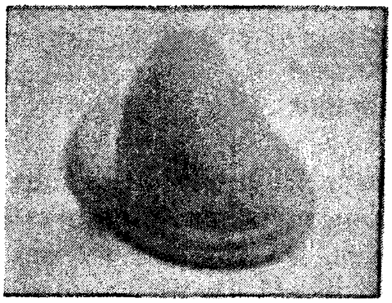
Test	Temp of Head	Temp of Barrel	Temp btw Head	Pressure	Shot Rate	Result
	^{0}C	^{0}C	and Barrel ^{0}C	MPa		
1	193	198	160	4.96	2	F
2	193	198	160	4.55	1	F
3	193	197	160	4.20	3/4	F
4	195	197	165	4.06	1/2	A
5	195	198	165	2.75	1/2	n/f
Note: F = fail, A = acceptable, n/f= not full						

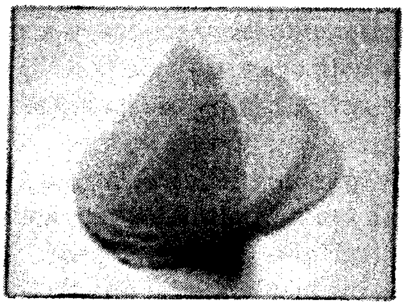
Table 1: The summary results of the injection-moulding test 1.

The results of tests 1 to 3 were "fail" due the quality of the finished parts being unacceptable, as the plastic parts were over flowed and material pierced into the mould tool. This was due to the high pressure and over shot rate. The quality of the finished parts of test 4 was acceptable, and shape of the models was good. The accuracy of the model of test 4 for the diameter was 38.95 mm compared to design of 38.7 mm, error 0.64 %, and thickness 5.09 mm compared to design of 3 mm.

Even though the shape of the finished parts was acceptable, the surface quality was not good. The surface quality of the finished part was dependent on the surface roughness of the Z-Corp mould. Part ejection is a major problem of this test. The finished part was very difficult to ejected since the plastic was stuck on the mould; therefore the method to take the part out is to break the mould apart.

Similar results were recorded for the other test tools, and a shot rate of 3/5 providing an injection pressure of 4.17 MPa was used to produce the bridge components Figure 6.





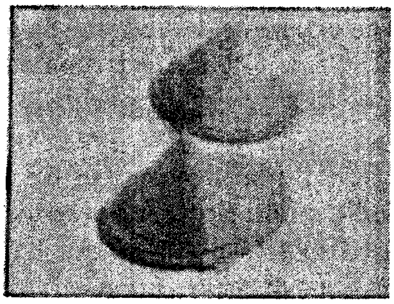


Figure 6: The finished "cyanoacrylate" part of Gateshead Millennium Bridge model.

3.2 Z-Corp Mould Tools with Wax Infiltration

In this test, mould tools produced by the Z-Corp printer were infiltrated by using paraffin low melt temperature wax. This study covered the quality of the finished part, affect of temperature, pressure, and shot rate against the mould. The experiment was divided into four tests according to the features of the mould block.

1. Test *5:* Cylinder Model.

Test	Temp of Head (^{0}C)	Temp of barrel (°C)	Temp btw Head and Barrel	Pressure (MPa)	Shot Rate	Result
T5.1	197	198	165	3.5	1/2	A
T5.2	197	198	165	3.93	1/2	S
T5.3	197	198	165	3.93	1/2	S
T5.4	197	198	165	3.96	1/2	A
T5.5	197	198	165	4.27	3/5	F
Note: A = acceptable, S = satisfactory, F = failed.						

Table 2: Summary results of injection moulding of test *5*.

From the injection moulding tests, the plastic parts of mould with wax infiltration are more acceptable than the finished part from mould compared with cyanoacrylate penetration. The characteristics such as shape and roundness of the parts were superior and ejected easier, Table 2 refers to the cylindrical parts, other test moulds yielded similar results. Figure 7, the Gateshead Millennium Bridge, it can be seen that the products have plastic flash at the split line. Therefore, the parts require post processing to improve the quality and shape of the finished part.

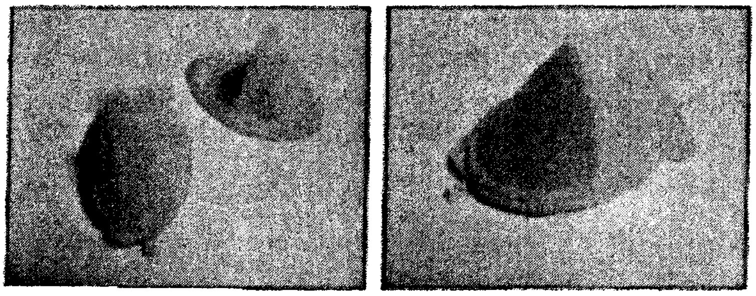


Figure 7: Sample picture of product from test 8.

4.0 CONCLUSIONS

In this research, the Z-Corp 3D printing machine was used as a rapid prototyping technique to produce sample plastic parts. The focus of this study was on the part design, mould design, creation of sample part and mould tool using a Z-Corp 3DP machine, injection moulding process, and injection moulding conditions.

The prototypes and mould tools had improved surface quality and strength by infiltration with cyanoacrylate and wax. The 2D and 3D parts were measured and checked for detail and dimensional accuracy, and the anisotropic scaling factor was changed to improve accuracy.
It can be concluded that injection pressure played a significant role in the process. Too high or too low injection pressure had a major effect up on the finished parts, such as over filled "flash", short filled, distortion, sink marks, warpage, etc. The pressure also affected the dimensional accuracy of the finished parts, too high injection pressure resulted in increased part thickness.

Temperature has little effect on the finished part and mould tool. This is because the mechanical properties of the plaster base powder and infiltration method can resist high temperature. However, high melt temperature can cause problems with part ejection and shrinkage in the mould.

Infiltration material was also a factor that has an influence on the part ejection and surface quality of the product. The surface quality of the product produced by wax-infiltrated mould was better than on the product manufactured by superglue infiltrated mould. Part ejection was the major problem of the Z-Corp mould with cyanoacrylate infiltration, as the plastic product reacted with the mould cavity material. The high temperature of injected material melted the cyanoacrylate to liquid, therefore, the part was adhered to the mould. Mould tools had to be destroyed in order to take the finished part out of the mould.

The accuracy and surface quality of the finished part were quite low due to the Z-Corp printing machine. Complexity of the part also had an effect on the quality of the finished parts. It was seen that simple models are easily manufactured when compared with the Gateshead Millennium Bridge model.

Circular and U shape models have higher quality than the Ellipse and Millennium Bridge models according to the complexity.

In this study, it was found that plastic parts manufactured by Z-Corp mould are acceptable, but still need post processing to improve the accuracy and quality. The Z-Corp rapid prototyping technology can be used as a mould tool to produce plastic parts. However, this manufacturing technique is not suitable for complex geometry or delicate products. This technology is more suitable for a simple product or a part that doesn't require high accuracy.

REFERENCES

1. A. E. W. Rennie, D. M. Jacobson, C. E. Bocking, Rapid Prototyping, Tooling, and Manufacturing, Professional Engineering Publishing Limited, London, 2002.
2. K. Stier, R. Brown, Integrating Rapid Prototyping Technology into the Curriculum, Journal of Industrial Technology, Volume 17, Number 1, 2000.
3. W. Palm, Rapid Tooling Primer, 1998, http://www.me.psu.edu/lamancusa/rapidpro/primer/chapter2.httn.
4. Rapid Tooling, http://www.atirapid.com/tech/te_rapidtool.html
5. A. Rosochowski, A. Matuszak, Rapid tooling: the state of the art, Journal of Materials Processing Technology 106,2000, pp. 191-198.
6. N. P. Karapatis, J.-P.S. van Griethuysen, R. Glardon, Direct Rapid Tooling, Rapid Prototyping Journal, Volume 4, Number 2, 1998, pp. 77-89.
7. W. Palm, Rapid Tooling Primer, 1998,http://www.me.psu.edu/lamancusa/rapidpro/primer/chapter3.httn.

8. E. Radstok, Rapid Tooling, Rapid Prototyping Journal, Volume 5, Number 4, 1999, pp. 164-168.
9. Z-Corp Materials, http://www.zcorp.com
10. R. Aluru, M. Keefe, S. Advani, Simulation of Injection Moulding into Rapid Prototype Moulds, Rapid Prototyping Journal, Volume 7, Number 1, 2001, pp. 42-5 1.

Development of systems to increase the green part strength of the 3D Printed Z-corps manufactured parts by infiltration processes to improve their range of application.

P M HACKNEY, and L C CHANNAPPA, Northumbria University, School of Engineering Science and Technology. UK
Phil.Hackney@unn.ac.uk, lokesh.channappa@unn.ac.uk

ABSTRACT

The ultimate goal of this research project is to increase green part strength and accuracy of Z-Corps manufactured parts by the infiltration process to increase its mechanical properties. An accurate 3D model of intricate parts can be produced using 3D printing technology but these produced parts do not have enough tensile and compressive strength since they are plaster based (powder and binder)
To date, the parts are infiltrated with wax which results in very less tensile and compressive strength, so the parts are very delicate. It is expected that by varying the different concentrations of other highly viscous materials, relative *strength, Temperature, Resistance, Durability* of these green parts can be changed, in turn the tensile and compressive strengths can be increased. With the strength increased, parts produced can be used directly for operations such as Injection moulding, casting processes, similar to the metal moulds strength would be created using this process of infiltration.

Keywords: Z-Corps 3D printing, Infiltration, Accuracy, Temperature, Strength,

1. INTRODUCTION

New Technologies for Rapid Prototyping are continuously improving and developing applications of Rapid prototype freeform fabrication technologies have fascinated observers throughout the world. Rapid prototyping (RP), also known as solid freeform fabrication or layer manufacturing, is a technology that produces prototype parts from computer geometric models. Unlike conventional machining which involves constant removal of materials, RP builds parts by selectively adding material layer by layer. Each layer takes the shape of the cross-section of the model at the layer [1]. It can happen very quickly. Ten years ago, a model could have taken a year to make. The company would start with product design, then made computer models in two dimensions, then a final computer model in three dimensions and finally a three dimensional prototype. Rapid prototyping, however, can now make a three-dimension model in less than a day. The process itself is not cheap. However, it can provide significant savings compared to the old ways of making prototypes and has the added advantage that the information used to generate the model can be directly shipped to tool and die makers as data, cutting additional time from the development cycle.

Rapid prototyping is an early design exploration and validation process in which executable models of a system are created that reflect some subset of properties of interest. These are evaluated to quickly uncover design errors or undesirable properties that help refine and flesh out requirements. The key idea is to be able to create revelatory prototypes quickly and with less effort than for full system implementation and production.

3D printing is one such rapid prototyping technology, it a powder-binder technology to "print" a physical model, layer by layer. Models are constructed from plaster or starch powders using water based binder that is sprayed through ink jet cartridges. The 3D digital data is imported into the system software where cross sectional views are taken at pre-determined intervals. These cross sections are "printed" on top of each other to rapidly build the prototype model. During construction the model is fully supported by the surrounding powder and when the binder has cured, the model is removed, de-powdered and then in filtered with wax to increase its strength and finish (appearance). The evolution from prototyping to production is stressed for the inherent advantages of the layered method. Surface finish and strength in 3D printing is, however, one of the major technological constraints on its widespread utilization. Surface finish and strength is an intrinsic limitation of powder-based processing [2]. Surface finish in 3D printed parts can be greatly improved by using very fine powders as they allow the use of thinner layers and also provide improved finish within each layer. In addition to that if these powder parts are in filtered with wax (Present Technology) good surface finish and strength can be obtained as shown in figure 1.

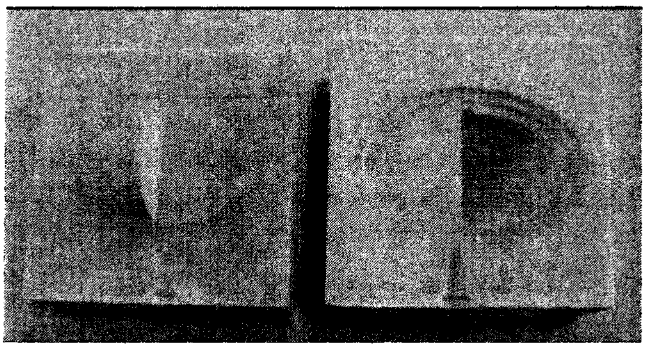


Figure 1. Die set produced by 3D printing RP

High dimensional accuracy and part stability are significant elements of the end product in rapid prototyping technology (RPT) processes, whether it is a component or a tool. And this report is based on alternative infiltration process to increase strength and finish of those green parts produced from Z-Corps 3D printing machine i.e. infiltration of porous parts is generally performed by dipping the part in a liquid infiltrated bath, which rises into the open pores through capillary action. Different methods of infiltration were carried out with different combinations of highly viscous chemicals with wax as the base material. The bending strength are calculated and compared with normal paraffin wax in filtered parts.

2. RESEARCH AIMS

Present green parts that are in filtered by paraffin wax, are being partially replaced by the following two highly Viscous materials, as the green parts produced from Z-corps rapid prototype machine is plaster based and 50% air filled. As it is more porous, these highly viscous materials can fill these pores and give the component a good finish, strength and accuracy.

From economic purposes even using wood polish, the bending strength has been checked as wood polish is also an highly viscous liquid, and it is more volatile in nature. Due to these properties wood polish was chosen as infiltrate.

2.1 The following High Viscous materials are being used for infiltration with wax as base.

- Araldite (GT 1999)
- Polyvinyl Alcohol (PVA Fully Hydrolysed)
- Paints (Chosen Wood Polish)
- Combination of Araldite and Polyvinyl Alcohol

2.2 The above materials are in filtered (applied) by using different processes.

- Spraying
- Dipping
- Brushing
- Compression

These are the highly viscous materials and processes planned to carry out the infiltration operation, in order to replace partially the present wax infiltration for the plaster based rapid prototype green parts, These experiments were carried out in order to improve the green part strength, as this is the only main disadvantage with this Z-Corps 3D printing Rapid Prototyping system.

3. EXPERIMENTAL METHOD

In this experimental procedure, initially the green parts were in-filtered with the combination of wax and resins, and in the second set-up the green parts were in filtered with wood polish, as wood polish is a volatile and highly porous liquid.

3.1 Using Paraffin Wax as Base material: - In this experimental procedure, infiltration is carried out using wax as the base material along with a combination of high viscous material in order to increase the strength and accuracy of porous green parts produced by the Z-corps 3D rapid prototyping system.

A brain storming session was carried out to identify and select suitable combination, which improved the performance of infiltration of porous green parts produced by the Z-Corps rapid prototyping machine.

Initially for 100gms of total infiltrate materials taken, out of which 75 gms of paraffin wax was taken, along with 12.5 gms of PVA plus 12.5 gms of araldite (GT 1999) was added. To start the wax was first heated in a beaker at temperature of 60^0 C (333^0 F), on a hot plate for 5 min. When the wax was totally melted, Araldite (GT1999) was added and stirred continuously for 5 min. Finally 12.5 gms of Poly-vinyl alcohol (PVA) was added and stirred for another 5 min maintaining the temperature of hot bath to 90^0 C as the PVA chosen is fully hydrolysed and dissolves at 90^{0}C.

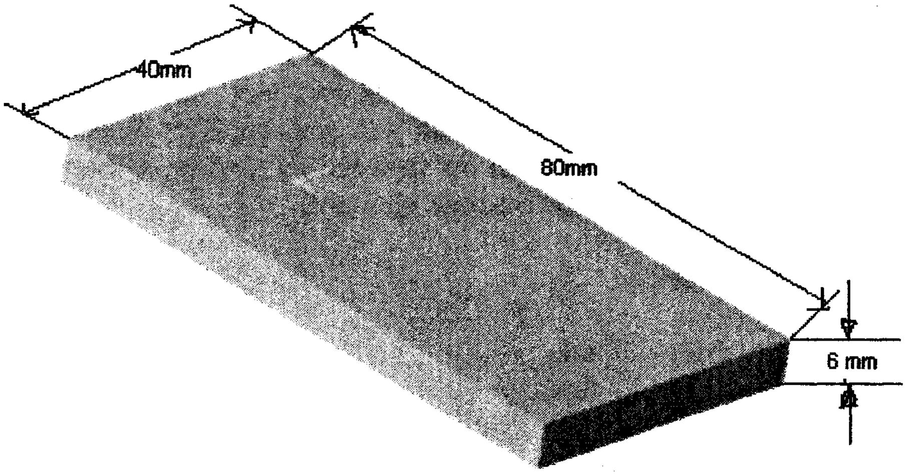


Figure 2. Sample piece for testing

The above specimen shown in figure 2. is used as the standard specimen through out this experiment. It has dimensions of 80 x 40 x 6 mm, and was specimen dipped in to the prepared wax combination liquid with pressurised compressed air maintained at 1 bar pressure. Pressurised compressed air was used in order to increase capillary action and this process was carried out for approximately for 60 seconds and then these standard specimen pieces were air dried for 2 hrs before it was taken to check its bending strength using three point bending test.

3.2 With wood polish: - This is a second set up, where the green parts produced with Z-corps rapid prototyping system were directly in filtered with wood polish by spraying process, and the pieces were air dried for 12hrs. This experiment was carried out in order to see if it works with wood polish, which is an economic process. The pieces were tested for bending strength, and set up for three point bending strength is as show below in Figure 3.

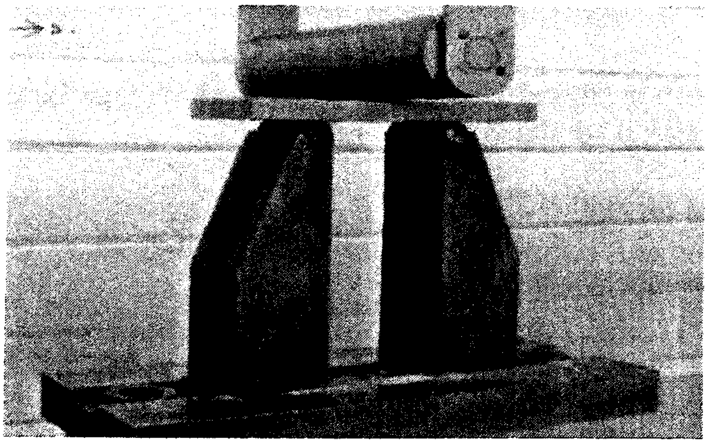


Figure 3. Three point Bending Strength Test

4. Results

The following test results were obtained by using standard set up of three point bending test.

To compare the above experimental work, the present standard paraffin wax infiltration, which uses only paraffin wax as infiltrate material was used, and 10 standard pieces of dimension 80 x 40 x 6 mm were in filtered, with wax machine ZW4 Waxer. The three point bending test was carried out in order to find out the bending strength of these standard pieces, and to compare with other experimental readings obtained.

ZW4 – waxer programmed details

Preheat – 30 min
Dip Speed – Low
Soak Time – 4 Seconds
Post heat – 25 min
Wax Temperature – 600 ^{0}C
Air Temperature – 700 ^{0}C

4.1 Paraffin Wax Infiltrate results: -

Average Bending Strength = 3.68 N/m^2
Average Displacement = 0.73 mm

4.2 Paraffin Wax + PVA + Araldite

As with the above experimental procedure, which consisted of paraffin wax as base material, along with PVA and Araldite (GT1999), the following results were obtained for 10 sample pieces.

Average Bending Strength = 4.59 N/m^2
Average Displacement = 0.88 mm

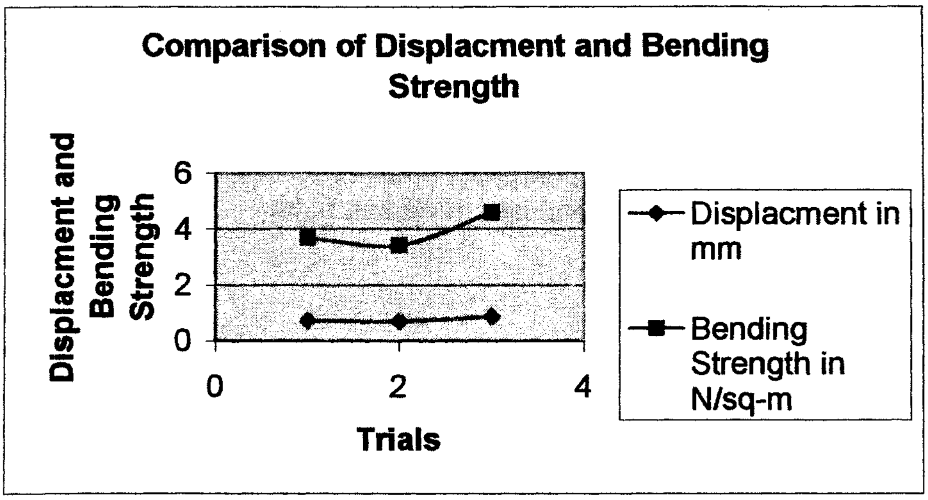
4.3 Wood Polish

Finally the wood polish in filtered pieces were tested to check their bending strength and the average bending strength is tabulated as show below.

Average Bending Strength = 3.42 N/m^2

Average Displacement = 0.71 mm

Infiltrate materials	**Displacement in mm**	**Bending strength N/m^2**
Wax	0.73	3.68
Polish	0.71	3.42
Wax + PVA +Araldite	0.88	4.59



Graph 1. Bending Strength comparison chart

5. CONCLUSIONS

From the above graph.1 it is very clear that with the combination of paraffin wax polyvinyl alcohol and araldite used as infilitrant, the strength of rapid prototype parts can be increased by 25 % as compared to present paraffin wax infilitration.

As well as the economic consideration, when wood polish is used as infiltrate it is seen that the bending strength of wood polish in filtered parts are very near to the present paraffin wax in-filtered parts. The only disadvantage with wooden polish is the time consideration for drying of pieces is longer compared to other processes.

The comparison graph.1 shows details of the bending strength and its displacement for different infilitration process

5. References: -

[1] Wenbin Hong, Yong Tsui Lee, Haiqing Gong: Thermal analysis of layer formation in a stepless rapid prototyping process, *Applied Thermal Engineering, Volume 24, Issues 2-3, February 2004, Pages 255-268*

[2] Michele Lanzetta, Emanuel Sachs : Improved surface finish in 3D printing using bimodal powder distribution, Rapid Prototyping Journal, Volume 9, number 3, Pages 157-166, 2003

[3] S. H. Choi and A. M. M. Chan a virtual prototyping system for rapid product development, *Computer-Aided Design, Volume 36, Issue 5, April 2004, Pages 401-* 412

[4] ARCHADIAN, F. KAWANO, T. OHGURI, T. ICHIKAWA & N. MATSUMOTO
Flexural strength of rebased denture polymers Department of Dental Technology, Faculty of Dentistry, Gadjah Mada University, Indonesia and Department of Removable Prosthodontics, The University of Tokushima School of Dentistry, *Japan, Journal of Oral Rehabilitation* 2000 27; 690–696

Investigation into Surface Finish of Parts Built by the EnvisionTec PerFactory® Rapid Prototyping Process

P M Hackney, G K Chinnaswamy, A C Arulraj, B T Nair,
School of Informatics, Engineering and Technology,
Northumbria University, Newcastle upon Tyne, United Kingdom.
E-mail: phil.hackney@unn.ac.uk

ABSTRACT

The PerFactory® technique from Envisiontec is unique in its method of manufacturing parts in discrete voxels, compared to the technique of smooth laser contouring implemented in the traditional SLA process. This method of approximating the contours with "Voxels" (3 dimensional pixels) has a pronounced effect on surface finish of the finished part. This work investigates the effect of pixel size, and also build angle and build direction on surface finish of parts built on the Envisiontec RP machine. A high surface finish is important because, apart from offering surfaces of high quality, it also helps to reduce post-processing time and to increase accuracy.

Keywords: Perfactory process, Surface finish, Layer thickness, Orientation, Pixels.

1. INTRODUCTION

1.1 The PerFactory® part building process

The PerFactory® technique utilises the technology called Digital Light Processing (DLP™) developed by Texas Instruments [1]. The process uses a high-powered, precise light projector working on the DLP™ technology, to polymerise a photosensitive resin layer-by-layer [2]. This polymerization is similar to that happening in SLA, but the laser positioning galvanic mirrors used in SLA are replaced by a DLP™ projector [3] with a mercury lamp. The galvanic mirrors in SLA trace the exact contours of the cross section [4], but the PerFactory® system builds each mask in discrete Voxels, approximating the boundaries. An illustration of the PerFactory® machine is shown in Figure 1. The method by which the Perfactory® and SLA techniques build a layer is shown in Figure 2.

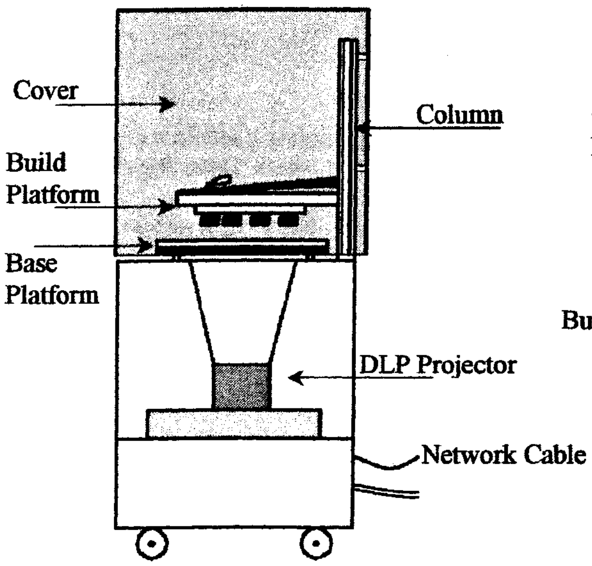


Figure 1 – The PerFactory® machine

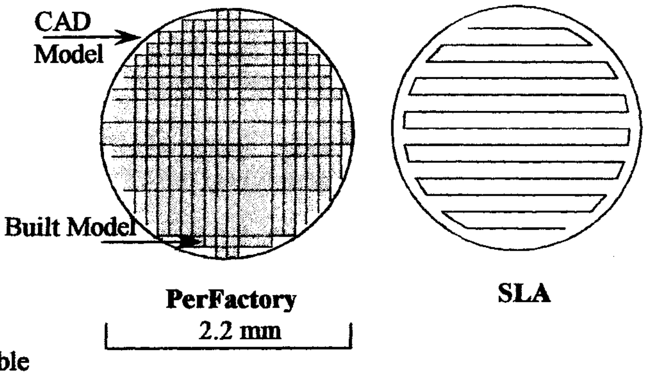


Figure 2 –Comparison of a layer built by the PerFactory® and SLA processes

The influence of build angle on the surface finish of a curved face that is built using "layer by layer" prototyping is shown in Figure 3.

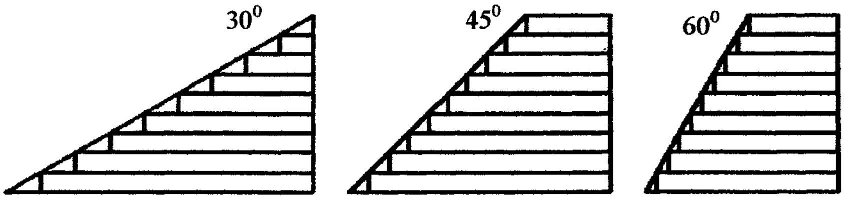


Figure 3 – Effect of build angle on surface finish

1.2 Need for good surface finish

Surface finish of rapid prototyped parts is a very important quality that is desired, be it a visual or a fit/function model. Poor surface finish results in poor accuracy and appearance. Certain prototyping techniques require manual post processing to impart acceptable levels of surface finish. But this practice is not advisable, since rapid prototyping is a time compression technique, and post processing would offset the gains made. Hence, the objective should be to impart acceptable level of surface finish as the part leaves the machine. The test sample that was built for surface finish measurements is shown in Figure 5.

1.3 Processes involved in formation of single layer

Exposure: This is the time for which the mask layer is projected onto the resin by the DLP™ projector.

Peeling: This refers to the action during which the base platform is pulled away from the newly formed layer, by a servomechanism. Peeling is achieved by pivoting the silicone base plate at the front, and pulling it down away from the build plate using a stepper motor driven mechanism.

Waiting: This is the period of time that the base platform waits at the bottom-most point, before returning to its original position.

Levelling: This refers to the action during which the base platform returns to its original position. This happens at a constant default velocity.

The above four processes are repeated for every layer.

Additional structures:

Base Layers: The build process starts by building a base layer, which acts as a foundation for the rest of the process. Default parameters are used for the base layer.

Supports: The building of supports is the next stage in the process. The supports are built with same parameters as that used the part.

2. SURFACE ROUGHNESS TESTS

The objective of these tests was to investigate the effect of pixel size, and also build angle and build direction on surface finish of parts built on the EnvisionTec RP machine. These terms are defined below, with the aid of the illustration in Figure 4.

Pixel size: This is the actual size of the pixels making up the mask, as projected by the DLP™ system. The smaller the build area, smaller will be the pixel size. Pixel size varies from 0.094mm to 0.148mm.

Build angle: This is the inclination of the face being built. In this work, all angles are measured with respect to the horizontal. Angles are marked by the symbol 'θ' in Figure 4.

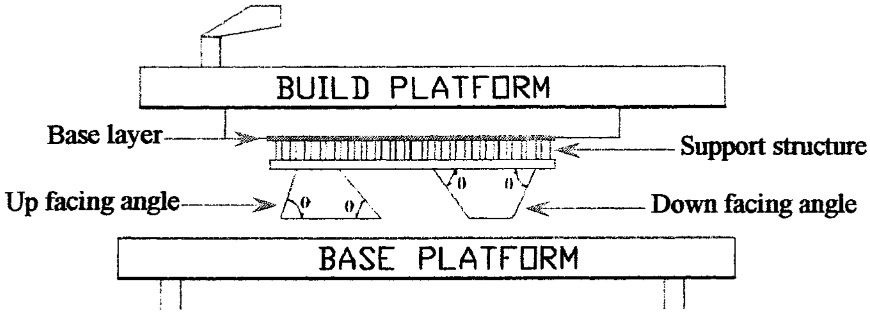


Figure 4 – Illustration of Up- and Down-facing angles

Build direction: This is the direction in which the angular face is being built. Direction can be classified as 'Up' or 'Down' facing. It has to be noted that parts are built upside down in the PerFactory® machine. In this work, all reference would be made to the direction that the angular face is oriented as it is being built on the platform.

2.1 Building the surface finish test parts

Simple test parts were built with 30, 45, 60 and 75 degree slopes on them, to study how the surface finish varied with angle. The parts were built with both up- and down-facing configurations of the afore-mentioned angles. They were built with a layer thickness of 0.05mm. Example of up and down-facing angles can be seen in Figure 4, and Figure 5 shows the model of the part that was built for the study.

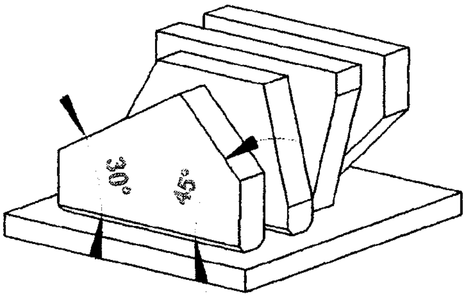


Figure 5 – The surface finish test sample

2.2 Testing the surface finish

The surface finish was measured with a Taylor Hobson Talysurf, for a cut-off length of 0.80mm for each measurement. The test set-up is shown in Figure 6. The results obtained are shown in Figure 7.

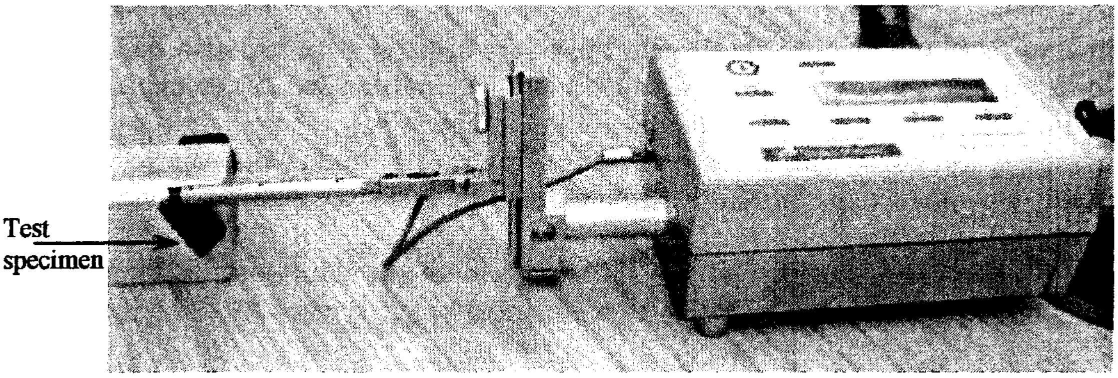


Figure 6 – Testing surface finish with a Taylor Hobson Talysurf

2.3 Results of the Surface Roughness test

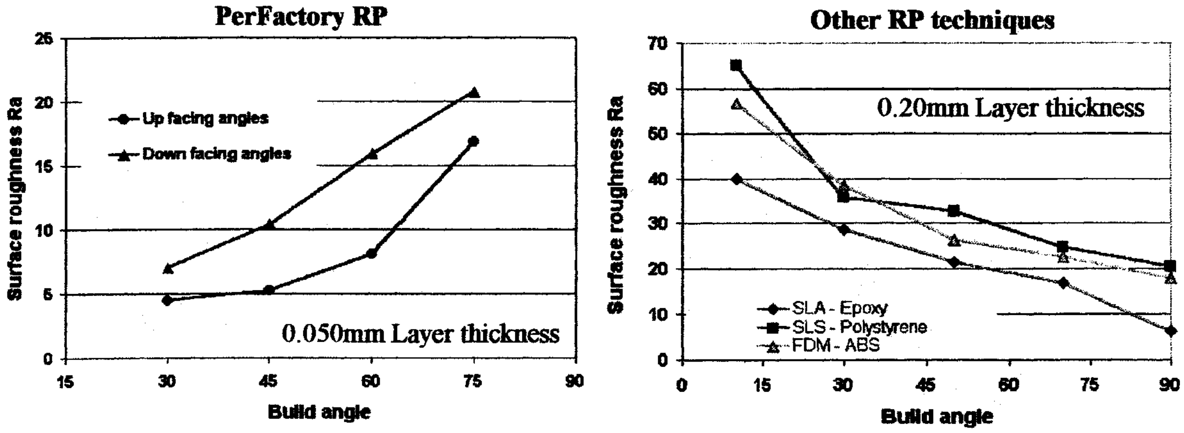


Figure 7 – Effect of build angle on RP part finish – Comparison

The results of the surface finish test are graphically represented in Figure 7a. It is observed that building in the Up facing direction consistently produced better results than in the Down direction, for the same parameters, layer thickness and build angles.

Another interesting trend can be observed when figures 7a and 7b are compared. It is seen that surface finish gets worse with increasing angle in the PerFactory® part, whereas the trend is exactly opposite for parts built on SLA, SLS and FDM [4]. The sensitivity of surface finish to build angle, for parts built on SLA, SLS, FDM and LOM techniques was also illustrated in Figure 3. The observation of this unique trend in the PerFactory® technique called for further analysis of the built specimen, as it seemed that the surface finish was not influenced by layer thickness and build angle alone, but also by some other additional factor.

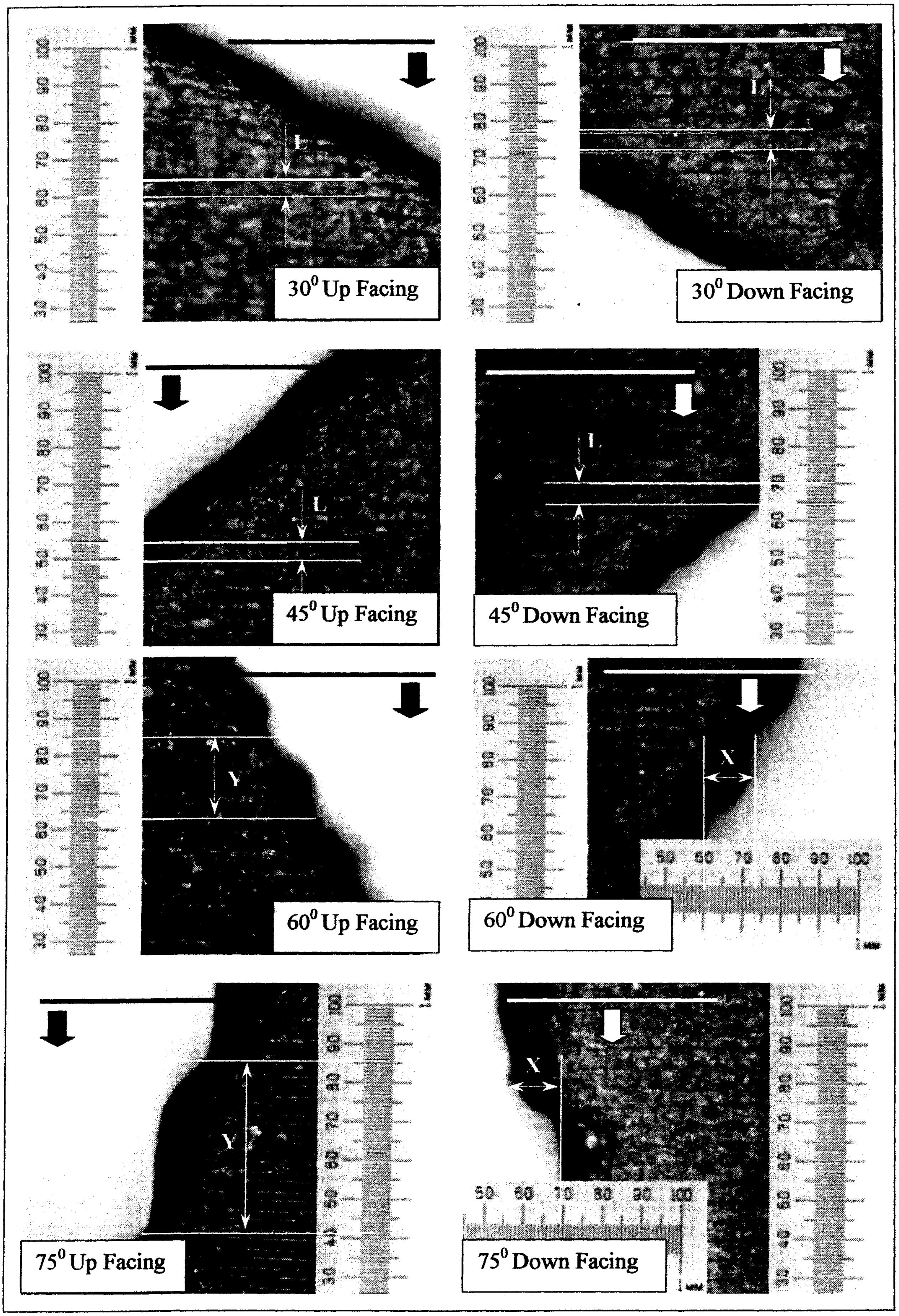
Micrographs of the experimental parts were made, to study this behaviour further. The micrographs are shown in figure 8. This would also help us to understand how the steps were formed, in building the angular face. It would be beneficial to define certain terms at this stage, for better understanding.

i. Layer thickness: This is the thickness of the build layer as specified by the user. The build platform moves upwards by this value, for each layer. It is marked by the letter "L" in the figure 10. In this experiment, a layer thickness of 0.05mm (50 microns) was used.
ii. Step thickness: Steps are formed when angular faces are built layer by layer. The step size is influenced by layer thickness and build angle. Step thickness has two components: Along the direction of build and perpendicular to it.
- **Thickness along the build direction**: This is always more than the layer thickness and is a multiple of it. It is indicated by the letter "Y" in Figure 8.
- **Thickness perpendicular to build direction**: It is indicated by the letter "X" in Figure 8.

2.4 Magnified views of different Up and Down facing angles

The part shown in Figure 5 was built using default process settings, and the various up and down facing angles were studied under the optical microscope, and micrographs obtained. All the micrographs are shown in figure 8. The solid line at the top of each image represents the build platform, and the block arrow signifies the direction in which the layers are added progressively.

Micrographs of different build angles and directions



30^0 Up Facing

30^0 Down Facing

45^0 Up Facing

45^0 Down Facing

60^0 Up Facing

60^0 Down Facing

75^0 Up Facing

75^0 Down Facing

Figure 8 – Different build angles and directions

2.5 Reason for better surface finish in the 'Up' direction

From the figure, it can be seen that the dimension "X" closely matches with the pixel size setting used for this build, 0.15mm. Hence it can be deduced that the trend in surface finish was caused by Pixel size. It can also be observed that the dimension "Y" increases as the angle of the face increases.

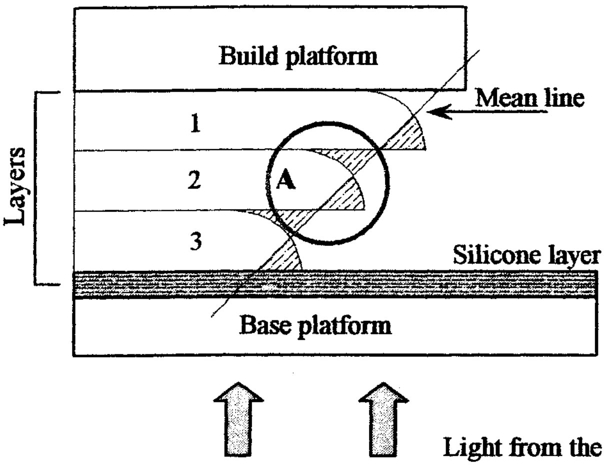


Figure 9a – Down facing build

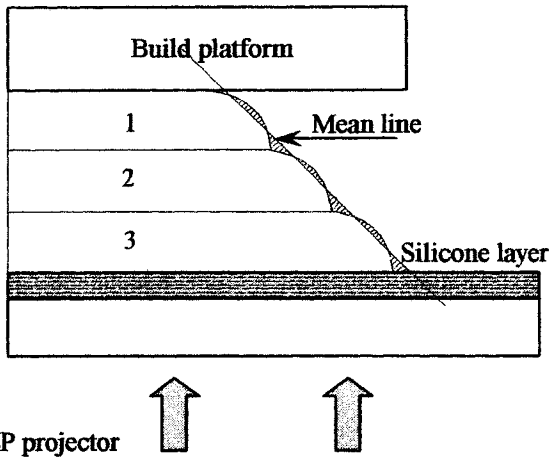


Figure 9b – Up facing build

The parameter 'Ra' used to express surface finish is defined as the "universally recognised, and most used, international parameter of roughness. It is the arithmetic mean of the departures of the profile from the mean line." [5]. The expression to derive Ra is as follows:

$$Ra = \frac{1}{L}\int_{0}^{L} |y(x)|\,dx$$

Effectively, it is the magnitude of the areas on either side of the mean line that dictate the Ra value – Higher the area, higher will be the value.

With information gained from the micrographs in Figure 8, the effect of build direction on surface finish are clearly illustrated in figures 9a and 9b. The shaded areas on either side of the mean line for the part built in the 'down' direction are much higher than that of the 'up' direction. This explains the lower Ra values of angular faces built in the 'up' direction.

The area "A" highlighted by the circle in Figure 9a shows how the edges of a layer are formed in the PerFactory technique. This effect is the same for both up and down direction builds. This could be due to refraction of light at the edges of the mask, as it passes through the glass and silicone layers of the base platform.

2.6 Illustration of part building using Voxels

Since it has been found that the Pixel size has a very pronounced effect on the step thickness and hence, surface roughness, a thorough understanding has to be gained as to how the RP part is built up using 3 Dimensional pixels (Voxels). This is illustrated clearly in Figure 10, along with the method of calculation of pixel size for any given work area setting.

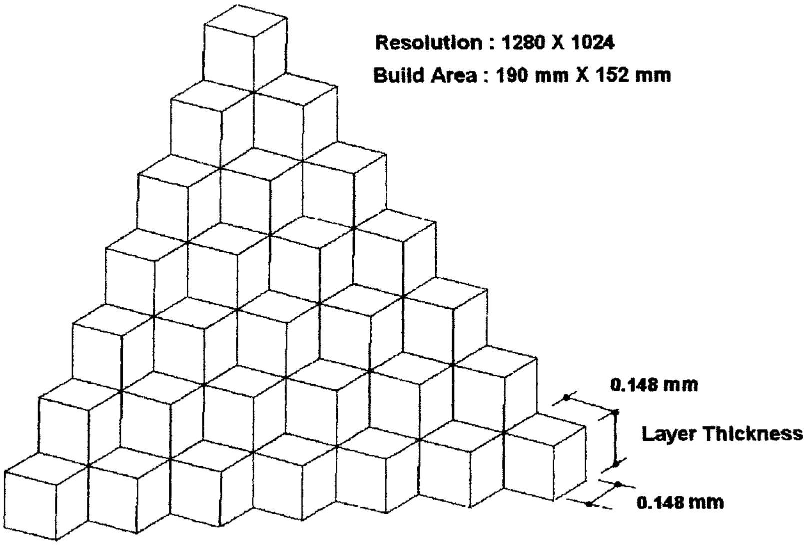


Figure 10 – Perfactory part building with Voxels

2.6.1 Calculation of Pixel size

Projector resolution = 1280×1024

- Therefore, total number of Pixels = 1,310,720

Work area selected = 190mm x 152mm (Maximum)

- Therefore, total work area = 28880mm^2

Area per pixel = 28880 / 1310720 = 0.0220mm^2

Since a pixel is square in XY Plane, side of pixel = $\sqrt{0.0220}$ = 0.148mm

- Hence, the resolution of the machine at maximum work area setting is 0.148mm.

Volume of a voxel for different layer thickness (at 190 x 152 Build area):

$V_{30\mu m} = .0006 \text{ mm}^3$, $V_{50\mu m} = .0010 \text{ mm}^3$, $V_{100\mu m} = .0020 \text{ mm}^3$

3. CONCLUSIONS AND FUTURE WORK

The results of the surface finish study show that the roughness increases with increasing inclination with respect to the horizontal. This trend is exactly opposite to that exhibited by other established techniques like SLA, FDM and SLS. On further investigation it was found that this was caused by selection of work area settings, and therefore by the pixel size used for the build.

It was also found that building in the up facing direction consistently produces better results than that of the down facing direction, for the same process parameters, layer thickness and build angle.

Future research has to be conducted in the following areas:

- Since it was found that pixel size has a pronounced effect on surface finish, and the technique itself is based on polymerisation of discrete 3 dimensional pixels, more research has to go into areas like pixel shifting, pixel size optimisation, etc.
- Influence of process parameters like waiting time, exposure time, X-Y orientation and peeling velocity on surface finish, using partial factorial design.

REFERENCES

[1] www.dlp.com [Accessed 25th January 2005] – Homepage of Texas Instruments Ltd, USA.

[2] www.envisiontec.de [Accessed 6th February 2005] – Homepage of Envisiontec Ltd., Germany.

[3] Hackney PM, Pancholi KP, Analysis of the Envisiontec Perfactory System for Rapid Production of Components and Validation Using Finite Element and Photo-elastic Analysis, Fifth National Conference on Rapid Design, Prototyping and Manufacture, Buckinghamshire Chilterns University, 2004.

[4] Upcraft S, Fletcher R, The Rapid Prototyping Technologies, Assembly Automation, vol. 23, No. 4, 2003, pp. 318–330.

[5] Users' manual for Taylor Hobson Talysurf Surtronic 3+, Rank Taylor Hobson Ltd., England, 1993.

Development of a Build Monitoring System for the EnvisionTec PerFactory® Rapid Prototyping Process

P M Hackney, B T Nair, A C Arulraj, G K Chinnaswamy,
School of Informatics, Engineering and Technology,
Northumbria University, Newcastle upon Tyne, United Kingdom.
E-mail: phil.hackney@unn.ac.uk

ABSTRACT

The EnvisionTec PerFactory® technique fabricates the part through layer-by-layer polymerisation of a photosensitive resin. It is unique in its method of part building, using discrete elements rather than smooth laser contouring implemented in the traditional SLA process. The build platform moves upwards as layers are added and the part is built upside down. Presently, there is no feedback system to warn the user if build failure has occurred. Continuing the build process after the part has failed, leads to time wastage, resin degradation and possible destruction of the base platform. A system for monitoring if part build failure has occurred is developed and tested in this work. Build failure can be predicted by studying the signature characteristics of base platform displacement during the peeling process.

Keywords: Perfactory process, Build failure prediction, Photo polymerisation.

1. INTRODUCTION

1.1 How the PerFactory® system builds the part

The PerFactory® technique utilises the technology called Digital Light Processing (DLP™) developed by Texas Instruments [1]. The process is based upon a high powered precise light projector working on the DLP™ technology, which polymerises a photosensitive resin layer-by-layer, resulting in a 3D part [2]. This polymerization is similar to that happening in SLA, but the laser positioning galvanic mirrors used in SLA are replaced by a DLP™ projector [3]. The galvanic mirrors in SLA trace the exact contours of the cross section [4], but the PerFactory® system builds each mask in discrete pixels. An illustration of the PerFactory® machine is shown in Figure 1.

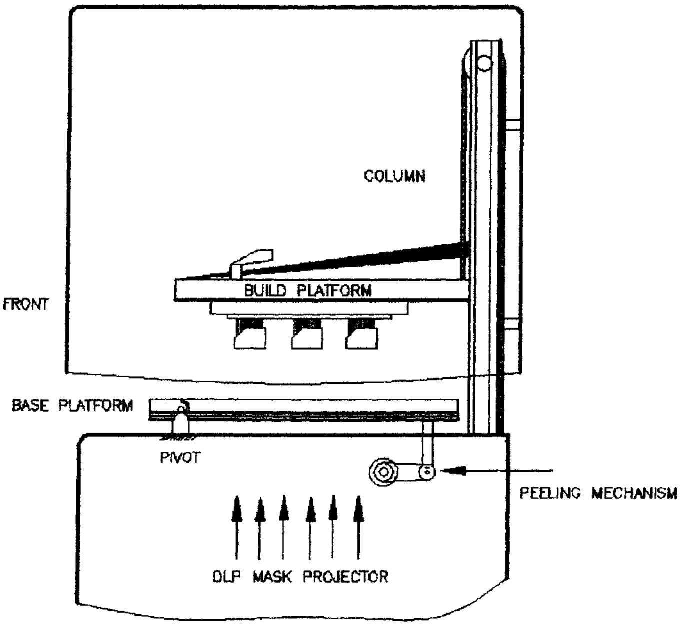


Figure 1 – Illustration of the part build area of the PerFactory® machine

1.2 The process of building a single layer

1. **Exposure**: This is the time for which the mask layer is projected onto the resin by the DLP™ projector. The bulk of the curing takes place at this stage.
2. **Peeling**: This refers to the action during which the base platform is pulled away from the newly formed layer, by a servo mechanism. Peeling is achieved by pivoting the silicone base plate at the front, and pulling it down away from the build plate using a stepper motor driven mechanism.
3. **Waiting**: This is the period of time that the base platform waits at the bottom-most point, before returning to its original position.
4. **Levelling**: This refers to the action during which the base platform returns to its original position. This happens at a constant default velocity.

The above four processes are repeated for every layer.

2. BUILD MONITORING AND FAILURE DETECTION SYSTEM

2.1 Need for a Build Monitoring System

At present, no feedback system is available to warn the user or to stop the process if failure has occurred during the build. Part build failure can happen due to one or more of the following reasons:

- Incorrectly set process parameters
- Inappropriate support structure
- Deterioration of Silicone coating on Base platform
- Large flat structure in XY plane
- Lamp power fluctuation due to ageing of bulb

2.2 Effects of build failure

The following are the losses incurred due to build failure:

- Time and resin wastage – causing probable increase in development time
- Deterioration of resin quality
- Deterioration of Silicone coating on base

2.3 Working principle of the Build monitoring system

A build monitoring system was designed based on the fact that the platform drive belt is subjected to forces during peeling, due to which it stretches for a while before reaching a steady state. This causes the platform to have a variation in velocity during the peeling process. This variation is proportional to the peeling forces encountered when the newly polymerised layer separates from the Silicone base. Part build failure can be detected if the platform moves with a constant velocity, indicating that it is not encountering any peeling forces.

2.4 Instrumentation used

Transducer: Linear variable resistance type, coupled to the cantilever arm at rear of the base platform. This is driven by a dc power source and outputs to an oscilloscope.

Digital Oscilloscope: This equipment displays the change in voltage with respect to time, on an LCD screen. The display can be frozen at required points and printed out.

Printer: The printer is coupled with the oscilloscope, and the shape of the printed Displacement - Time curve indicates whether the build is going on successfully or has failed.

2.5 Schematic of the Build Monitoring System

A schematic representation of the build monitoring system developed at Northumbria University is shown in Figure 2a. A close-up of the belt drive system is shown in Figure 2b.

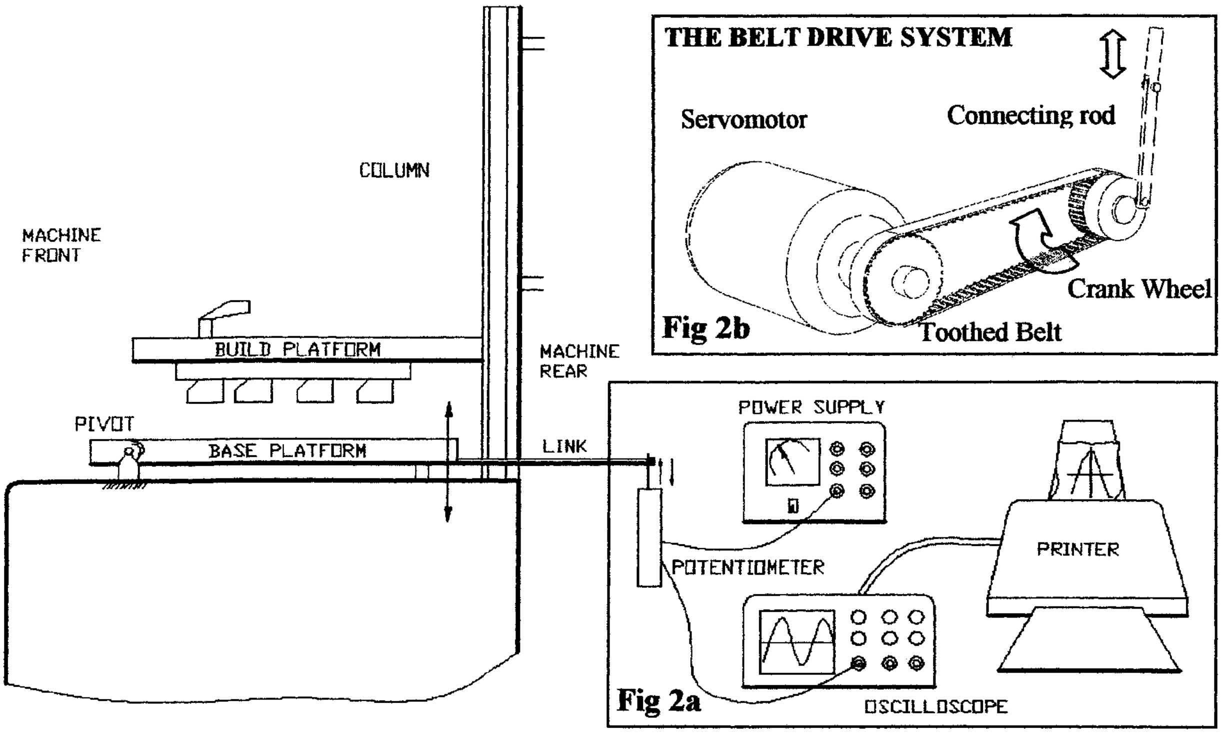


Figure 2 – The Build monitoring system

2.6 Working of the system

- The link transfers the motion of the base platform to the transducer and also serves to amplify the displacement of the platform during peeling.
- The output voltage of the transducer is processed by the oscilloscope, to show a graph against time.
- The plot can be printed by a printer interfaced directly with the oscilloscope.

2.7 Types of layers built during the entire build cycle

2.7.1 Base Layers

The build process starts by building a base layer, which acts as a foundation for the rest of the process. Default parameters are used for the base layer. The displacement of the base platform is at a maximum during building of the base layer. Considerable peeling forces are encountered at this stage, as is indicated by the velocity drop in the section labelled ‘a’ in Figure 3 – Base Layers.

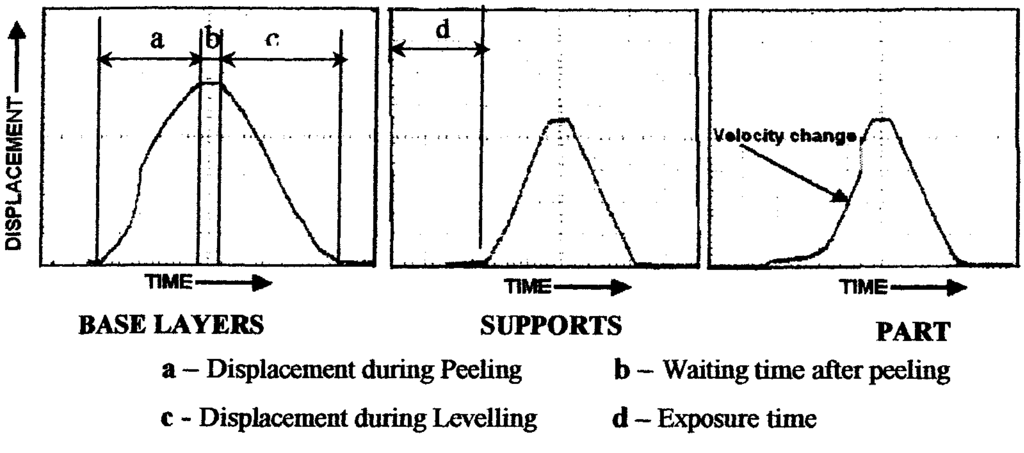


Figure 3 – Build characteristics graph

2.7.2 Supports

The building of supports is the next stage in the process. The supports are built on the same parameters as that of the part. We can see from Figure 3 – Supports, that peeling forces encountered at this stage are very small compared to that during the part build stage.

2.7.3 Part build

This stage, in which the part is built, takes the bulk of the total build time. Here, the magnitude of peeling forces depends on many process parameters, as well as cross-section of the layer being peeled away. The change in velocity due to peeling force can be clearly seen in Figure 3 – Part.

2.8 Investigation of the working of the system

All the instruments were connected as shown in figure 3, and the oscilloscope readings were studied continuously, as the part was being built. The graphs were printed at intervals of 0.3 mm part build height. Figure 4 shows the test part that was built for this experimentation. The steps are provided to study the sensitivity of the system at different build cross sections.

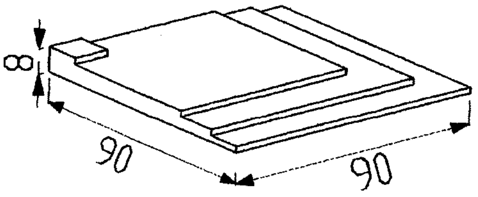


Figure 4 – Sample part used for testing the system

The Displacement – Time graphs obtained at selected intervals during the part building stage, for a successful and a failed part are shown in figure 5. The part geometry and all process and machine parameters are similar in both cases. It has to be noted that the graphs have been plotted during build of the main part, after the supports have been completed.

It can be clearly seen from the figure that the peeling forces encountered during successful build causes a reduction in velocity. But in the case of a failed part, the peeling happens at a constant velocity, indicating that there is no peeling force encountered. This means that the part has failed. The peeling and levelling velocities are equal in this case, but they need not be so every time.

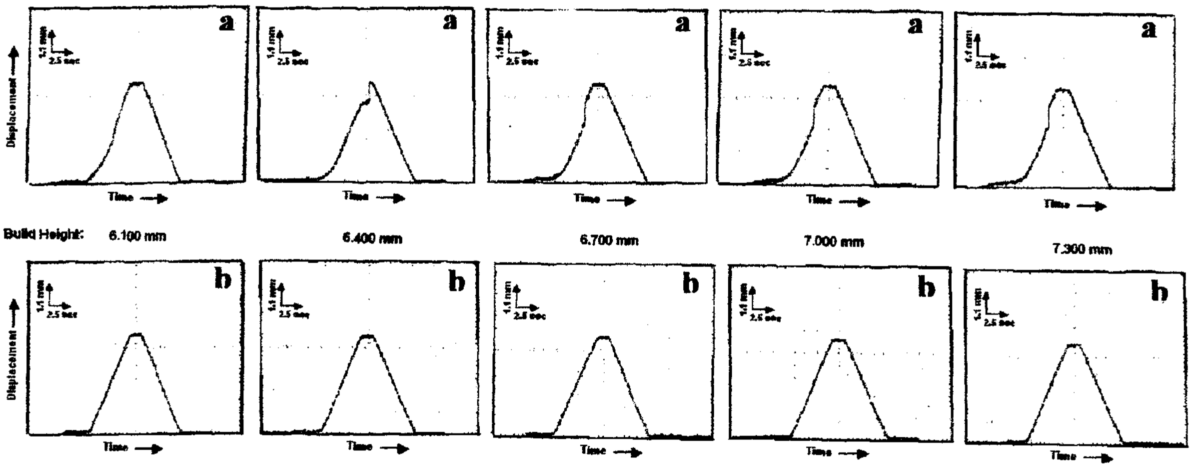


Figure 5 – Displacement vs. Time graphs for Successful (a) and failed (b) parts

These experiments have been repeated five times in order to test the consistency of the results.

2.9 Development of a build-monitoring algorithm

An algorithm was developed, that could be incorporated into the PerFactory® software, and is shown in Figure 6. It is designed to abort the process if it senses that build failure has occurred.

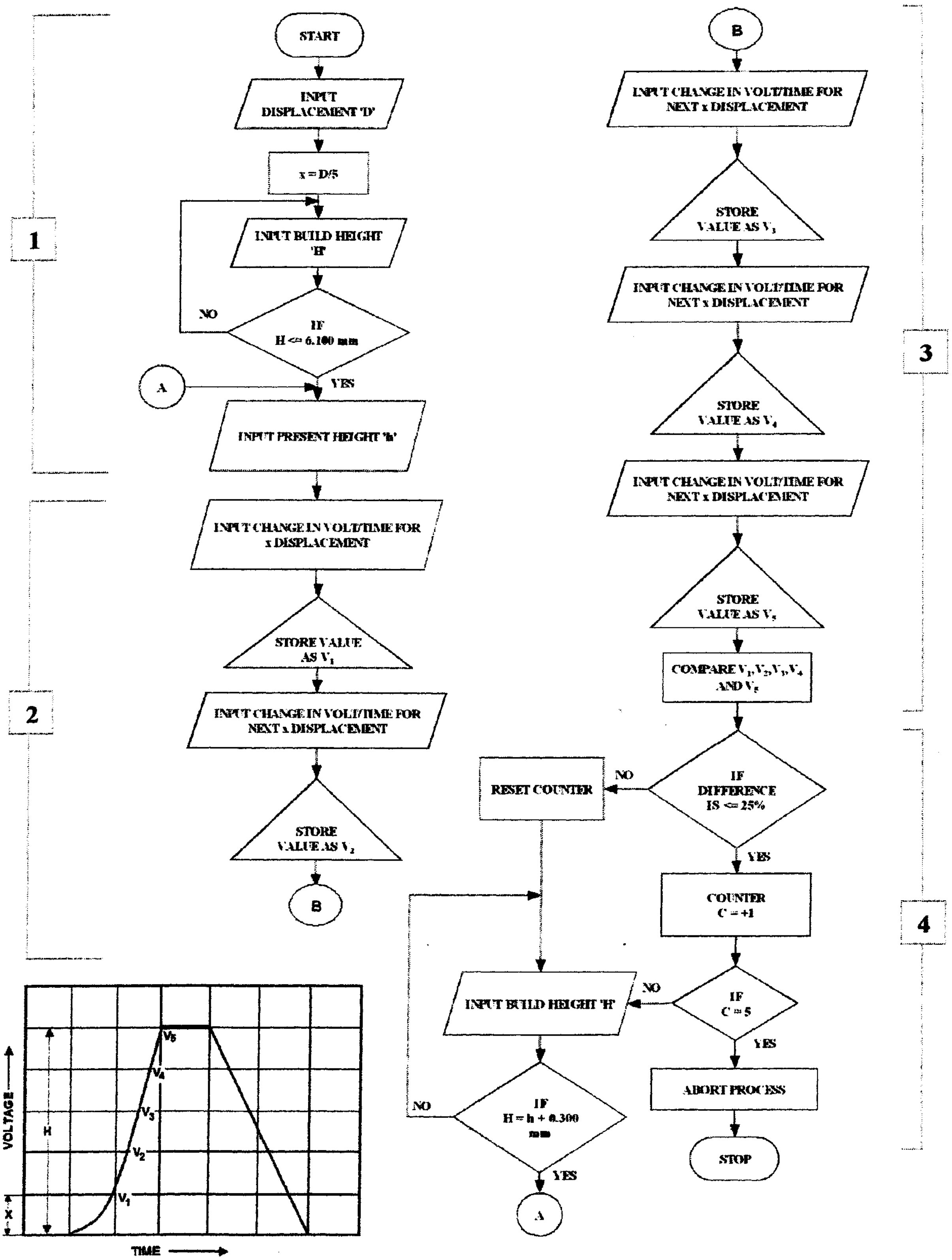


Figure 6 – The failure detection algorithm

2.9.1 Logic of this algorithm

This algorithm works by measuring the slope (displacement / time) at five different sections along the curve representing peeling. The measurements are started after the base and support layers are built. The peeling curve of a failed part would have the slopes of all the five points equal. A counter is activated in this case. These slope measurements are made every 0.3mm of part height. The build process is aborted if failures are recorded five consecutive times, that is, when the counter reaches five in as many measurements. The different sections of the algorithm are listed below:

1 – Resets counter for new build
2 – Calculation of slope for first segment in the peeling characteristics graph
3 – Comparison of five consecutive slope readings. If the difference between slopes is within 25% of each other, they are considered to be equal, and a counter is incremented.
4 – The process is aborted or an alarm is sounded if the counter reaches five.

2.10 Limitations of this system

This failure detection system has a few limitations and they are listed below. They can be attributed to the hardware as well as to the algorithm.

- Initial build failure occurring at the base or support layers cannot be detected by this system
- It is not sensitive at very small layer cross sectional areas. This is due to the resolution of the transducer. This fact can be observed from figure 4, where no change in velocity can be seen in the peeling curve of the graph.

3. CONCLUSIONS AND FUTURE WORK

A concept for build monitoring was developed and tested successfully. The user can identify if build failure has occurred, from the signature characteristics of the output graph during peeling action. The algorithm developed could be implemented into the PerFactory® software, and along with the displacement transducer and oscilloscope, could be programmed to automatically stop the build if it detects build failure.

This algorithm has to be implemented into the PerFactory® software in such a way that it acquires information like build height, support height etc., and also aborts the building if it senses that failure has occurred. Work also has to be conducted on improving the sensitivity and repeatability of the system. Use of an LVDT (Linear Variable Differential Transformer) would help to record even minute changes in velocity, which is typical during build of parts with very small cross sections.

Progressing from this stage, work has to be conducted in the following areas:

- Implementation of the build-monitoring algorithm into the PerFactory® software
- Use of more accurate transducers like LVDT to enable detection of build failure even in very small models, thereby widening the working envelope of the system
- Improvement of sensitivity and repeatability of monitoring system.
- Identification of a relationship between the mask white area and peeling force.
- Development of build platform surface for better adhesion to the base layer

REFERENCES

[1] www.dlp.com [Accessed 25th January 2005] – Homepage of Texas Instruments Ltd, USA.

[2] www.envisiontec.de [Accessed 6th February 2005] – Homepage of Envisiontec Ltd., Germany.

[3] Hackney PM, Pancholi KP, Analysis of the Envisiontec Perfactory System for Rapid Production of Components and Validation Using Finite Element and Photo-elastic Analysis, Fifth National Conference on Rapid Design, Prototyping and Manufacture, Buckinghamshire Chilterns University, 2004.

[4] Upcraft S, Fletcher R, The Rapid Prototyping Technologies, Assembly Automation, vol. 23, No. 4, 2003, pp. 318–330.

Investigation into the EnvisionTec PerFactory® Rapid Prototyping Process for Production of Accurate and Strong Functional Parts

P M Hackney, A C Arulraj, G K Chinnaswamy, B T Nair,
School of Informatics, Engineering and Technology,
Northumbria University, Newcastle upon Tyne, United Kingdom.
Email: phil.hackney@unn.ac.uk

ABSTRACT

The PerFactory® technique was introduced by Envisiontec Ltd., Germany in 2002. This relatively new process has comparable accuracy levels with FDM and SLS processes and it builds one whole slice simultaneously, rather than a line or a point, at a time. Its main advantages are low initial investment, low operating costs and high build-speed. This makes it very attractive to both small and large organisations alike.

This work deals extensively on researching the development process and the resultant mechanical properties of parts fabricated using the new Acrylate R5 based resin. The aim of this work is to establish a relationship between the desired outputs and the process parameter settings using Taguchi techniques and Statistical tools. In this case, the desired outputs are Tensile strength, Build accuracy and Surface hardness. With this knowledge in hand, RP parts can be engineered according to functional requirements.

Keywords: Accuracy, Strength, Perfactory, Digital Light Manufacturing, Taguchi.

1. INTRODUCTION

The PerFactory® technique utilises the technology called Digital Light Processing (DLP™) developed by Texas Instruments [1]. The process is based upon a light projector working on the DLP™ technology, which polymerises a photosensitive resin layer-by-layer, resulting in a 3D part [2]. This technique also can be classed as Stereolithography (SLA), but the only difference is that a mercury lamp replaces the expensive CO_2 laser used in conventional SLA machines [3]. This is one of the main reasons that contribute to the low cost of the system. Here again, the models are built layer by layer.

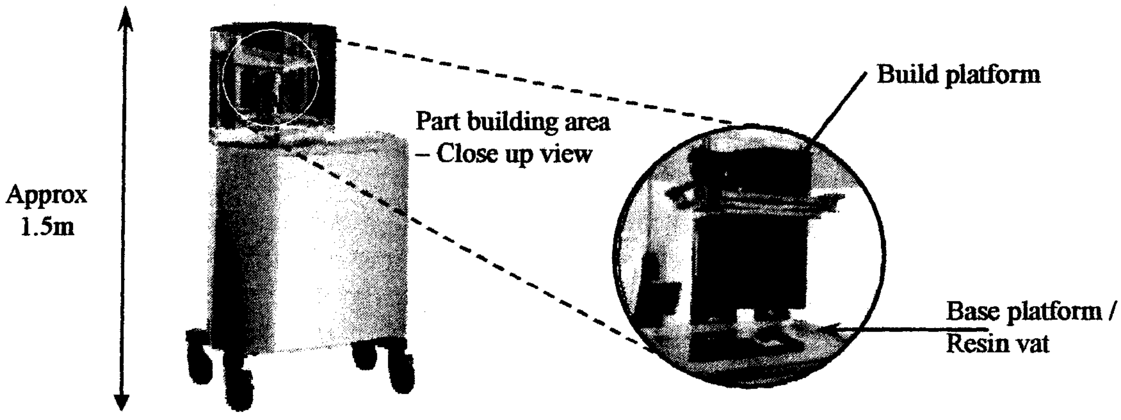


Figure 1 – The Perfactory machine

1.1 Key features of the PerFactory Process

- Build time per layer is constant throughout the process, unlike techniques like SLS and FDM where time depends on the area of the layer [4,5]
- Economic material usage and low capital costs [2]
- Very few moving parts and few consumable components
- Very little post processing is required, as nearly 100% curing is achieved during build
- The machine footprint is only 736.6 mm (l) x 482.6 mm (w) x 1244.6 mm (h) and can be used in an office environment, with no need for air conditioning.

2. IMPORTANT PROCESS PARAMETERS & SETTINGS

It has been learnt from previous operating experience that the following parameters would have the maximum effect on Accuracy, Strength, and Hardness. It is important to narrow down the parameters in the experimentation, so that costs and time involved can be kept at a minimum. The available process parameters and machine settings are shown in Tables 1 and 2.

Process parameters

	Parameter	Unit	Minimum	Maximum
1	Layer thickness	µm	30	100
2	Peeling velocity	µm/s	1000	3000
3	Waiting time	ms	0	2000
4	Exposure time	ms	4000	15000

Table 1 – Process parameters

Machine settings

	Parameter	Unit	Minimum	Maximum
5	Work area	mm^2	120mm x 96mm	190mm x 152mm
6	Orientation	x, y and z		

Table 2 – Machine settings

2.1 Explanation of Process parameters and Machine settings

2.1.1 Layer thickness: This is the thickness of the build layer. It is specified in microns and ranges from 30 to 100 microns. It is the gap between the Silicone base and the solidified layer above. Only the resin within this gap is solidified by mask projection from the DLP projector.

2.1.2 Peeling velocity: This is the velocity with which the build platform is peeled away from the lower platform. In effect, it is the velocity with which the newly formed and cured layer is separated from the silicone platform below it. Peeling is achieved by pivoting the silicone base plate at the front, and pulling it down away from the build plate using a stepper motor driven mechanism.

2.1.3 Waiting time: This has two components -
- Waiting time after peeling
- Waiting time after levelling

The user specifies individual values for the waiting time after peeling and levelling. They are independent of each other. These components are combined in our experiments and are set equal.

2.1.4 Exposure time: This is the time during which the bulk of the curing takes place i.e. the liquid resin is exposed to the mask layer, which results in curing. However, some curing takes place after the part building process is completed.

2.1.5 Work area: A small work area would result in the light being focussed in a very concentrated manner, as compared to a larger work area. This is because the size of the pixels is fixed in the projector, and the effective size falling on the resin is varied by moving the projector lens either upwards or downwards. Henceforth in this report, the term *"Pixel Size"* would be used in place of work area. A higher pixel size implies that a high work area has been used. The work area settings available on the machine are shown in Table 3. The limits of pixel size are also indicated along side the table.

	Working area, mm^2
1	120.00 x 96.00
2	128.00 x 102.40
3	140.80 x 112.64
4	153.60 x 122.88
5	160.00 x 128.00
6	166.40 x 133.12
7	179.20 x 143.36
8	185.60 x 148.48
9	190.00 x 152.00

Pixel size
0.094mm
↓
0.148mm

Table 3 – Working area settings available

It has to be noted that the ratio between the two dimensions (aspect ratio) in all the cases is 1.25. This is an advantage in the Design of experiments process, since Maximum and minimum values can be straightaway assigned to the area without being concerned about the relationship between length and breath.

2.1.6 Orientation: The part can be built in any of the three orientations x, y and z, as shown in Figure 2. The orientation is chosen considering the following factors:

- Geometry of the part
- Surface finish requirements
- Areas to be supported (Faces in contact with the support end up with a rougher finish)

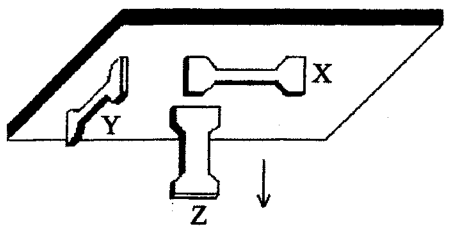


Figure 2 – Different build orientations

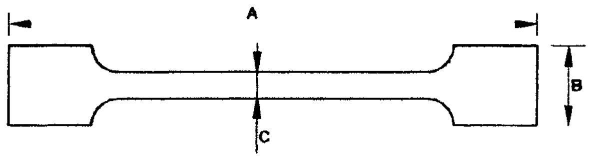


Figure 2a – The test specimen

3. LAYOUT OF THE EXPERIMENTS

The L18 Orthogonal Array (OA) was chosen to layout the experiments. This array can accommodate up to seven 3-level and one 2-level factors. Moreover, an interaction is inbuilt between the first two columns. Interactions between three-level columns are distributed more or less uniformly to all the other three-level columns, which permits investigation of main effects. This makes it a highly recommended array for experiments [6]. The various parameters their values to be used in the experimentation are shown in Table 4. The level notations (in square brackets) and their corresponding values can be seen in Table 5. The first and last columns have not been used since there were only six parameters.

Level	Pixel size	Peeling Vel	Waiting time	Exposure time	Orient.	Layer Thick.
1	120.00x 96.00	1000 μm/s	0 ms	4000 ms	x	0.03 mm
2	153.60 x 122.88	2000 μm/s	1000 ms	10000 ms	y	0.065 mm
3	190.00 x 152.00	3000 μm/s	2000 ms	15000 ms	z	0.1 mm

Table 4 – Parameters and levels

	1	2	3	4	5	6	7	8
Run No		Pixel Size	Peeling Vel. (μm/sec)	Waiting time (ms)	Exp Time (ms)	Orientation	Layer (mm)	
1	1	[1] 120x96	[1] 1000	[1] 0	[1] 4000	[2] Y	[1] 0.030	1
2	1	[1] 120x96	[2] 2000	[2] 1000	[2] 10000	[1] X	[2] 0.065	2
3	1	[1] 120x96	[3] 3000	[3] 2000	[3] 15000	[3] Z	[3] 0.100	3
4	1	[2] 153x122	[1] 1000	[1] 0	[2] 10000	[1] X	[3] 0.100	3
5	1	[2] 153x122	[2] 2000	[2] 1000	[3] 15000	[3] Z	[1] 0.030	1
6	1	[2] 153x122	[3] 3000	[3] 2000	[1] 4000	[2] Y	[2] 0.065	2
7	1	[3] 190x152	[1] 1000	[2] 1000	[1] 4000	[3] Z	[2] 0.065	3
8	1	[3] 190x152	[2] 2000	[3] 2000	[2] 10000	[2] Y	[3] 0.100	1
9	1	[3] 190x152	[3] 3000	[1] 0	[3] 15000	[1] X	[1] 0.030	2
10	2	[1] 120x96	[1] 1000	[3] 2000	[3] 15000	[1] X	[2] 0.065	1
11	2	[1] 120x96	[2] 2000	[1] 0	[1] 4000	[3] Z	[3] 0.100	2
12	2	[1] 120x96	[3] 3000	[2] 1000	[2] 10000	[2] Y	[1] 0.03	3
13	2	[2] 153x122	[1] 1000	[2] 1000	[3] 15000	[2] Y	[3] 0.100	2
14	2	[2] 153x122	[2] 2000	[3] 2000	[1] 4000	[1] X	[1] 0.030	3
15	2	[2] 153x122	[3] 3000	[1] 0	[2] 10000	[3] Z	[2] 0.065	1
16	2	[3] 190x152	[1] 1000	[3] 2000	[2] 10000	[3] Z	[1] 0.030	2
17	2	[3] 190x152	[2] 2000	[1] 0	[3] 15000	[2] Y	[2] 0.065	3
18	2	[3] 190x152	[3] 3000	[2] 1000	[1] 4000	[1] X	[3] 0.100	1

Table 5 – The run parameters table

4. EXPERIMENTATION AND TESTING

The experiments were grouped by pixel size and run in increasing order of the same. This was carried out, as it requires about an hour to adjust the pixel size settings and recalibrate the machine, while all the other parameters could be set within a matter of seconds. Runs 3, 5 and 17 failed due to process settings.

4.1 Testing Procedure

The equipment used to test the hardness and tensile strength of the specimens is shown in Figures 3 & 4. The values obtained form the Barcol Impressor are called Barcol Numbers and are universally accepted alongside Shore hardness values, for plastic materials.

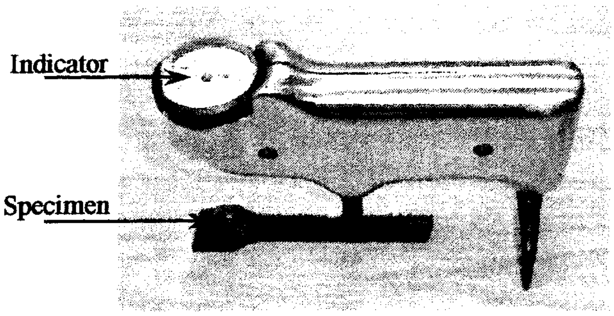


Figure 3 – The BARCOL Impressor

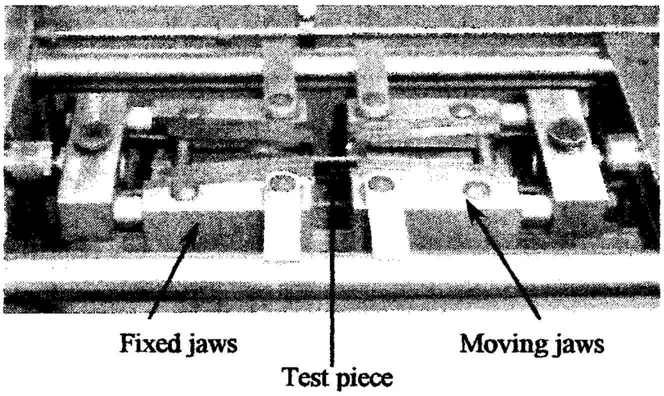


Figure 4 – The Tensometer

The tensile strength sample itself was used for accuracy measurements. Accuracy was determined by calculating the deviation of the part dimension from the actual, at different points across the sample. They are marked 'A', 'B' and 'C' in Figure 2a. Two different types of accuracy can be obtained in the case of RP techniques in which the part is built layer by layer – XY and Z (dimension along build direction). The dimension obtained by building up of the layers is affected only by the accuracy of thickness of each layer. In this work, we focus on the XY accuracy, as that is the factor that is directly influenced by projector performance.

5. RESULTS

The hardness and strength values obtained are shown in Figure 5. In order to draw comparisons, hardness values of typical engineering plastics are shown in Table 6. Accuracy values measured ranged from 0.04mm to 0.62 mm, depending on the parameter combination used. Note that these values are the measured deviations from the actual specified values. The 95% confidence intervals for all the responses, as obtained from the Analysis Of Variance (ANOVA) study are specified in Table 8.

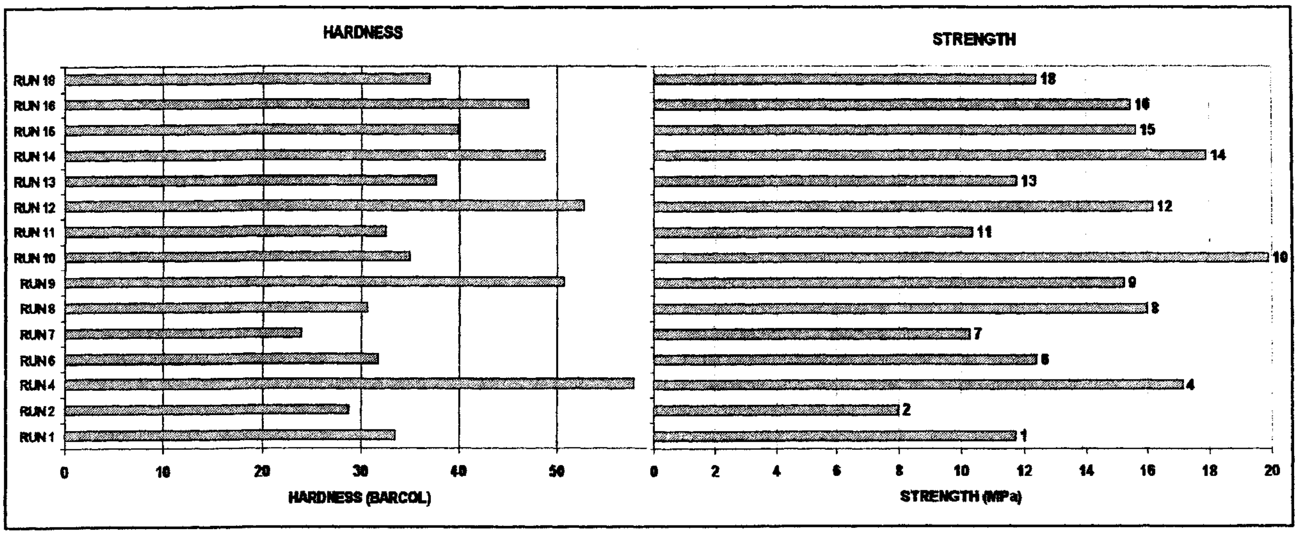


Figure 5 – Hardness & Strength values of successful runs

Material	BARCOL Hardness
Melamine	80
Acrylic	50
ABS	55

Table 6 – Hardness of some common plastics

Response	C.I
Hardness	±2.19
Strength	±1.25
Accuracy	±0.10

Table 7 – Confidence intervals for responses

5.1 Normalised Responses

The normalized response values are shown in Figure 6. All values have been normalised against the lowest in each class. Normalised values for Accuracy and build speed have been multiplied by a suitable factor, for presentation purposes. Since rapid prototyping is all about saving time, it would be a good idea to consider the build speed for a particular combination of parameters, even if they look promising in terms of part properties.

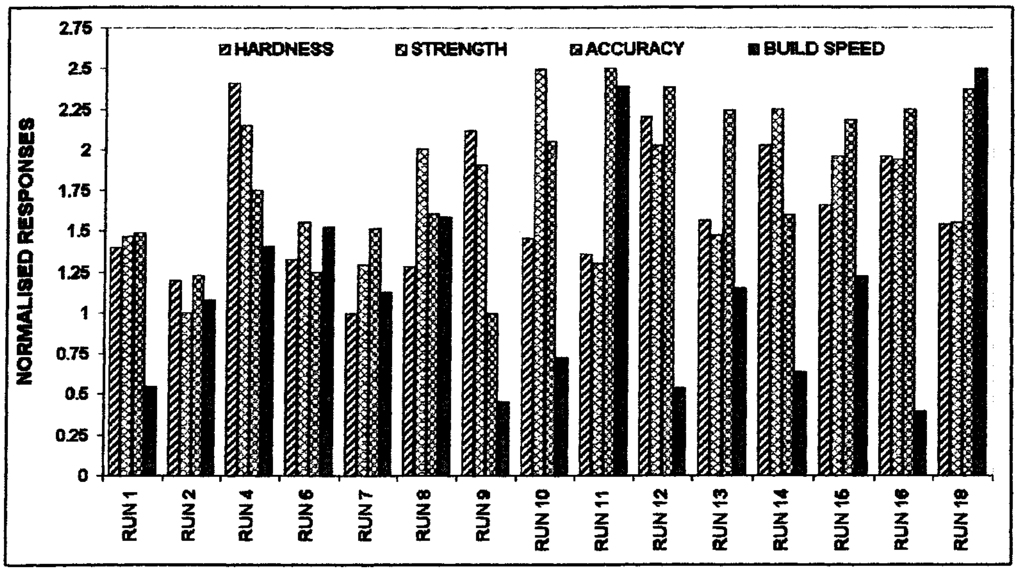


Figure 6 – Normalised response values

5.2 Percentage contribution of factors

As the Taguchi methodology involves only partial factorial experimentation, statistical tools are needed to establish confidence levels in the results obtained. This is done using an ANOVA, which uses the variance in results obtained to fix those confidence levels [7]. Conducting the ANOVA also provides us very useful data like the percentage contribution of each parameter. The percentage contribution of each of the factors is shown in Figure 7.

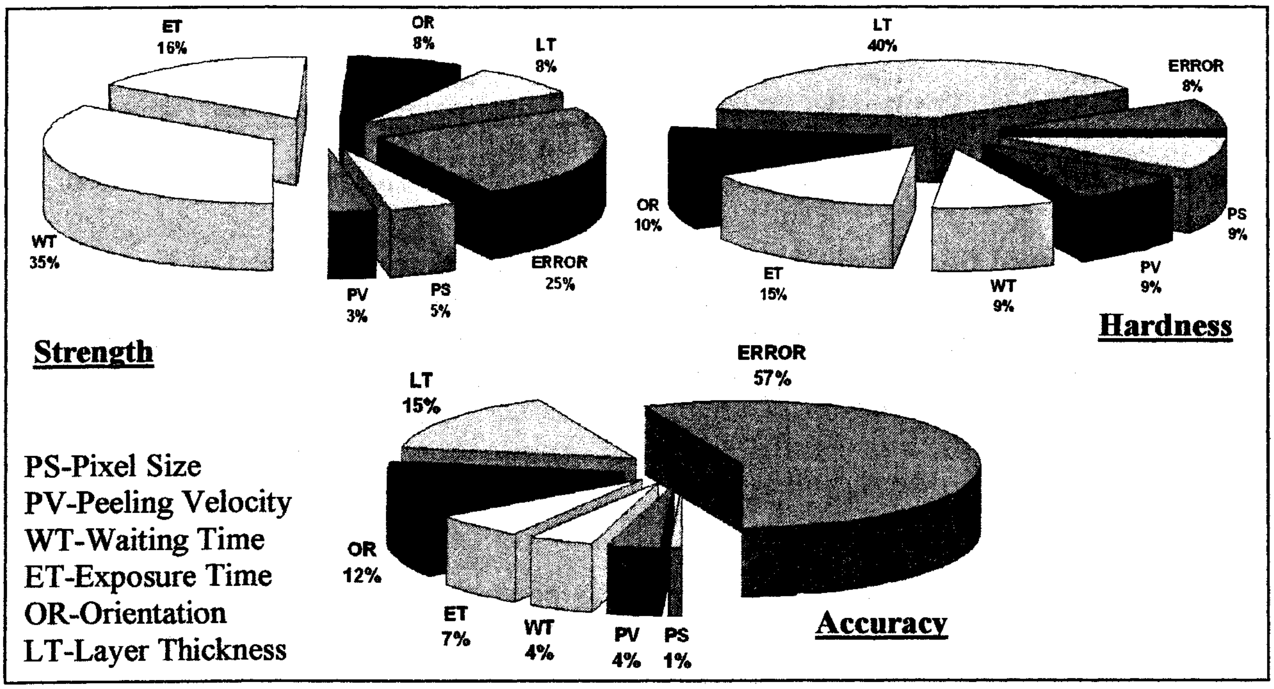


Figure 7 – Percentage contribution of factors

5.3 Factor effects on response

The previous section explained the percentage contribution of all the factors on the desired response. In this section, the effect of the most important on each response is shown graphically, in Figures 8,9 and 10.

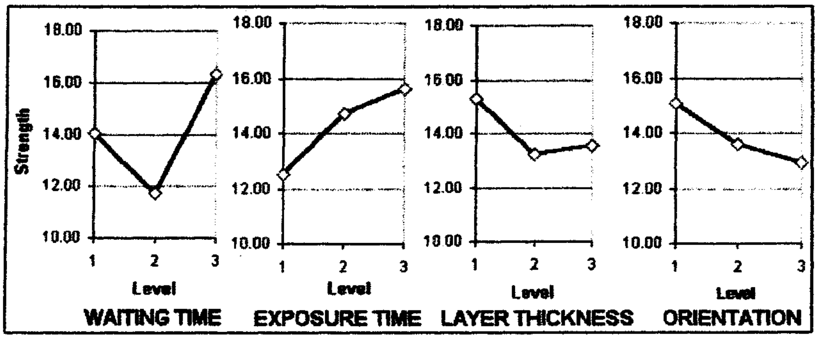
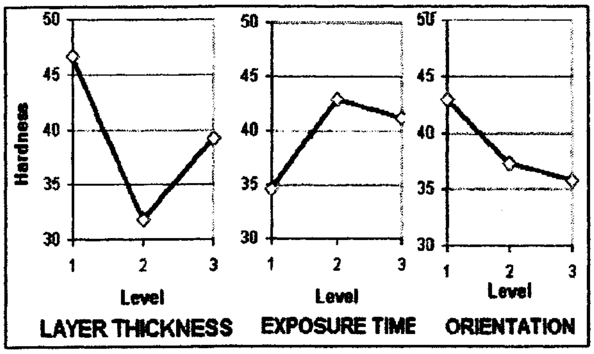
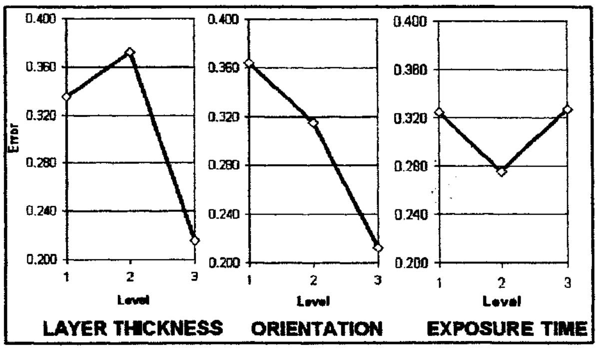


Figure 8 – Effect of parameters on Strength



<u>Figure 9</u> – Effect of parameters on Hardness



<u>Figure 10</u> – Effect of parameters on accuracy

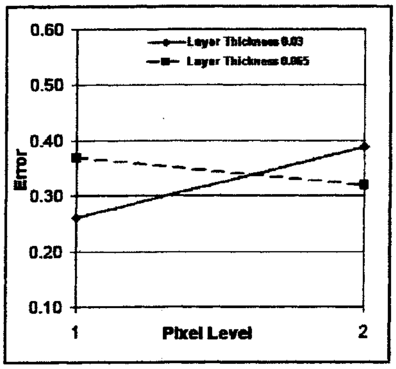
It can be observed from figures 8, 9 and 10 that exposure time and orientation have nearly the same effect on strength, hardness and accuracy. Increasing the exposure time above 10,000ms does not cause any significant improvement in response in all the three cases. Building along the x direction produced the best results, whereas building along the z direction produced the worst. Only in this case, accuracy is an exception, because the trend is exactly reversed, with the z direction producing the smallest error. This means that in this process, layer thickness can be more tightly controlled than x, y dimensions.

5.4 Interaction

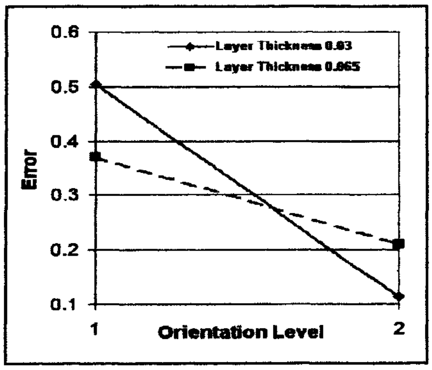
No interaction was observed between any of the parameters, for both strength and hardness. However, as far as accuracy was concerned, strong interaction was observed between the following two pairs.

- Pixel size and Layer thickness
- Orientation and Layer thickness

Hence, accuracy tests have to be run over again, with interacting factors placed in suitable columns of the array. This method would help us to discover the effect of each interaction on the response. The interacting pairs are shown in Figures 11 and 12.



<u>Figure 11</u> – Interaction – Pixel size and Layer thickness



<u>Figure 12</u> – Interaction – Orientation and Layer thickness

6. CONCLUSIONS AND FUTURE WORK

The experiments were conducted as per the selected orthogonal array and the parts were tested for strength, hardness and accuracy, and the combination of parameters for the best values of these responses were obtained. It was found that both hardness and strength increase with exposure time, but the effect peaks at 10,000ms. Building along the x direction produced the best results for strength and hardness, the z direction producing the lowest responses. However, the trend is reversed in case of accuracy with the z direction producing the lowest error. Further, strength, hardness and accuracy improve with lower layer thickness. It is learnt by now that since the trends are similar for all these responses studied, an appreciable value of one can be achieved without sacrificing the others.

A thorough ANOVA test was performed on the data obtained for all the tests. The results indicated the following:

- Layer thickness and exposure time contributed maximum towards hardness, while peeling velocity and waiting time contributed the least.
- Waiting time and Exposure time contributed the most towards strength, while peeling velocity and Pixel size contributed the least. The effect of waiting time was a totally unexpected and interesting one.
- Layer thickness and Orientation contributed the most towards a high accuracy value, whereas Pixel size and Peeling velocity contributed the least.
- Interaction was observed between Pixel size and Layer thickness, and orientation and Layer thickness, in the accuracy tests.

Future work to be conducted in the following areas:

- Why the response values were affected by orientation, even though the pixel density was same along x and y-axes. The behavior along the Z direction is understandable.
- A detailed study into why waiting time contributed the most towards part strength.
- Determination of the Young's and Bending moduli of parts built by this technique.
- Accuracy tests have to be repeated, with interaction included in the array.

REFERENCES

[1] www.dlp.com [Accessed 25th January 2005] – Homepage of Texas Instruments Ltd, USA.
[2] www.envisiontec.de [Accessed 6th February 2005] – Homepage of Envisiontec Ltd., Germany.
[3] Hackney PM, Pancholi KP, Analysis of the Envisiontec Perfactory System for Rapid Production of Components and Validation Using Finite Element and Photo-elastic Analysis, Fifth National Conference on Rapid Design, Prototyping and Manufacture, 2004.
[4] Gibson I, Shi D, Material Properties And Fabrication Parameters In Selective Laser Sintering Process, Rapid Prototyping Journal, Vol. 3, No. 4, 1997, pp. 129–136.
[5] Agarwala et al, Structural Quality of Parts Processed by Fused Deposition, Rapid Prototyping Journal, Vol. 2, No. 4, 1996, pp. 4–19.
[6] Roy Ranjith K, A Primer on the Taguchi Method, Van Nostrand Reinhold Publications, New York, 1990.
[7] www.itl.nist.gov/div898/handbook [Accessed 15th January 2005] - e Handbook: . Engineering Statistics, NIST.

Rapid Manufacturing of Polymer Injection Mould Tool Inserts for Prototype Tooling Production

P M HACKNEY
School of Computing, Engineering and Information Sciences, Northumbria University, Tyne and Wear, NE1 8ST, UK, Phil.Hackney@unn.ac.uk

Abstract

Product design is a multi-criteria decision process with the complexity of selecting the optimum between functionality, cost, reliability, manufacturability and many other conflicting criteria.
The only true way to really know how a component will perform under real world conditions is to manufacture it, in the production intent materials using production tooling. However, this is not only costly but can take several months to produce the tooling to produce the part.

Computer modelling, analysis and simulations such as 3D Computer Aided design, Finite Element Analysis, Flow Analysis etc can reduce the test programmes, there is still a requirement for prototype parts to test under various load and climatic scenarios.

This paper will present the application of Rapid prototyping processes to produce direct tooling inserts in hard (metals) and soft (polymer) materials for prototype production tooling.

Key Words: Rapid Tooling, AIM Tooling, Direct tooling, Rapid Prototyping, Rapid manufacture

1. INTRODUCTION

Productivity, short product lifetime and cost savings have become the main concerns of industries worldwide. Industries increasingly need to develop and manufacture new products more cost effectively in shorter lead times. The problems of product design and the production of prototypes are significant obstacles to the launch of new products because design iterations add time to the product development process, and prototypes are required to confirm the design and customer requirements.

To this end, 3D Computer Aided Design (3D-CAD) and Rapid Prototyping (RP) techniques have been developed to produce physical prototypes in an effort to reduce time to market [1]. Rapid prototyping was once considered as a technology for only automotive and aerospace industries, but it is becoming more commonplace in the governmental, military, academic institutions, business machines, consumer products, and medical industries [2]. Rapid Prototyping refers to technologies that are for build physical models of a component and prototype parts directly from 3D CAD data. The technologies are available to produce objects of complex geometry. The use of RP facilitates the early detection and correction of design flaws.

The slowest and most expensive step in the manufacturing process is tooling. Since moulds and dies often have complex geometries and require high quality, they are traditionally made by CNC machining, i.e. lathe, milling, grinding, electro-discharge machining (EDM), or by hand all of which are time consuming [3]. Rapid tooling is a natural progression from RP that can build prototype tools directly from CAD models. It is able to reduce lead times and costs for low volume tooling and prototype tooling. At present, rapid tooling has been developing robust technologies to be used for manufacturing processes such as vacuum forming, die casting, injection moulding. There are many different rapid tooling processes available for producing injection moulded prototype parts, e.g. SLA Aim tooling, SLS tooling RapidSteel, epoxy tooling, Keltool and other processes.
This research focuses on mould design and the use of the Envisiontec Digital Light Manufacturing (DLP) process machine to produce injection mould tooling to manufacture simple and aesthetic 3D plastic parts. The low cost DLP printing machine is able to produce physical prototypes quickly, easily and inexpensively from 3D CAD data.

The investigation looked at the manufacture of a simple part first to establish build parameters, post manufacturing settings were applicable. The results then being utilised to manufacture an aesthetic 3D component based upon the Northumbria University's paper clip logo, this was used to validate the process. To verify the design of the mould tooling, Moldflow Plastics Adviser^{TM} software package was used to predict the quality of the plastic product. It was also used to analyse the best gate location of the injection sprue, pressure, flow analysis, and temperature in the injection moulding process.

The original definition of Rapid Tooling (RT) was "A 3D CAD driven process that generates tooling inserts in a layer by layer process for the production of components in end use materials [4]. RT is a natural extension of rapid prototyping. It originated from the need to assess rapid prototyping models in terms of their performance [5], it has introduced a new generation of tool making techniques, and has defined as a technique to produce low volume metal and plastic products from the rapid prototyping process. Rapid tooling is a process that allows a tool for injection moulding or die casting to be manufactured quickly and efficiently. It is the ability to build prototype tools directly as opposed to prototype products directly from 3DCAD models resulting in compressed time to market solutions. RT offers a high potential for a faster response to market needs, creating a new competitive edge. In addition, the rapid tooling process provides higher quantities of models in a wider variety of materials. The purpose of rapid tooling is not the manufacture of final parts, but the preparation of the means to manufacture final parts [6].

Rapid tooling can be divided into two methods, which are indirect and direct. The indirect process is a method that requires a pattern, typically produced from a rapid prototyping system, to create the tooling inserts. The direct method produces the inserts from a rapid prototyping system without an intermediate process.

Indirect rapid tooling methods use rapid prototyping master patterns to create moulds or dies. This method can be used for production of both plastic and metal parts, for example, injection, vacuum casting, blow moulding, extrusion, sand casting, investment casting, sheet metal forming, etc. Indirect rapid tooling can be divided into soft tooling and hard tooling.

Soft tooling can be obtained via replication from a positive pattern or master. The alternative definition is based on the rigidity and durability of the tooling [5]. It is possible to define soft tooling by the method and material of manufacturing, such as silicone, epoxy resin, wax, low melting alloys, etc.

Hard tooling is often referred to as that made from hard metals, usually steel processes such as Keltool Tooling, Cast Metal Tooling and Electroformed Tooling.

Direct rapid tooling is aimed at the realization of production tooling directly from CAD data files, with the smallest possible number of operations [6].

- Direct AIM: A technique from 3D Systems in which stereolithography produced cores and cavities are used, with traditional metal moulds for injection moulding of high and low density polyethylene, polystyrene, polypropylene and ABS plastic [7]. Tools can be produced within 2 to 5 days with good accuracy.

- LENS/Laser Generating: Sandia developed Laser Engineered Net Shaping; LENS involves blowing powder into a molten pool, a laser beam melts the top layer of the part in areas where material is to be added. Powder metal is injected into the molten pool, which then solidifies. Layer after layer is added until the part is complete [7]. This technique offers fully dense parts, since the metal is melted, not merely sintered. There are varieties of metals including stainless steel, tool steel, titanium carbide cements, etc.

- SLS/DTM/RapidSteel: DTM sells a steel powder; coated with a thermoplastic binder. A product is built by melting the thermoplastic with a 50W laser [8]. DTM process is used to produce a metal mould for injection moulding. RapidSteel can also be used for pressure die casting of metals.

Injection moulding is one of the most common processing methods for polymers. The injection moulding process is a complex process that involves a series of sequential process steps. The different phases of the injection moulding process include the mould filling phase, the packing phase, the holding phase, the cooling phase, and part ejection. Solid plastic is melted, and the melt is injected into the mould under high pressure (usually between 10 and 100 MPa) [10].

1.1 PerFactory® Digital Light Processing machine

At the heart of the PerFactory® machine is the Digital Light Processing (DLP™) projector developed by Texas Instruments [9]. A collection of approximately 1.3 million miniature mirrors called Digital Micromirror Devices (DMD™) reflect light from a mercury lamp into a photosensitive resin, thereby curing a layer. Repeating this process layer-by-layer results in a 3D part [10]. This lamp-mirror combination replaces the laser used in conventional SLA machines [11], which cures the resin one point at time, as it scans the layer.

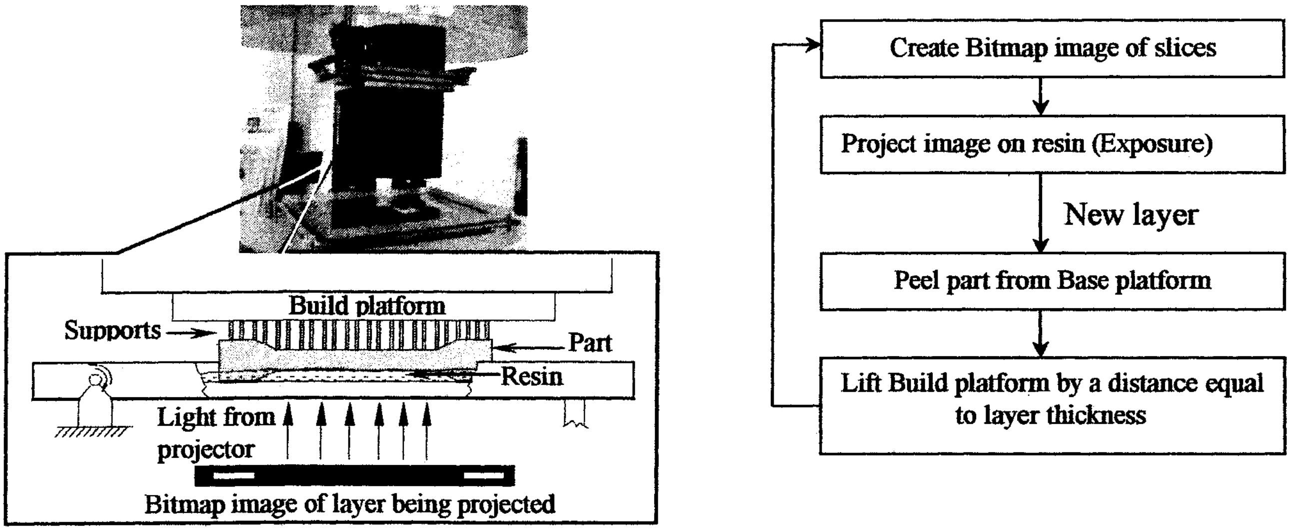


Figure 1: The DLP part building process

1.2 Advantages of the PerFactory® Process

- Build time per layer is constant throughout the process, unlike techniques like SLS and FDM where layer-scanning time depends on the area of the layer [12,13].
- Economic material usage and low capital costs [10].
- Very few moving parts and consumable components.
- Very little post processing is required, as nearly 100% curing is achieved during build.
- The machine footprint is only 736.6 mm (l) x 482.6 mm (w) x 1244.6 mm (h) and can be used in an office environment, with no need for air conditioning.

1.3 Limitations of this technique

- Build size is limited to a volume of 190mm x 152mm x 230mm (height).
- The technique is new to the market.
- Supports are required, resulting in need for manual post processing.
- Raster XY image – layer image formed by rectangular light pixels.
- Short life of projector bulbs – approximately 700 hours. Cost - £300 per bulb.

1.4 Important process parameters & settings

It has been learnt from previous operating experience that the parameters and settings in Table 1 would have the maximum effect on Accuracy, Strength, and Hardness. It is important to narrow down the parameters in the experimentation, so that costs and time involved can be kept at a minimum. The process parameters and settings used in the experiments are shown in Table 1.

Table1: Process parameters

	Parameter	Unit	Minimum	Maximum
1	Layer thickness	μm	30	100
2	Peeling velocity	μm/s	1000	3000
3	Waiting time	ms	0	2000
4	Exposure time	ms	4000	15000
5	Work area	mm^2	120mm x 96mm	190mm x 152mm

1.5 Explanation of Process parameters and Machine settings

Layer thickness: It ranges from 30 to 100 microns. During the build, it is the gap between the base platform and the cured layer above it. Only the resin within this gap is solidified during exposure. It is controlled by the upward movement of the build platform after each layer is cured.

Peeling velocity: This is the velocity with which the build platform is peeled away from the base platform. Peeling is achieved by pivoting the silicone base plate at the front, and pulling it down away from the build platform using a stepper motor driven mechanism.

Waiting time: This has two components – time after peeling and after leveling. The user specifies individual values for the waiting time after peeling and leveling. They are independent of each other. These components are combined in our experiments and are set equal.

Exposure time: This is the time during which the liquid resin is exposed to the bitmap projection (mask), which results in curing. The bulk of the curing takes place during this stage. However, some curing might place even after the part building process is completed.

Work area: This represents the maximum area of the part that can be built. The range is 120mm x 96mm to 190mm x 152mm. It has to be noted that the number of pixels in the projector (1280 x 1024) remains the same, and the work area is changed by moving a projector lens up or down. Due to this, the light intensity decreases as the work area increases.

2. RESEARCH METHODOLOGY

2.1 Research Aim

The aim of this research is an investigation into the application of DLP machine for sample plastic part production. The method for this investigation can be divided into five stages.

1. Concept generation and 3D CAD model
2. Using rapid prototyping for part checking
3. Using Moldflow for injection mould analysis
4. Create mould tool design from 3D CAD
5. Using DLP machine to build mould tool
6. Injection moulding trials

Stages 1 to 3 were undertaken to design, accurately manufacture and validate the test mould tooling for the sample parts and the desired design component as per Figure 2.

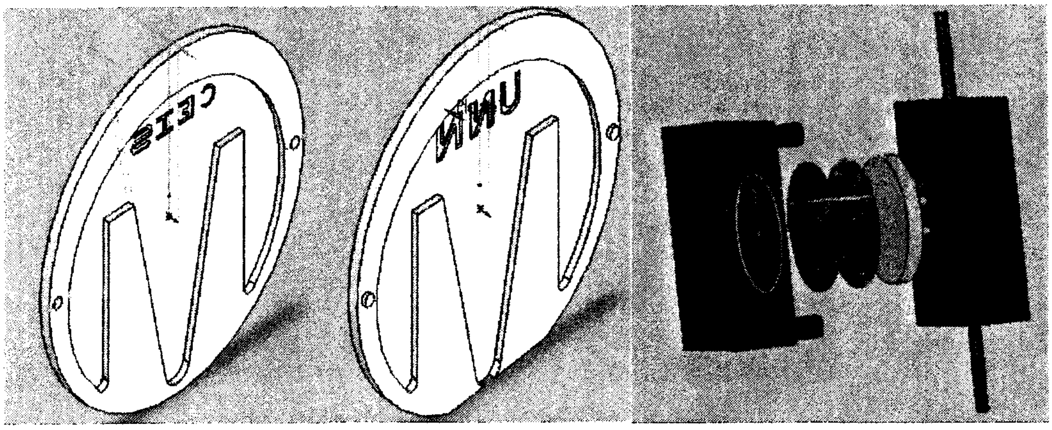


Figure 2: 3D design of logo paper clip design showing both sides of insert and mould tool assembly

The finished parts of the rapid prototyping process were then measured by digital vernier calliper, to identify any errors in build accuracy.

Plastic flow analysis involves an investigation of best gate location, flow analysis, confidence of fill, quality prediction of the parts.

The Mould tools were then designed to fit the Manimould process and the bolster manufactured to support the 3DP inserts as per Figure 2.

2.2 *Mould Tool Production*

The material used to create the mould tool was orange coloured methacrylate release R5 . It solidifies by the process of photopolymerisation.

Parameters of the die:

- Diameter: - 43.5mm
- Thickness: - 3mm(1.5*2)
- Time taken to build 5 replica parts: - 4.7hrs
- Type of resin used: methacrelate R5
- Colour of resin: orange

2.3 *Injection Moulding*

In this experimental test, the injection-moulding machine used to produce the plastic product is "Plunger injection machine" Manimould as shown in Figure 3. The temperature at barrel was set at 200°C and the temperature at barrel head was set at 180°C. The thermoplastic used was polystyrene with a melt temperature of approximately 200°C.
The melt is forced into the mould through the injection nozzle of the injection unit. This operation is known as the shot rate. This shot rate can also refer to the pressure of the process. In this research, shot rate and various pressures are controlled in order to know the suitable shot rate and pressure for the DLP mould tools.

From the injection nozzle, the material passes through the sprue bush of the mould. It is then distributed to the cavities. When the cooling period has elapsed, the mould is opened and the finished parts are ejected.

The mouldings were tested with the different shot rate and various injection pressures. The shot rate used in this research can be divided into 2 shots, 1 shot, 3/4 shot, 3/5 shot, and 1/2 shot. Various pressures are used to force the melt material into the DLP mould. The temperature is set in the range of 180°C to 200°C.

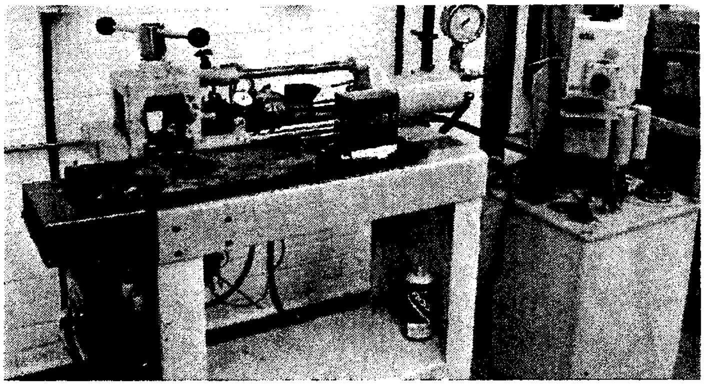


Figure 3: Manimould injection moulding Machine

3. RESULTS AND ANALYSIS

The parts produced were tested as described below for accuracy and surface finish

3.1 Accuracy testing:

The main object of the project is to test how accurate the mould part is with that of the prototype, the mould exactly fits and can be easily separated with the prototype without using excessive force, the accuracy of the final mould part was 98% and the 2% of error can be compensated for at the design stage, that is the mould part tends to shrink after cooling due to the changes in the mechanical properties.

The following figure 4 shows a manufactured component and Table 2 shows the tabulated values for accuracy for the mould and the prototype.

Table 2: Accuracy test for mould part

Prototype dimensions	Mould dimensions
Thickness of prototype (2mm)	Thickness of the mould (2.056mm)
Radius of the prototype (43.50 mm)	Radius of the mould (43.55)
Radius of concentric circle 8.24 & 6.18 mm	Radius of concentric circle 8.28 & 6.21 mm

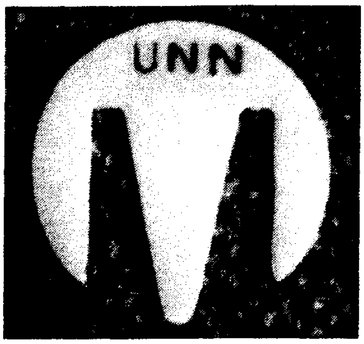


Figure 4: Finished product

The accuracy of the mould tends to vary with injection pressure and temperature, the precision of the mould can be increased only when the temperature of the molten polymer is maintained between 200~220 0C if the temperature is increased above 220^{0}C the prototype of methacrelate tends to fail due to fractures and tearing.

3.2 Surface Finish testing:

The surface finish is one aspects of a products perception in the competitive world. To satisfy customers and make the product more attractive and feel good it normally requires a good surface finish.

The Suface finish parameter Ra is the universally recognised and most used international parameter of roughness. It is the arithmetic means of the absolute departures of the roughness profile from the mean line figure 6 and results shown in Table 3 for five samples produced.

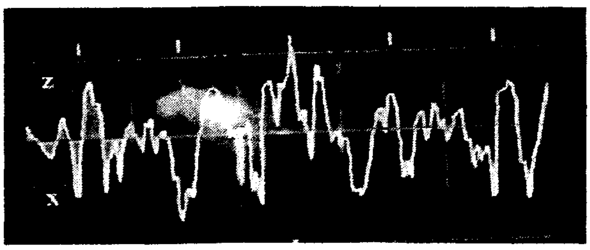


Figure 6: Example of surface Ra value

No of Specimen	Ra value Average (5 readings)
1	1.22μm
2	1.08μm
3	1.09μm
4	1.96μm
5	0.98μm
Average Ra value =	1.266μm

Table 3: Average Ra values for five specimens produced

4. DISCUSSION

In today's competitive world there is no place for delay in manufacturing of products. Every day a new product emerges therefore the need to design and develop the product in a specific time is necessary. The main aim of the designer is to cut down production time since 50% of production time is required for modelling, die making, and analysis since traditionally dies are built using the metal dies, which was considerably more difficult and time dependant to the designers and manufacturers. Since the metal can not be used to build the complex parts and patterns resulting in many supplements, thus the problem arises with the solution leading towards the RP using Envisiontec machine to build the prototype parts.

The use of this machine has solved many problems for designers, as the part can be built with ease and analysed without making costly mistakes, this results in making the product more cost effective in less time.

The main areas to be looked in before using Envisiontec machine for making a die are as follows:

- Can the die withstand high temperature?
- Can the die be reused for making multiple models?
- Can the pattern and the die be separated easily?
- Can we get the accuracy that we get, when we use the metal die?
- Will the product have the smooth surface finish, when compared to the metal die finish?
- Can it withstand the pressure that is used when the molten metal is injected into the die?

Defects of the products, such as warpage, shrinkage, sink marks, and residual stress, are caused by many factors during the production process. These defects influence the quality and accuracy of the products. The most important factor is the dimensional stability for the minimum warpage of thin shell plastic part. Reducing warpage is one of the top priorities to improve the quality of injection-moulded parts.

The Injection temperature: The temperature should be maintained between 210~220^{0}C, above this temperature, it resulted in the rupture of the die and collapse of the product as show below.

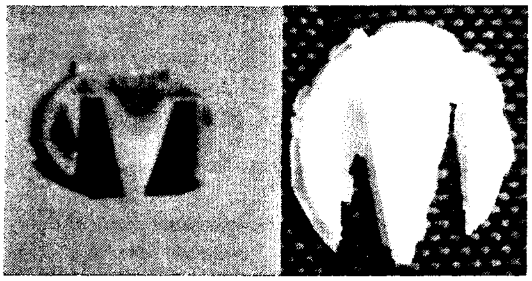


Figure7. Deformed mould & die due to high temperature and injection pressures

<u>The pressure:</u> The pressure should not exceed a maximum found to be 80 MPa, if exceeded the die may rupture and tends to splits off (press fit) resulting in the damage of the product.

<u>Accuracy of the mould:</u> The accuracy of the mould mainly relies on the accuracy of the RP build. The accurate build

of die results in a perfect mould.

Surface roughness: To obtain a smooth surfaced finish product, the prototype mould tool requires a smooth surface finish; this can be obtained easily by using Envisiontec because this method doesn't require Post machine operations on the die.

All the restrictions detailed above regarding temperature and pressure are due to the thermal and mechanical properties of the methacrylate resin used. When the resin is raised above 220^0C, the polymeric bonds begin to loosen which causes rupture and collapse of die along with product. Therefore the usefulness of the die totally depends on the properties such as toughness, melting point, compressive strength, etc. of resin used for making the die.

5. CONCLUSIONS

One application the of PerFactory DLP system is in the manufacture of moulds for the polymer Injection Moulding process. Though it is still in its preliminary stage, experimentally information was investigated in this paper.
A mould for Injection moulding machine was manufactured with the PerFactory DLP machine by rapid prototyping technique (layer by layer).

- The die can be used up to an injection temperature of 220^0C. If it is used above this temperature as shown in figure 7 it begins to tear due to the loosening of polymeric bonds.
- The die injection pressure should not exceed the pressure 80 MPa.
- The accuracy of die and product is quite impressive. The quality of product depends on surface finish of die. Here the product obtained is of good quality which provides s a good surface finish up on the product.

In this study, it was found that plastic parts manufactured from a DLP mould are acceptable, but still need post processing to improve the accuracy and quality. The DLP rapid prototyping technology can be used as a mould tool to produce plastic parts. However, this manufacturing technique is currently not suitable for all complex geometry or delicate products. This technology is more suitable for a simple product or parts, which do not require high accuracy.

REFERENCES

1. *A. E. W. Rennie, D. M. Jacobson, C. E. Bocking, Rapid Prototyping, Tooling, and Manufacturing, Professional Engineering Publishing Limited, London, 2002.*
2. *K. Stier, R. Brown, Integrating Rapid Prototyping Technology into the Curriculum, Journal of Industrial Technology, Volume 17, Number 1, 2000.*
3. *W. Palm, Rapid Tooling Primer, 1998, http://www.me.psu.edu/lamancusa/rapidpro/primer/chapter2.httn.*
4. *Rapid Tooling, http://www.atirapid.com/tech/te_rapidtool.html*
5. *A. Rosochowski, A. Matuszak, Rapid tooling: the state of the art, Journal of Materials Processing Technology 106,2000, pp. 191-198.*
6. *N. P. Karapatis, J.-P.S. van Griethuysen, R. Glardon, Direct Rapid Tooling, Rapid Prototyping Journal, Volume 4, Number 2, 1998, pp. 77-89.*
7. *W. Palm, Rapid Tooling Primer, 1998,http://www.me.psu.edu/lamancusa/rapidpro/primer/chapter3.httn.*
8. *E. Radstok, Rapid Tooling, Rapid Prototyping Journal, Volume 5, Number 4, 1999, pp. 164-168.*
9. *www.dlp.com [Accessed 25th January 2005] – Homepage of Texas Instruments Ltd, USA.*
10. *www.envisiontec.de [Accessed 6th February 2005] – Homepage of Envisiontec Ltd., Germany.*
11. *Hackney PM, Pancholi KP, Analysis of the Envisiontec Perfactory System for Rapid Production of Components and Validation Using Finite Element and Photo-elastic Analysis, Fifth National Conference on Rapid Design, Prototyping and Manufacture, 2004.*
12. *Gibson I, Shi D, Material Properties And Fabrication Parameters In Selective Laser Sintering Process, Rapid Prototyping Journal, Vol. 3, No. 4, 1997, pp. 129–136.*
13. *Agarwala et al, Structural Quality of Parts Processed by Fused Deposition, Rapid Prototyping Journal, Vol. 2, No. 4, 1996*

ANALYSIS OF THE APPLICATION OF THE "DIGITAL LIGHT PROCESSING" RAPID PROTOTYPING PROCESS FOR FUNCTIONAL RAPID MANUFACTURED COMPONENTS.

P M Hackney, Northumbria University,
School of Computing, Engineering & Information Sciences

ABSTRACT

Rapid Prototyping is widely known as being able to fabricate 3D objects with complex geometries directly from accurate digital CAD data. Rapid prototyping can shorten the product development cycle and improve the design process by providing rapid and effective feedback to the designer. This paper presents the findings of an investigation into the accuracy, build strength and detail of the EnvisionTec PerFactory^{TM} Digital Light Processing (DLP^{TM}) based system, applied to rapid manufactured parts. The multi-directional material properties of Rapid prototyping resins are used predict the functional design parameters applied to rapid manufactured components using Finite Element analysis methods.
The results will allow designers and manufacturing engineers to access the validity of the components and the range of applications for this new evolutionary system.

Key Words: Rapid Prototyping, Digital Light Processing, Accuracy, Rapid Manufacturing

1.0 INTRODUCTION

Rapid prototyping (RP) is widely regarded as being able to manufacture one off or a small number of components in materials properties other than the intended end-use properties.

The move from rapid prototyping to rapid manufacture can be attributed to many factors. The major influences are:

- The development of these systems in recent years has been to improve accuracy and repeatability of components produced by understanding the interaction of the manufacturing processes.
- The advantage of new materials, for example materials with reduced shrinkage and improved inter-molecular and inter-layer bonding, has increased the range of applications and the more accurate parts can be utilised for aerospace, automotive, medical and consumer products.
- The reduction in initial investment requirements, particularly in the low cost office based "3 D Printers" has improved the economics of application of RP parts as direct manufacture of components.
- The need for lean and rapid product development to remain competitive and meet ever more demanding customer requirements.

To be able to use these new rapid prototyping processes as rapid manufacturing processes, then we must first understand the capabilities and limitations of each and every process and materials used.

This research paper looks at the capability of the Stereolithography variant that is the EnvisionTech Perfactory™ Digital Light Processing System.

In the past, studies such as the "Implementation of Product Design by the Introduction of Rapid Manufacturing, EPSRC GR/R13517/01 [1], the Stereolithography SLA and Selective Laser Sintering SLS processes.

This paper complements this study by adding to the knowledge base of materials data for the DLP process and will allow designers to design for this new low cost process.

In the first instance, the materials properties of the Acrylate resin used in the DLP process are investigates, and secondly, using this materials data allowed designers to assess their designs using Finite Element Analysis techniques[2], and finally, will validate the analysis with case studies.

2.0 THE ENVISIONTEC DLP PROCESS

The PerFactory® technique utilises the technology called Digital Light Processing (DLP™) developed by Texas Instruments [1]. The process uses a high-powered, precision light projector working on the DLP™ technology, to polymerise a photosensitive resin layer-by-layer [2]. This polymerization is similar to that the sterolithography SLA process, however the laser positioning galvanic mirrors used in SLA are replaced by a DLP™ projector [3] with a mercury lamp. The galvanic mirrors in SLA trace the exact contours of the cross section [4] and area fill, however the PerFactory® system builds each mask in discrete Voxels, approximating the boundaries. The method by which the Perfactory® and SLA techniques build a layer is shown in Figure 1.

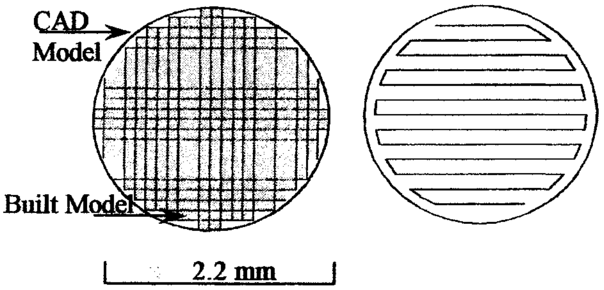


Figure 1 : Comparison of a layer built by the PerFactory® and SLA processes

1.1 Advantages of the PerFactory® Process

- Build time per layer is constant throughout the process, unlike techniques like SLS and FDM where layer-scanning time depends on the area of the layer [4,5]
- Economic material usage and low capital costs [2]
- Very few moving parts and consumable components

- Very little post processing is required, as nearly 100% curing is achieved during build
- The machine footprint is only 736.6 mm (l) x 482.6 mm (w) x 1244.6 mm (h) and can be used in an office environment, with no need for air conditioning.

1.2 Limitations of this technique

- Build size is limited to a volume of 190mm x 152mm x 230mm (height)
- The technique is new to the market
- Supports are required, resulting in need for manual post processing
- Raster XY image – layer image formed by rectangular light pixels
- Short life of projector bulbs – approximately 700 hours. Cost - £300 per bulb

1.3 Test sample preparation

The test samples were manufactured in the three major axis, figure 3 shows a x-z axis build and figure 4 shows the build slice procedure.

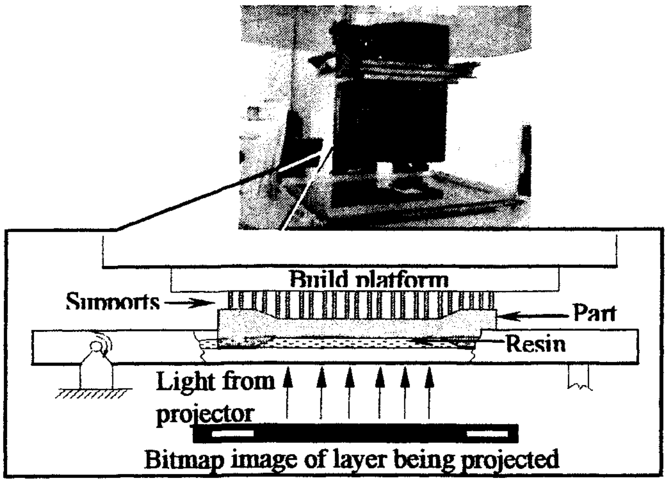


Figure 3 : The PerFactory machine

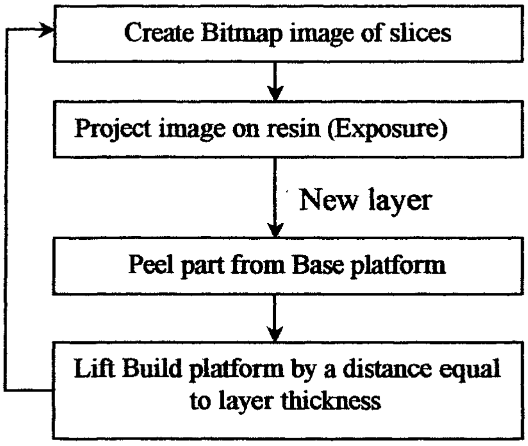


Figure 4 – The part building process

The part can be built in any of the six orientations x, y and z, as shown in Figure 4a and 4b.

The orientation is chosen considering the following factors:

- Geometry of the part
- Surface finish requirements
- Areas to be supported (Faces in contact with the support end up with a rougher finish)

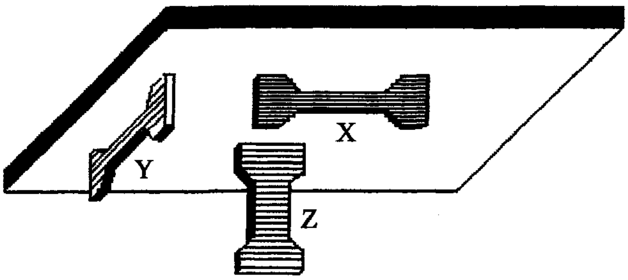


Figure 4a : Different build orientations

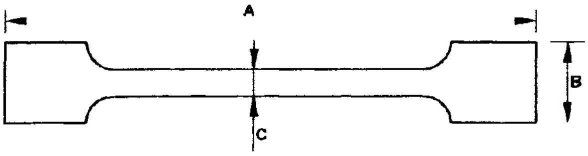


Figure 4b: The test specimen

3.0 Build Parameters

The build parameters set have been derived from previous part optimisation [4,5] studies undertaken, Table 1 shows the major parameters utilised for the specimen builds.

Material	**Acrylate R5 Resin**	**Units**
Separation Distance	**3000**	**µm**
Positioning Velocity	**1000**	**msec**
Separation Velocity	**1000**	**msec**
Exposure Time	**9000**	**msec**
Work area	**152 * 120**	**mm**
Layer thickness	**50**	**µm**

Table 1 : Build parameters

The samples where manufactured in the **x** – y, **x** – z, **y** – z, **y** - x, **z** – x and **z** – y where the bold axis indicates the major axis of length for the sample.

4.0 THE MATERIALS TESTING AND RESULTS

4.1 Testing Procedure

Tensile strength tests on the specimens were conducted on the Monsanto Tensometer, the results for each axis over a sample of 12 parts averaged are shown in Table 2.

Direction	Young's modulus *10^9 N/m^2	Poisson's Ratio	Shear Modulus *10^9 N/m^2
X - Y	2.00	0.35	0.65
Y - X	2.20	0.38	0.67
X - Z	2.70	0.39	0.68
Z – X	2.35	0.39	0.68
Y – Z	2.40	0.37	0.67
Z - Y	2.54	0.38	0.69

Table 2 : Results of tensile test in 6 planes

A matrix was then produced to apply the corresponding Young's modulus, Poisson's ration and Shear modulus to each of the test components under investigation; this proposed that the component was analysis as if it was in each of the six orientations. Therefore each finite element analysis was repeated six times to evaluate the best orientation for the production component.

5.0 THE FINITE ELEMENT ANALYSIS (FEA)

5.1 Background to Finite Element Analysis

Design analysis is a software tool for simulating physical behaviour on a computer. Will it break? Will it deform? Will it get too hot? These are the types of questions for which design analysis provides accurate answers. Instead of building a prototype and developing elaborate testing regimens to analyze the physical behaviour of a product, engineers can elicit this information quickly and accurately on the computer. The application of design analysis can minimise or even eliminate the need for physical prototyping and testing; the technology has gone main stream in the manufacturing world over the past decade as a valuable product development tool and has become present in almost all fields of engineering. Design Analysis employs the finite element analysis (FEA) method to simulate physical behaviour of a product design.

The FEA process consists of subdividing all systems into individual components or "elements" whose behaviour is easily understood and then reconstructing the original system from these components. This is a natural way of performing analysis in engineering and even in other analytical fields, such as economics. For example, a control arm on a car suspension is one continuous shape. An analysis application will test the control arm by dividing the geometry into elements, analysing them, then simulating what happens between the elements.

The application displays the results as colour-coded 3D images, red usually denoting an area of failure, and blue denoting areas that maintain their integrity under the load applied.
Engineers use design analysis for just about every type of product development and research effort imaginable. Analysing machine designs, injection moulded plastics, cooling systems, products that emit electromagnetic fields, and systems that are influenced by fluid dynamics are just some examples of how companies leverage design analysis.

The design analysis procedure can be broken down into a series of steps

- Decide upon the analysis type i.e. static analysis
- Generation of 3D CAD model of component
- Reduction of component to reduce complexity by looking for symmetry, removal of detail i.e. text etc
- Assigning material properties this case in x, y and z axis directions
- Applying restraints that hold the component
- Applying forces or deflections to reflect real world loading
- Creating a mesh of elements
- Running the analysis
- Refining the mesh in key critical areas
- Re-running the analysis
- Verification of analysis results by hand calculations or physical testing

5.2 Application of FEA to Non-Isotropic Structures

The following Non-Isotropic components were considered. The restraints and loading for part 1 shock strut, figure 5a, 5b as both tensile and compressive load, part 2 as a tensional load held at the larger bore and loaded through the pin hole.

Other parts analysed included a garage door opening bracket and a tensile test piece these will not be shown here.

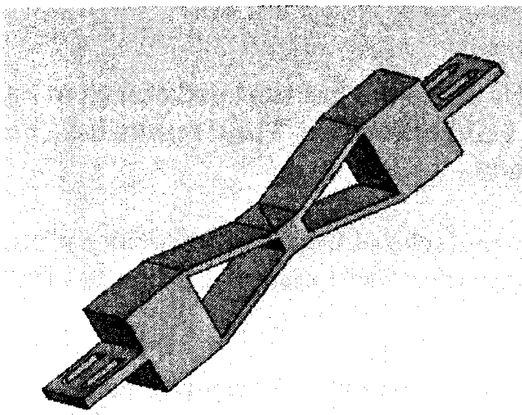


Figure 5a : Part 1 Shock Strut

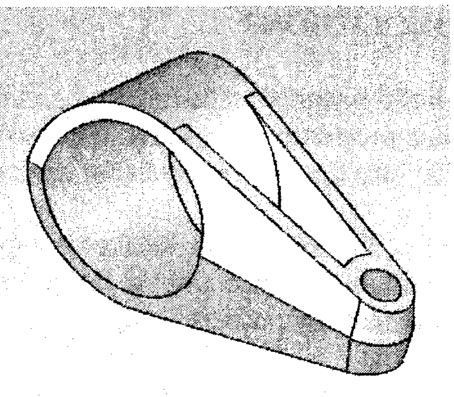


Figure 5b: Part 2 Rocker Arm

The loadings of 15,000 N where applied the analysis load values shown in Table 3 reflect the test carried out on the shock strut, Part 1, these where then repeated for the subsequent parts.

6.0 CASE STUDIES

The FEA analysis can be seen for Part 1 and 2 in figures 6a, 6b The tabulated analysis results are shown in table 3 shows the verification of the analysis.

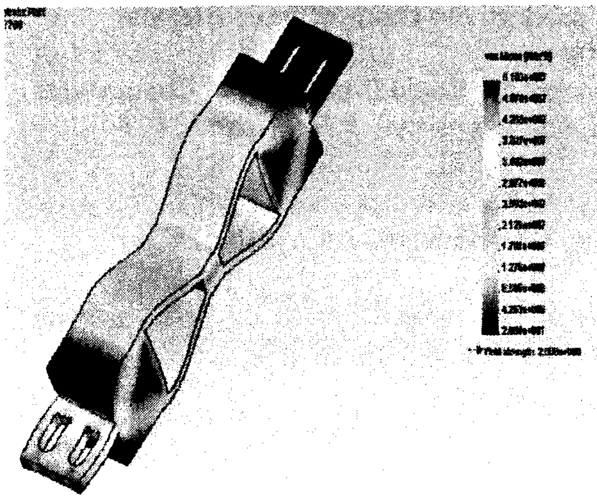


Figure 6a: FEA analysis Part 1 in compression

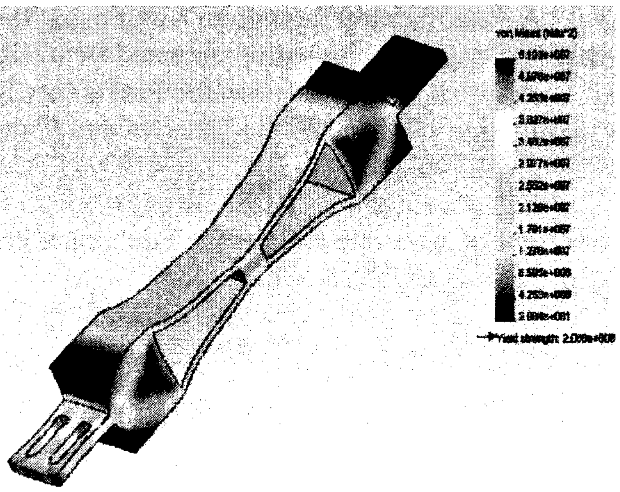


Figure 6b : FEA analysis Part 1 in tension

Test/ Major Plane	1 X – Y	2 Z – Y	3 Y - Z	4 Y - X	5 X - Z	6 Z - X
Max stress (* 10^6 N/m^2)	32.00	33.71	32.69	32.57	32.03	33.00
Displacement (mm)	5.15	4.148	4.515	4.509	5.158	4.148
Factor of Safety (F.O.S)	6.5	6.135	6.326	6.349	6.456	6.268

Table 3: Results for Part 1 in six possible orientations

7.0 CONCLUSIONS

Extensive build orientation testing of the materials properties has been undertaken to establish key materials properties for each of the possible build orientation. These results have been incorporated into the FEA analysis for several parts.

This paper has shown how physical prototypes manufactured from the PerFactory process can be analysed taking into account the different unique directional materials properties that many RP process inherently possess.

The example part chosen showed the best orientation for build for strength to be orientation 1 i.e. in the x – y plane however for strain the best orientation was found to be in the either the z - y or z – x plane.

Due to time restraints no physical tensile testing was under taken, this is a recommendation for further work to validate the results found.

REFERENCES

[1] Design Opportunities with Rapid Manufacturing, R Hague, S Mansour & N Saleh. Assembly Automation, Vol 23, No 4, 2003, pp 346 – 356

[2] A manufacturer's guide to maximising the productivity Gains of finite Element Analysis, Cosmos white paper, accessed 01/02/2006

[3] Analysis of the EnvisionTec PerFactory System for Rapid Production of Components and Validation Utilising Finite Element and Photo-elastic Analysis. P M Hackney, K P Pancholi, CRDM 2004

[4] Investigation into the EnvisionTec PerFactory® Rapid Prototyping Process for Production of Accurate and Strong Functional Parts, P M Hackney, A C Arulraj, G K Chinnaswamy, B T Nair, CRDM 2005

[5] Investigation into Surface Finish of Parts Built by the EnvisionTec PerFactory® Rapid Prototyping Process, P M Hackney, G K Chinnaswamy, A C Arulraj, B T Nair, CRDM2005

APPENDIX B

Regional Computer Aided Engineering Project final report
Centre for Rapid Product Development Overview
Centre for Rapid Product Development Executive Summary

CENTRE FOR RAPID PRODUCT DEVELOPMENT

at the University of Northumbria at Newcastle

Overview

The Centre for Rapid Product Development (CRPD) provides a regional facility offering SMEs services for rapid prototyping of small volume and large size components and products. The specific focus of the Centre is on the application of advanced technologies, such as time compression techniques, methods and processes for design automation, assistance with product, process design and prototype manufacture.

The Centre houses unique facilities which include Laminated Object Manufacturing (LOM) rapid prototyping facility, advanced 3D CAD/CAM systems, computing facilities, 3-D scanning and advanced CNC machining, metal casting and plastic forming capabilities.

The Centre is located within the School of Engineering in the University of Northumbria at Newcastle (UNN).

Aim of the Centre

The aim of the Centre is to support manufacturing SMEs to create and develop new products through the exploitation and development of rapid design, prototyping technologies and related technology and processes often referred to as “Time Compression Techniques”.

Facilities

The Centre will focus upon the area of rapid product design to reduce the cost and lead time for the regions SMEs to produce new and innovative products by providing :

- The ability to create prototypes directly from 3D CAD data using :-
    - Laminated Object Manufacture (LOM) process. Paper, polymer and ceramic sheet based materials.
    - CNC 5 axis machine tools and lathes
- The ability to create one off and low volume dies and moulds for secondary process from the LOM process and other processes.
- The ability to produce one-off and small volume components in a variety of materials.
- The ability to reverse engineer components and incorporate with 3D CAD/CAM data
- Design and manufacturing expertise in areas of : -
  concurrent engineering, design automation, design for manufacture
- Advice, counselling and training to SMEs in any of the above areas.

For Further Details Contact

Prof M Sarwar	**☎(0191) 227 4589**	**Project Leader**	Mohammed.Sarwar@UNN.ac.uk
Phil Hackney	**☎(0191) 227 3644**	**Centre Manager**	Phil.Hackney@UNN.ac.uk

FAX(0191) 227 3854

GOVERNMENT OFFICE
FOR THE NORTH EAST

northumbria
UNIVERSITY

THIS PROJECT
IS BEING PART-
FINANCED BY
THE
EUROPEAN

EXECUTIVE SUMMARY

CENTRE FOR RAPID PRODUCT DEVELOPMENT
PHASE II
September 1999 – December 2001

Professor M Sarwar (Project Leader)
Head of Industrial Research & Consultancy Centre
Faculty of Engineering, Science & Technology
Northumbria University
Ellison Building
Newcastle upon Tyne
NE1 8ST
Tel: 0191 227 4589
Fax: 0191 227 3854
Email: Mohammed.Sarwar@unn.ac.uk

Mr P M Hackney (Centre Manager)
Senior Lecturer
School of Engineering
Northumbria University
Ellison Building
Newcastle upon Tyne
NE1 8ST
Tel: 0191 227 3644
Fax: 0191 227 3854
Email: Phil.Hackney@unn.ac.uk

26th March 2002

CENTRE FOR RAPID PRODUCT DEVELOPMENT

ERDF PROJECT
SEPTEMBER 1999 – DECEMBER 2001

INTRODUCTION

Many companies experience difficulty in creating and introducing new products which is often due to their existing systems, practices and resources failing to support this vital function. Until recently approximately 10% of new products have used the concept of 3D modelling for product definition, and this has been undertaken mainly in large enterprises with high value systems and costing support. This has changed radically in the last three years with the advent of low cost 3D CAD systems coupled with a growing awareness and implementation of time compression techniques such as computer aided analysis, computer integrated manufacture, concurrent engineering, business re-engineering, new manufacturing materials, new processes such as rapid prototyping and soft tooling.

At the end of 1995 the North East region had one commercially available rapid prototyping, tooling and modelling facility, (Arrk-Styles Prototyping at Thornaby) and one University based facility (AMSYS at Sunderland University). These were suitable for the small to medium sized components using the process of steriolithography and selective laser sintering respectively. These two processes have overlapping areas of functionality and application.

In discussion with SMEs and design centres in the region it emerged that there was a requirement for a regional centre offering prototyping facilities for medium to large components, at low cost with appropriate secondary processes for one-off and low volume production.

New ideas and innovations often flounder due to lack of technical support and knowledge. The CRPD provides this focussed technical support in the form of traditional design assistance coupled with leading edge technology not available from elsewhere within the region.

Many centres and commercial enterprises offer design consultancy, but a design with a market at the right time which meets customers'expectations and quality is the key to successful product development. The CRPD acts as a focus for product development and brokers product development expertise for items such as market requirements, forecasting, finance, specialist applications to relevant organisations and companies allowing the company's concept to move to product and profit in the most effective way.

The CRPD use a cross-functional core team with direct support from over 40 academic staff from the School of Engineering, Northumbria University. The expertise lies in the design of economically viable manufacturing products using time compression techniques such as 3D design, analysis, simulation and rapid prototyping.

The Centre for Rapid Product Development (CRPD) is a regional centre for the North East region which provides innovation and manufacturing support from SMEs.

The Centre's primary role is to support and nurture small enterprises, or enterprises in their infancy, in establishing a market share by exploiting innovation and time compression technologies for the benefit of the region.

The Centre was established in 1996, Phase I, with the aid of the European Regional Development Fund, to a total project value of £523,000 (ERDF capital £127,500, Revenue £90,915). In the first phase (1996 – 1998) over 500 visitors from 245 companies within the region have benefited from the Centre's facilities. The Centre has successfully designed and manufactured a range of commercial products such as small car components, breaking systems, safety items and large size castings. These have assisted companies in reducing lead times and improving their competitiveness and hence market share.

Further ERDF and ESF funding was secured for Phase II of the project (Sept 99 – Dec 01). The additional project was valued at £395,589 (ERDF £178,485, NU £154,104, SME income £63,000). This has allowed the purchase of a new rapid prototyping machine, laser based reverse engineering machine, 3-axis coordinate measuring machine. This has further enhanced the facilities for assisting small and medium sized enterprises (SMEs) and exposing students to cutting edge technologies.

The Centre has been successful in collaborating with the Universities of Durham, Teesside and the CADCAM Centre, in an ESF funded interdisciplinary project (Aug 99 – Dec 00) which combines the expertise of these institutions to directly assist SMEs in computer aided engineering. The total ESF grant was, with the CRPD receiving £43,000 in cash to cover staffing costs. This service has informed, trained and assisted SMEs in the use and application of a range of advanced computer aided engineering tools and techniques.

The CRPD has acted as a catalyst within the region to:

- Develop awareness of the advantages and limitations of the RP processes and facilities within the region
- Assisted in the collaboration of the separate RP Centres within the region to provide a united front
- Developed products and technology for SMEs allowing them to expand and employ more personnel (Probe Industries expanded by 50%, MKT Containers from 10 to 450 employees)
- Completed over 36 technology transfer events to SMEs and more are scheduled

BENEFITS TO THE SCHOOL OF ENGINEERING

- Capital equipment acquisition
- Use of above for SoE undergraduate and postgraduate activities (PDT, MDT, CAE)
- New technology for SoE which is recognised by the Professional Bodies (IMechE, IEE) as a major contribution to developing our courses and course material
- Contributors to the Regional Innovation Strategy through the development of the CRPD activities
- Forming links with SMEs for undergraduate training
- Recruitment of students to all courses
- QAA visits
- Staff development in new technologies
- Raising profile of the School regionally, nationally and internationally
- Contribution to SoE research profile

This copy of final report from Teesside

from

JM

Project Part-Financed by the European Union
European Regional Development Fund

RCAE
Regional Computer Aided Engineering

Final report for project [illegible]
(Regional Computer Aided Engineering)

Prepared by
The RCAE Project Team
ref : rcae_report_interim

For further information contact:
Stephen Russell, Project Manager
01642 384089 or email: s.russell@tees.ac.uk

Contents

Executive summary

The project concluded on the 31st of December 2005 slightly exceeding, at 58, the required outputs of 55 Small and Medium sized Enterprises receiving assistance. The effective outcomes, despite just 30% of evidenced implementation available at this time, have produced primary results exceeding target by between three and thirteen times. The single exception being new jobs created, which shows an actual of 30 against a target of 64.

Private match funding has exceeded target by an average of 40% and private sector cash has met it target.

Project overview

The Regional Computer Aided Engineering (RCAE) project formally commenced on the 26th of June 2003. The core project team was in place by 5th January 2004.

At commencement there were four partner organisations, working in collaboration to deliver the project.

- The CADCAM Centre
- Durham University
- Northumbria University
- The University of Teesside

The University of Teesside being the designated lead partner.

During the initial six months the main focus was on staffing the core team (Project Manager, Developers and Administration), with modest activity on SME assistance. The exception to this being Durham University, who had an existing infrastructure which was complementary to the project.

With the core team in place, the following three months where employed developing the following elements.

- Familiarisation of project requirements
- Strategy for project execution
- Generation of administration system to ensure compliance with evidence requirements
- Marketing material
- Team skills

This period did not evidence SME assistance activity to any great extent, but it was deemed necessary to develop the above elements to ensure that the project would be successful.

Unfortunately, as the project was exiting this phase it experienced a minor setback.

In March 2004 the CADCAM Centre announced redundancies within its staff, which resulted in the loss of the RCAE developer and a replacement developer was assigned. Further to this, in April 2004, the CADCAM Centre announced its closure. At this point it was agreed that the University of Teesside would employ the replacement developer and absorb the targets of the CADCAM Centre.

Summarised outputs and results

The following table demonstrates the final results against the set targets.

Ref	Project Outputs and Results	Target	Actual
	Outputs		
01.2	10 to 24 days assistance	15	17
01.3	25+ days assistance	40	41
	Planned Results		
R1	Gross New Turnover (£1000's)	3000	11773
R2	Gross Safeguard Turnover (£1000's)	2200	7219
R3	Gross New Jobs created	64	30
R4	Gross New Safeguarded Jobs	34	187
R5	SME Investment (£1000's)	50	655
RR1	Implementation of Outcome	46	14
RR2	Improvement of environmental performance	46	8
RR3	Enhanced application of ICT	46	15
RR4	Introduction of new / improved products	20	14
RR5	Implementation of process improvements	20	14
	[illegible]		
	Private Sector Cash	33.0	32.8
	Specialist consultancy	95.5	117.0
	Student placement in kind time	81.9	131.0

The project team

The following list, details the team deployed to deliver the project.

Steering Group Executives

Prof Munir Ahmad	University of Teesside	m.m.ahmad@tees.ac.uk
Dr Ahmed Abbas	University of Teesside	s.a.abbas@tees.ac.uk
Prof Ernie Appleton	Durham University	ernest.appleton@durham.ac.uk
Prof Mohammed Sarwar	Northumbria University	mohammed.sarwar@unn.ac.uk

Regional Office

Ms Lindsey Ayre	Durham University
Ms Theresa Kirby	Northumbria University
Mr David Pratt	University of Teesside
Mr Andrew Rowlands (Finance)	University of Teesside

Administration

Ms Jennifer Stephens	University of Teesside
Ms Fiona Ward	Northumbria University
Ms Helene Labarre	Durham University

CAE Development

Mr Nigel Cochrane	University of Teesside
Mr John Garside	Durham University
Mr Phil Hackney	Northumbria University
Dr Peter Mathews	Durham University
Mr Darryl Okey	University of Teesside
Dr Tim Short	Durham University
Mr Jason Van Bedaf	Northumbria University
Dr Qing Wang	Durham University

Project Director

Mr Stephen Russell	University of Teesside	s.russell@tees.ac.uk

The above list shows those active in the project at its conclusion, recognition is given to the following, who have also contributed.

The late Mr Tony Reid, who was instrumental in the project conception and was the Steering Group Executive representative for the CADCAM Centre.

Following the closure of the CADCAM Centre, Tony continued to support the project through part-time consultancy work, where he demonstrated his unrelenting passion to contribute to the development of the region through his work.

As well as a respected colleague, Tony was also a personal friend of several of the RCAE team and will be remembered for his commitment and, above all else, his unique sense of humour.

Mr Mike Murphy, the initial Developer from the CADCAM Centre.

Ms Karen Clegg and Mrs Suzanne Thompson, providing support from the Regional Office at the University of Teesside, from project conception and several of the following months.

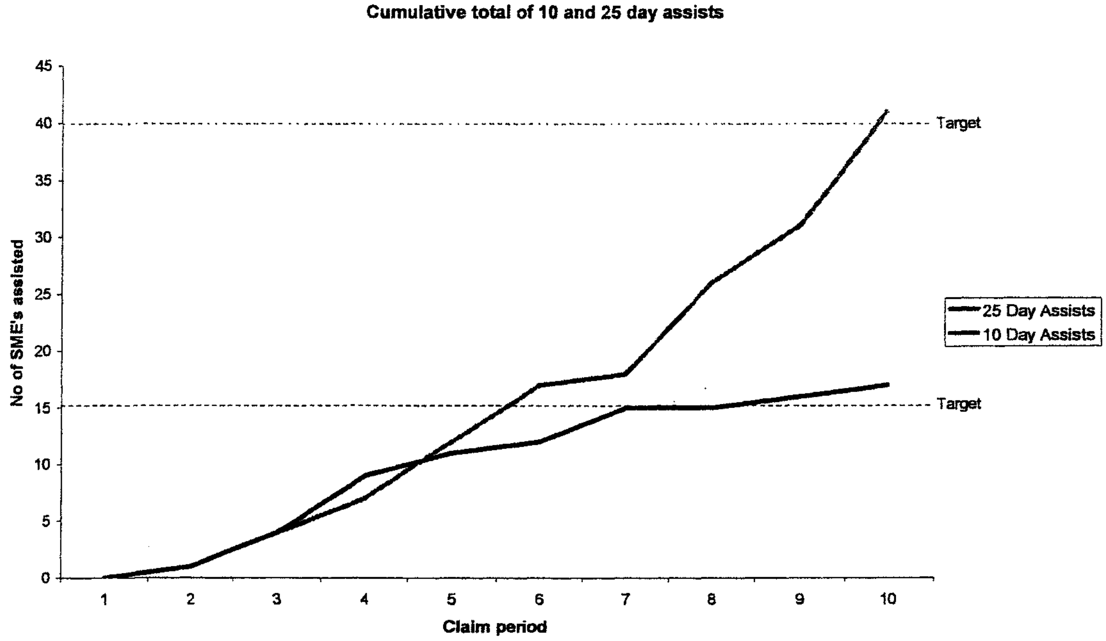
Mr Andy Baxter, the Administrator at the University of Teesside until October 2005.

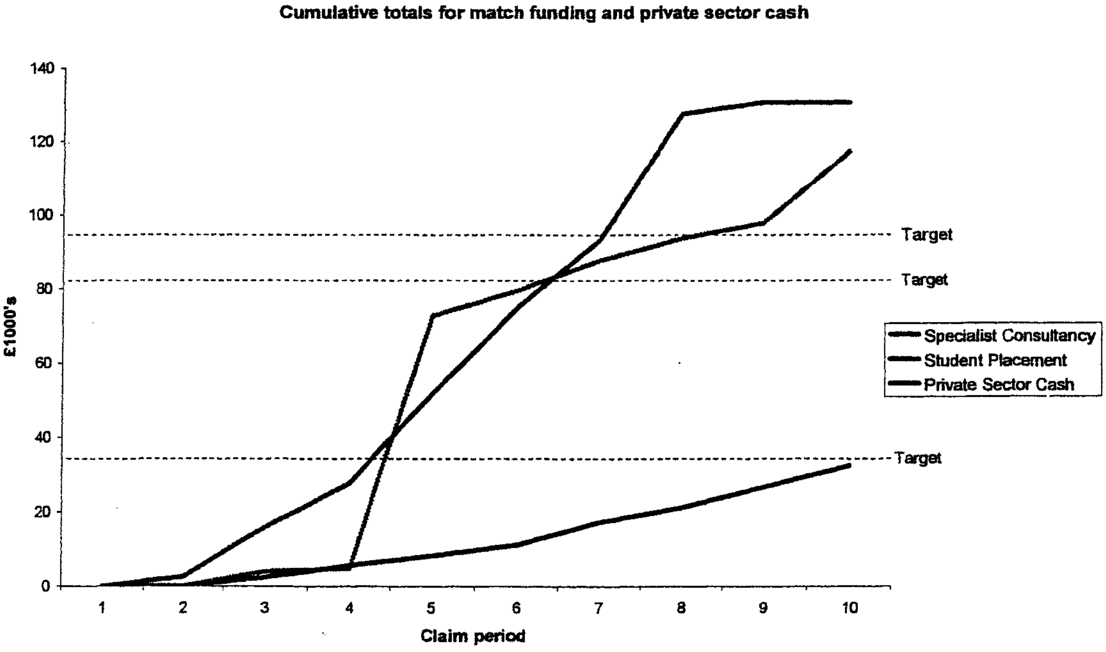
Ms Joanne Wandless and Ms Kelly Hodge, representing Finance at the universities of Durham and Northumbria respectively.

The project team and subgroups meet on an as required basis to resolve or discuss specific issues. Formally, a Steering Group meeting (Steering Group Committee, Administrators, Developers and Project Manager) meet every six weeks and are joined by the Regional Office members every alternative six weeks to hold Quarterly meetings. Formal reports are submitted to Government Office North East each quarter.

Project delivery

The following charts demonstrate the progress of the outputs, private match funding and private sector cash over the period of the project. Four out of the five elements show a steady progression, the exception being the specialist consultancy, which received particular focus during claim period 4 when it was evident that the target would not be achieved at its current pace.





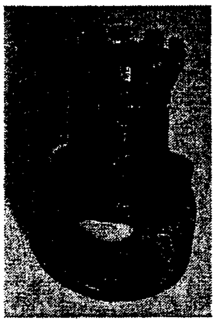
10+ day and 25+ day projects

The assistance provided to SMEs has covered a spectrum of activity ranging from the investigation of CAE technologies for jewellery design and manufacture, the development of an educational board game through to design and process improvements for a number of engineering products. The project has also witnessed the direct investment of CAE technology within SMEs.

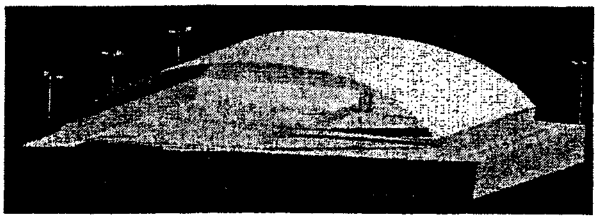
The activity has been support directly by the Developers in some cases, with student assistance and time in-kind from industrial and academic specialists, in others. Thus ensuring that the SME receives the most appropriate mechanism for the realisation of proposed solutions.

Project examples

Kim Thomson Design Specialises in the design and manufacture of contemporary jewellery predominately manufactured from acrylic sheet. Owing to the current manufacturing processes limitations in terms of product range produced have been experienced. The staff at the Centre For Rapid Product development based in the School of Engineering & Technology at Northumbria University (UNN) worked with the company to utilise Computer Aided Engineering (CAE) technologies to overcome this problem.

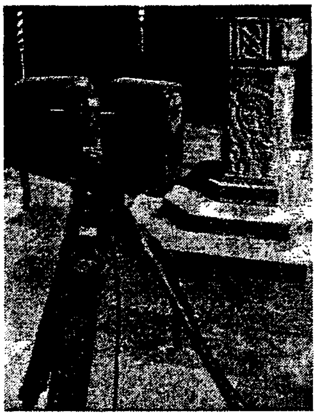


Airadome UK Limited has been working with The University of Teesside, who have been offering assistance in realisation of the product launch of a unique and inflatable tennis dome system.



Within the remit of the University of Teesside, RCAE project, a concept design of a single skin, four court inflatable tennis dome including the addition of specified entry and exit doors, air lock and inflation system, has been produced. This initial design is available for submission to the Lawn Tennis Association to provide an impression of the proposed new product and to aid in funding purposes.

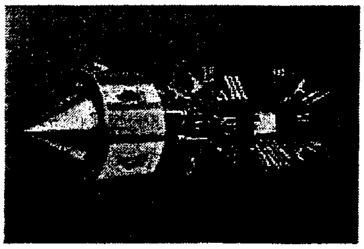
Heritage Design Projects utilise in-house patternmaking and machining expertise along with the casting facilities of a joint partnership, and wanted to evaluate the potential benefits of introducing CAE technology within the process.

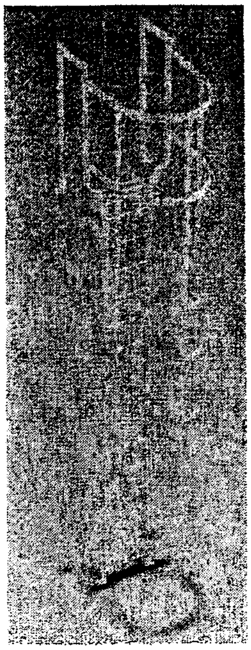


The project activity covered the analysis and benchmarking of 3D optical laser scanning equipment and reverse engineering software. A feasibility study was produced on behalf of the company, considering the suitability of processes for downstream production of mould tools and cast designs. This required data capture to a physical prototype part and consideration to the suitability of this for the downstream production.

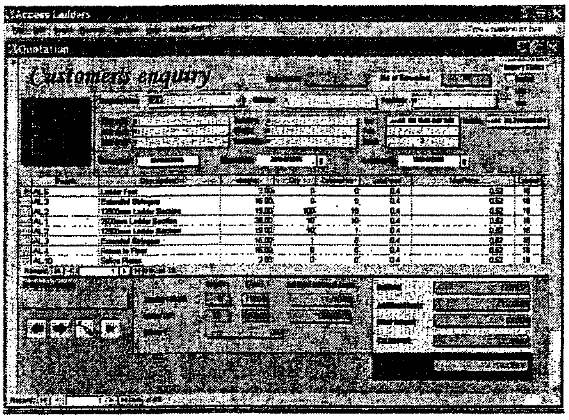
Solutions, a consultancy firm based in Marske near Redcar, approached the University's RCAE project to assist with the design of a new board game. One of the main areas of the project was the development of the game characters. The company was quickly teamed up a university design student, who took Malcolm's concept sketches and turned them into virtual characters using 3D design software. Members of the RCAE team guided the design process ensuring the characters could be efficiently injection moulded and produced two sets of rapid prototype parts.

Durham Pipeline Technology is a supplier of innovative technical solutions for pipeline access, inspection and cleaning based on patented bristle tractor technology. An ambitious R&D programme backed by an extensive network of leading industrial and academic resources, they continue to devote a considerable amount of resources to fundamental research and development in the field of pipeline technology and recently completed a finite element analysis project with RCAE at Durham University.



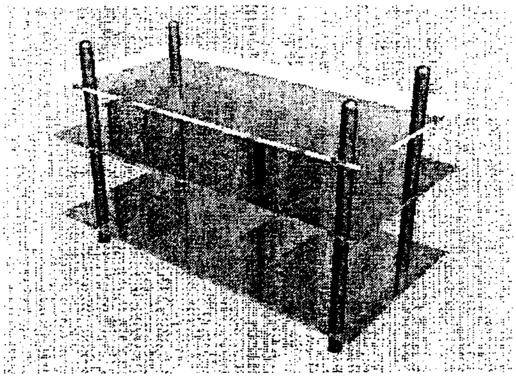


Access Ladders required assistance with the development of a new product range of modular ladders. From the clients two dimensional drawings, images were produced in 3D, which were used for marketing purposes on the company website and to complement a newly generated costing database.

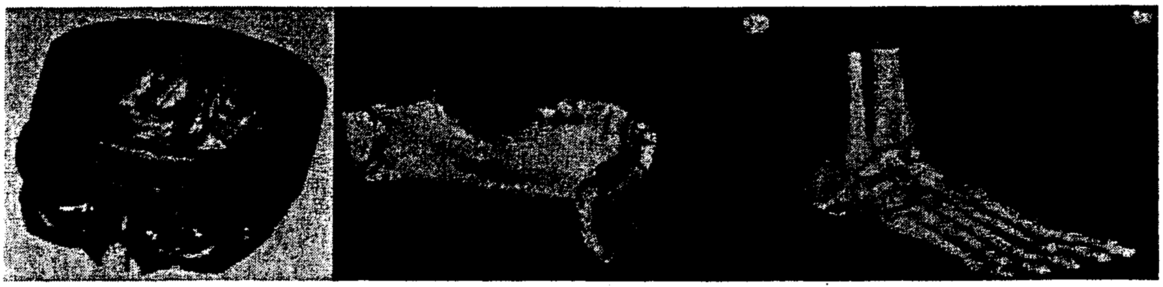


Creative Glass and Mirrors were assisted with the selection and implementation of a 3D CAD system, allowing them to diversify their market by producing a standard range of products.

The selection process was support by a final year MSc student, who worked with the company to understand their requirements and propose a "best fit" solution.

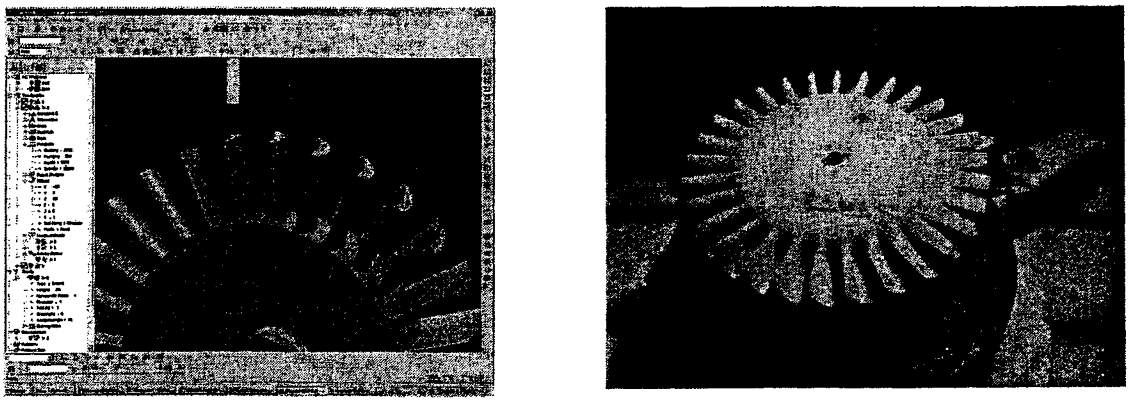


Dartek UK wanted to explore the potential of utilising MRI scan data for the creation of 3D CAD models, allowing the creation of physical and representative bone parts through current rapid prototyping techniques. This will allow them to create parts through traditional sand casting, rather than the costly method of C.N.C. maching for small quantities.



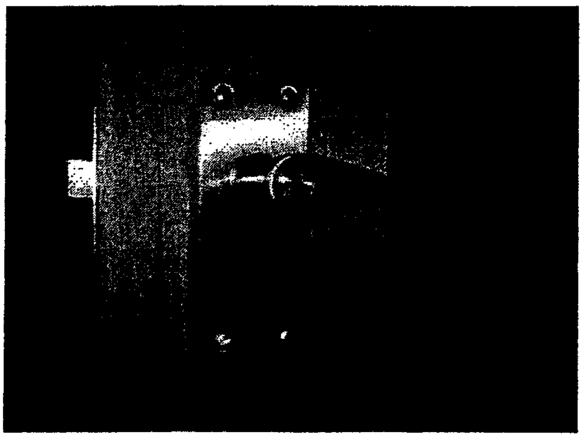
Private sector cash

The private sector cash has been achieved from a variety of sources, some from direct activity with the assisted SMEs and the balance, primarily, from utilisation of the key resources at the partnering universities. The three principle elements being reverse engineering, product/prototype development and production and rapid prototyping.



Machine tool path strategy for a turbine blade manufacture for Durham Pipeline Technology.

Reverse engineering scanning of thermoforming moulds for Easter egg packaging for Thermodynamix.



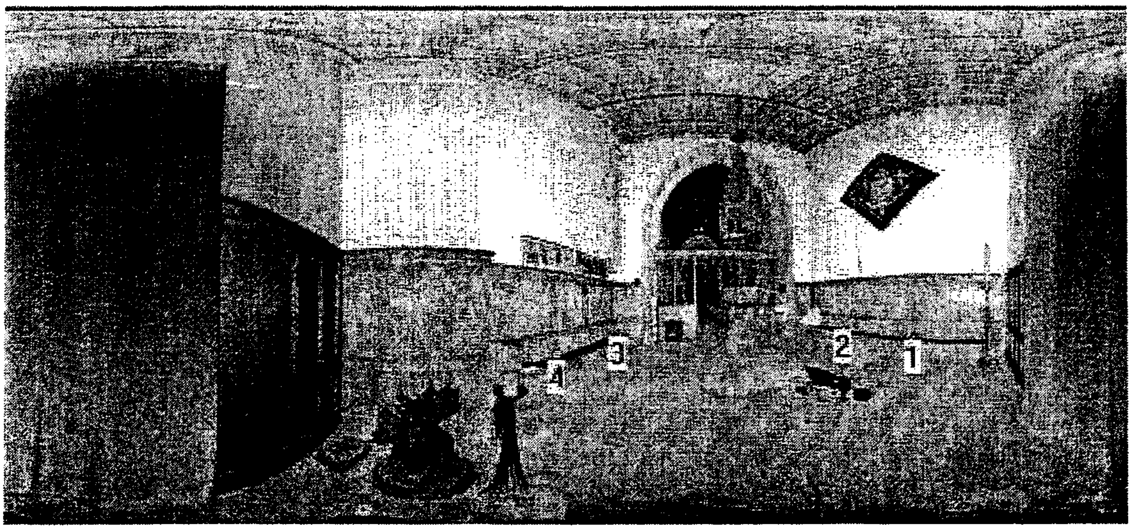
Development and prototype model of alternative privacy locking and release door handle mechanism for Easylock.

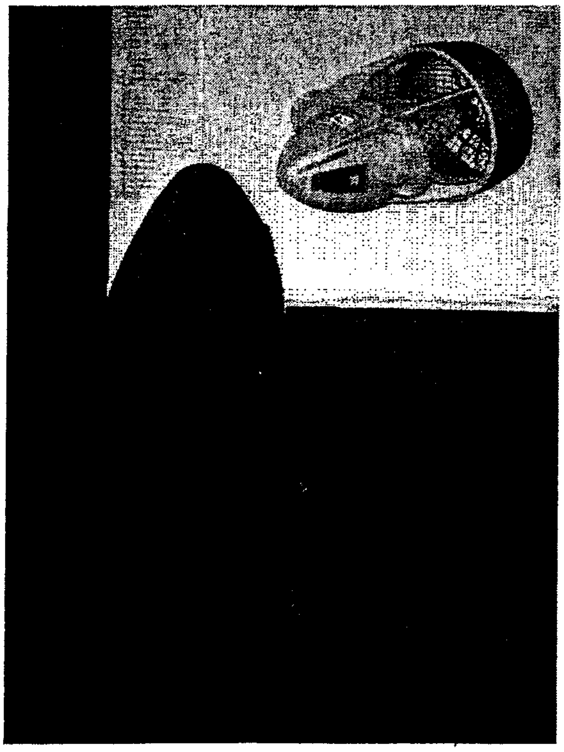
Specialist consultancy

This element of match funding has been attained from a variety of sources ranging from technical presentations at SME and partner locations to specific technological development and understanding through joint projects with non assisted organisations.

Examples include:

The development of laser scanning technology skills and knowledge through the provision of equipment and access to sites to perform the activity.





CAD software demonstration with a number of invited SME representative attendees.

The event demonstrating the benefits an organisation can gain by investing in 3D CAD.

Student in-kind time

This element of the project has been one of the most rewarding, with students gaining "real life" exposure to industrial problems and the organisations benefiting from proposed solutions. This activity, backed-up by industrial and academic expertise and equipment resource, has ensured that effective conclusions has been proposed.

The assistance projects, again, cover a wide variety with projects ranging from product improvement, through effective analysis, to CAD/CAM selection benchmarking, to the development of interface software improving the development process.

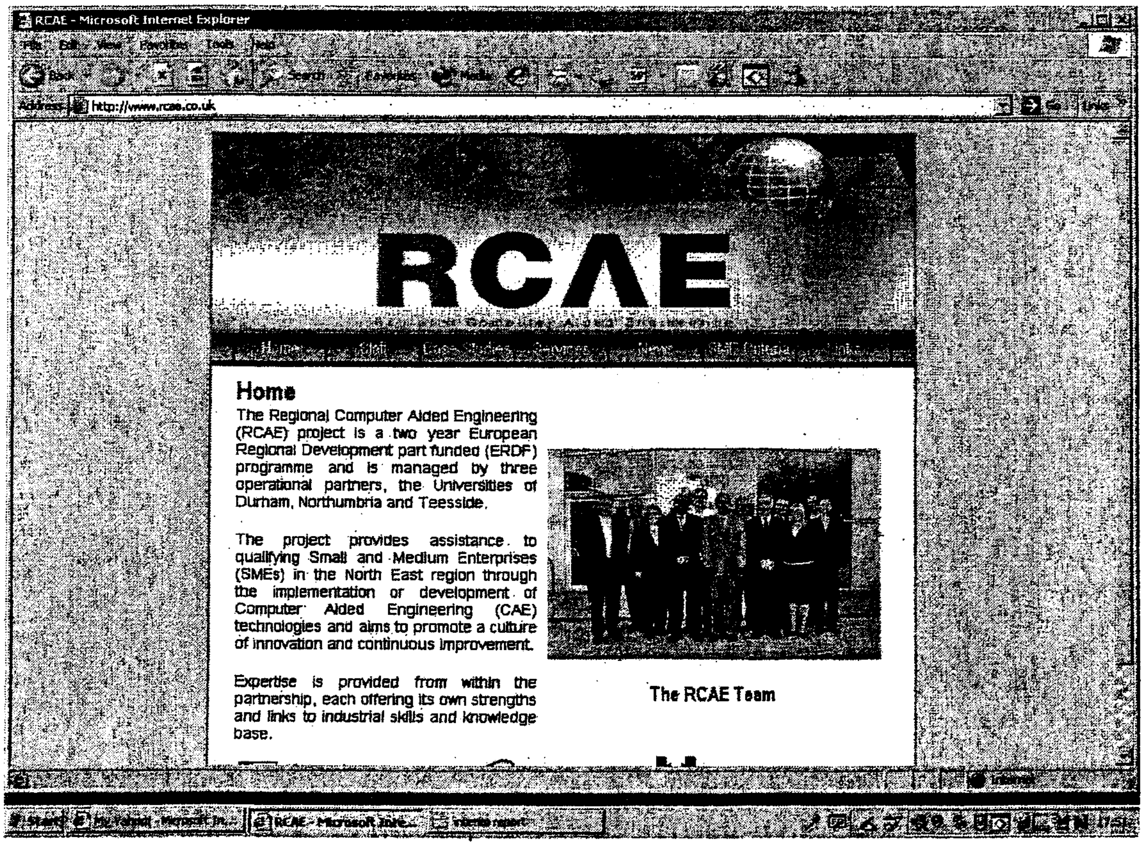
Student in-kind time has not only contributed to the assistance of SMEs but has provided valuable assistance in the progression of staff development through the involvement of specialist input from non SMEs.

Marketing

The marketing of the project has been achieved via a number of avenues.

- Attendance at networking and industry related events
- Direct mail shot and telemarketing
- Personal contacts
- Word of mouth
- Development of links with regional development organisations
- Running of events with industrial partners

In addition, a website, promotional material and newsletter have been produced.



Home

The Regional Computer Aided Engineering (RCAE) project is a two year European Regional Development part funded (ERDF) programme and is managed by three operational partners, the Universities of Durham, Northumbria and Teesside.

The project provides assistance to qualifying Small and Medium Enterprises (SMEs) in the North East region through the implementation or development of Computer Aided Engineering (CAE) technologies and aims to promote a culture of innovation and continuous improvement.

Expertise is provided from within the partnership, each offering its own strengths and links to industrial skills and knowledge base.

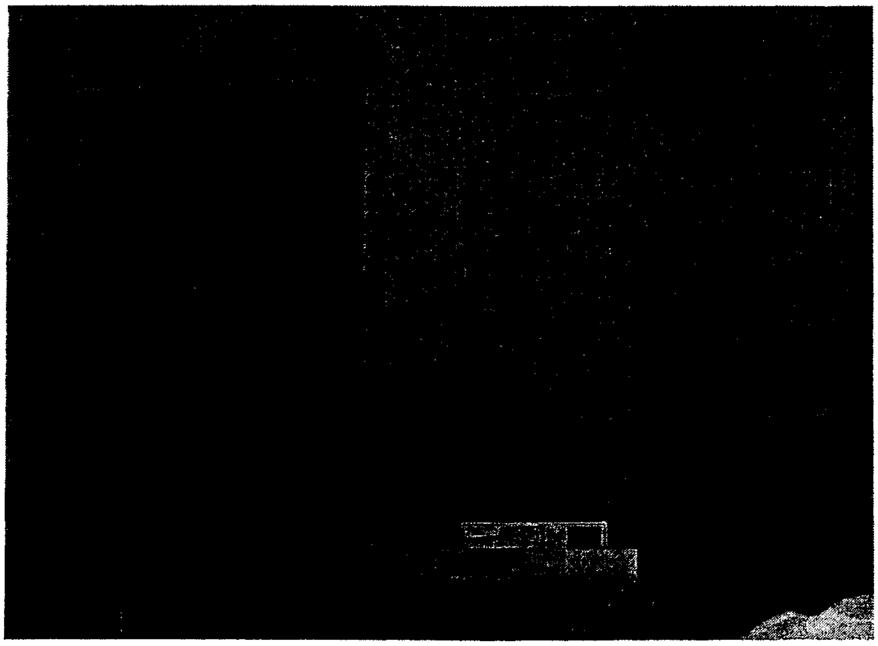
The RCAE Team

RCAE web home page

The project has been promoted at Flexible Automation and Intelligent Manufacturing (FAIM) conference 2005, held in Bilbao, Spain, July 18th – 20th, where three papers were presented:

- Reverse Engineering – Speeds up manufacture of thermoforming tools
- Implementing time compression technologies to assist SMEs for product development
- Integrated Forms and Sculptured Surfaces: Reverse Engineering for Manufacture of Sculptural Organic Forms

The conference was attended by approximately 120 delegates from 22 countries and the ethos of the conference was on modern engineering with a focus on subjects such as intelligent manufacturing and simulation modelling. The conference was well attended and the participants took a keen interest on the papers presented by the RCAE project team members.



Project presentation at FAIM 2005

Summary

The project has been successful in its delivery and attainment of outputs, despite the initial late start and the closure of the CADCAM Centre. In addition, it is beginning to demonstrate an achievement of the required results, which will naturally develop in the months following the implementation of the individual projects.

Upon reflection, the project has achieved the majority of its key objectives but has struggled to deliver the quantity of intended peripheral activities, such as specific events. This appears to have resulted from a saturation of similar events being promoted within the region.

The project has provided benefit to most stakeholders.

- The Developers have gained new skills, which have not been limited to technological elements, but have included sales and marketing and project management.
- The students have had exposure to "real-life" engineering problems.
- The universities have developed a greater understanding of each others technical strengths and will continue to work together on future individual projects.
- SMEs have received a variety of forms of assistance and most will continue to support future student and commercial activity.
- Relationships have been established with industrial and development partners.

Summary of SMEs assisted

Partner	Client Details	Brief Description	Start /End	Assistance	
				01.2	01.3
UoD	**Slaters Electrical** Scotswood Bridge Works Toll Bridge Road Blaydon Tyne & Wear NE21 5TE	Service company looking to develop their first product (student assistance).	12/03 12/03		X
UoD	**Cummings Engine Comp** Yarm Road Darlington County Durham DL1 4PW	Development of a single jig (transportation pallet) for the remaining non standard 20% of production handling requirements (student assistance).	12/03 12/03		X
UoD	**Geospatical Research Ltd**	Computer Aided Engineering geology project for a new start-up company	03/04 03/04		X
UoD	**DPT Ltd** North East Innovation Centre Neilson Road Gateshead Tyne & Wear NE10 0EW	Finite Element Analysis project for a nuclear tractor	03/04 03/04		X

Partner	Client Details	Brief Description	Start /End	Assistance	
				01.2	01.3
UoD	**Edwin Trisk Ltd** Pallion Ind Est Pallion Sunderland Tyne & Wear SR4 6SN	Design improvement project for a prototype product	03/04 03/04		X
CADCAM	**Century Composites** 58-59, Hutton CloseCrowther Ind Est Washington Tyne and Wear NE38 0AH	Implementation of CNC system (£800)	03/04 03/04	X	
UoT	**Plastic Mouldings Northern** Unit 4 Longfield Road South Church Enterprise Park Bishop Auckland County Durham DL14 6XB	Evaluation of 5-axis CNC capabilities	03/04 05/04	X	
UoN	**Tech Projects Ltd** I68, Queensway Team Valley Trading Estate Gateshead Tyne and Wear NE11 0NX	Evaluation of reverse engineering and CNC machining to expand the potential range of services offered	03/04 05/04		X

Partner	Client Details	Brief Description	Start /End	Assistance	
				01.2	01.3
UoD	**Blagdon Pump Ltd** Lambert Road Armstrong Ind Est Washington Tyne & Wear NE37 1QP	Design for Assembly improvements	04/04 05/04	x	
UoD	**Victor Products Ltd** New York Way New York Ind Est Newcastle upon Tyne Tyne & Wear NE27 0QF	Design for Assembly improvements	04/04 05/04	x	
UoD	**Mechatronics Ltd** South Church Enterprise Park Bishop Auckland County Durham DL14 6XF	Component standardisation for cost reduction on a range of 3 products. ROHS, WEEE & Component standisation	04/04 05/04		x
UoD	**PSI (Global) Ltd** South Ind Estate Bowburn County Durham DH6 5AD	Design for assembly improvements	04/04 05/04	x	

Partner	Client Details	Brief Description	Start /End	Assistance	
				01.2	01.3
UoD	**SEV Group Ltd** 16 Marquis Way Team Valley Ind Est Gateshead Tyne & Wear NE11	Design of component part and standardisation of new product	04/04 05/04		x
UoD	**Stephenson Gobin Ltd** South Road High Etherley Bishop Auckland County Durham DL14 0HY	Competitive design evaluation of fail-safe component	04/04 05/04	x	
UoD	**Armitage Eng Ltd** 23-24 Hertburn Estate Hertburn Washington Tyne & Wear NE37 2SF	Design for assembly evaluation	04/04 05/04	x	
UoD	**Hydram Engineering Ltd** Avenue 2 Chilton Industrial Estate Chilton County Durham DL17 0SG	New product introduction	07/04 09/04		x

Partner	Client Details	Brief Description	Start /End	Assistance	
				01.2	01.3
UoN	**Thermodynamix** Sandgate House 102 Quayside Newcastle upon Tyne Tyne & Wear NE1 3DX	An investigative project looking at making improvements to the current cooling methods in a thermoforming tool by utilising Computational Fluid Dynamics.	07/04 09/04		x
UoN	**Kim Thomson Design** 17 Blakelaw Road Alnwick NE66 1AZ	Investigation of the use of R.P for the production of masters parts to use in the production of moulds for casting	07/04 09/04	x	
UoT	**Creative Glass Ltd** Design House 20 –22 Lustrum Avenue Portrack Lane Stockton TS18 2RB	Evaluation and selection of CAD system	07/04 09/04		x
UoT	**Pikaport** Unit 6 Leeholme Road Industrial Estate Billingham TS23 3TA	Design and costing for product housing	07/04 09/04		x

Partner	Client Details	Brief Description	Start /End	Assistance	
				01.2	01.3
UoT	**Interpat Limited** 9 Cumbie Way Aycliffe Industrial Park Newton Aycliffe County Durham DL5 6YA	Evaluation and selection of CAM system	07/04 09/04		x
UoT	**F Hann & Co** 7 Dovecote Close Marske Cleveland TS11 6BL	Design of rotating reflector	08/04 09/04	x	
UoD	**North East Innovation Centre Co Ltd** Neilson Road Gateshead Tyne & Wear NE10 0EW	Consider the potential applications of a product developed by Microbac	11/04 12/04		x
UoD	**TNEI Services Ltd** 2nd Floor Kelburn House 7-19 Mosely Street Newcastle upon Tyne NE1 1YE	Investigation of mounting Vertical Axis Wind Turbines (VAWTs) on the top of lamp posts as a commercial venture	11/04 12/04		x
UoD	**PC Henderson Ltd** PC Henderson Limited Durham Road Bowburn Durham DH6 5NG	"Creativity" & included teaching & practical work on the use of the 6-3-5 and "pack of cards" methods	10/04 12/04		x

Partner	Client Details	Brief Description	Start /End	Assistance	
				01.2	01.3
UoN	**Stephanie Summerhill Contemporary Jewellery** 4 Knutsford Walk Cramlington, Northumberland NE23 2XF	An evaluation of the uses of CAE technologies in the design and manufacture of contemporary jewellery	10/04 12/04		x
UoT	**Solutions** 17 Cleveland View Skelton Green Saltburn-by-sea TS12 2DL	Assistance with the Design and Development of an educational board game	05/04 10/04		x
UoT	**Icon Informatics** 3 Branklyn Gardens Ingelby Barwick TS17 0NA	Investigation into internet network connectivity for remote NC function.	08/04 11/04		x
UoT	**Power and Design** Anderson Barrowcliffe Waterloo House Teesdale South Thornaby TS17 6SA	Assistance with the design and development of an industrial brickwork-pointing machine	05/04 11/04	x	
UoT	**Airadome UK Ltd** 8 Avill Grove Ingleby Barwick Stockton TS17 0FX	Conceptual design and identification of architectural support for an inflatable tennis court cover	07/04 09/05		x

Partner	Client Details	Brief Description	Start /End	Assistance	
				01.2	01.3
UoT	**Autoserve GB Ltd** Ezone Kingsway Team Valley Gateshead NE11 0EG	Reverse engineering of an emission control device	02/05 03/05	x	
UoT	**K Home Engineering** Ingram House Allensway Thornaby Stockton TS17 9HA	Investigation into a CAD to costing system interface	05/04 03/05		x
UoT	**Thermal Detection Ltd** Unit 6 Orde Wingate Way Primrose Hill Ind Est Stockton-on-Tees TS19 0GA	Investigation into a cost effective solution to enable in-house CNC drilling function	10/04 06/05		x
UoT	**Hart Ind Tooling** White Hart Court Hartlepool TS27 2AW	Development of acoustic canopy, allowing existing product to meet EEC regulations.	11/04 06/05		x
UoD	**Culligan Int. UK Ltd** Daimler Drive Cowpen Lane Ind Est Billingham, Cleveland TS23 4JD	Industrial problem solving activity	04/05 04/05		x

Partner	Client Details	Brief Description	Start /End	Assistance	
				01.2	01.3
UoN	**Ind. Pattern Makers** Unit 1 Tanfield Lea Bus. Park Stanley Co Durham DH9 9QF	Industrial Problem solving – Moving from Reverse Engineering data to a set of Manufacturing drawings	05/05		**x**
UoN	**Honeywell Elm Wood** North Shields Tyne and Wear NE29 8SA	Student Placement – Looking at part verification using a CMM.	05/05		**x**
UoN	**Miller UK Ltd** Bassington Ind Estate Cramlington Northumberland NE23 8BN	Design & RP assistance for new component manufacture	05/05		**x**
UoN	**Victoria Coatings Ltd** Unit 11a Victoria Ind Est Hebburn Tyne and Wear NE31 1UD	Group Student Project – Product Design and Development of a work holding bracket	05/05		**x**
UoN	**Express Conveyors Ltd** 16b Queensway Team Valley Gateshead NE11 ONX	Group Student Project – Design a lead time reduction task using Parametric Design and 3D CAD modelling	05/05		**x**

Partner	Client Details	Brief Description	Start /End	Assistance	
				01.2	01.3
UoT	**Design & Development Technologies** 273 Linthorpe Road Middlesbrough TS1 4AS	Modelling of components for the evaluation of production process	07/05 12/05		x
UoT	**CADConnect Ltd** Bede House St Cuthberts Way Newton Aycliffe Co Durham DL5 6DX	Development of an electronic link between SolidWorks and Sage	07/05 09/05		x
UoT	**Evoflex** Nunthorpe Middlesbrough Cleveland TS7 0ZR	Development of an environmentally friendly mechanism for the utilisation of "cling film" packaging wrapping system.	07/05 09/05		x
UoT	**N-Sign** 5, Cannon Park Rd Middlesbrough TS1 5JP	Development of an innovative fencing securement system.	08/05 09/05	x	
UoN	**Komprex** 58-59 Hutton Close Crowther Ind Estate Washington Tyne & Wear NE38 0AH	Reverse engineering of a propeller for a new product.	06/06 09/05	x	

Partner	Client Details	Brief Description	Start /End	Assistance	
				01.2	01.3
UoN	**Salamander Pumps** Unit 2c Colima Avenue Sunderland Enterprise Park SR5 2TA	Design, rapid prototypes and machining of impellers.	06/06 09/05		x
UoN	**Visitech Ltd** Unit 92 Silverbriar Sunderland Ent Park East Sunderland SR5 2TQ	Design evaluation of current product.	09/05 12/05	x	
UoN	**Hautin Ltd** Unit 8B Royce Avenue Billingham Cleveland TS23 4BX	Rationalisation of product portfolio			x
UoT	**Heritage Design Projects** 9 Cumbie Way Aycliffe Ind Park Newton Aycliffe Co Durham DL5 6YA	Evaluation of laser scanning and reverse engineering for heritage applications.	05/05 12/05		x

Partner	Client Details	Brief Description	Start /End	Assistance	
				01.2	01.3
UoT	**Aircon Refrigeration** Dukesway Teesside Ind Est Stockton TS17 9LT	Reverse engineering of 2D drawings to allow future modifactions.	06/05 12/05		x
UoT	**Dartek UK** 10 Bernaldby Avenue Guisborough TS14 8DB	Evaluation of the converstion of MRI scan date to CAD data for the creation of physical parts through rapid prototyping techniques.	06/05 12/05		x
UoT	**Pnu-Point Ltd** 8 Broadway Avenue Trimdon Co Durham TS29 6PU	Development of a mould tool for new product conception	07/05 12/05	x	
UoT	**Plastic Design Solutions** 80 Church Road Stockton TS18 1TW	Reverse engineering from existing drawings and physical parts for a locomotive chassis	07/05 12/05		x
UoT	**Hotspot Marketing** 20 Carlisle Rd Durham DH1 5XE	Creation of a mould tool to allow the evaluation of heat sensitive material	12/05 12/05	x	
UoT	**Access Ladders** 15 Bowesfield Cresent Bowesfield Ind Est Stockton TS18 3BL	3D modelling of a new product range to allow the creation of marketing material	08/05 12/05		x

Partner	Client Details	Brief Description	Start /End	Assistance 01.2	 01.3
UoT	**Trevic Ltd** Queens Court Business Centre Newport Rd Middlesbrough TS1 5EH	Development of a generic locking device.	05/05 12/05		x
UoT	**Disability Fitness** Unit A Foundry Yard Bellingham Hexham NE48 2DA	Assistance with the development of a concept for a new walking aid	07/05 12/05		x