TOOL MANUFACTURING BY METAL CASTING IN SAND MOULDS PRODUCED BY ADDITIVE MANUFACTURING PROCESSES

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DECLARATION WITH REGARD TO

INDEPENDENT WORK

I, KASONGO DIDIER NYEMBWE, identity number [redacted] and student number 205269011, do hereby declare that this research project submitted to the Central University of Technology, Free State for the Degree DOCTOR TECHNOLOGIAE: ENGINEERING: MECHANICAL, is my own independent work; and complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of the Central University of Technology, Free State; and has not been submitted before to any institution by myself or any other person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

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ABSTRACT

In this study an alternative indirect Rapid Tooling process is proposed. It essentially consists of producing sand moulds by Additive Manufacturing (AM) processes followed by casting of tools in the moulds. Various features of this tool making method have been investigated.

A process chain for the proposed tool manufacturing method was conceptually developed. This process chain referred to as Rapid Casting for Tooling (RCT) is made up of five steps including Computer Aided Design (CAD) modeling, casting simulation, AM of moulds, metal casting and finishing operations. A validation stage is also provided to determine the suitability of the tool geometry and material for RCT. The theoretical assessment of the RCT process chain indicated that it has potential benefits such as short manufacturing time, low manufacturing cost and good quality of tools in terms of surface finish and dimensional accuracy.

Focusing on the step of AM of the sand moulds, the selection of available AM processes between the Laser Sintering (LS) using an EOSINT S 700 machine and Three Dimensional Printing using a Z-Corporation Spectrum 550 printer was addressed by means of the Analytic Hierarchy Process (AHP). The criteria considered at this stage were manufacturing time, manufacturing cost, surface finish and dimensional accuracy. LS was found to be the most suitable for RCT compared to Three Dimensional Printing. The overall preferences for these two alternatives were respectively calculated at 73% and 27%. LS was then used as the default AM process of sand moulds in the present research work.

A practical implementation of RCT to the manufacturing of foundry tooling used a case study provided by a local foundry. It consisted of the production of a sand casting pattern in cast iron for a high pressure moulding machine. The investigation confirmed the feasibility of RCT for producing foundry tools. In addition it demonstrated the crucial role of casting simulation in the prevention of casting defects and the prediction of tool properties. The challenges of RCT were found to be exogenous mainly related to workmanship.

An assessment of RCT manufacturing time and cost was conducted using the case study above mentioned as well as an additional one dealing with the manufacturing of an aluminium die for the production of lost wax patterns. Durations and prices of RCT steps

were carefully recorded and aggregated. The results indicated that the AM of moulds was the rate determining and cost driving step of RCT if procurement of technology was considered to be a sunk cost. Overall RCT was found to be faster but more expensive than machining and investment casting.

Modern surface analyses and scanning techniques were used to assess the quality of RCT tools in terms of surface finish and dimensional accuracy. The best surface finish obtained for the cast dies had Ra and Rz respectively equal to 3.23 µm and 11.38 µm. In terms of dimensional accuracy, 82% of cast die points coincided with die Computer Aided Design (CAD) data which is within the typical tolerances of sand cast products. The investigation also showed that mould coating contributed slightly to the improvement of the cast tool surface finish. Finally this study also found that the additive manufacturing of the sand mould was the chief factor responsible for the loss of dimensional accuracy. Because of the above, it was concluded that light machining will always be required to improve the surface finish and the dimensional accuracy of cast tools.

Durability was the last characteristic of RCT tools to be assessed. This property was empirically inferred from the mechanical properties and metallographic analysis of castings. Merit of durability figures of 0.048 to 0.152 were obtained for the cast tools. It was found that tools obtained from Direct Croning (DC) moulds have merit of durability figures three times higher than the tools produced from Z-Cast moulds thus a better resistance to abrasion wear of the former tools compared to the latter.

To my parents: Patrice Tshikumambila Nyembwe and Leontine Kela Bajika

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LIST OF ABBREVIATIONS

AFS: American Foundry Society

AHP: Analytic Hierarchy Process

AM: Additive Manufacturing

CAD: Computer Aided Design

CNC: Computer Numerical Control

DCP: Direct Croning Process

DCLSP: Direct Croning Laser Sintering Process

DSSRP: Direct Shell Sand Rapid Prototyping Process

DMLS: Direct Metal Laser Sintering

EDM: Electrical Discharge Machine

EOS: Electro Optical Systems

GDP: Gross Domestic Product

LS: Laser Sintering

LOM: Laminated Object Manufacturing

RCT: Rapid Casting for Tooling

RP: Rapid Prototyping

RT: Rapid Tooling

SLS: Selective Laser Sintering

STL: Standard Triangulation Language

SLA: Stereolithography

SEM: Scanning Electron Microscope

TDM: Tool and Die Manufacturing

3DP: Three Dimensional Printing

CHAPTER 1

INTRODUCTION

1.1 Foreword

Mass production processes such as forging, stamping, casting and injection moulding require metallic tools in the form of dies, patterns and moulds. The quality, cost and lead time of these tools directly affect the quality of parts and the economics of entire production planning. There is therefore an ongoing search for improved and innovative Tool and Die Manufacturing processes to meet the stringent customer requirements for products (Peres & Mafokhami, 2001; Jiang, Liu, & Zhang, 2005). In the present project an alternative tool manufacturing process based on metal casting in sand moulds produced essentially through an Additive Manufacturing (AM) processes is investigated.

1.2 Problem Statement

Sand casting is traditionally not considered for the production of metallic tooling. The limitations of this metal casting method in relation to Tool and Die Manufacturing (TDM) mainly stem from the need for a pattern, the fabrication of which is notoriously cost and time consuming. In addition, sand cast tools are of relatively poor quality in terms of surface finish and dimensional accuracy compared to processes such as precision casting, machining and Rapid Tooling. Castings are also prone to contain defects that negatively affect the tool durability (Beeley, 2001).

In recent times, significant progress has been achieved in sand casting to alleviate some of its shortcomings. Amongst this, is the use of casting simulation software to predict the properties of the final casting and to prevent defects (Sakuragi, 2005; Fu & Yong, 2009). In addition the application of AM processes such as Laser Sintering (LS) and Three Dimensional Printing (3DP) to produce sand moulds directly from Computer Aided Design (CAD) files without the need for a pattern is also an important development in sand casting. Taking into account these advances, sand casting could be revisited and reassessed for the manufacturing of metallic tools. In this instance metallic tooling will be produced by metal casting in sand moulds obtained by AM processes. This alternative method is referred to in this study as Rapid Casting for Tooling (RCT).

Therefore the research problem investigated in this study relates to the integrated understanding of the RCT process as an alternative route for tool manufacturing in terms of its relevance and effectiveness. In the next section, details are provided regarding the hypothetical resolutions of this question.

1.3 Hypothetical resolutions

The hypothetical resolutions in order to gain an understanding of RCT as alternative route for the production of tools by metal casting in moulds produced by AM processes are as follows:

i. The development of an RCT process chain combining CAD modelling, casting simulation, AM of sand moulds, metal casting and finishing operations of the final cast tool.
ii. The multi-criteria based selection of a suitable AM process for the production of moulds, in order to optimise the quality of cast tools at low cost and short lead time.
iii. The coating of AM moulds in order to further improve surface finish and dimensional accuracy of cast tools.
iv. The follow-up and optimisation of the casting procedure in a real foundry environment.

1.4 Purpose of the study

Based on the problem statement and hypothetical resolutions mentioned above, the major objectives of the current investigation are:

i. To conceptually develop an RCT process chain that should combine various input and output parameters as well as processing and validation steps.
ii. To select the most suitable AM processes for the production of sand moulds.
iii. To implement the RCT concept using locally available CAD and casting simulation software as well as casting technologies.
iv. To analyse factors governing the manufacturing time and cost of tools produced by RCT.
v. To assess the quality of moulds and tools produced through the RCT process chain in terms of surface finish, dimensional accuracy and durability.

1.5 Importance of the study

The importance of the present study resides at two levels namely the tool and die manufacturing (TDM)ield and the small and medium enterprise in South Africa. At its first level this investigation is important as there is always a quest for new TDM methods to respond to stringent requirements for cost effectiveness and better quality in finished goods production (Altan, 2001). TDM is not a stagnant field but one that is developing at a rapid pace with the improvements of existing processes or introduction of new technologies such as all the relatively new Rapid Tooling processes including Laser Cusing and Metal Matrix Printing (Rosochowski et al., 2000).

At the second level, TDM firms are small and medium enterprises that are supposed to significantly contribute to the country's overall Gross Domestic Product (GDP) and serve as a catalyst for job creation. In that sense this study adequately responds to the national imperative of strengthening this small and medium industry.

A recent study that surveyed the state of the local South African tooling industry (FRIDGE, 2005) revealed among other findings that it was non-competitive. The study uncovered the following reasons:

i. Because of the low tool making capacity and the lack of qualified skills in the country, the South African TDM represented only 1% of the manufacturing GDP. There were only 240 tool rooms in the country. Hence the local tooling manufacturing industry cannot meet the growing local demand from the packaging and automotive industry. South Africa was found to be a net importer of tooling from overseas.
ii. The local capability measured in terms of delivery time and tool quality was observed to be below par. The general inefficiency was essentially attributed to the use of aged equipment and old technologies as well as the lack of skills.

The consequence of the above is that the South African small and medium enterprises involved in mass production of goods for automotive, mining and packaging industries have also demonstrated a lack of competitiveness in the global market. They have been surpassed among others by their Chinese and Indian counterparts (Viljoen, 2005).

The study made several recommendations to re-invent the local tooling manufacturing industry. These include government support, skills development and training and technology initiative.

The technology initiative is aimed at adopting modern techniques from developed countries through collaborative and joint venture projects. This technology initiative also encourages innovation in the field of TDM to develop technologies that are suitable to the local industry and also addresses the limitations of the current manufacturing methods such as machining and Rapid Tooling. In the spirit of the technology initiative, the present research is proposing an alternative manufacturing route for metallic tooling. It is believed that this process will be well suited for South Africa and developing countries as well as address the limitations of current TDM processes.

1.6 Research methodology

The methodology followed in order to achieve the objectives of the current research includes:

i. The conceptual development of a process chain combining casting design tools, AM of sand moulds and sand casting methods.
ii. The multi-criteria based optimum selection of the most suitable available AM processes choosing amongst Electro Optical Systems (EOS) Laser Sintering and Z-Corp Three Dimensional Printing using the Analytic Hierarchy Process (AHP).
iii. The use of two selected case studies related to foundry tooling manufacturing for the RCT practical implementation and its economic assessment.
iv. The production of sand moulds by the most suitable available AM processes.
v. Gravity casting of the final tools in the AM moulds.
vi. The uses of modern techniques of surface finish analysis, 3D scanning respectively and scanning electron microscopy (SEM) for the assessment of surface finish, dimensional accuracy and durability of sand moulds and cast tools.

1.7 Scope of the study

The current research is concerned with tool manufacturing and not the design of the tools. In addition, only AM processes available in South Africa have been used for the practical implementation of RCT. Finally standard setup parameters were used on the AM machines for the production of the moulds. At this stage, no optimisation attempt was made.

1.8 Layout of the Thesis

The "paper format" is the layout adopted for the presentation of this thesis. Eight publishable papers of approximately 3000 words each will constitute the core of the thesis. The structure of each paper consists of the following sections: Abstract, Introduction, Experimental or Methodology, Results, Discussion, Conclusion, References and Appendices.

In particular the abstract section of each article contains the following sub-sections:

- Purpose clarifying the objectives of the article
- Design/method/Approach describing the paper methodology
- Findings summarising the main results obtained from the study.
- Originality/Value highlighting the unique contribution of the paper
- Keywords listing the main words of the article
- Paper type specifying the type of paper that can be a review or a research paper.
- Paper status indicating if the article has been published, is under peer reviewing or has not been submitted (prepared).

Thus, the layout of the current thesis is as follows:

- Chapter 1 constitutes the introduction of the thesis. In this chapter the problem statement, the study objectives and its importance are explained.
- Chapter 2 reviews the literature review on Rapid Tooling processes and metal casting methods used for the production of metallic tools.
- Chapter 3 examines the recent advances in AM processes for the production of sand moulds.
- Chapter 4 deals with the conceptual development of RCT.

- Chapter 5 is dedicated to the multi-criteria based optimum selection of AM processes using the AHP.
- Chapter 6 deals with the practical implementation of RCT for the manufacturing of foundry tooling.
- Chapter 7 investigates the RCT economics in terms of manufacturing time and cost.
- Chapter 8 evaluates the quality of tools produced by RCT in terms of surface finish and dimensional accuracy of moulds and cast tools.
- Chapter 9 assesses the durability of RCT tools.
- Chapter 10 draws general conclusions and makes recommendations relating to the RCT process.

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CHAPTER 2

A REVIEW OF ALTERNATIVE MANUFACTURING PROCESSES DIFFERENT FROM MACHINING FOR THE PRODUCTION OF METALLIC TOOLING

Abstract

Purpose – The objective of this paper is to report on the recent advances and modern trends of alternative manufacturing processes apart from machining for the fabrication of metallic tooling.

Design /methodology/approach – A literature review of Rapid Tooling (RT) and metal casting was conducted.

Findings - It was also found that RT is a dynamic and growing field offering real benefits in terms of lead design time compression and low manufacturing cost compared to machining. However the durability of tools obtained by RT is still a challenge because of porosity issues. Metal casting is sometimes used essentially because of its low cost, near net shape advantage and excellent quality in the case of precision casting methods. However metal casting has an important limitation in that tooling is required in the form of patterns or dies, the manufacturing of which is time and cost consuming. Sand casting is generally not considered for tool making essentially because of additional problems regarding inferior quality of cast tools in terms of surface finish and dimensional accuracy.

Originality/ value - The paper focuses on the manufacturing of metallic tooling. It also reveals the shortcomings of exiting Tool and Die Manufacturing (TDM) processes thus the need for innovative TDM.

Keywords- Rapid Tooling, Additive Manufacturing, Metal casting, Precision casting

Paper type Review paper

Paper status: Prepared

2.1 Introduction

Metallic tooling in the form of dies, sand casting patterns and permanent moulds constitutes an important class of production tooling used in processes such as metal casting, injection moulding, forging, etc. The significance of this class of hard tooling derives from the interesting properties of metals. Compared to other engineering materials such as ceramics and polymers, metals are generally characterised by a combination of properties such as good mechanical properties at low and high temperatures, superior thermal and electrical conductivity and high resistance to wear. These characteristics make metallic tooling suitable for severe operational conditions such as the ones prevailing during sand moulding or injection moulding.

Considerable forces are required to cut through the metallic bonding in order to shape a block of material and produce the final tooling. Therefore special manufacturing processes, equipment and tools are required to accomplish the above. Machining includes all the processes that achieve manufacturing of metallic tooling through cutting and material removal. The various types and forms of machining processes are described in detail in literature and academic textbooks (Kalkpakjan et al., 2006; Altan et al., 2005, Krajuik et al., 2004). Machining is the *de facto* manufacturing processes for metallic tooling. It provides an excellent surface finish to the final metallic tooling as well as tight dimensional accuracy.

Machining processes have several shortcomings that can be classified into two broad groups namely technical and operational. The main technical deficiencies include long machining time during manufacturing and the exorbitant price of equipment (Agarwala, 2000; Altan et al., 2005). The operational shortcomings encompass excessive running cost of the equipment, scarcity of skills, a steep learning curve to operate machining equipment and environmental unfriendliness with regards to the production of metallic waste (Morrow et al., 2005).

Developing countries do not have enough resources to adequately deal with the machining limitations explained above. The situations results in non-competitiveness of the tool and die making (TDM) industry in developing countries. In the case of South Africa, a survey conducted on behalf of the government in 2005 revealed that the TDM industry was ageing, non-competitive and incapable to serve the local demand (FRIDGE, 2005).

There is therefore a need for alternative approaches in tooling manufacturing that could alleviate the limitations of machining and be better suited for specific applications in different countries. The present paper review two types of such tool manufacturing processes namely Rapid Tooling (RT) and metal casting.

2.2. Rapid Tooling

2.2.1 Description of Rapid Tooling

RT is the application of Additive Manufacturing (AM) commonly known as Rapid Prototyping (RP) or free-form fabrication to the manufacturing of tooling. AM is defined as the growing of parts, layer-by-layer in special machines directly from computer three dimensional model files (www.astm.org). AM techniques employ five basic steps to produce a part (Palm, 2002; Yan et al., 2009). These steps are:

i. Modeling of the part using a Computer-Aided Design (CAD) software package such as SolidWorks®.
ii. Conversion of the CAD file into Standard Triangulation Language (STL) format. This format represents a three dimensional surface as an assembly of planar triangles. It is a well defined and easy-to-handle format that enjoys wide support in the CAD fraternity. It is the preferred format for visualisation, analysis programmes and RP manufacturing.
iii. Slicing of the CAD part in virtual layers for the manufacturing process using software such as Magics® from Materialise®. This is followed by preparation of the STL file to be built by carefully choosing the suitable build orientation and creation of support structure for the model during building.
iv. AM of the part using one of the several techniques listed in Section 2.2.2.
v. Cleaning and finishing followed by curing to provide strength and surface treatment.

Several AM processes are commercially available, well established and described in detail in literature and textbooks (Ashley, 1995; Kalpakjan et al., 2006). They include stereolithography (SLA), Laminated Object Manufacturing (LOM), Three Dimensional Printing (3DP), Laser Sntering (LS), etc. AM is a very dynamic manufacturing field with new processes continuously being developed with various applications in the area of RT (Wolhers, 2009).

2.2.2 Rapid Tooling processes

A classification of RT processes has been proposed based on its practical use for tooling (Rosochowski et al, 2000). Figure 2.1 shows that three major groups can be considered: those that are used to produce patterns for casting, those used to produce patterns for both soft and hard tooling (indirect tooling) and those that produce production-ready tools directly from RP methods (direct tooling) (Altan, 2005; Knights, 2005; Pal, & Ravi, 2007).

From the above classification, the RT processes that are used for the manufacturing of metallic tooling include: Spray metal tooling, Cast metal tooling, Keltool tooling, the metal powder process and microcast tools. The other processes provide soft tools or hybrid tools that are a mixture of metal and other materials. A great deal of development is taking place in the field of RT with new AM processes being applied to the production of tooling. Some of the latest ones that merit to be mentioned are Direct Metal Laser Sintering (DMLS) and metal printing (Strategies, 2008). They fall in the Direct Tooling manufacturing processes. In random order these processes are described in the section below.

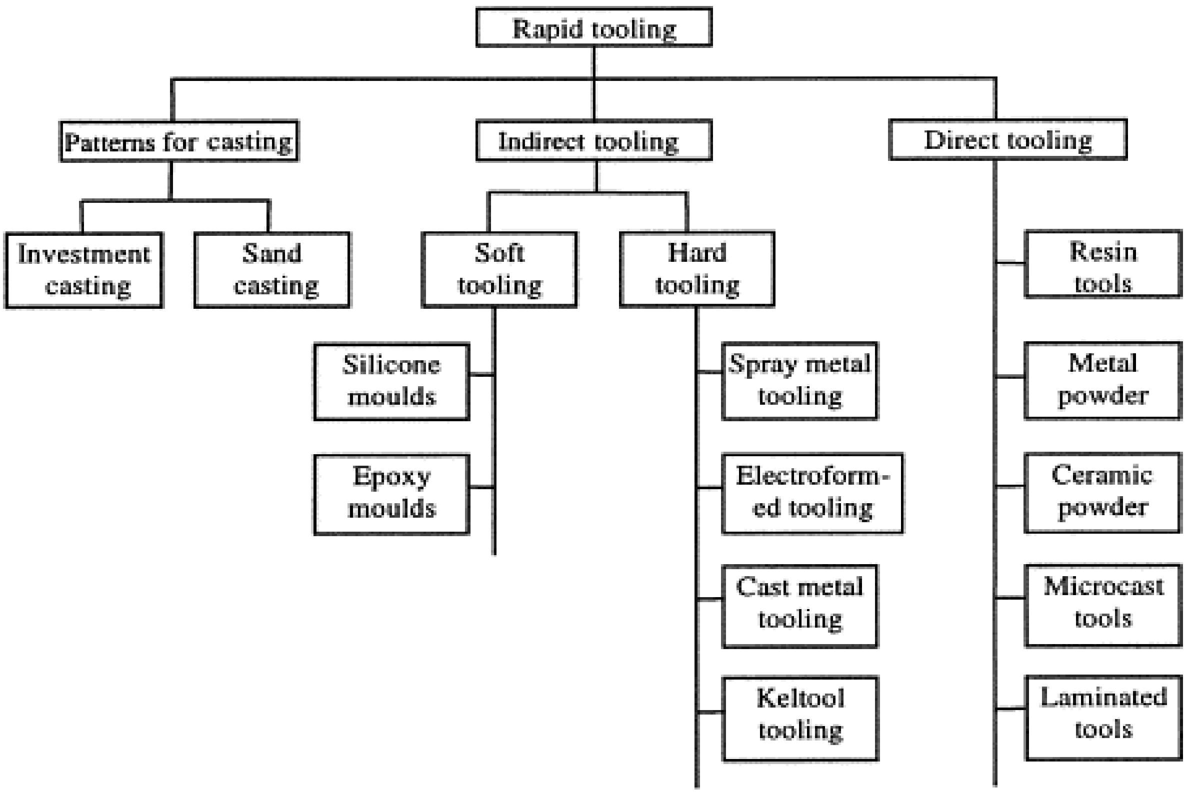

Figure 2.1 *Classification of RT processes (Altan, 2005).*

2.2.2.1 Spray metal tooling

Spray metal tooling is an indirect tooling process in which the tool is obtained after spraying molten metal around a pattern produced by AM such as LS in polycarbonate or, Fused Deposition Modelling (FDM) in Acrylonitrile Butadiene Styrene (ABS). Another related method called the Rapid Solidification Process (RSP) (Monroe, 2006) involves spraying molten H13 tool steel onto a ceramic pattern. The developers claimed the RSP produces tool steel shells with superior strength, hardness and surface finish.

2.2.2.2 Cast metal tooling

Cast metal tooling is an indirect tooling process whereby the metallic tooling is produced by casting in an investment casting shell. The shell patterns are produced by AM processes such as SLA or LOM. Machining may be necessary to improve the surface finish. Tooling can be cast in various alloys such as aluminium and zinc for prototyping purposes or in tool steel for high volume production.

2.2.2.3 Keltool tooling

The Keltool is an indirect tooling process that requires a master pattern obtained by SLA that can be used to develop a silicone mould that will then be used to produce the Keltool mould. The Keltool mould is then processed with a copper infiltration and sintered to cure the mould and increase its strength. The finished Keltool part has the hardness of an A6 tool steel (and can be machined like a traditional hard tool. Accuracies are typically 0.125 to 0.375 mm. This process has mainly been used for injection moulding dies and inserts. The method is advantageous for small, complex moulds that would require much time to make with Computer Numerical Control (CNC) machining or Electrical Discharge Machining (EDM) techniques. The 3D KeltoolTM was owned and licensed by 3D Systems (Zelenski, 1997).

2.2.2.4 Metal powder

Powder processing is the precursor of the DMLS explained in the next section. This is a direct tooling process whereby the tool is manufactured from metallic powder by LS or 3D ink-jet printing methods. Several metal powdered methods that have successfully been used for the manufacturing of tooling for injection moulding and die casting are mentioned in literature. Amongst them is the LS RapidTool process that uses 420 stainless steel based particles, coated with a thermoplastic binder. Consolidation of the metal powder is achieved by selective melting of the binder by the laser. The green part is converted into a fully dense metal part by infiltration with molten bronze in an oven at between 450 and 650 degrees Celcius (Dimov et al, 2001).

2.2.2.5 New developments in the field of direct tooling

The RT field is developing everyday with applications of new AM methods. Some of these include the production of dies and moulds by DMLS in which single-component metallic powders are fused directly, layer-by-layer (Knirsch, 2003). It produces high-density products with excellent mechanical properties (Buijs, 2005; Herzog, 2008). Metal Printing Process (MPP) is another innovative AM technique that uses photo-masking and electrostatic attraction forces to achieve the layer-by-layer production of dies and moulds (Eijk et al, 2005).

2.2.3 Advantages and limitations of Rapid Tooling processes

The major benefits of RT processes are the reduced manufacturing cost and time to produce metallic tooling compared to machining. Savings of 50% in time and cost are often reported by companies (Kochan, 2000; Rosochowski, 2000; Knights, 2005; Twarog, 2007; Strategies, 2008; Unknown1, 2011). These benefits are important for the competitiveness of the TDM industry as well as the outbound industries down the supply chain such as metal casting and injection moulding industries.

The main limitations of RT processes include the quality in terms of dimensional accuracy, surface finish, durability and cost. The surface finish is still inferior to machining due to the layer-by-layer texture. The porosity of direct tooling is generally high, reducing the tooling durability except in the case of DMLS where part density is around 99.7%. Finally the cost is still on the exorbitant side due to the fact that AM processes are still relatively new technology (Rosochowski, 2000).

RT processes address to some extent the concerns expressed as to the suitability of machining in tool making processes. However, their availability and cost are still hurdles in developing countries. For example in South Africa there are only 15 high-end RP machines exclusively found in academic institutions that have enough funding to purchase such equipment, the cheapest of them was imported to South Africa for around half a million Rand. The market is currently flooded with low cost 3D printers but the up market DMLS machines are still expensive.

2.3 Metal casting

2.3.1 Description

Metal casting is a manufacturing technique for metallic components that consists of pouring molten metal in the cavity of a refractory mould or die. The metal flows and solidifies in a controlled manner inside the mould or die. At the end of the solidification process, the mould or die is separated from the casting. Various casting methods exist and are well documented in specialised textbooks on foundry technology. Amongst the casting processes are sand casting, die casting, lost foam casting, investment casting and many others. (Beeley; 2004; Campbell, 2004; Brown, 1999). The basic steps in the sequence of casting production with minor modifications depending on specific casting processes are summarised in Figure 2.2 (Beeley, 2004).

The casting methods that are used for the manufacturing of metallic tooling essentially belong to the group of investment casting processes in which moulds are produced from liquid slurries of fine refractory materials. The processes fall into two distinct categories, based on whether the pattern is expendable or permanent. These are explained in the next sections.

2.3.2 Metal casting processes used for manufacturing metallic tooling

2.3.2.1 Lost wax investment casting

Investment casting processes based on expendable patterns are also known as lost wax investment casting where the pattern is made of wax, a fusible material melting in the range of 55 to 90 degrees Celsius to form a low viscosity liquid. The essential steps of investment casting are schematically shown in Figure 2.3 (Beeley, 2004).

When lost wax investment casting is used for the manufacturing of metallic tooling, the wax pattern will represent the mould or die. “Cast metal tooling” (Rosochowski et al, 2000) is a lost wax investment casting process that has been used for the production of injection moulding and die casting tooling. RP technologies produce sacrificial patterns for investment casting. The combination of RP and investment casting will be explained later in this section.

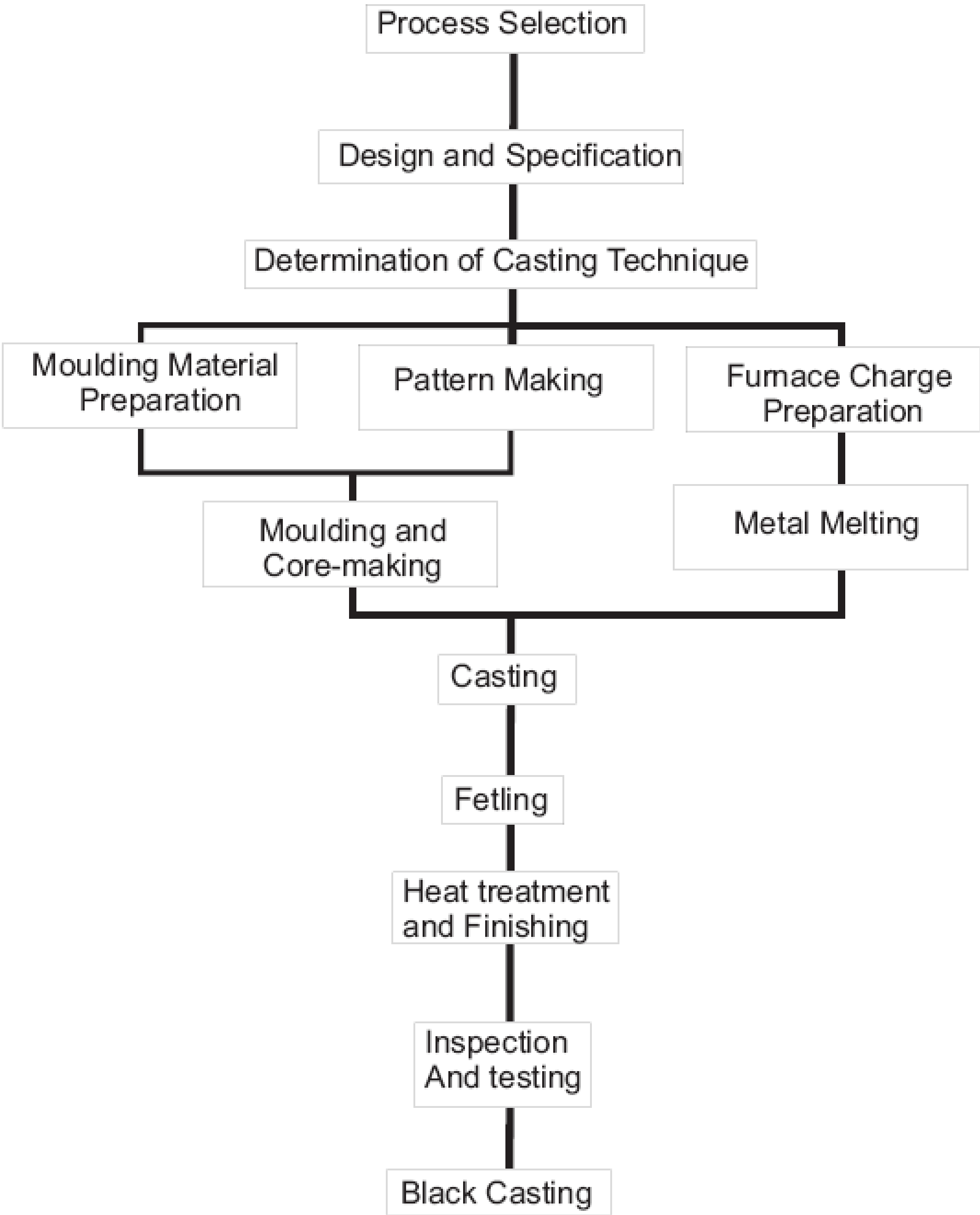

Figure 2.2 *Flow diagram of casting production (Beeley, 2004)*

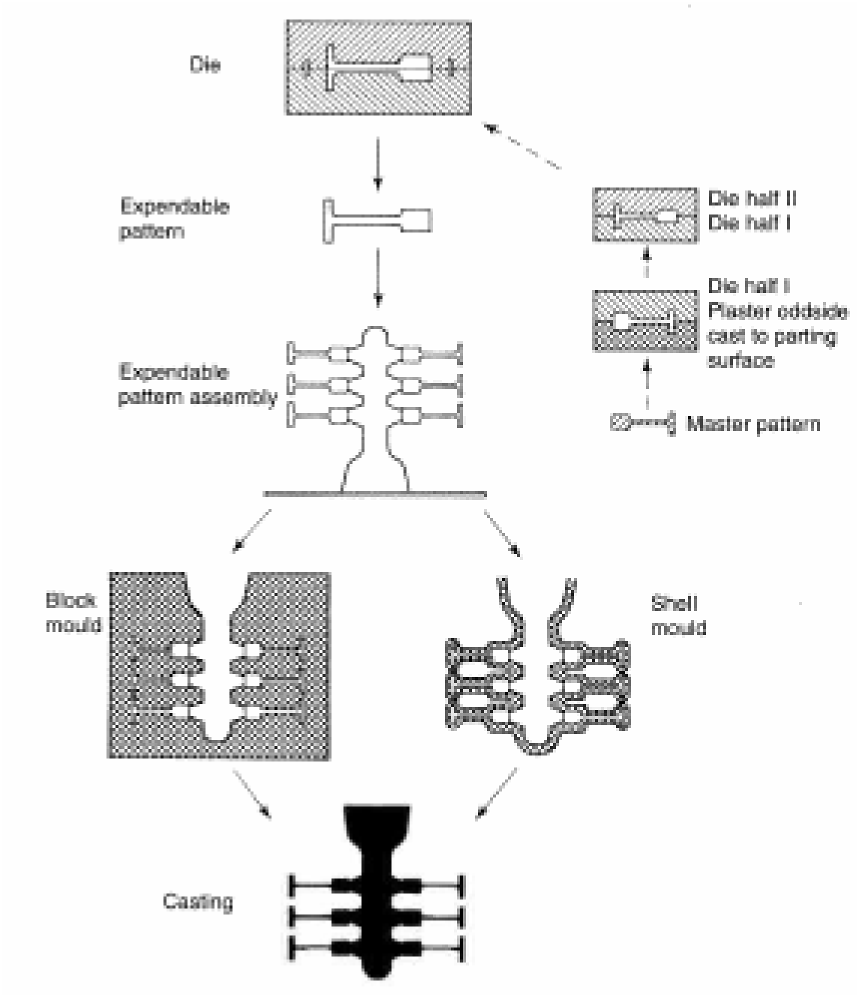

Figure 2.3 *Production sequence in investment casting (Beeley, 2004)*

2.3.2.2 Investment casting from permanent patterns

In this group of investment casting processes, the patterns are permanent metal, wood or plaster. The moulds are also made from plaster of Paris ($CaSO_4$) slurries that are dried at high temperatures. Other variants of the plaster of Paris process include the Antioch process and the Shaw process where the plaster of Paris is mixed with silica sand and zircon or mullite with ethyl silicate respectively. The castings have a high standard of accuracy and surface finish but the degree of precision is inferior to that of castings produced from expendable patterns because of the occasional misalignment of cope and drag of moulds.

Literature mentions application of investment casting for the manufacturing of metallic tooling. The Paris process is claimed to be suitable for manufacturing of aluminium lost wax pattern dies (Beeley, 2004). Beeley also reports that the Shaw process can be applied for production of steel cast dies for forging, drawing, extrusion, die casting and glass making. A further example is the application of the Unicast process in production cast to size metallic tooling (Greenwood, 1976).

2.3.3 Advantages and limitations of metal casting processes

Investment casting processes produce near net shape components with very good surface finish and dimensional accuracy. The cross-sectional limits for investment castings are 0.6 mm to 75 mm. Typical tolerances are 0.1 mm for the first 25 mm and 0.02 mm for each additional centimetre. A standard surface finish is 1.3–4 microns Root Mean Square (RMS) (Degarmo, Black, Kohser, 2003). Generally the quality of tooling obtained by casting will be better than RT processes but second to machining processes. The durability of tools is better than direct RT and can be comparable to machining. In addition the manufacturing cost is generally inferior to machining and RT. Metal casting is relatively simple and easy to understand. From the foregoing, metal casting partly addresses the limitations inherent in machining and RT.

One of the main limitations of the conventional investment casting processes is the use of a pattern. The manufacturing of the pattern is generally dexterous and time-consuming. Expendable patterns are produced from a permanent tool such as a die that has to be manufactured usually by machining or precision casting. On the other hand, permanent patterns also need to be produced by skilful pattern makers or by precision machining. The pattern-producing step is generally the bottleneck in the casting process chain, thus limiting its use in manufacturing of tooling. This is especially true in developing countries where there is acute skills shortage of qualified pattern makers (Viljoen, 2005).

Developments in the field of investment casting have looked at incorporating AM processes such as SLA and LOM for manufacturing expendable and permanent patterns (Yury et al, 2001). Processes such as Quick Cast whereby the lost wax pattern is produced by SLA have been successfully used in commercial investment casting applications (Jacobs et al, 2000; Cheah, Chua, Lee, Feng, & Totong, 2005).

A further application of AM to metal casting is the direct AM processes of refractory moulds and shells. These processes offer huge potential for manufacturing metallic tooling but have not been fully investigated in literature. The present work on Rapid Casting for Tooling process endeavours to close the gap. The stages of this process are reviewed in a follow-up paper.

2.4 Conclusion

RT and metal casting are the two groups of alternative TDM processes apart from machining. RT is a dynamic and growing field offering real benefits in terms of lead design time compression and low manufacturing cost compared to machining. However, the durability of tools obtained by RT is still a challenge because of porosity issues. Metal casting is sometimes used essentially because of its low cost, near net shape advantage and excellent quality in the case of precision casting methods. However, metal casting has an important limitation in that tooling is required in the form of patterns or dies, the manufacturing of which is time and cost consuming. Sand casting is not mentioned for tool making essentially because of additional problems regarding inferior quality of cast tools in terms of surface finish and dimensional accuracy.

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CHAPTER 3

ADDITIVE MANUFACTURING PROCESSES FOR THE PRODUCTION OF SAND MOULDS: MODERN TRENDS AND USE IN THE SOUTH AFRICAN FOUNDRY INDUSTRY

Abstract

Purpose – The objective of this paper is to find out the recent advances and modern trends of Additive Manufacturing processes for the production of sand moulds.

Design /methodology/ approach – A literature review of Additive Manufacturing processes for the production of sand moulds and their application for metal casting.

Findings - The paper indicates that Laser Sintering and Three Dimensional Printing are the two major Additive Manufacturing processes for the fabrication of sand moulds. The processes are essentially used during the design stage of metal casting for the production of casting prototypes. Modern applications include the mass production of casting and high-tech casting applications such as aerospace components.

Originality/ value - The paper focuses on the Additive Manufacturing processes for the production of sand moulds and their application to sand casting. The recent advances justify revisiting sand casting for the manufacturing of tooling.

Keywords - Additive Manufacturing**,** Laser Sintering, Three Dimensional Printing, Metal casting

Paper type - Review paper

Paper status: Published

3.1 Introduction

Additive Manufacturing (AM) is the fabrication of solid parts, layer-by-layer directly from three dimensional files of computer generated models. AM essentially consists of five basic steps including:

i. Modeling of the part using a Computer-Aided Design (CAD) software package.
ii. Conversion of the CAD file into Standard Triangulation Language (STL) format. This standard format represents a three dimensional surface as an assembly of planar triangles. It is a well defined and easy-to-handle format that enjoys wide support in the CAD fraternity. It is the preferred format for visualisation, analysis programmes and Rapid Prototyping manufacturing.
iii. Preparation of the STL file by carefully choosing the suitable build orientation and creation of support structure for the model during building.
iv. Manufacturing of the part using one of the several AM techniques.
v. Cleaning and finishing operations such as curing to provide strength.

A number of AM systems are commercially available. New versions of processes are continually appearing on the market (Wolhers, 2009). Examples of well established AM processes include sterolithography, laminated object manufacturing, Three Dimensional Printing, fused deposition modeling, Laser Sintering, laser cusing and metal printing. Fundamental differences between these processes reside at the type of raw materials used such as metallic, ceramic or plastic powders and the binding mechanism employed to bond the powder such as laser, glue, resins, and electrostatic forces. The different AM processes are described in detail in literature (Ashley, 1995; Kalpakjan et al., *2006*).

AM has been used in making parts in different scientific disciplines such as medicine (Bou et al., 2004), tool and die making (Altan et al., 2005) and metal casting (Beaudoin et al., 1997; Wirtz & Freyer, 2000). AM processes consist of three conventional applications namely, prototyping, Rapid Tooling and rapid manufacturing (Palm, 2002). The main benefits of AM processes have generally been a reduction of lead design time, short time to market of new products, decrease in manufacturing cost for low volume production and the ability to produce complex shapes.

Metal casting using AM techniques was first employed for foundries fifteen years ago mainly in Rapid Tooling (RT). In this application, tools such as sand casting patterns, lost wax patterns for investment casting, permanent moulds and dies are manufactured directly or indirectly using AM processes. Metal casting for RT is comprehensively reviewed in literature (Lerner et al., 2002; Chua et al., 2003). This paper focuses on the use of AM for the direct production of sand moulds. This is a relatively new application where interesting developments are taking place and new trends are emerging. The paper attempts to widen the scope for the application of AM for the present and future in relation to its potential significance in transforming the South African foundry industry.

Two types of AM processes namely Laser Sintering and Three Dimensional Printing, have been dominant for the production of sand moulds over the years. These processes are briefly described in the next section.

3.2 Additive Manufacturing processes for the production of sand moulds

The AM processes for producing sand moulds for casting are refractory powder based systems and subdivided in two categories; Laser Sintering (LS) technology and Three Dimensional ink jet printing (3DP) technology. LS was developed at the University of Texas in the mid-1980s while 3DP was invented at the Massachusetts Institute of Technology (MIT) in the late 1980s. Since then these academic institutions have sold licenses to several business institutions to manufacture machines that can grow sand moulds.

3.2.1 Laser Sintering

Sand moulds can be produced directly from CAD files by AM processes based on LS. In this process a laser beam is used to selectively fuse powder particles into a solid part that will become a component of the sand mould. LS processes are divided into two categories namely, the direct process and the indirect process. The indirect process generally makes use of foundry sand that is pre-coated with a chemical binder while the direct process does not use any binder at all.

In indirect LS, the heat generated by the laser beam melts the binder, which then glues the sand particles together. This type of binding mechanism is based on partial melting of binder during liquid phase sintering. After the green part is grown, excess powder is removed from the surfaces followed by curing in a furnace to develop optimum strength and high density. The two indirect LS based processes that produce commercial moulds for metal casting are the Direct Croning Laser Sintering Process (DCLSP) by Electro Optical Systems (EOS) GmbH and the Sand Form Process by DTM (currently known as 3D Systems).

Some technical characteristics of the Direct Shell Sand Rapid Prototyping (DSS RP) processes are summarised in Table 3.1 (Beeley, 2001; Chua et al., 2003). Figure 3.1 shows a schematic diagram of the Laser-sintering of Croning®-molding material. DSS RP is currently commercialised by companies such as EOS in Europe and DTM in the United States of America. The DSS RP is based on the use of phenolic resin coated sand (shell sand).

Table 3.1 Technical characteristic of commercial DSS RP processes

Processes	Companies	Equipments	Mould/shell materials	Casting alloys	Accuracy/ tolerances
DCLSP	EOS GmbH/ Ac Tech	EOSINT S series	Croning moulding material (silica, zircon sand)	All foundry alloys	few tenths of a mm
Sand Form	DTM	Sinterstation 2005	Silica and zircon sands	All foundry alloys	-

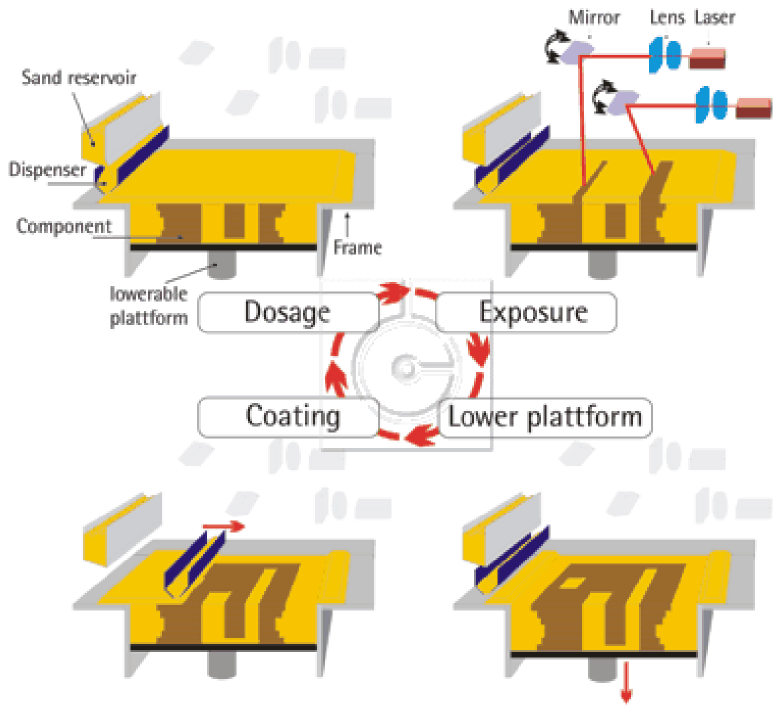

***Figure 3.1** Procedure of Laser-sintering of Croning®-molding material (AcTech, 2012).*

3.2.2 Three Dimensional Printing

Three dimensional ink-jet printing (3DP) technology is the alternative AM method that is used to grow refractory sand moulds and shells directly from CAD file. The principle is similar to ink impression on a piece of paper from an ink-jet printer. An ink-jet head selectively deposits or "prints" binder fluid that glues the powder particles together (Palm, 2002). Figure 3.2 shows the functioning principle of typical 3DP equipment. The powder which is either synthetic or a natural refractory material is able to withstand high temperature and is coated with a catalyst. The proprietary binder fluid which is in a way similar to foundry resin, chemically bonds sand moulds through a chemical reaction that hardens the mould.

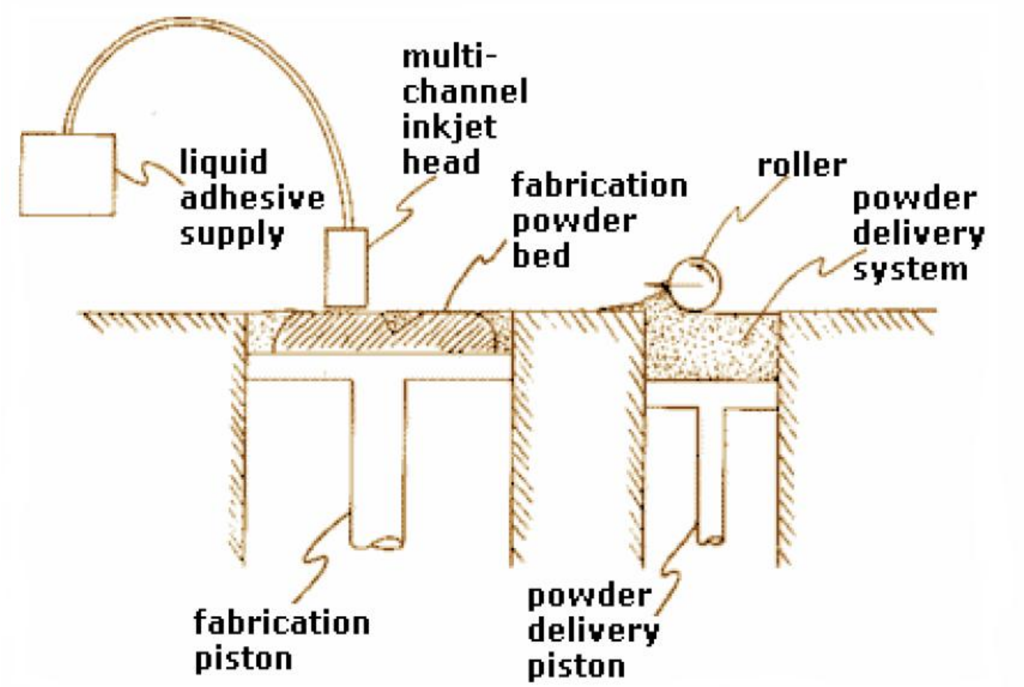

Figure 3.2 *Functioning principle of 3DP Additive Manufacturing (Chua* et al.*, 2003)*

Some 3DP processes for the commercial manufacture of casting sand moulds include Direct Shell Production Casting (DSPC) from Soligen Technologies (www.soligentechnologies.com), the Z-Cast process from Z-Corporation (www.zcorp.com), the ProMetal RCT process from ProMetal RCT GmbH, the Generis Sand process from Generis GmbH and the Patternless Casting Modelling (PCM) process from Beijing Yinhua Ltd. Some technical characteristics of these processes are summarised in Table 3.2

3.2.3 Comparison of the various Additive Manufacturing processes

Several features differentiate the commercial AM processes able to grow sand moulds and shells (Pham et al., 1997). Some of the characteristics that are relevant in the production of casting moulds and shells include resolution, accuracy, scan speed, maximum part dimensions and cost. Tables 3.1 and 3.2 presented some additional technical data in terms of types of materials, suitable alloys and surface finish. Further technical characteristics of the AM equipment that can be found on supplier websites include achievable mould strength, binder content, etc.

Table 3.2 Technical characteristics of 3DP processes for manufacturing of casting moulds (Uziel, 1993; Anonymous, 2007; Ederer, 2005)

Processes	**Companies**	**Equipments**	**Mould/shell materials**	**Casting alloys**	**Accuracy**
DSPC	Soligen Technologies	DSPC system: Shell Design Unit (SDU) + Shell Production Unit (SPU)	Ceramic shell (investment casting)	All foundry alloys	-
Z-Cast 501	Z-Corporation	Spectrum Z510 ZPrinter 310 lus	Mixture of foundry sand, plaster, and other additives	Non ferrous metals	± 0.0150 in per build Surface finish 300μ, 100μ with core wash
Generis	Generis	GS 1500	Silica sand and Magetite Furan bonded sand	All foundry alloys	0.1% (max ± 0.5mm)
ProMetal RCT	ExtrudeHone ProMetal RCT GmbH Horne	S-15, S-Max, S-Print	Quartz and specialty sands	All foundry alloys	-
PCM	Beijing Yinhua	PLCM1200	Foundry sands	All foundry alloys	0.5 – 1.0 mm

Literature contains some comparative studies of these processes when used for rapid casting applications. For example, it was found (Dimitrov et al., 2005) that sand parts produced on

EOSINT S equipment that uses LS technology had better dimensional accuracy than the parts that were manufactured on Z-Corporation equipment that uses 3DP technology. In addition the LS process was faster than the 3DP process. The single advantage of the 3DP process in this investigation was the production cost as it was found to be cheaper than the LS process. In general 3DP printers are cheaper and smaller than the counterpart LS machines that are bulkier and more expensive. In addition the price of the 3DP printer is declining faster (Wolhers, 2009). In another comparative study of rapid mould making technologies including quick tooling, direct sand moulding by LS and direct sand milling (Hanh et al., 2005), the speed and accuracy advantages of the LS Croning Sand process were significant especially for small to medium size mould components that are highly detailed, intricate and delicate.

From the foregoing, a non exhaustive list of important characteristics of moulds and shell produced by AM processes is presented in Table 3.3. The effects of these properties on the final casting will be explained in the next section.

3.3 Modern trends of Additive Manufacturing processes

Modern trends and developments in AM processes to produce sand moulds and shells have been driven by a better scientific understanding of processes, an improvement of technologies and experimentation with new applications. These trends are described below.

3.3.1 Better scientific understanding of Additive Manufacturing

Better understanding of AM is made possible by research in the field. The types of investigations include benchmarking studies, optimisation and characterisation:

3.3.1.1 Benchmarking studies

Benchmarking studies are conducted to compare the different AM processes and technologies available (Gill & Kaplas, 2009). Benchmarking assists in the selection of most suitable AM processes for a particular casting application. In these studies AM processes and machines are compared on various criteria such as mechanical properties, dimensional accuracy, surface finish, manufacturing speed and material costs of part manufactured.

Comparative studies of these processes for use in rapid casting are published in literature. For example Dimitrov et al., (2005) found that sand parts produced on EOSINT S 700 equipment that uses LS technology had better dimensional accuracy compared to parts that were manufactured on Z-Corporation equipment using 3DP technology. In addition the LS process was faster than the 3DP process. The major advantage of 3DP process was found to be the lower production cost of parts in comparison with that produced through the LS process. In addition 3DP printers are generally cheaper and smaller than the counterpart LS machines (Utela, 2008). Furthermore, the prices of 3DP printers continue to decline (Wolhers, 2009). In another comparative study of quick tooling between direct sand moulding by LS and direct sand milling, the LS Croning Sand process was noted for speed and accuracy, especially for small and medium size mould components that are highly detailed, intricate and delicate (Hahn et al., 2005).

The factors that influence the quality of the casting moulds and shells are similar to those for the LS process. The departure lies in the parameters of laser beams and the binder content which is critical for the 3DP moulds. Some parameters such as shell thickness have an effect on the quality and mechanical properties of the shell as well as the dimensional accuracy of the castings (Singh & Verner, 2008). It was also shown that the type of powder can have significant influence on precision and dimensional accuracy (Dimitrov et al., 2003).

3.3.1.2 Process optimisation

Various factors influence the quality of final sand casting moulds obtained by DSS RP processes. These variables include the environment (humidity and atmosphere), the laser settings (wavelength, diameter, and operation mode), the powder characteristics (composition, homogeneity, particle size, and shape and thermo-physical properties) and the post-treatment and the equipment processing parameters (temperature, time and atmosphere). Some fundamental studies on the effects of LS parameters on phenolic resin sand parts have been conducted by various researchers (Casalino et al., 2002; Casalino et al., 2004; Jain et al., 2008; Singhala et al., 2009). Specific LS parameters included scan spacing, scan speed, laser beam power and laser spot diameter. The characteristics of the sand investigated include sintered layer thickness, permeability, compressive strength and fracture morphology. In these studies interactions between the LS parameters and the part properties were analysed statistically.

Findings revealed that the interaction between LS parameters and sand part properties is complex. Carbon dioxide lasers proved better for LS sintering in terms of wider operating window, better quality and precision than diode lasers. It is possible to optimise a set of working LS parameters for optimum properties of sand compaction. For all combinations of laser parameters and curing processes there were an inverse relationship between the permeability and the compressive strength.

3.3.2 Bond characterisation

Commercial RP machines differ for example in the method of powder deposition (i.e. either by roller or scraper), an inert atmosphere (Ar or N_2) and in the type of laser they use (CO_2 laser, lamp or diode pumped Nd:YAG laser, disk or fiber laser). Another useful classification of LS processes is based on the bonding mechanisms that consolidate the part. The four principal binding mechanisms are shown in Figure 3.3 (Kruth et al., 2004). The interactions between the laser and the various materials including foundry sands have been reviewed by other authors such as (Kruth et al., 2003) arriving at the conclusion about the dominant phenomena that define the feasibility and quality of any LS process.

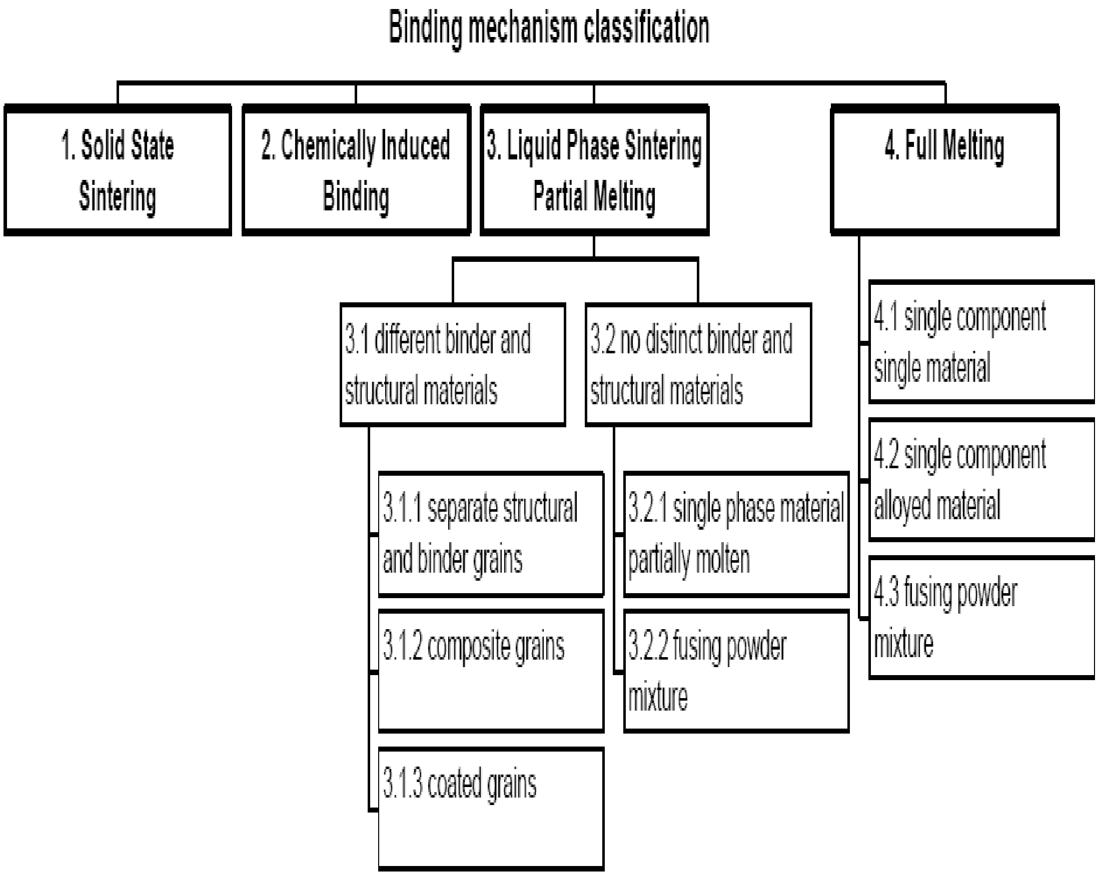

Figure 3.3 *LS binding mechanisms (Kruth* et al, *2003)*

3.3.3 Improvement of Additive Manufacturing processes

The improvement of AM processes for the production of sand moulds include the development and use of new materials and the testing of technologies in terms of laser and printer heads.

Powder materials that have been successfully experimented to produce casting moulds and shells by LS include among other zirconium silicate (Klocke et al, 2000; Wirtz and Freyer, 2000) and zirconium oxide (Harlan et al, 2001). In the case of zirconium silicate the bond is due to the formation of silica gel between the grains of the powder material. This type of binding mechanism is classified as chemically induced binding. This material allows the production of ceramic shells for investment castings. Some of the advantages of zirconium silicate over phenolic coated silica or zircon sand are high strength, the reproduction of delicate details and thin-walled parts and suitability to a wide variety of foundry alloys. In the case of zirconium oxide a low melting copolymer binder is initially used and replaced during the post-treatment of the green mould by infiltration of unstabilised zirconia. In a case study cited in literature, a zirconium oxide sand mould was used to successfully cast a titanium human prosthetic femur (Harlan et al, 2001).

An interesting experimentation of LS for the production of sand moulds is the direct laser sintering of silica sand with no binder used (Tang et al, 2003). The sintering of silica sand in a self-developed high-temperature laser sintering machine (200W CO_2 laser) is due to superficial melting of particles and connection through bridges. It was revealed by Energy Dispersive X-rays (EDX) analysis that superficial melting of silica sand is possible because of the presence of small traces of aluminum oxide inclusions decrease the melting temperature of silica sand. This type of binding mechanism is defined as Solid State Sintering (SSS). Phenix Systems in France commercialises an LS-like system that realises SSS using a high temperature process chamber reaching 900°C (http://www.phenix-systems.com/). The compacted powder, which is close to the SSS temperature, is sintered due to the energy contribution of a Nd:YAG laser source. This way, ceramic materials can be processed as well as metal powders. To obtain the desired characteristics, a post sintering operation is necessary.

3.3.4 New applications

New applications of AM processes for the production of sand moulds and shells to metal casting include Rapid Manufacturing and casting of exotic alloys.

3.3.4.1 Rapid manufacturing of sand moulds and shells

Traditionally AM processes were used for the production of prototype castings that were used for testing purposes. This was particularly evident in the automotive industry where new parts are continuously required for new models of cars. AM processes are being employed for production of sellable castings. This application is referred to as Rapid Manufacturing or Rapid Fabrication where AM processes are used to produce sand moulds similar to conventional methods. One example is the Generis Process that produced furan bonded sand moulds (Ederer, 2005). With improvements in technology, new systems with high productivity will be developed to manufacture sand moulds and shells.

3.3.4.2 Casting of new alloys

Sand moulds produced through AM processes can be used for the casting of new alloys for which no tooling has been developed for mass production. Titanium alloys for example are extremely reactive therefore special moulds of materials such as zirconia are used for casting without the use of part-specific tooling or wax patterns (Harlan, 2001).

3.4 Additive Manufacturing use in the South African foundry industry

AM processes for the production of sand moulds are available in South Africa but currently reside in two academic institutions. The Central University of Technology in Bloemfontein possesses an EOSINT S 700 LS system while the University of Johannesburg has a Z-Cast Spectrum 510 3DP machine. These equipments are currently mainly used for fundamental research including benchmarking studies (Dimitrov et al, 2003). One of the rare practical casting applications is currently the development of an aircraft engine for which components are cast in sand moulds produced by LS (Adept, 2011).

The local foundry industry has not yet taken advantage of AM technologies. Bearing in mind that this sector is made up of close to 80% of sand casting foundries mainly jobbing, AM processes can be beneficial to this industry and thus possibly alleviating its lack of global competitiveness (Viljoen, 2005). The latter situation is due to factors such as the obsolescence of existing foundry equipment that is responsible for the low casting productivity and high level of scrap. In addition, there is a scarcity of foundry skill including pattern making. This contributes to the bottleneck in the procurement of foundry tooling and the long lead time to supply castings on the market.

Probable reasons that explain why local foundries have not yet embraced AM processes include the fact that AM technologies are still relatively expensive in terms of equipment procurement. Local foundries are mainly small to medium enterprises with limited budgets. The newness of the AM processes is another factor considering that local foundries are late adopters of recent technologies. Finally, there is a skill barrier in the use of CAD technologies crucial for AM processes.

3.5 Conclusion

The AM processes is a growing and dynamic field that is finding application in the production of moulds as evidenced by the number of systems commercially available on the market. The innovative use of these processes as well as cutting edge research is proving beneficial to the industry. However, further investigation in the application of AM for metallic tooling is required with regard to selection of suitable processes, process optimisation and financial implications of acquiring these technologies in relation to viability (e.g. net present value and break event point).

There are huge benefits of AM applications for the local foundry industry that is facing challenges related to procurement of tooling, scarce skills in terms of pattern making, etc. The adoption of AM processes can significantly contribute to competitiveness of the foundry industry, once the barriers of entry of new technologies are removed.

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CHAPTER 4

A CONCEPTUAL FRAMEWORK FOR THE MANUFACTURING OF TOOLING BY METAL CASTING IN REFRACTORY MOULDS AND SHELLS PRODUCED BY RAPID PROTOTYPING (RAPID CASTING FOR TOOLING)

Abstract

Purpose – The objectives of this paper is to design a process chain for the manufacturing of tooling by casting in additive manufactured sand moulds.

Design/ methodology/ approach – The integrated process chain referred to as Rapid Casting for Tooling (RCT) comprises five steps including Computer-Aided Design (CAD), Casting Simulation, Rapid Prototyping (RP) Metal Casting and Finishing Operations. A validation is provided that determines a suitable tool to be manufactured by RCT on the basis of minimum wall thickness of tool design and chemical composition of the tool material.

Findings - The study indicates that RCT offers potential for significant time compression, cost efficiency as well as good quality of the cast tool in terms of surface finish and dimensional accuracy.

Originality/ value – In the paper sand casting is proposed as an alternative tool manufacturing process.

Key words - Tooling, Rapid Prototyping, Metal Casting, Rapid Tooling, CNC Machining

Paper type Research paper

Paper status: Published

4.1 Introduction

Metallic tooling includes dies, sand casting patterns and permanent moulds used in mass production processes such as forging, metal casting and injection moulding. They are essentially manufactured by Computer Numerical Control (CNC) machining and Rapid Tooling (RT). These two die and tool making processes change very rapidly as a result of the ever increasing demand to satisfy the stringent requirements of the tooling market. Users insist on superior quality of tools in terms of durability, surface finish and dimensional accuracy. Furthermore short delivery times and premium price are critical to increase profitability as well as quick turnover of new products on the market.

New challenges have emerged in the last ten to fifteen years. First, the worldwide shortage of the tool making skills due to the threat of the digital revolution is one of the current problems facing the tooling manufacturing industry. Second, the environmental quest to reduce waste and elimination of pollution has contributed to the challenges. Thirdly, the stiff competition from countries such as China and India that are able to produce very cheap products has given rise to an incessant demand for new tool manufacturing methods that are easy to learn, competitive, technologically advanced and green.

RT processes have appeared in the last ten to fifteen years ago in response to some of the challenges mentioned above. RT is the application of Rapid Prototyping (RP) technologies to the manufacturing of tooling. RP itself is the Additive Manufacturing (AM) of physical parts in various materials including metal layer-by-layer directly from Computer-Aided Design (CAD) files. Various RT processes are commercially available and extensively reviewed in literature (Rosochowski & Matuszak, 2000). Their major benefits compared to CNC machining include the reduction of lead design time and the cost efficiency.

In reviewing the different applications of RP to tooling manufacturing, it is clear that the RP of sand mould has not been fully used for tool and die making. One rare case study in the literature reports the manufacturing of metallic tooling for injection moulding by casting in a sand mould produced on an EOSINT S RP machine (Chua, Leong, & Lim, 2003). The reasons for the limited application of RP sand moulds for casting of metallic tooling are due to the disadvantages of sand casting as a manufacturing process including the difficulty to produce thin wall parts, segregation, coarse microstructure of castings as well as poor dimensional accuracy and surface finish of parts. These technical challenges have restricted the use of metal casting for the production of quality tooling.

The low thermal conductivity of sand moulds results in coarse metallographic microstructure of castings with inferior mechanical properties compared to metallic processes such as forging and machining. Furthermore shrinkage during metal solidification and cooling combined with mould wall movement due to the metallostatic pressure are at the origin of dimensional accuracy problems. Finally chemical reaction of metal and sand as well as the presence of interstices between sand particles at the surface of the mould are responsible for poor surface finish of castings. These metallurgical phenomena are explained in detail in various specialised foundry technology manuals.

Major developments have taken place in the field of metal casting to improve the cast structure and the quality of castings. Worth to be mentioned is the use of advanced and powerful casting simulation software, synthetic refractory sand and superior mould coating technologies and products. Casting simulation is now common practice in modern foundries and reduces scrap rate due to porosity and shrinkage defects. Synthetic sands with improved thermal properties allow for the production of thin wall casting of superior mechanical properties. In addition new mould coating with fine suspension and high refractoriness are continuously being developed to improve the surface finish of sand casting. These coatings minimise metal penetration and reduce the mean surface roughness of castings.

Taking into account the above sand casting developments, the use of RP moulds for the casting of metallic tooling deserves attention as a feasible tool manufacturing option. Its main benefits will possibly comprise the short manufacturing time and cost deriving from metal casting and Rapid Prototyping advantages.

In order for this proposed tooling manufacturing to be recognised amongst the tool making technologies, its conceptual framework needs to be formalised. This framework referred to in the present paper as Rapid Casting for Tooling (RCT) will validate tool design that can be successfully manufactured by casting in RP moulds. It will also describe the various steps that need to be performed in order to produce a sound and high quality tool.

The conceptual development and theoretical assessment of RCT is the objective of the present paper. In a future paper RCT will be assessed with the aid of case studies. The next section is a background to the fundamentals and recent developments of the RP of sand moulds and metal casting.

4.2 Background

4.2.1 Metal Casting

Metal casting is a manufacturing technique for metallic components that consists of the solidification of liquid metal in the cavity of a refractory sand mould or metallic die. The basic steps in the sequence of production with minor modifications depending on specific casting processes are shown in Figure 4.1. Some of these steps have experienced fundamental changes over the years in casting design, patternmaking and preparation of moulding materials.

The design of parts to be produced by metal casting is specific and critical to the process. Amongst several principles the drawings of castings need to include contraction allowances to compensate for shrinkage during solidification. In addition the filleting of sharp corners is essential to prevent hot tear defects. Finally, section transitions in the part should be optimal and modified if necessary to avoid hot spot defects or the formation of carbide compounds in thin sections. CAD software are nowadays used by the foundryman to speedily assist in the creation of three dimensional models of castings (Ravi, 2005; Fu & Yong, 2009). These models are used for 3D visualisation and prediction of possible problems during production.

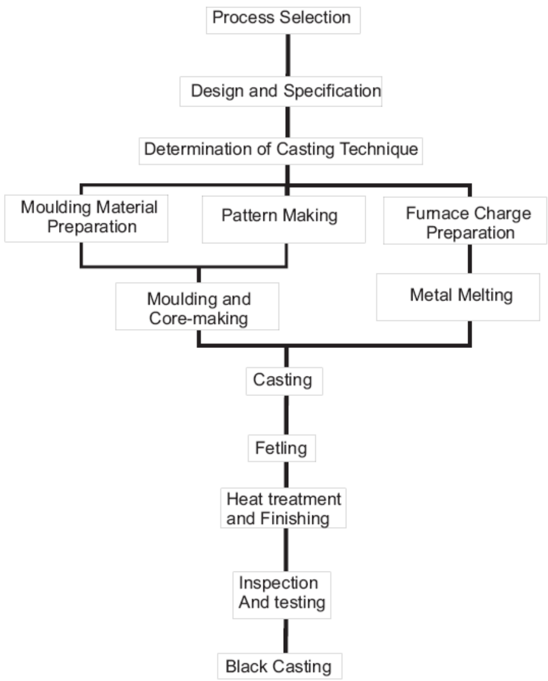

Figure 4.1 *Flow diagram of casting production (Beeley, 2005)*

In addition to the physical dimensions and shape of the casting, casting design also provide accurate dimensions of gating and feeding systems. These features will be part of the mould and die. The gating system constitutes the piping system of the mould to allow complete filling of the mould cavity in a manner that prevents casting defects such as formation of oxides, non-metallic inclusions, mould erosion, cold laps and short runs (Gebelin, Jolly, & Hsu, 2006). The feeding system serves as reservoir of molten metal to compensate for liquid metal shrinkage and thus avoids macro-shrinkage defects (Nayak & Sundarraj, 2009). Modern metal casting methods make use of casting simulation computer programs to design and dimension feeding and gating systems. Many of these software packages are available including Magmasoft and Procast that are predominantly used locally. The main advantage of these simulation programs is the right first time (RFT) concept that leads to considerable reduction of casting defects during production and elimination of trial and error.

Patternmaking is an essential step of traditional metal casting to manufacture the foundry tooling that is used to create the mould cavity. This step is generally the rate determining step and cost driver of the metal casting process. The reason for the high cost is the required skill as well as the cost of technology involved such as CNC machining to produce a sand casting pattern or a tool steel die. Since mid 1990 several RP technologies have been successfully used to manufacture foundry tooling (Lerner, Rao, Kouznetsov, 2002). The benefits have been the reduction of tool manufacturing time and cost. Lately new patternless processes based on the RP have been able to directly produce sand moulds and shells for metal casting thus eliminating the need for patternmaking. These processes are described in section 4.2.

Moulding materials are mixed together and mechanically or chemically processed to produce strong moulds and shells that can withstand the metallostacic pressure of liquid metal during casting. These raw materials essentially comprise various refractory sands and binders. They have a profound impact on the final properties of the casting in terms of minimum section thickness, mechanical properties, dimensional accuracy and surface finish. Developments in the field of refractory sands have seen the emergence of synthetic sand with better thermal properties to produced thin wall castings and high integrity with superior mechanical properties (Campbell, 2003) The use of fine sands has tremendously improved the surface finish. New mould coatings based on high melting point fillers have reduce the incidence of surface defects such as metal penetrations and burn on. Finally modern catalysts and resins have improved the strength of moulds thus reducing the problem of mould wall movement that poses of dimensional accuracy challenges (Brown, 1999).

4.2.2 Rapid Prototyping of sand moulds

RP is the AM of parts, layer-by-layer in special machines directly from computer three-dimensional model files. RP techniques employ five basic steps to produce a part (Palm, 2002.) These steps are:

i. Model creation: Modeling of the part using a CAD software package.
ii. Conversion: Conversion of the CAD file into Standard Triangulation Language (STL) format. This standard format represents a three dimensional surface as an assembly of planar triangles. It is a well defined and easy-to-handle format that enjoys wide support in the CAD fraternity. It is the preferred format for visualisation, analysis programs and RP manufacturing.
iii. Slicing: Preparation of the STL file to be built by carefully choosing the suitable build orientation and creation of support structure for the model during building.
iv. Layer-by-layer construction: Manufacturing of the part using one of the several techniques listed below.
v. Clean and finish: curing to provide strength, surface treatment, etc.

New developments in the field of RP have seen the production of investment casting shells or sand moulds directly from 3D-CAD files (Wohlers, 2009.) The manufacturing processes are based on Laser Sintering (LS) and 3-Dimensional Printing (3DP) technologies. In LS a laser beam is used to selectively fuse pre-coated foundry sand into a solid part that will become a component of the mould or shell. In 3DP the principle is similar to ink printing on a piece of paper from an ink-jet printer. In this case in a layer-by-layer fashion, a printing head selectively deposits or "prints" binder fluid that fuses the powder particles together in desired areas. Commercial examples of technologies for sand mould and shell production based on SLS and 3DP include the Direct Croning Laser Sintering Process (DCLS) (www.actTech.com) and the Direct Shell Production Casting (DSPC)(www.soligentechnologies.com).

The main advantages of RP processes of sand moulds and shells have been the reduction of lead design time. Prototype casting for visualisation and metallurgical evaluation can be produced quickly because no pattern is required. In addition because of their patternless nature, RP processes have reduced design time cost. These processes have also been used for manufacturing low volume casting (Ederer & Ochsmann, 2005.) It has been shown that for low volume casting RP processes are more cost efficient than conventional sand casting processes.

The development of RP of sand moulds and shells as well as the achieved progress in metal casting to overcome previous technical limitations are opening new possibilities for this manufacturing method of metallic components as describe in the section below.

4.3 The Rapid Casting for Tooling Framework

4.3.1 Rapid Casting for Tooling (RCT)

In the present study Rapid Casting for Tooling (RCT) is proposed for the manufacturing of metallic tooling. Essentially dies, permanent moulds and sand casting patterns will be produced by metal casting in refractory sand moulds or shells obtained by RP processes. These RP processes have been introduced in Section 4.2. As such RCT is approached as an indirect tool manufacturing process based on two pillars; RP and Metal Casting. These two key elements characterise and differentiate RCT from the other tooling manufacturing processes. They will also confer to RCT the advantages of near net shape and time compression. RCT is further refined by the use of CAD and analysis techniques such as solid modelling and casting simulation. Benefits such as right first time of RCT will be directly derived from these computer aided techniques.

RCT does not deal with the initial design stage of the tooling nor does it concern itself with the selection of the suitable alloys for the dies or moulds. These considerations depend on the final application of the tooling as well as the type of finished parts that will be produced. The inputs to RCT are the drawings of the final metallic tooling accompanied with the exact material specifications.

4.3.2 RCT Process chain steps

The steps of RCT process chain are linked together and interact with each other in what is referred to in this study as the RCT framework. The framework is made up of two structural parts comprising the validation stage and the process chain. The validation stage determines if a tool is able to be manufactured by RCT based on its minimum wall thickness and its material chemical composition. Metal casting limitations in terms of difficulty to produce thin wall parts as well as segregation have been explained in the background section. Only the design that successfully passes the validation test criteria can be considered for manufacture by the RCT process.

The RCT process chain is made up of five steps including; Solid Modelling, Casting Simulation, RP, Casting and Finishing operations. The flowchart of RCT framework is presented in Figure 4.2. The functions and main characteristics of these processing stages are summarised in Table 4.1. These are described in the next sections.

Table 4.1 Functions and main characteristics of RCT process chain steps

RCT Steps	**Functions**	**Main characteristics**
Solid Modelling	Casting and mould design	STL file format
Casting Simulation	Gating and feeding systems design	Rule-based software
RP	Moulding and core-making	• Laser Sintering • Three Dimensional Printing
Metal Casting	Casting of tool	Gravity casting
Finishing Operations	• Minimal machining • Polishing • Heat treatment	• Annealing • Homogeinization

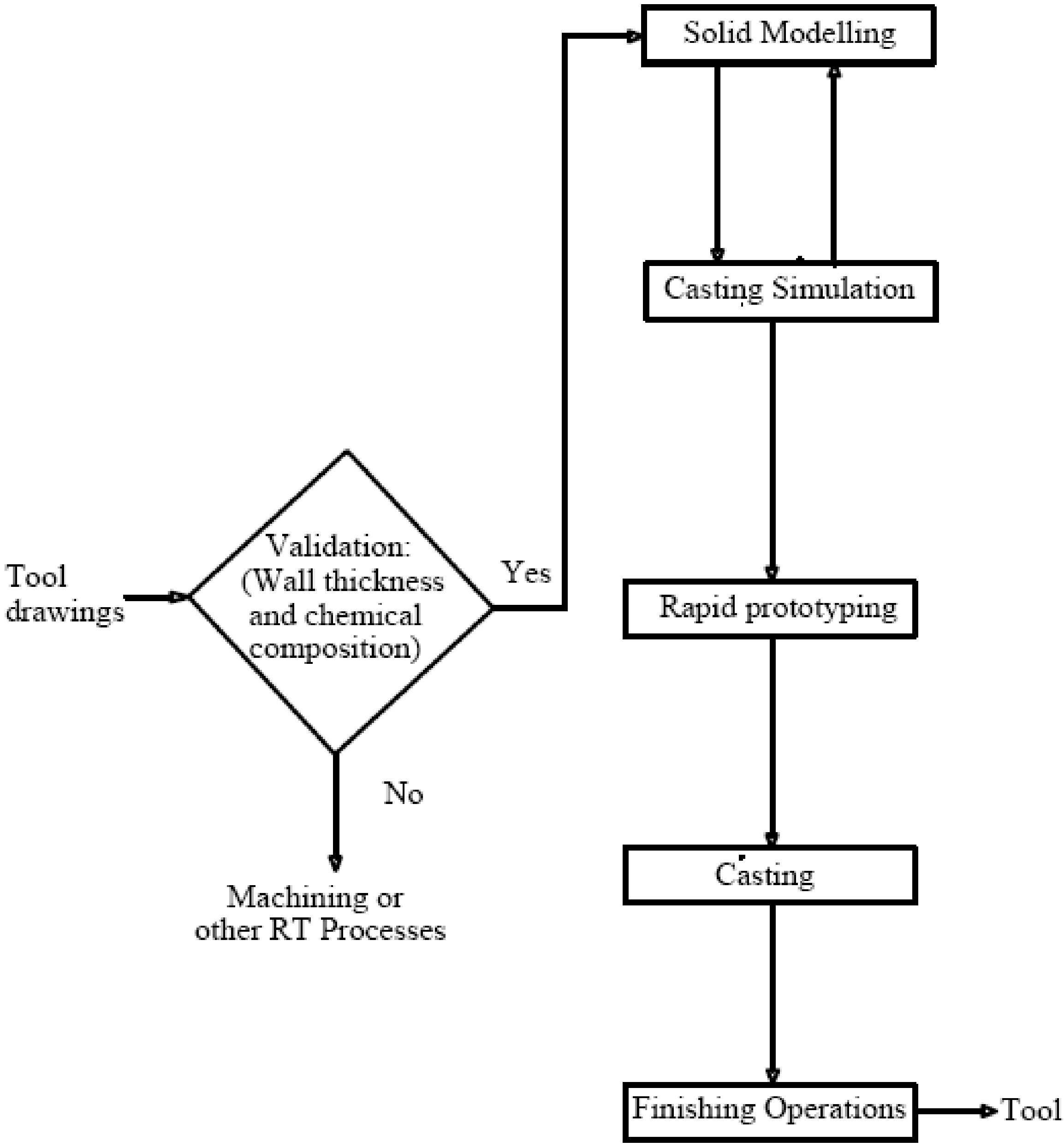

Figure 4.2 *RCT framework diagram showing the two structural pillars: Validation and Process Chain*

4.3.2.1 Solid Modelling

In the solid modelling step, 3D representations of the tool and the mould are created using suitable CAD software. This first step forms the backbone of the RCT process chain ensuring three main functions namely:

i. The input definition for downstream steps
ii. The casting design of the tool
iii. The modelling of the shell or sand mould components.

The downstream steps such as casting simulation and RP require solid models in order to function. The CAD software that will be used should therefore be able to save solid models in a compatible format throughout the process chain thus facilitating exchange between steps and avoiding alteration of the accuracy during transfer. STL format can be one such format.

Casting design consists of the modification of the original tool design to incorporate contraction allowance and filleting. Casting section transitions are also carefully examined and altered if necessary to avoid contraction defects such as hot spot and hot tears. Finally the modelling of mould or shell follows soon after the casting design. Here shell and mould cavities are generated from the 3D drawings. This will include the drafting of the sand mould features namely cope and drag cavities, parting line, core with its support (or print), gating and feeding system.

The solid modelling of the metallic tooling and the shell and mould components are saved as STL files to be used at the casting simulation and RP stages. The casting simulation step needs to be completed before the RP manufacturing of the mould can start. There is an iterative loop connecting casting simulation and solid modelling. Ideally this loop ends as soon as the casting simulation confirms that the design is satisfactory with no defect expected during the metal casting step.

4.3.2.2 Casting Simulation

Casting simulation is carried out for two reasons including ensuring defect-free casting, i.e. devoid of shrinkage cavities, solid inclusions and oxidation and a reduction of manufacturing time by eliminating the reliance on trial and error. These two elements of the casting simulation provide cost advantage for RCT because of the “right first time” approach philosophy.

The following steps are followed during RCT casting simulation to ensure product quality:

i. Import the appropriate casting model from solid modeling
ii. Carry out solidification and mould filling analysis to determine the location of the last freezing region and the possible flow pattern likely to cause turbulence and splashing
iii. Select the correct riser unit and gating system to attach to the mould
iv. Repeat casting analysis to check efficacy of the procedure
v. If turbulence, splashing and shrinkage persist modify the feeder unit
vi. Verify new feeding design until elimination of all problems
vii. Send STL file to solid modelling step for modification of mould and casting design. This is shown in Figure 4.2 by the double arrows between the solid modelling and the casting simulation steps.

4.3.2.3 Rapid Prototyping

RP step constitutes the moulding stage of RCT. No pattern is required as sand moulds and shells are produced directly layer-by-layer from the STL file obtained in step 1 and 2. Processes such as DCLSP or DSPC can be used to manufacture sand moulds and refractory shells for metal casting in RCT. The moulds and shell are coated in order to improve the surface finish of the castings.

4.3.2.4 Casting

The casting stage of RCT combined three steps of the traditional casting production flowsheet (Figure 4.1) including metal melting, casting and fettling. The suitable alloy specified in the tool material is melted in a furnace. The liquid metal is poured in the sand mould or shell and feeds by gravity. The casting is fettled to remove the gating and feeding components then sand blasted to a rough tool.

4.3.2.5 Finishing Operations

In this last stage of RCT, the near-net cast tool is brought to the required final dimension and surface finish. This is achieved by minimal machining and polishing that form part of the finishing operation step. This step also includes possible heat treatment in order to improve the mechanical properties and durability of the tool by altering the internal metallurgical structure of the tool.

4.4 Assessment of RCT

Now that the RCT conceptual framework has been presented and described, it is necessary to critically discuss how it addresses the requirements mentioned in the Introduction. In particular, a theoretical assessment of the manufacturing time and cost, the overall implementation cost, the tooling quality in terms of the surface finish and the dimensional accuracy need to be performed. The user-friendliness of the process will also be determined in order to establish if RCT can compete with CNC machining and other existing RT processes for metallic tooling.

In the RCT analysis that follows below only the RP and metal casting steps are considered because they have the biggest impact on the manufacturing time and cost as well as the tool quality when RCT is compared to other tool manufacturing processes such as CNC machining and RT. The other RCT steps that are solid modelling, simulation and finishing operations are also found in some form or another in other tool manufacturing processes.

4.4.1 Manufacturing time

RCT manufacturing time will essentially depend on the RP step which is the rate determining step generally measured in terms of days while the metal casting that consists of melting and pouring of casting is measured in hours. Pouring is controlled by the Bernoulli equation (Campbell, 2004) and generally expressed in time of the order of second. The melting time will be a function of the type of the melting furnace used and will be controlled by conduction, convection and radiation equations of heat transfer. The RP manufacturing time is a function of the size of the component to grow and the scan speed of RP equipment.

RCT is an indirect tooling manufacturing technique. In this case a mould or shell is grown to form the casting cavity. It can therefore be expected that it is quicker to build the shell or the mould than it is to grow the part itself. In this sense RCT will be quicker than direct tooling and machining. Correspondingly, RCT is expected to be faster than investment casting because there is no need for pattern manufacturing. Even in the case where lost wax patterns are produced by AM, RCT provides better time-saving because the shell is manufactured by RP instead of the usual and time-consuming procedures of dipping in refractory slurry. This was demonstrated by a study (Wirtz & Freyer, 2000) that compared the investment casting of shells by LS to traditional investment casting using RP patterns.

4.4.2 Manufacturing cost

The RCT manufacturing cost is mainly driven by the AM stage that is more expensive than the melting and casting stages. The melting cost factors are listed in literature (Ravi, 2005) and include energy and labour costs. Of importance is the energy cost that will be a function of the type of furnace used and the superheat required. In general electrical furnaces are cheaper and more environmentally friendly than fossil fuel furnaces based on coke or natural gas (Brown, 1999). Regarding the superheat necessary for good metal fluidity, the larger the superheat, the more the energy required, hence the higher will be the energy cost.

The cost of RP is determined by the technology used, whether LS or 3DP. Because of the use of a laser, the manufacturing cost with the LS is generally higher than with 3DP. Laser usage time is the costing basis used when using LS. The reason for this practice is that the laser components have a limited lifetime and need to be replaced frequently.

Many studies on the benefits of direct or indirect RT (Monroe, 2006, Buijs, 2005 & Argrwala et al, 2000) seem to indicate that AM of tooling is cheaper than machining. Cost savings of 50% are often reported by companies offering tooling manufacturing services (Rosochowski& Matuszak, 2000). This advantage of AM is likely to be extended to RCT over machining.

Studies have also shown that for a lower number of parts direct manufacturing of mould and shell considerably decrease the overall cost of metal casting compared to casting processes that require patterns (Ederer, et al, 2005 & Jacobs et al., no date). RCT has been designed for the production of single component and therefore this benefit applies when compared with traditional metal casting processes for tooling.

4.4.3 Tool quality

The tool quality refers to the mechanical characteristics, the dimensional accuracy and the surface finish of the final metallic tooling. All the RCT steps from CAD to finishing operations will influence the tool quality.

4.4.3.1 Mechanical properties

The mechanical properties which include ductility, elongation and hardness are all affected during the solidification of the casting. The factors that affect the cast structure and subsequently the properties are well explained in foundry technology textbooks (Beeley, 2001& Campbell, 2003). They include the cooling rate, the microstructure, the alloy chemical composition, the presence of inclusions and shrinkage porosity, etc.

The prediction of these defects and the necessary preventive measures to avoid their occurrence is made during the casting simulation step of RCT. In particular shrinkage and oxide inclusions can be eliminated by proper design of the gating and feeding systems.

It is possible to produce sound castings of superior mechanical properties making the final tooling superior to tooling obtained by direct tooling that generally suffer from porosity causing low durability (Song et al, 1997). Machining will generally produce part of superior mechanical properties than as-cast part.

4.4.3.2 Dimensional accuracy

Dimensional accuracy will depend on solid modelling and the RP steps. In the RCT description, it was explained that contraction allowance are included during the solid modelling in order to compensate for the metal shrinkage during solidification. On the other hand the accuracy of AM will be a function of the technology used. Studies have been conducted to compare LS of sand parts and the 3DP process found that LS was in general more accurate than 3DP (Dimitrov et al, 2004). Hence, dimensional accuracy will be comparable to RT processes but inferior to machining.

4.4.3.3 Surface finish

The surface finish of the final metallic tooling will be a function of the mould surface smoothness. In the study mentioned above (Dimitrov et al, 2004) the surface finish of LS parts is compared to that of 3DP parts. It was found that LS produced better surface finish. With the use of mould coating, it is possible to improve the surface finish of RP moulds and shells and produce a final tool with an improved surface finish compared to a RT part. However the surface finish of machining will always be superior.

4.4.4 Ease of use and learning curve

The AM process is easy to learn. Once the CAD modelling is completed, the file is sent to the RP machine where the part is grown with limited human involvement. RP set-up requires no programming. In addition the process is automatic and environmentally friendly. These benefits of RCT confer its advantages over CNC machining and ordinary metal casting.

4.4.5 The overall implementation cost

Since their introduction a decade ago in most developing countries, the cost of RP processes have been in free fall and lower than complete installation of machining centres. As such RCT is expected to be cost effective to implement. An additional advantage of RP of refractory moulds and shells is that they can also be used for the production of casting, thus having a dual role in foundries.

4.5 Conclusion

In this paper the RCT framework has been conceptually described, explained and assessed. It is made up of a validation stage to determine if a tool can be manufactured by RCT based on its chemical composition and its minimum wall thickness. This is followed by the RCT process chain itself consisting of five steps including CAD modelling, casting simulation, RP, metal casting and finishing operations. The casting produced at the end constitutes the metallic tool that can be used in mass production processes of finished goods such as metal casting and injection moulding. As such RCT is an alternative tool and die making process along with CNC machining and RT.

From the theoretical assessment, an appreciable understanding of RCT in terms of factors influencing the manufacturing time and cost as well the precision of casting has been gained. It was found that RP and metal casting were the two pillars of RCT with profound impact on the characteristic of the final tooling. Benefits of these two steps comprising amongst other time compression, low manufacturing cost and good quality of parts are extended to the entire RCT process chain, thus providing its potential advantages compared to conventional tool and die making processes. In future publications, these advantages will be evaluated using experimental case studies.

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CHAPTER 5

A CASE STUDY OF ADDITIVE MANUFACTURING PROCESS SELECTION FOR A CASTING APPLICATION USING THE ANALYTIC HIERARCHY PROCESS

Abstract

Purpose – The objective of this paper is to select the more suitable Additive Manufacturing (AM) process between two alternatives, namely the Direct Croning process and the Z-Cast process. The chosen process is to be used to produce sand moulds for the casting of metallic tools and dies.

Design/ methodology/approach - The Analytic Hierarchy Process (AHP) is used as the selection method. The AHP criteria included four mould requirements that are surface finish, dimensional accuracy, manufacturing time and cost.

Findings - The weights obtained after the ranking of these four criteria were respectively 42%, 42%, 11% and 5%. The pairwise comparisons of the two AM processes with regards to each of the criterion were carried out using available results of recent AM benchmarking studies. The Direct Croning process was found to be superior to the Z-Cast process. The overall preferences for these two alternatives were respectively calculated at 73% and 27%.

Originality/ Value – The AHP has proven to be an effective method for the selection of the most suitable Additive Manufacturing processes for a specific casting application.

Keywords - Additive Manufacturing, Direct Croning Process, Z-Cast Process, Analytic Hierarchy Process, Benchmarking

Paper type - Research paper

Paper status: Published

5.1 Introduction

One of the applications of Additive Manufacturing (AM) processes also known as Rapid Prototyping (RP) processes to metal casting is the direct fabrication of sand moulds and shells (Lerner et al, 2002). Currently two main technologies are used namely Laser Sintering (LS) and the Three Dimensional Printing (3DP). In the LS process, foundry Shell sand is sintered with the aid of heat generated by a laser beam. 3DP on the other hand makes use of a refractory material that is aggregated by the selective deposition of a chemical binder through the nozzles of a printing head. Close to ten commercial processes based on LS or 3DP are available on the market and well described in literature (Chua, Leon & Lim, 2003). Many technical characteristics such as layer thickness, scan speed, dimensional accuracy, resolution and maximum part dimensions differentiate the various systems (Pham & Gault, 1998).

Sand moulds and shells obtained by AM processes can be used for several casting applications amongst them, the production of metallic tools and dies for manufacturing processes such as metal casting and injection moulding. This indirect Rapid Tooling (RT) method has attractive potential benefits compared to traditional direct RT and machining processes. Depending on the case at hand, advantages include lower manufacturing cost, high manufacturing speed and good tool quality defined by dimensional accuracy, surface finish and durability. This tool manufacturing method is currently being studied by researchers at the Central University of Technology, Free State in South Africa (Nyembwe, De Beer & Bhero, 2010). The proposed manufacturing framework includes a five steps process chain comprising CAD modeling of the mould, casting simulation, mould production by AM, gravity casting of the tool and finishing operations consisting of minimal machining and heat treatment of the tool.

The initial problem faced in manufacturing tooling by casting in RP sand moulds or shells is the choice for a suitable AM process and within a given AM process class the selection of the right machine. This challenge is due to the proliferation of commercial AM processes and systems on the market (Wolhers, 2009) as well as the large number of technical characteristics to take into account for a specific casting application. Even in the case of the two locally available AM processes, namely the Direct Croning Process (DCP) and the Z-Cast process, choosing which one to use is not always easy because each system has characteristic strengths and weaknesses. In addition all the system characteristics are often to be evaluated together and may include subjective considerations such as customer service and reliability.

Some researchers have proposed benchmarking testing and expert systems to assist choosing the most suitable available AM process (Kim et al, 2008). These methods are however not the best for the AM of sand moulds to be used for the casting of metallic tooling. In this case characteristics such as excellent dimensional accuracy and surface finish as well as low manufacturing cost and short processing time are collectively required from the mould and will be transferred to the cast metallic tool. Benchmarking studies fall short because existing processes are often compared on the basis of single criteria. Expert systems on the other hand have shortcomings of reliance on technical performances provided by manufacturers. Specified performance levels are not always achieved in reality. In addition expert systems require constant database update to include new AM systems.

In this paper the use of the Analytic Hierarchy Process (AHP) based on recent benchmarking results is proposed for selection of suitable AM processes for a casting application. In some way this methodology is a combination of the benchmarking selection technique and expert system taking advantage of each of these selection techniques. The methodology is applied and illustrated in the case of the manufacturing of tooling in sand mould produced by RP. Direct Croning and the Z-Cast processes were compared evaluated. These AM processes are based on LS and 3DP respectively.

The AHP was found to be easy to use and clear. The technique accommodates subjective criteria and speed of execution. It is cost effective and has a general applicability in the face of the frequent introduction of new RP processes. In addition the use of the AHP can allow a better understanding of the AM processes for other casting applications such as the production of prototype casting and direct RT. In the next section a brief description of this technique is provided after the review of existing selection methods of AM processes in order to understand some of their main disadvantages.

5.2 Background

5.2.1 Selection of AM processes

5.2.1.1 Benchmarking Studies

Benchmarking studies can be used to select suitable AM processes and equipment (Dinesh, Pal, & Ravi, 2007; Gill & Kaplas, 2009). In these studies AM processes and machines are compared on various criteria such as mechanical properties, dimensional accuracy, surface finish, manufacturing speed and material costs. In one recent benchmark study (Kim & Oh, 2008); processes and machines that are also used for the manufacturing of sand moulds and shells were compared. It was found that the LS process was superior to the 3DP process with regard to geometric and dimensional accuracy. Error frequencies in LS parts followed a normal distribution with higher number of points coinciding with the original CAD data. The 3DP process was found to be advantageous in terms manufacturing time and manufacturing cost. For the simulation of three different benchmark parts, the 3DP machine used was faster in manufacturing compared to the LS machine. In addition the 3DP process is more amenable to recycling of raw materials than the LS process and therefore material costs are lowered. Recyclable materials are not damaged by the heat as in the case of LS. Some of the data obtained in this benchmarking study are presented in Table 5.1. Other comparative studies of AM processes including the ones available in South Africa corroborate these results concerning the 3DP and LS (Pham et al, 1998). In one of the investigations the surface roughness with LS part was found to be less than 20μm (Dimitrov, et al, 2005).

Table 5.1 Comparison between LS and 3DP

Part Characteristics	**LS**	**3DP**
Dimensional Accuracy (Error distributions) [%]	88 % coincided with CAD data within the error range of ± 0.2mm	63 % coincided with CAD data within the error range of ± 0.2mm
Surface Finish Average Roughness at 0^0 inclination (R_a) [μm]	-	20
Manufacturing Time [hours]	19 - 55	17- 20
Material Cost [$]	30 - 300	310 - 860

Benchmarking studies reveal the real strength and weaknesses of the AM processes. Characteristics of AM are very often different from technical specifications provided by manufacturers. In this respect these comparative studies are very useful. However, a limitation is that only one criterion at a time can be assessed. In cases where multiple criteria are to be considered together, the comparison becomes difficult. Additional disadvantages of benchmarking reported in literature include the time and cost of the studies (Masood & Soo, 2002).

5.2.1.2 Expert Systems

Various expert systems have been developed to assist in the selection of suitable AM processes and systems. Modern expert systems are based on methodologies such as rule based (Masood & Soo, 2002) and fuzzy synthetic evaluation (Lan, Ding & Hong, 2005). A rule based system uses cascading procedures based on decisions from if/then scenario in the main programming codes to select the suitable process and machines depending on the user inputs. The fuzzy synthetic evaluation makes use of complex multi-criteria decision analysis algorithms to evaluate several criteria and alternatives in order to suggest a suitable process and machine. These computer programs possess database application for storage of information on the AM processes, manufacturers, machine models and technical specifications. Graphical user interface allows the interaction between the user and the program.

The advantage of computer programs is the speed and the user-friendliness. However they regularly require updating of software in order to accommodate new processes, machines and manufacturers' technical specifications. Furthermore these expert systems are often black boxes lacking transparency of what is really going on.

5.2.2 Analytic hierarchy process

The AHP is a well known Multi-Dimensional Criteria Analysis method that can be used for comparison and selection of alternatives when faced with multi-variable considerations. This technique has been applied to various fields of manufacturing (Pal, Ravi, & Bhargava, 2007), transportation and telecommunication.

As a scholarly discipline, AHP is well developed and many manuscripts by Saaty, the inventor of this method are dedicated to the subject (Saaty, 2000). The essence of the AHP can be summarised as follows:

i. Modeling of the problem as a hierarchy: The hierarchy contains a goal, the alternatives and the criteria for evaluating the alternatives.
ii. Establishing priorities among the elements of the hierarchy: The pairwise comparisons of the criteria. During this comparison the importance of criteria is determined using the scale shown in Table 5.2. Intensities are allocated based on the judgments or experiences of individuals on a particular topic
iii. Determination of overall priorities for the hierarchy: The information obtained is consolidated in a comparison matrix.
iv. Consistency checking: Consistency of decisions made in previous steps is determined by computing a consistency ratio. This ratio should be less than 10%
v. Final decision: Based on the normalized principal priority vector (Eigen vector) obtained from a comparison as built matrix.

Computer programs assist in the calculations of step 4 and 5 (Expert choice, 1995). For a small number of variables it is possible to use a simple spreadsheet to perform the AHP, which is the case in this paper.

Table 5.2 The Fundamental Scale for Pairwise Comparisons

Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Two elements are equal with regards to the objectives
3	Moderate importance	One element is slightly preferred over another
5	Strong importance	One element is strongly prefer over another
7	Very strong importance	One element is preferred very strongly over another.
9	Extreme importance	One element is dominantly preferred over another
Intensities of 2, 4, 6 and 8 can be used to express intermediate values		

5.3 Methodology

A three steps methodology was adopted in this investigation including:

i. The implementation of the AHP hierarchy and description of criteria
ii. The pairwise comparison of criteria
iii. The ranking of alternatives based on results of benchmarking studies and technical specifications

5.3.1 AHP hierarchy

The AHP hierarchy has been implemented as follows:

i. The goal: Determination of the most suitable AM process between the DCP and Z-Cast process for the manufacturing of sand moulds that will be used for the casting of a metallic tool. The assumption in this case is that the tool material can be cast in DCP and Z-Cast moulds.
ii. The criteria: The dimensional accuracy, surface finish, manufacturing time and cost. The dimensional accuracy represents the deviations of actual mould dimensions to the original CAD dimensions of the mould. The surface finish is the average roughness of the sand mould. The manufacturing time is the total duration to grow a mould including the pre and post- processing. The manufacturing cost essentially includes the material cost for the mould.
iii. The alternatives: At the time of writing up this paper, the only two types of AM processes available in South Africa to produce sand moulds and shell were the DCP at the Central University of Technology in Bloemfontein and 3DP at University of Johannesburg.

5.3.2 The Pairwise comparison of criteria

Table 5.3 shows the criteria pairwise comparison with the accompanying allocation of intensity of importance. The surface finish and the dimensional accuracy criteria have equal importance higher than the manufacturing time and cost. The manufacturing time is in turn more important than the manufacturing cost.

An intensity of 7 has been allocated to indicate the very strong preference for the quality of the mould compared to its cost. On the other hand an intensity of 5 was given to the mould surface finish and dimensional accuracy when compared to the manufacturing time meaning that the former mould characteristics is more strongly favoured than the latter. Mould surface finish and dimensional accuracy will be transferred to the metallic tool and therefore are crucial properties. An intensity of 3 (representing a moderate intensity importance) is allocated to the time criteria compared to the cost. Tool users insist on a quick delivery in order to market new products. Therefore they will accept to pay a premium price for the tool instead of waiting longer.

Table 5.3 Pairwise comparison of criteria

Criteria **A**	 **B**	**More Important**	**Intensity**
Surface finish	Dimensional accuracy	A= B	1
Surface finish	Manufacturing cost	A	7
Surface finish	Manufacturing time	A	5
Dimensional accuracy	Manufacturing cost	A	7
Dimensional accuracy	Manufacturing time	A	5
Manufacturing cost	Manufacturing time	B	3

5.3.3 Alternative comparison

Table 5.4 shows the pairwise comparison between the DCP and the Z-Cast with regard to each criterion; surface finish, dimensional accuracy, manufacturing time and cost. Recent benchmarking studies mentioned in the Background section of this paper have been used to allocate the intensities. The DCP is better than the Z-Cast process with regard to the quality of the tool in term of surface finish and dimensional accuracy. An intensity of preference equal to 5 has been used to indicate the superiority of the DCP. On the other hand the Z-Cast scored higher in terms manufacturing cost and time. For these criteria preference intensity equal to 5 was used.

Table 5.4 Pairwise comparison of criteria

Criteria	**Better Process**		**Intensity**
	DCP	Z-Cast	
Surface Finish	X		5
Dimensional Accuracy	X		5
Manufacturing Time		X	5
Manufacturing Cost		X	5

5.4 Results and Discussion

Table 5.5 shows the weights of the four criteria considered. Details of weight calculations can be found in Appendix 5.1. The results indicate that 84% of the goal weight is on surface finish and dimensional accuracy while the remaining 16% is shared between the manufacturing time (11%) and the manufacturing cost (5%). A consistency ratio of 2.8% was obtained (http://www.cci-icc.gc.ca/tools/ahp/index_e.asp).

Table 5.5 Criterion weights

	A	**B**	**C**	**D**
Weights	0.42	0.42	0.11	0.05
A = Surface finish B = Dimensional accuracy C = Manufacturing time D = Manufacturing cost				

Table 5.6 shows the weights of the two alternatives with regards to each criterion. Details of the mathematical processing involved are presented in Appendix 5.2. It can be seen that for the mould (casting) quality the DCP has a local priority of 83% while the Z-Cast process has a weight of 17%. However with regards to manufacturing time and cost it is the opposite whereby DCP has a local priority of 17% while the Z-Cast has a weight of 83%.

Table 5.6 Weights of alternatives

	DCP	Z-Cast
Surface Finish	0.83	0.17
Dimensional Accuracy	0.83	0.17
Manufacturing cost	0.17	0.83
Manufacturing time	0.17	0.83

From the foregoing the overall preferences for the two alternatives have been determined in Appendix 5.3. The DCP scored 73% while the Z-Cast process only scored 27%. Figure 5.1 shows the complete AHP with all the weighted scores of criteria and alternatives. The end results indicate that the DCP is better than the Z-Cast process for the casting application at hand.

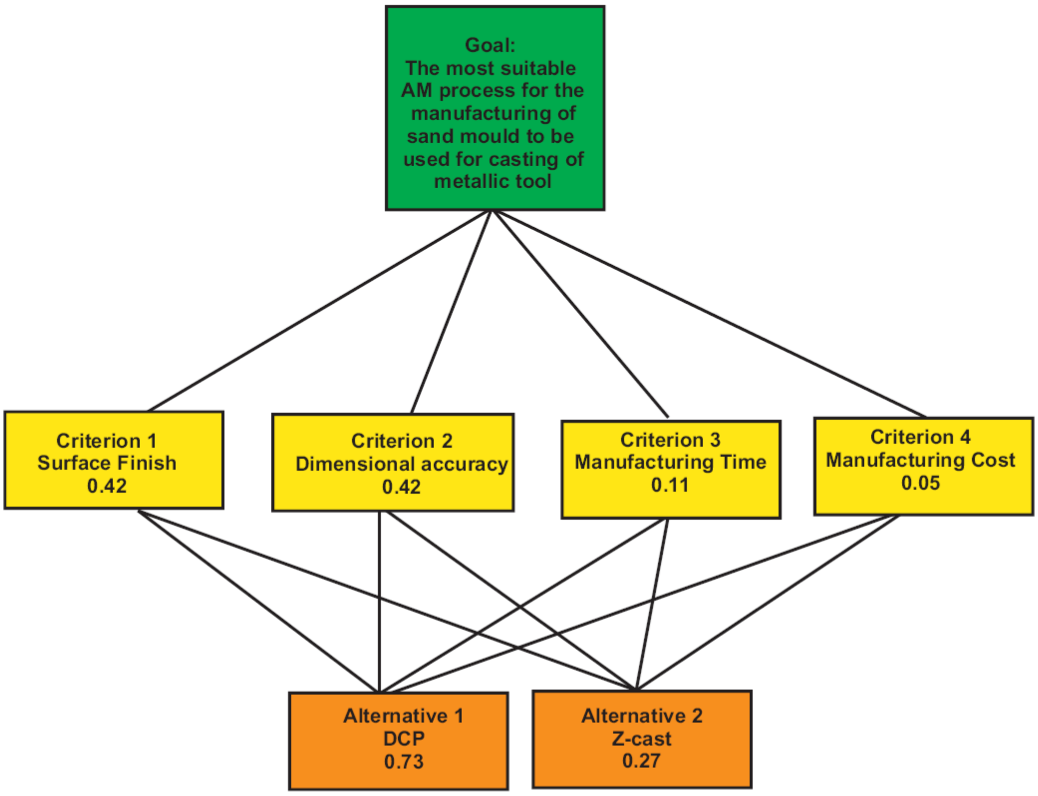

Figure 5.1 *AHP with weights of criteria and alternative*

Two reasons explain the final overall preferences obtained. First is the fact that the dimensional accuracy and surface finish were ranked higher than the manufacturing time and cost. This ranking is specific to the casting application at hand. These mould characteristics are critical requirements in order to obtain a good metallic tool. However, they will not necessarily be the dominant factors for other casting application where the mould manufacturing time and cost can be more important. Second the LS scored higher for the high ranking criteria compare to the 3DP according to the benchmarking studies used.

5.5 Conclusion

In this paper AHP was applied for the selection of two AM processes to produce sand moulds to be used for the casting of metallic tooling. The choice was made possible because of the mathematical quantification of AM process preferences. Through this exercise a better understanding of the available processes has also been gained in relation to of their strengths and weaknesses. Because of its simplicity and transparency as illustrated in this investigation, AHP can be used for the selection of AM processes in the cases where various methods can be employed for complex metal casting applications. Thus the AHP saves the foundryman time and money for conducting experimental trials. However, one of its limitations is that the final results very much depend on the human inputs in the rankings of criteria. To that end future work will consist in conducting surveys amongst foundrymen in order to obtain optimum ranking of criteria. Additional AM processes and systems not available locally are also considered for the construction of a bigger AHP hierarchy.

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Appendices

Appendix 5.1 Determination of criterion weights

Table 5.1.1 Preference on criteria

	Surface finish	Dimensional accuracy	Manufacturing cost	Manufacturing time
Surface finish	1	1	7	5
Dimensional accuracy	1	1	7	5
Manufacturing cost	1/7	1/7	1	1/3
Manufacturing time	1/5	1/5	3	1

Table 5.1.2 Weights on criteria

	Surface finish	Dimensional accuracy	Manufacturing cost	Manufacturing time	Average
Surface finish	0.427	0.427	0.389	0.441	0.421
Dimensional accuracy	0.427	0.427	0.389	0.441	0.421
Manufacturing cost	0.061	0.061	0.056	0.029	0.052
Manufacturing time	0.085	0.085	0.167	0.088	0.106

Each element in Table 5.1.2 is obtained by dividing the entry in Table 5.1.1 by the sum of the column it appears in. For instance the (manufacturing time, manufacturing cost) element in Table 5.1.2 is calculated as: 3/ (7+7+1+3) = 0.167. Values in the Average column are obtained by averaging values in the different rows. The Average column represents the weights of criteria.

Appendix 5.2 Determination of alternative weights

Step 1: Weights of alternatives with regards to each criterion

Table 5.2.1.1 Comparison of RP processes on surface finish

	DCP	Z-Cast
DCP	1	5
Z-Cast	1/5	1

Table 5.2.1.2. **Weights of alternatives with regards to surface finish**

	DCP	Z-Cast	Average
DCP	0.833	0.833	0.833
Z-Cast	0.167	0.167	0.167

Table 5.2.1.3. **Comparison of RP processes on dimensional accuracy**

	DCP	Z-Cast
DCP	1	5
Z-Cast	1/5	1

Table 5.2.1.4 Weights of alternatives with regards to dimensional accuracy

	DCP	Z-Cast	Average
DCP	0.833	0.833	0.833
Z-Cast	0.167	0.167	0.167

Table 5.2.1.5 Comparison of RP processes on manufacturing time

	DCP	Z-Cast
DCP	1	1/5
Z-Cast	5	1

Table 5.2.1.6 Weights of alternatives with regards to manufacturing time

	DCP	Z-Cast	Average
DCP	0.167	0.167	0.167
Z-Cast	0.833	0.833	0.833

Table 5.2.1.7 Comparison of RP processes on manufacturing cost

	DCP	Z-Cast
DCP	1	1/5
Z-Cast	5	1

Table 5.2.1.8 Weights of alternatives with regards to manufacturing cost

	DCP	Z-Cast	Average
DCP	0.167	0.167	0.167
Z-Cast	0.833	0.833	0.833

Step 2 Weights of alternatives

Table 5.2.2.1 Weights of Alternatives*

	DCP	Z-Cast
Surface Finish	0.833	0.167
Dimensional Accuracy	0.833	0.167
Manufacturing cost	0.167	0.833
Manufacturing time	0.167	0.833

* Values in Table 5.2.2.1 rows are obtained from Average column in tables above

Appendix 5.3 Determination of overall weights

Table 5.3.1 Determination of overall weights of alternatives

Appendix 5.1 data	**Appendix 5.2 data**				
A	**B**	**C**	**D**	**E**	**F**
Criterion Weights	**Alternative Weights**				
		DCP	Z-Cast	DCP	Z-Cast
0.421	Surface Finish	0.833	0.167	0.349	0.071
0.421	Dimensional Accuracy	0.833	0.167	0.349	0.071
0.052	Manufacturing cost	0.167	0.833	0.009	0.042
0.106	Manufacturing time	0.167	0.833	0.018	0.088
				0.726	0.274

The results of columns E and F are obtained by multiplying A by C and A by D respectively. The overall weights are summing values in columns E and F

CHAPTER 6

A CASE STUDY OF TOOL MANUFACTURING BY METAL CASTING IN SAND MOULDS PRODUCED THROUGH RAPID PROTOTYPING

Abstract

Purpose - The objective of this paper is the practical implementation of the Rapid Casting for Tooling (RCT) concept using local Computer-Aided Design (CAD) and casting simulation software as well as casting technologies. RCT is a tool making process chain essentially consisting of metal casting in sand moulds produced by Rapid Prototyping.

Design/ methodology / Approach - The production of a sand casting pattern for a high pressure moulding machine is the selected case study used for the implementation of RCT. Technologies employed for the RCT steps include Pro-Engineer software for CAD modeling, Magmasoft software for the casting simulation, Electro Optical Systems (EOS) Laser Sintering for the growing of sand moulds and gravity casting as the metal casting method. The final cast tool was visually examined for casting defects.

Findings – The success of the practical implementation of RCT and the related known-how are closely associated with the casting simulation step on one hand as well as the elimination of exogenous factors linked to workmanship on the other hand.

Originality/ Value – The application of RCT to the production of foundry tooling.

Keywords – RCT, Metal casting, Rapid Prototyping, Sand casting pattern

Paper Type: Case study

Paper status: Prepared

6.1 Introduction

Rapid Tooling (RT) is the application of Rapid Prototyping (Additive Manufacturing) to produce tools and dies used in mass production processes such as metal casting, forging and injection moulding. Several RT processes have been proposed and are well documented in literature (Altan et al, 2001). The advantages of these processes when compared to the traditional tool making by Computer Numerical Control (CNC) machining include short manufacturing time and low cost of production.

Rapid Casting for Tooling (RCT) is one of the RT process chains proposed for manufacturing metallic tools (Nyembwe et al, 2010). It consists of five steps that include Computer-Aided Design (CAD), casting simulation, Additive Manufacturing (AM), metal casting and finishing operations. In this process, the tool or die is basically obtained by casting a suitable metallic alloy in a sand mould produced through an AM process such as Laser Sintering (LS) or Three Dimensional Printing. Potential advantages of RCT over CNC machining comprise an easy learning curve, suitability for producing foundry tooling and low overall processing cost. A study (Nyembwe et al, 2011) conducted on the selection of the best AM system available using the Analytic Hierarchy Process (AHP) shows that the LS process is the best process for RCT when considering four criteria that were manufacturing cost, manufacturing time, dimensional accuracy and surface finish.

This paper investigates a practical implementation of RCT concept using a real case study obtained from the local foundry industry. No experimental trial of RCT has been published so far therefore tool and die makers do not know the technical challenges involved and how to resolve them. For example, the types of defects that are typical in the tool due to casting in sand moulds produced by AM. Thus, the study contributes to the initial development of knowhow and the building of knowledge around RCT.

6.2 Methodology and preliminary considerations

In this section, the case study used for the RCT trial is presented. The experimental procedure of RCT implementation is also described.

6.2.1 Case study

The case study was provided by a local foundry and involved the manufacturing of a sand casting pattern for moulding with a DISAMATIC machine. The pattern layout is shown in Appendix 6.1. This tool will be used as one of the two DISAMATIC machine plates for making greensand moulds for a steel engineering bonnet shown in Figure 6.1. DISAMATIC moulding machines are very popular in South African greensand foundry industry for the production of small to medium size castings. These machines achieve sand compaction by blowing followed by squeezing of the sand between two metallic pattern plates. The resulting sand block is then pushed onto a moving belt for casting (Beeley, 2001).

The pattern material is SG 60 ductile cast iron. Its minimum thickness is 7.8mm which is higher than the recommended 3.2 – 6.3mm minimum wall thickness for cast iron in sand moulds (Beeley, 2001). In addition detrimental metallurgical segregation is generally not a problem in SG cast iron. The plate was therefore suitable to be produced by RCT as its validation conditions on minimum thickness and chemical composition were satisfied.

The maximum dimension of the DISAMATIC pattern plate is 600mm. The mould parts (cope and drag) were too large to be grown as single components on most commercial AM systems. It therefore required partitioning of the mould components. The flat geometry of the tool also required careful design of the gating system and provision for venting to allow complete filling of the mould and escape of the gases. Finally the size and weight of the plate necessitated a strong mould to prevent mould wall movement and loss of casting dimensional accuracy.

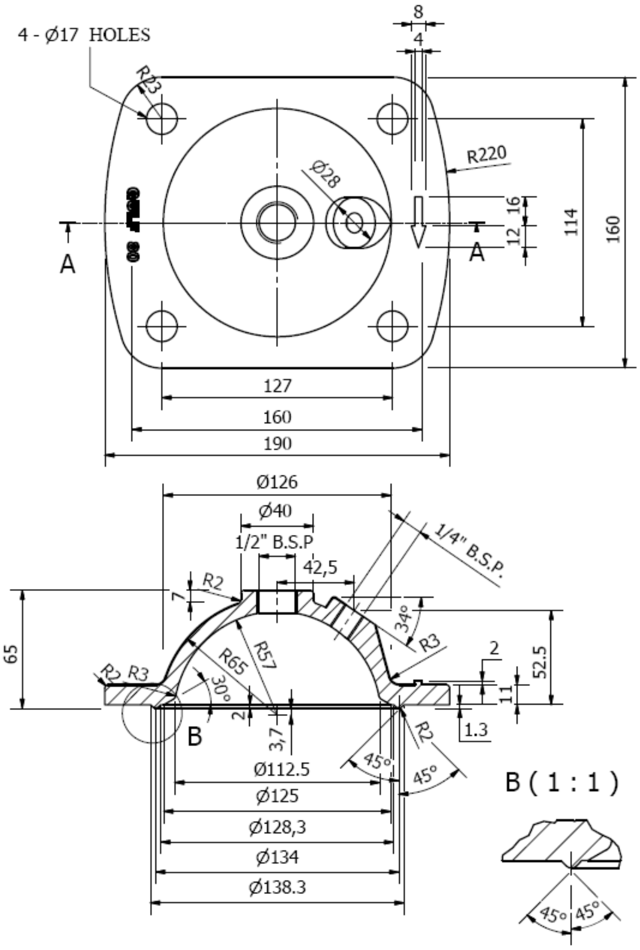

Figure 6.1 *Two dimensional drawing of the steel bonnet to be produced using the pattern to be manufactured by RCT*

6.2.2 Experimental procedure

The experimental procedure followed in the casting trial of the sand casting pattern is summarised in Table 6.1. The entire mould is made of four sand parts that were grown using an EOSINT S700 LS machine at the Centre for Rapid Prototyping Manufacturing (CRPM) at the Central University of Technology, Free State in Bloemfontein. The various sand parts were glued together to form the cope and the drag. The internal cavity of the mould was spray coated to improve the surface finish of the final casting (Figure 6.2). Before pouring the molten metal, the mould was placed in a frame filled with sand and weights were placed on top as shown in Figure 6.3. This was done in order for the mould to withstand the metallostatic pressure of the liquid metal. Gravity casting using a manually operated ladle was employed to cast the metal in the mould.

Table 6.1 Software, equipments and casting parameters used in the casting trial of the sand casting pattern

RCT Steps	Experimental parameters
CAD Modeling (Pro Engineering software: Wildfire II)	- Filleting of designs (default setting of the casting toolbox software) - Shrinkage allowance factor: 1.10 - 10mm machining allowance added
Casting simulation (Magmasoft software)	- Objectives: complete filling of the mould and escape of air during pouring - Iterations: 3
Rapid Prototyping (LS EOSINT S 700 machine)	- Standard operating parameters - Curing of mould parts at 75^0 C - Shell sand (silica)
Metal Casting (Gravity casting)	- Charge: Pig iron + steel scrap - Induction melting - George Fisher inoculation (Magnesium treatment) - Pouring temperature: 1400^0 C
Finishing operation	- Sand blasting followed by fettling for the plate

Figure 6.2 *Drag component of the mould with the internal cavity of the tool to be cast.*

Figure 6.3 *Assembled mould with weights and required inclination (see magnetic angle finder tool) ready to be poured.*

6.3 Results

Figure 6.4 and 6.5 show the casting simulation results in terms of methoding design and fluid flow. An inclination of 15 degree was recommended. Vents were also included. The dimensions of the running, vents and feeding system are shown in Appendix 6.2. Other simulation results on air entrapment, shrinkage and hardness are shown in Appendix 6.3 predicting a sound final casting.

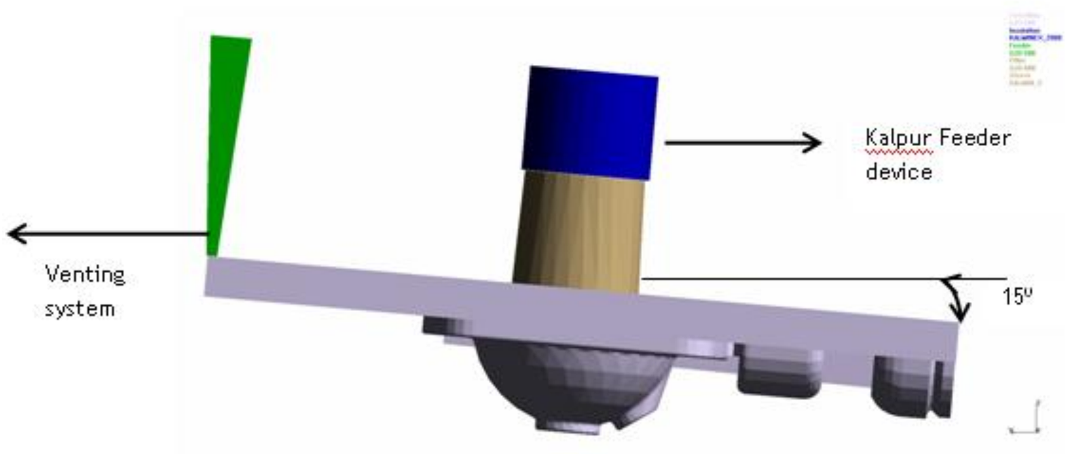

Figure 6.4 *Casting methoding design suggested after simulation*

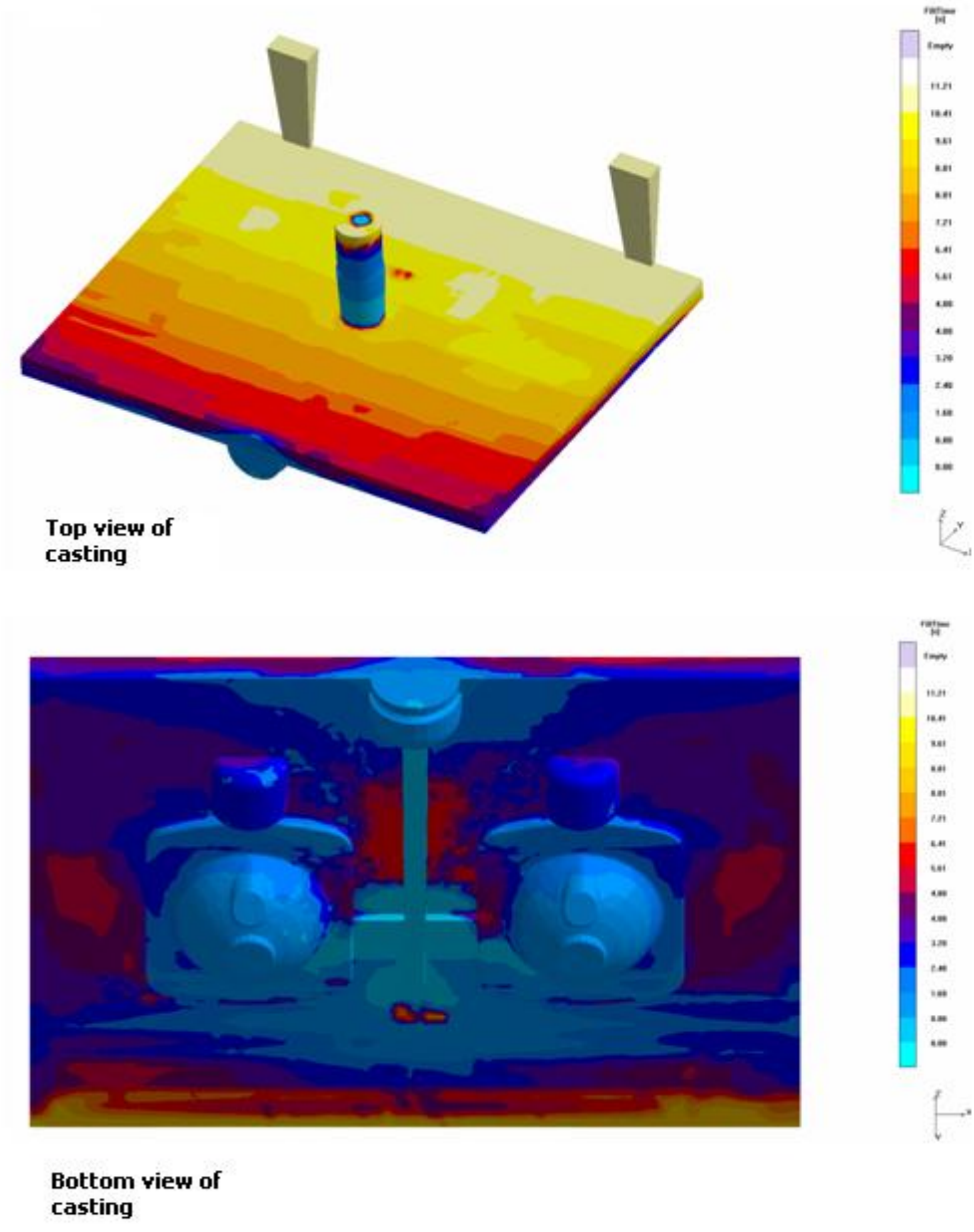

Figure 6.5 *Mould filling results*

Figure 6.6 shows the front view of final sand casting plate. The finishing operations included sand blasting and fettling to remove the casting runners. No machining of the cast pattern was performed. The picture shows the features of the component to be produced as well as the gating and feeding system. The casting picture also shows evidence of defects including:

1. Cold lap mainly visible in the top half of the casting
2. Shrinkage porosity in top right region
3. Vertical alignment fault in the middle of the casting

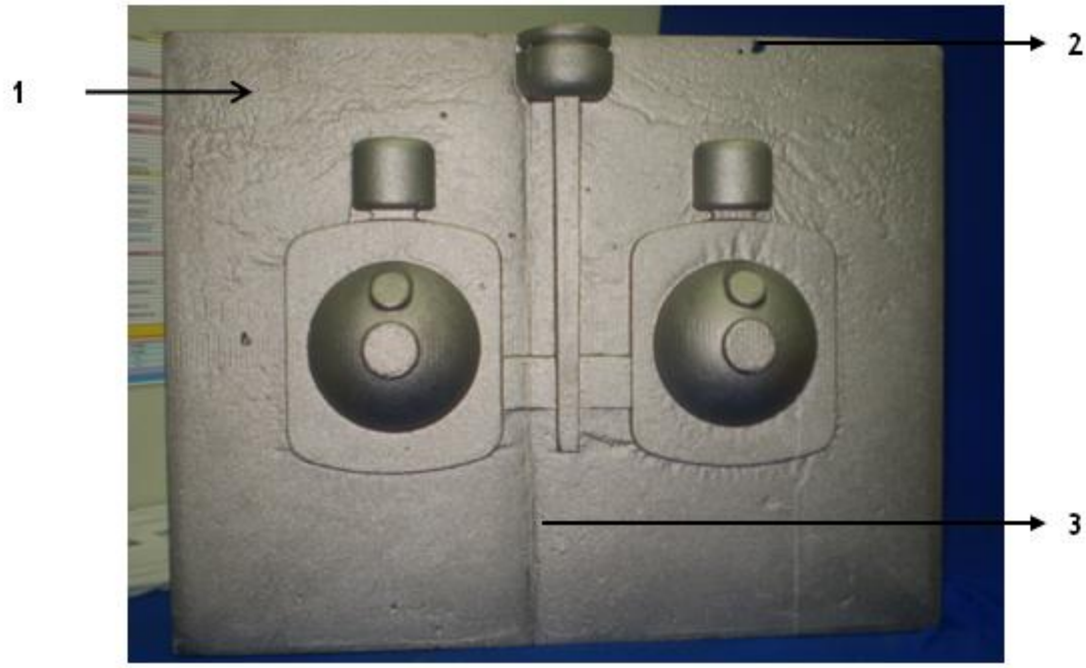

Figure 6.6 *Final casting exhibiting some defects*

6.4 Discussion

Due to the flat geometry of the casting, the simulation results suggest that the mould should be inclined to allow its complete filling. The metal will fill the bottom part of the mould by gravity and as it rises the air escapes from the vents located in the upper section of the mould. Fluid flow results indicate that with such methoding design, it is possible to prevent gas defects due to air entrapment in the casting, shaping faults caused by slow filling due to poor fluidity or inadequate gating system design.

With regards to the final casting, the details of the drawings have been transferred through RCT from the first step CAD to the last step that is casting and finishing operations. Although the transfer involved AM and metal forming by solidification, it is fairly accurate in revealing the intended features that appear on the final cast pattern. The details of the part to be produced were well formed and considered adequate for sand casting.

An unfortunate mould leak occurred during the casting trial. It was due to poor joining of the sand parts during the mould assembly. The leak explains the various defects appearing on the cast tool. The top section was subsequently filled with cold metal, thus the presence of cold lap defect. The feeding system reservoirs could not be adequately filled with molten metal hence the occurrence of shrinkage defects. Finally the poor joining is responsible for the vertical misalignment. The cast tool could be salvaged during machining without losing dimensional accuracy since 10mm machining allowance was provided.

6.5 Conclusions and recommendations

The case study illustrates the practical implementation of RCT using the locally available technologies that included CAD, casting simulation, AM and casting that are combined to constitute an alternative manufacturing of metallic tooling.

Although casting simulation predicts that the casting will be free of defects, this case study has shown that the RCT success also depends on exogenous factors such good workmanship during mould assembly and casting. These stages were found to be the most challenging.

Future work will involve a less complex case study which will investigate in depth economic and quality aspects of tools produced by RCT.

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Nyembwe, K., De Beer, D. & Bhero, S. (2010). A conceptual framework for the manufacturing of tooling by metal casting in refractory moulds and shells produced by Rapid Prototyping. *24th Annual South African Institute of Industrial Engineers Conference*, October 6-8, 2010, Glenburn Lodge, Gauteng, 160-171.

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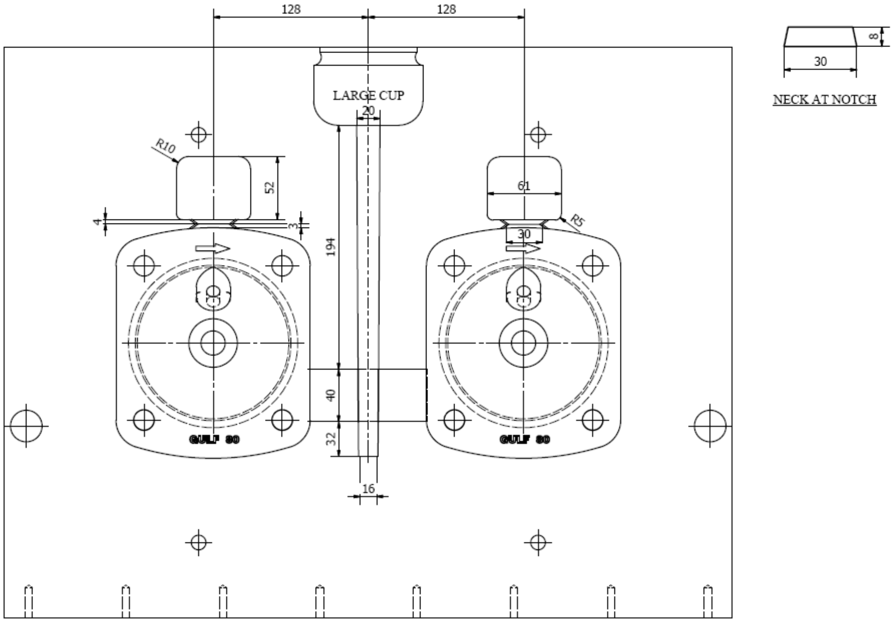
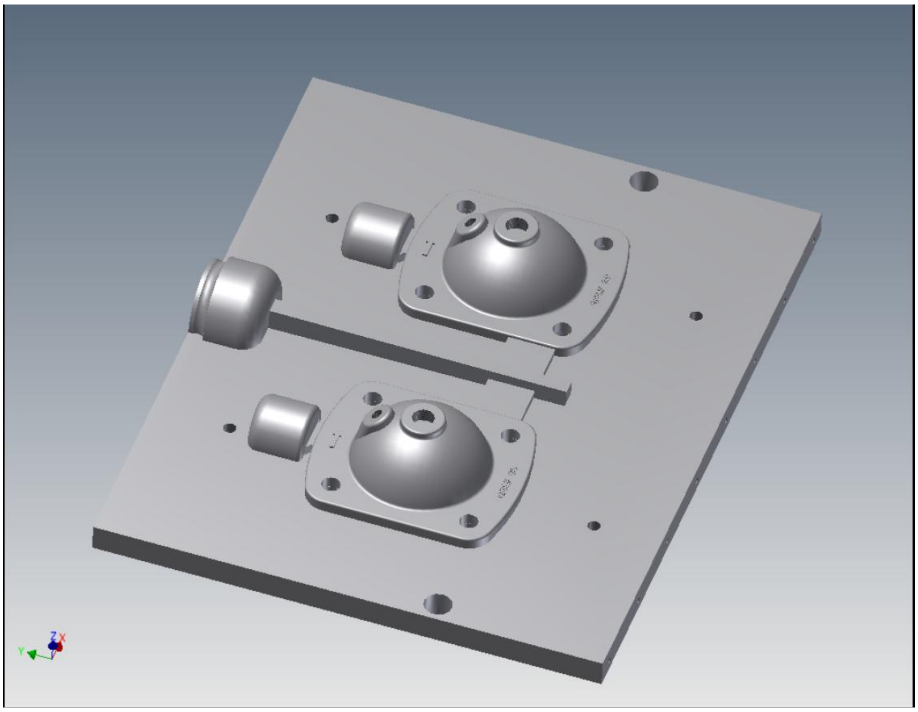
Appendices

Appendix 6.1 2D Layout and 3D model of the plate to be cast





Appendix 6.2 Dimensions of the running, vents and feeding system

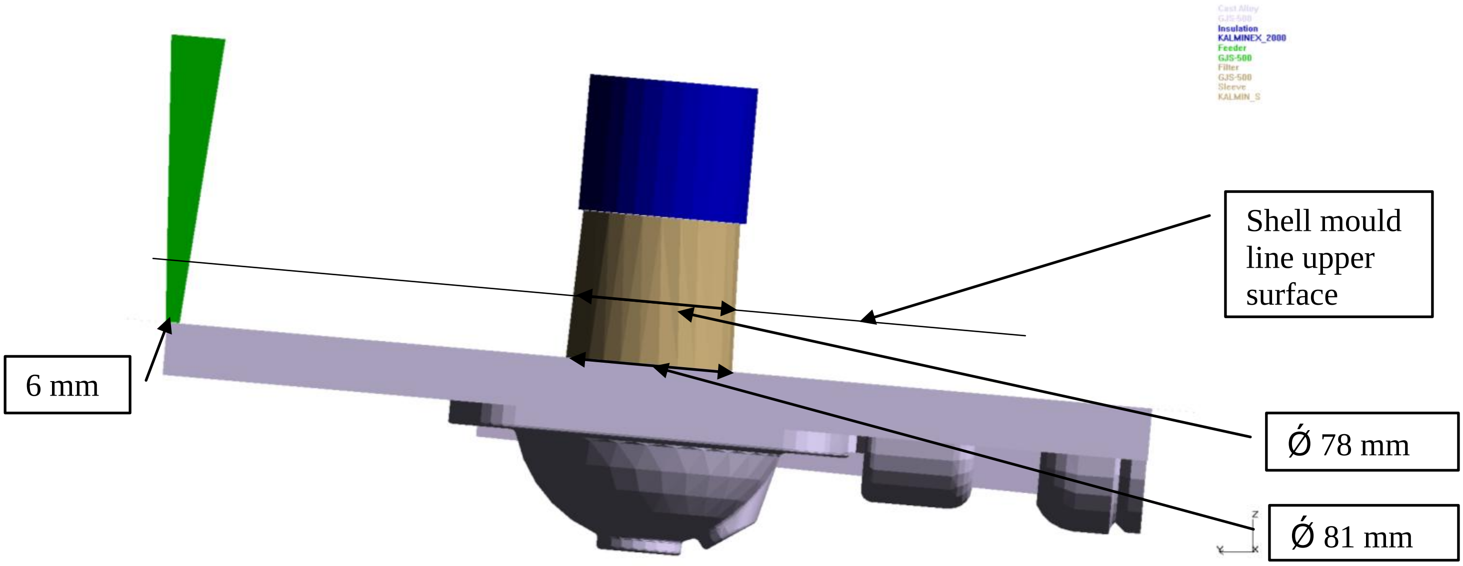


Figure 1, left view

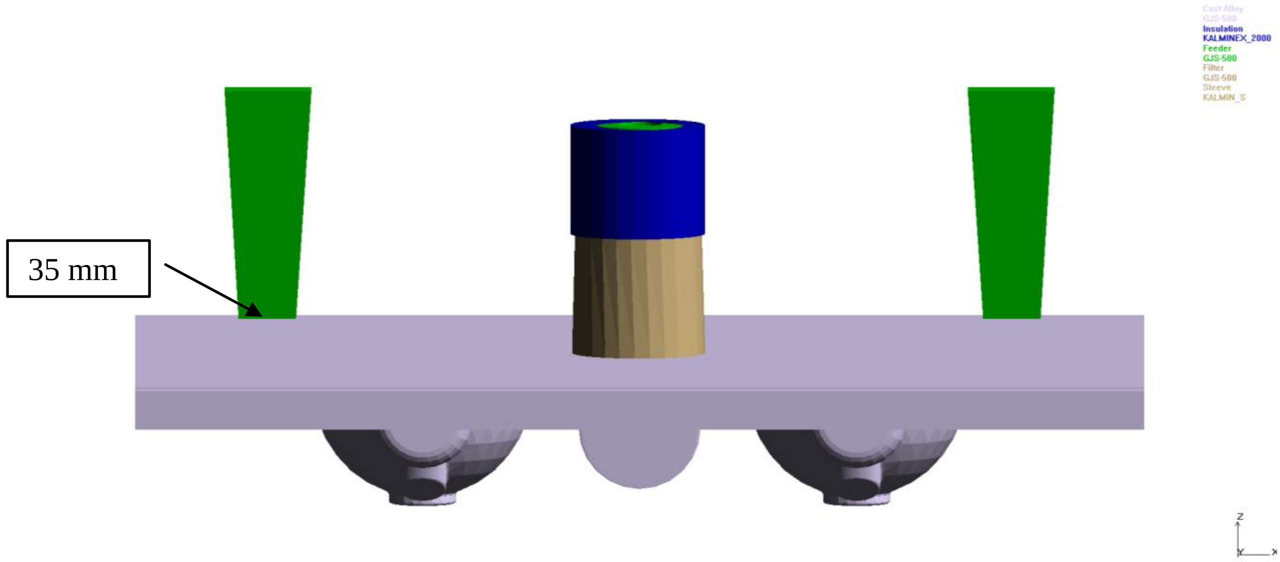


Figure 2, front view

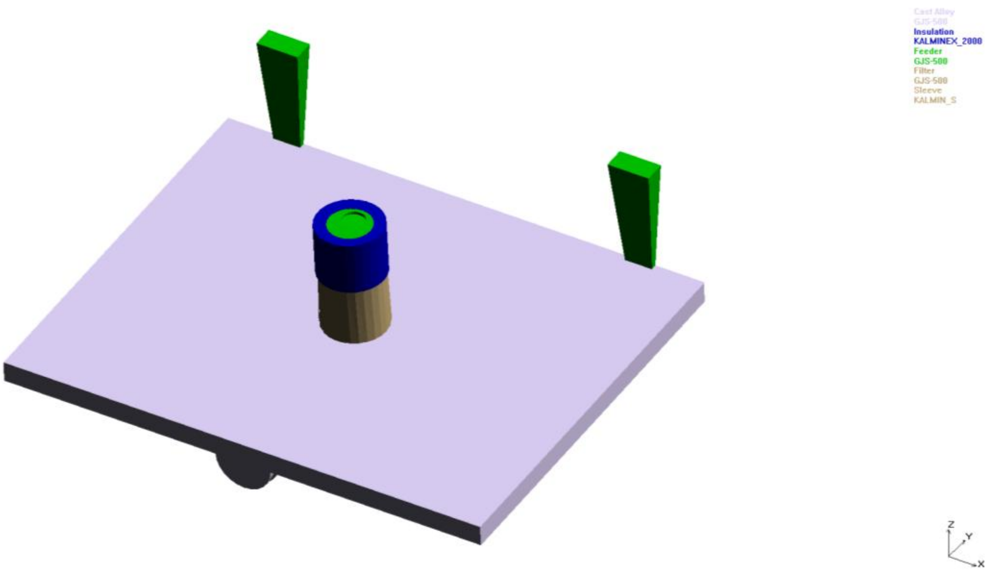


Figure 3, isometric view

Casting Method instructions

- Grennsand mould: Total box size: 890 x 740 x 350 mm. Cope height: 160 mm

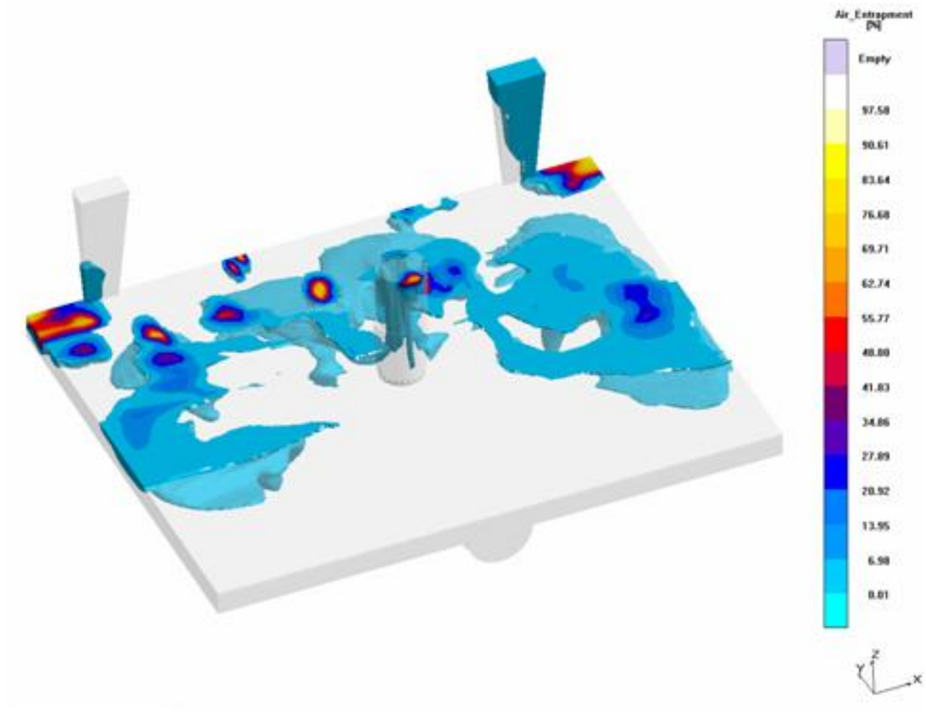
- Feeder size: Kalpur 6/7 with Dia50 x 22mm 10ppi Sedex filter
- Wedge vents to be placed at top of casting as in Figure 1 and 3. Placement of feeder in centre of casting.

- Vent dimensions on casting surface (lower mould surface): 35 x 6 mm (profile is constant)

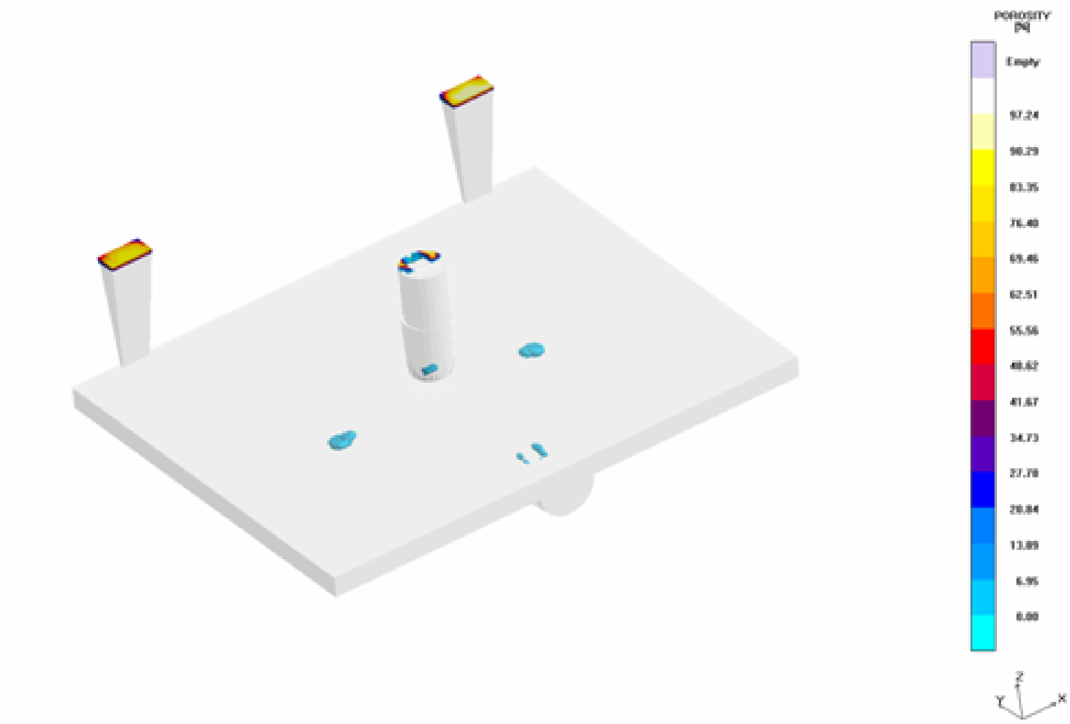
- Riser dimension on mould upper surface = 78 mm
- Riser dimension on lower mould surface = 81 mm

- Pouring temperature 1390 - 1400°C

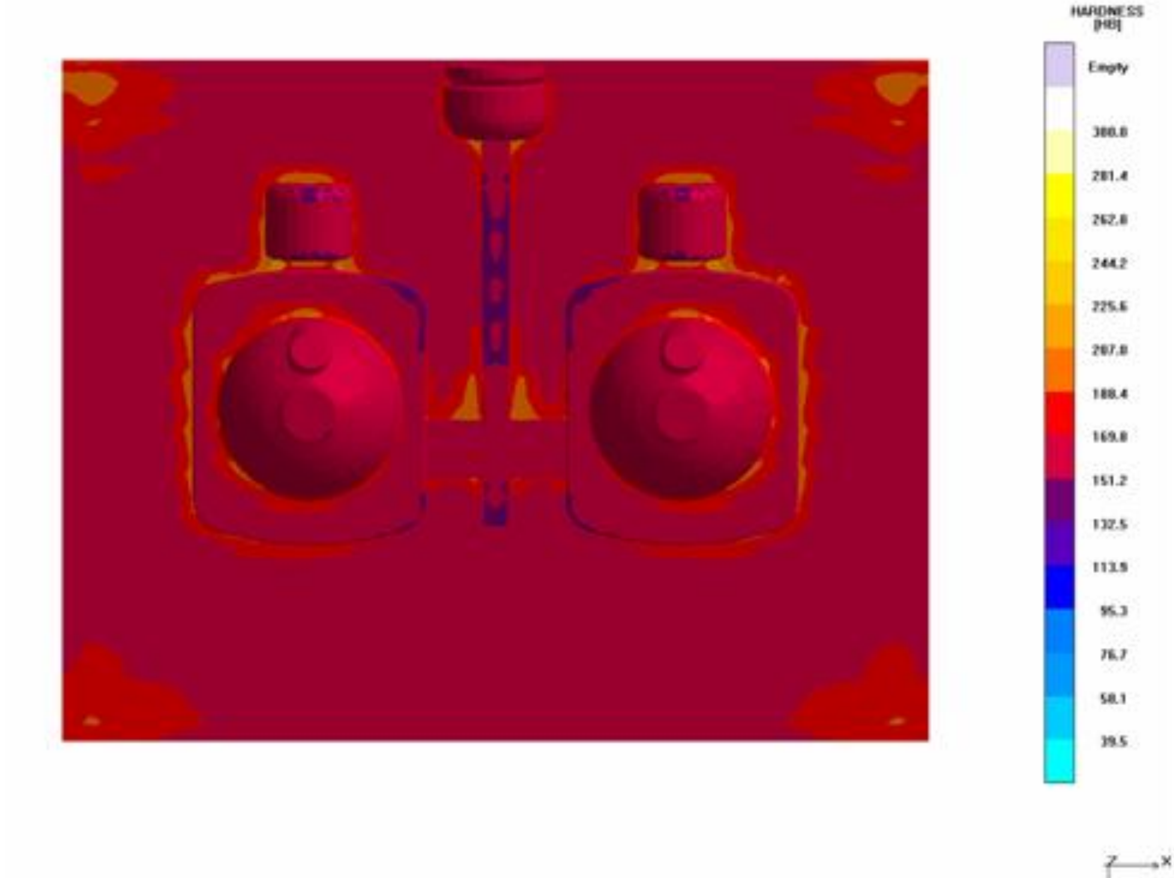
Appendix 6.3 Selected results of casting solidification simulation



Air entrapment at 100% filled, 1 % upwards



1% shrinkage and upward



Casting Hardness

CHAPTER 7

AN ANALYSIS OF THE MANUFACTURING TIME AND COST OF TOOL AND DIE MAKING BY METAL CASTING IN RAPID PROTOTYPING SAND MOULDS

Abstract

Purpose – The objective of this paper is to assess the manufacturing time and cost parameters of tool production by metal casting in additive manufactured sand moulds.

Design / Methodology/ Approach – Foundry tools including a aluminium die for lost wax patterns and a sand casting pattern for a high pressure moulding machine were manufactured according to a five steps process chain including Computer Aided Design (CAD) modelling, casting simulation, Rapid Prototyping, metal casting and finishing operations. The methodology is referred to as Rapid Casting for Tooling (RCT). Duration and cost of each step were recorded and aggregated.

Finding – The paper shows that the Additive Manufacturing (AM) of sand moulds is the cost driver as well as the rate determining step of RCT. In addition it was found that RCT was faster but more expensive than machining and investment casting.

Originality/ Value – Controlling AM of moulds step will go a long way in making the RCT process chain more competitive compared to existing metallic tooling manufacturing processes including machining and the Paris process.

Key words – Tooling, Metal Casting, Rapid Prototyping, CNC Machining, Laser Sintering, Three Dimensional Printing

Paper type – Research paper

Paper status: Submitted

7.1 Introduction

Investment casting is occasionally employed for the manufacturing of metallic tooling. The literature mentions applications of the Paris and Shaw processes for the production of cast dies used for die casting, forging, drawing and extrusion processes (Beeley, 2001). Sand casting process on the other hand is traditionally not considered for the production of metallic tooling. The limitations of this metal casting method in relation to Tool and Die Manufacturing (TDM) mainly stem from the need for a pattern, the fabrication of which is notoriously cost and time consuming. In addition sand cast tools are of relatively poor quality in terms of surface finish, dimensional accuracy and durability compared to processes such as precision casting, machining and Rapid Tooling

In recent times, significant progress has been achieved in sand casting to alleviate some of its shortcomings. Amongst these advances is the use of casting simulation software to predict the properties of the final casting and to prevent defects (Sakuragi, 2005; Fu, et al, 2009). In addition the application of rapid prototyping (RP) or additive manufacturing (AM) processes such as Laser Sintering (LS) and Three Dimensional Printing (3DP) to produce sand moulds directly from Computer Aided Design (CAD) files without the need for a pattern is also an important development in sand casting (Lerner, et al, 2002; Klocke, et al, 2003; Ederer, 2005; Hahn, et al, 2005).

In the LS process a laser beam is used to selectively fuse pre-coated foundry sand particles into a solid part that will become a component of the mould or shell. In 3-DP, the principle is similar to ink printing on a piece of paper from an ink-jet printer. In this case, in a layer-by-layer fashion, a printing head selectively deposits or “prints” binder fluid that fuses the powder particles together in desired areas (Palm, 2002; Chua et al, 2003)

Taking into account the above development sand casting has been conceptually revisited by some researchers as an alternative method for the manufacturing of metallic tools (Figure7.1). In this instance metallic tooling are produced by metal casting in sand moulds obtained by RP processes. The method is referred to as Rapid Casting for Tooling (RCT). It is made of five steps including computer aided design, casting simulation, and rapid prototyping, metal casting and finishing operations The process chain makes provision for a validation stage to determine if a tool is suitable for RCT manufacturing based on its minimum wall thickness and chemical composition.

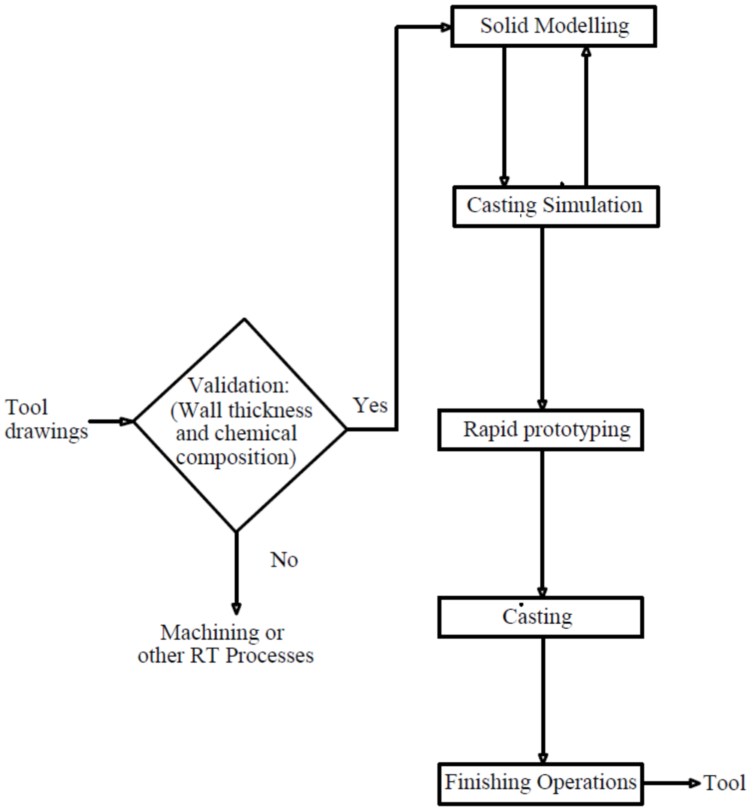


Figure 7.1 *RCT process chain (Nyembwe et al, 2010)*

At the present moment, the characteristics of RCT process chain in terms of manufacturing time and cost have not been investigated and assessed. It is well known that time and cost determine the economic viability of a tool making processes (Altan, 2001). The manufacturing time should be as short as possible in order to allow quick turnaround to market new products. Tool manufacturing cost needs to be as low as possible so as to increase the profit margin of mass production processes of finished goods that use the tools.

In this paper the time and cost parameters of producing metallic tooling in RP sand moulds are assessed by means of case studies. Time and cost of AM processes are also compared to the ones of conventional tool making processes such as CNC machining and investment casting (Paris Process). As such the study intends to provide a preliminary understanding on the competitiveness of RCT

7.2 Methodology

The methodology followed in this investigation was made up of the following tasks:

i. Obtaining suitable case studies
ii. Conducting casting trials using RCT process chain
iii. Recording manufacturing time and cost of the tool produced

Details of each task are provided below.

7.2.1 Case studies

The case studies consisted of the replication of existing tools using the route of casting in RP sand moulds. This approach made it possible to compare experimental cost with the actual ones. The two different case studies were selected on technical grounds including the size, the minimum wall thickness, the range of shape complexity and the material specifications of the tool that had to be suitable for RCT manufacturing and compatible with the available local RP machines and the gravity sand casting possibilities (Table 7.1).Shape complexity is calculated taking into account the volume, the surface area and number of cores required. Details of the mathematical expression and explanation can be found in literature (Ravi, 2005).

Table 7.1 Technical characteristics of tool used for the case studies

	Material specifications	**Minimum thickness [mm]**	**Maximum dimension [mm]**	**Complexity [-]**
Wax pattern die	Al 6082	4.6	203	0.11
Sand casting plate	SG 60	7.8	600	0.25

The case studies were obtained from local foundries. The first case study deals with the manufacturing of an aluminium die for investment casting wax patterns and the second case study was the production of a cast iron sand casting pattern for a DISAMATIC moulding machine

7.2.1.1 Wax pattern die

This tool is used for the production of a wax pattern for the investment casting of a steel automotive bracket (Appendix 7.1). The production die was manufactured by CNC machining in a local tool room. Its actual manufacturing time and cost provided by the foundry are respectively 40 hours and 14 000 Rands. The cheapest local quotation obtained to produce the same tool by investment casting (Paris process) was 10 000 Rands in 120 hours.

7.2.1.2 Sand Casting plate

The pattern is used for the production of sand moulds on a DISAMATIC moulding machine for the casting of a steel engineering bonnet (Appendix 7.2). The production plate was manufactured by CNC machining and assembly at the foundry. The actual manufacturing time is 80 hours at a cost of 20 000 Rand. The cheapest local quotation to manufacture this plate by investment casting (Paris process) was 8 000 Rand in 240 hours.

7.2.2 RCT casting trials

The tool manufacturing trials followed the Rapid Casting for Tooling (RCT) process chain. The latter comprises five sequential steps described below: Local companies assisted in conducting the various steps of the casting experiments. These companies were selected on the basis of the cheapest price and shortest time to execute a task. The best proposal was in the case of CAD, casting and finishing operation selected from three quotations. For the casting simulation step only one quote was obtained because the market is still monopolistic in South Africa dominated by Magmasoft. The Metal Casting Technology Station at the University of Johannesburg and the Centre for Rapid Prototyping and Manufacturing at the Central University of Technology, Free State are the only two institutions offering RP technologies in 3DP and LS respectively.

In total three casting experiments were conducted. The first two produced the aluminium dies using two different RP technologies: 3DP and LS. The third experiment produced the plate by casting in a LS RP mould. Additional experimental conditions are summarised in Appendix 7.3.

7.2.3 Manufacturing time and cost

The manufacturing time is the actual working time devoted to a specific step and recorded during the execution. The manufacturing cost is the invoiced price a particular step provided at its completion.

7.3 Results

The manufacturing time and cost results of RCT steps for the three experiments are respectively shown in Table 7.2 and Table 7.3. Proportions in percentage of the total time and cost of the manufacturing time and cost of each RCT step are shown in Figures 7.2 and 7.3. It can straight away be seen from these tables and figures the importance of the RP step with regard to its contribution to the total time and cost.

Table 7.2 Experimental manufacturing time results

Casting Experiments	**CAD Modelling**	**Casting Simulation**	**RP**	**Casting**	**Finishing Operation**	**Total [hour]**
Wax Pattern Die (SLS)	5.5	5	24	1	1	36.5
Wax Pattern Die (3DP)	5.5	5	16	1	1	28.5
Sand Casting Plate	6.5	9	48	2	2	67.5

Table 7.3 Experimental manufacturing cost

Casting Experiments	**CAD Modelling**	**Casting Simulation**	**RP**	**Casting**	**Total [Rand]**
Wax Pattern Die (SLS)	790	2280	12000	2000	17070
Wax Pattern Die (3DP)	790	2280	8000	2000	13070
Sand Casting Pattern	910	5700	40000	3032	49642

7.4 Discussion

7.4.1 RCT manufacturing time and cost

The growing of the sand mould by RP is the slowest step and therefore RCT rate determining step (Figure 7.2). This step contributed 54% to 73% of the total RCT time respectively for the die manufacturing using the Spectrum 510 printer and the sand casting plate using the EOSINT LS machine. In the case studies conducted layer-by-layer manufacturing is slower possibly because of the processes technical limitations.

Furthermore in all cases the manufacturing of sand moulds by RP is the most expensive step therefore RCT cost driver. This step contributed 61% to 78% of the total RCT cost respectively for the die manufacturing using the Spectrum 510 printer and the sand casting plate using the EOSINT LS machine. A possible reason for the expensiveness of the RP step is the newness of the AM processes and the lack of competition with regards to providing RP services locally.

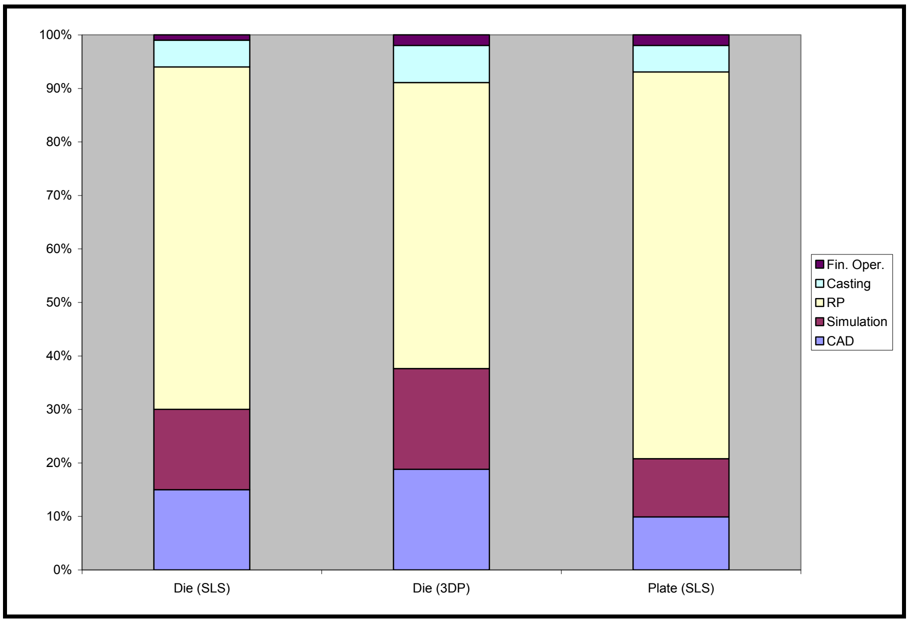


Figure 7.2 *Contribution of RCT steps to the final manufacturing time*

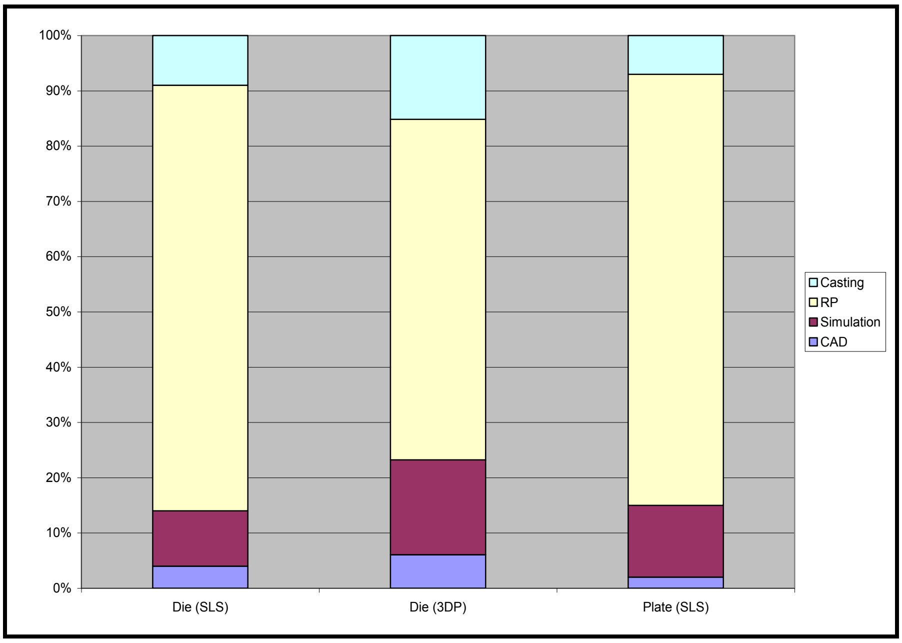


Figure 7.3 *Contribution of RCT steps to the final manufacturing cost*

7.4.2 Comparison of RCT with casting and machining

Figure 7.4 shows the comparison in terms of manufacturing time of RCT process chain versus machining and metal casting for the case studies conducted. RCT is the fastest process chain. A manufacturing time improvement of 68% to 72% can be obtained compared to metal casting and 6% to 18% versus machining. Casting was the slowest process chain because of the required manufacture of a pattern prior to casting. On the other hand machining was slower than RCT possibly because of the intricacy of the case study tools.

Figure 7.5 shows the comparison of manufacturing cost of RCT process chain versus machining and metal casting for the case studies conducted. It can be seen that RCT is most expensive when compared with casting and machining. RCT was respectively 124% to 453% and 60% to 176% more expensive than metal casting and machining. The possible reason for this finding is the expensiveness of RP processes as mentioned earlier. Manufacturing of tooling by metal casting appeared to be extremely undervalued.

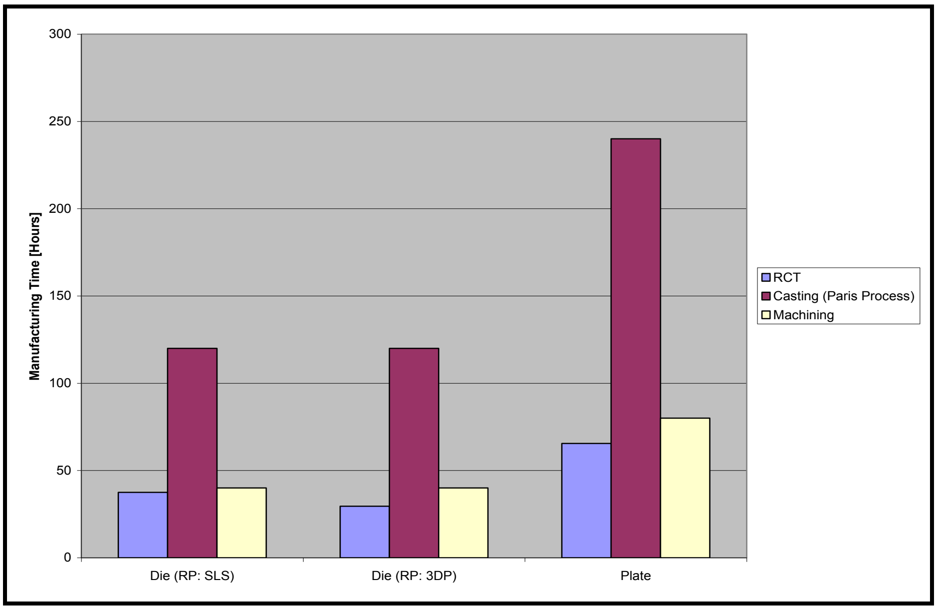


Figure 7.4 *Manufacturing time comparison between RCT and other tool manufacturing processes*

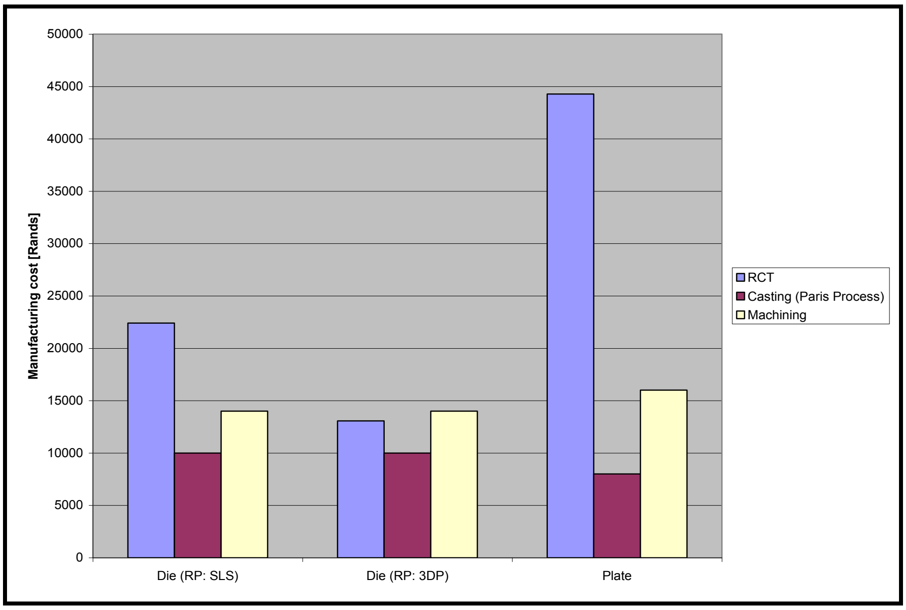


Figure 7.5 *Manufacturing cost comparison between RCT and other tool manufacturing processes*

7.5 Conclusion

In this investigation, three casting trials were carried out to understand the manufacturing time and cost of producing metallic tooling in RP sand moulds. Two main findings were obtained from these experiments using locally available technologies:

1) The manufacturing of sand moulds by RP was found to be the rate determining and cost driver step.
2) The proposed tooling manufacturing was found to be faster than machining and metal casting (Paris process) but more expensive.

In the present situation these results are important for future optimisation work to make the manufacturing of tooling in sand moulds produced by RP processes faster and cheaper than other tool manufacturing processes such as machining. This will be achieved by concentrating the effort to minimise the cost and time of the AM of sand mould step as it is the one that has been identified as strongly controlling the cost and delivery time of the final tool.

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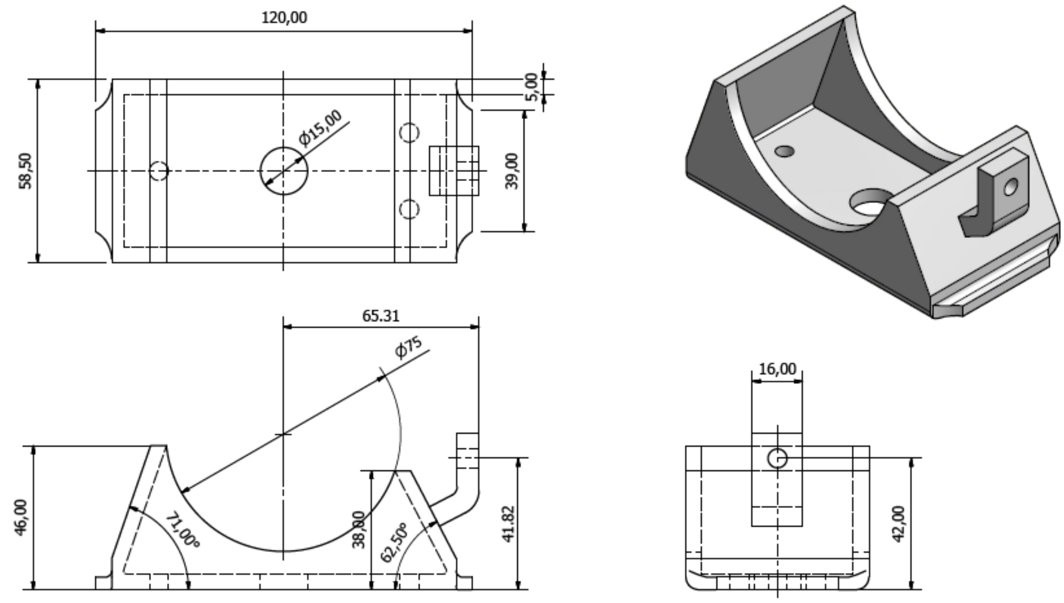
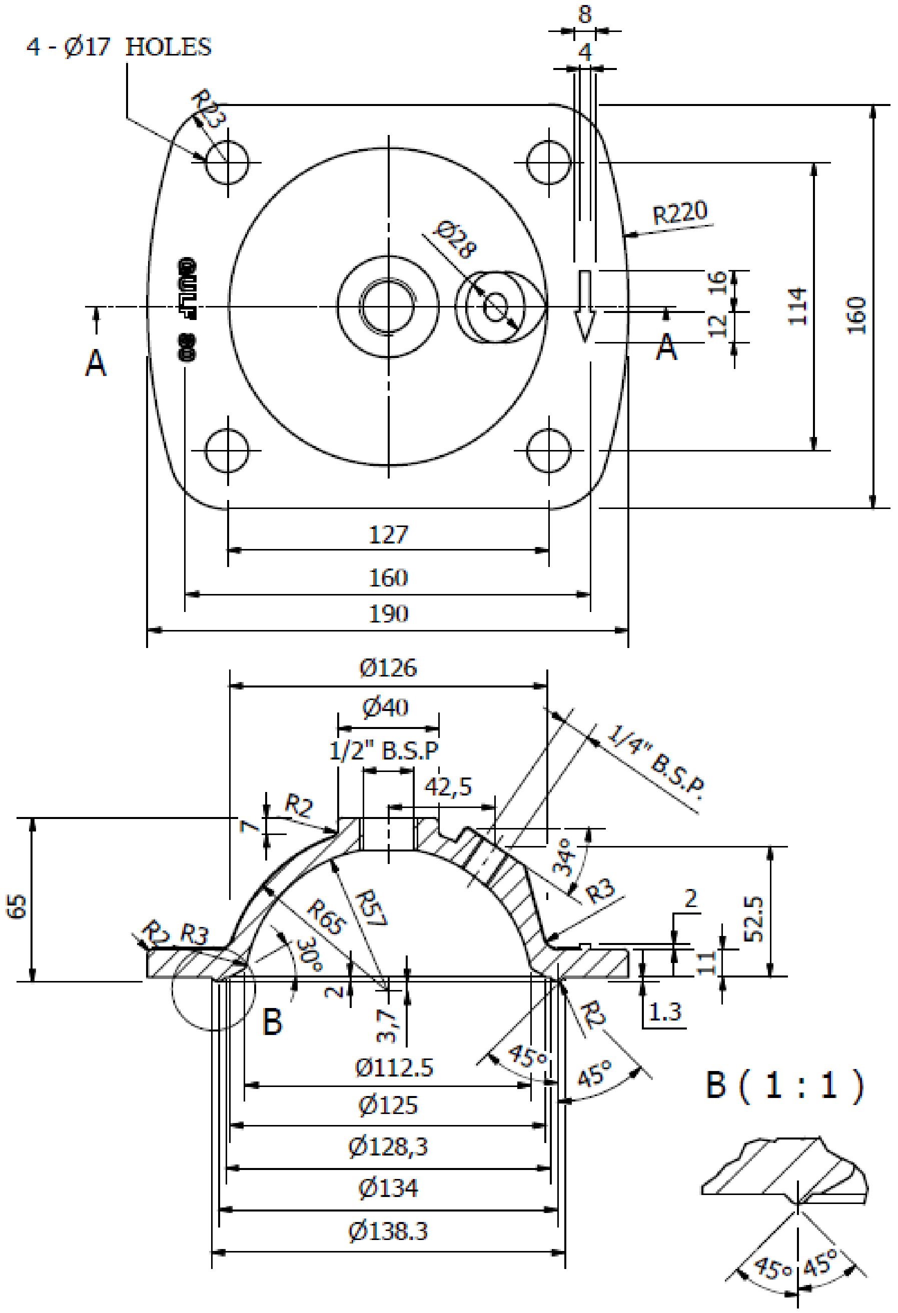
Appendices

Appendix 7.1 2D drawing of steel bracket



Appendix 7.2 2D drawing of steel bonnet



Appendix 7.3 Technical characteristics of RCT steps during tooling manufacturing trials

RCT Steps	Experimental conditions
CAD Modelling (Pro Engineering software: wildfire II)	- Filleting of designs - Al and SG contractions added - 1mm machining allowance added
Casting simulation (Magmasoft software: Frontier)	**Aluminium die:** - Objectives: minimise shrinkage and oxidation during filling - Iterations: 5
	DISA plate: - Objectives: complete filling of mould - Iterations: 3
Rapid Prototyping (LS EOSINT S 550 and 3DP Spectrum 510 RP machines)	**EOSINT S 550:** - Standard operating parameters - Curing of mould parts at 750 ^{0}C - - Shell sand (silica)
	Spectrum 510: - Standard operating parameters - No curing of moulds - Synthetic sand
Metal Casting (Gravity casting)	**Aluminium die:** - Charge: LM 4 - Resistance furnace - Nitrogen degassing - Pouring temperature: 7500 C - Kalpur direct pouring device
	DISA plate: - Charge: Pig iron + steel scrap - Induction melting - George Fisher inoculation - Pouring temperature: 14000 C - Kalpur direct pouring device
Finishing operation	Sand blasting

CHAPTER 8

ASSESSMENT OF SURFACE FINISH AND DIMENSIONAL ACCURACY OF TOOL MANUFACTURED BY METAL CASTING IN RAPID PROTOTYPING SAND MOULDS

Abstract

Purpose – The objective of this paper is to assess the surface finish and dimensional accuracy of tools produced by metal casting in additive manufactured sand moulds.

Design/ methodology/ approach – Aluminium dies were produced by metal casting in laser sintered sand moulds. Modern techniques including surface roughness analysis and three dimensional scanning were used to assess the surface finish and dimensional accuracy of the dies.

Findings – The best surface finish obtained for the cast die had Ra and Rz respectively equal to 3.23 µm and 11.38 µm. In terms of dimensional accuracy, 82% of cast die points coincided with die Computer Aided Design (CAD) data which is within the typical tolerances of sand cast products. The investigation showed that mould coating contributed slightly to the improvement of the cast tool surface finish. The study also found that the additive manufacturing of the sand mould was the chief factor responsible for the loss of dimensional accuracy.

Originality/ Value – Modern techniques for the determination of surface finish and dimensional accuracy of additive manufactured moulds and cast tools were used. An in depth understanding of factors that govern the quality of tools manufactured by casting in additive manufactured sand mould has been gained.

Keywords - Metal Casting, Rapid Prototyping, Sand Moulds, Dimensional Accuracy, Surface Finish.

Paper type – Published

Paper status: Published

8.1 Introduction

Rapid prototyping (RP) or additive manufacturing processes for the fabrication of sand moulds include laser sintering (LS) and three dimensional printing (3DP) (Lerner et al., 2002). In LS, resin coated sand grains are sintered together by means of the heat generated by a laser beam. 3DP technology on the other hand makes use of selective deposition of foundry resin on sand grains to achieve their agglomeration into solid parts. In both systems, post-treatment of the mould is required in order to obtain optimal strength of the parts. This is achieved through curing of the mould in a furnace. The two RP systems locally available in South Africa are the Direct Croning Casting Process (DCCP) based on LS and the Z-Cast process based on 3DP (Chua et al., 2003).

RP processes for sand moulds do not require pattern making that is time consuming and costly. They are therefore extensively employed especially in the automotive foundry industry for the production of casting prototypes used for design and metallurgical evaluation prior to mass production. As such RP processes decrease the lead casting design time and accelerate introduction of new components.

Recent technological developments of these RP processes include short manufacturing time with the advent on the market of large machines capable of producing several moulds in a few hours. The S Max machine from ProMetal-RCT Company is an example of an equipment based on 3DP (ProMetalRCT, 2011). Another modern trend is in the use of RP sand moulds for the manufacturing of aerospace components. This has already started taking place locally with the production of the Adept light craft engine block from laser sintered moulds (Adept, 2011). Internationally, Prometal-RCT Metal recently signed an agreement with the Fonderie Messier, a French aluminium and magnesium foundry, to produce casting parts for aerospace applications in RP sand moulds (ProMetalRCT, 2011).

Considering the above applications, some researchers have gone one step beyond to propose the manufacturing of metallic tooling by casting in RP sand moulds. This alternative tool-making process is referred to as Rapid Casting for Tooling (RCT) (Nyembwe et al., 2010). It is a contribution to the ongoing search for improved and innovative tool manufacturing processes to meet the stringent customer requirements for quality and economics (Peres &

Mafokhami, 2001; Jiang et al., 2005). RCT is an addition to the plethora of indirect rapid tooling methods that are continuing to be developed and diversified since their appearance in the last 15 to 20 years (Wolhers, 2009).

RCT essentially consists of five steps including Computer Assisted Design (CAD), casting simulation, RP, casting and finishing operations (Figure 8.1). The authors claimed that RCT offers potential advantages over traditional tool making processes such as machining and existing rapid tooling, namely near net shape, quick manufacturing and low cost of production.

In a theoretical study comparing locally available RP processes using the Analytical Hierarchy Process (AHP) technique, it was found that DCCP is more suitable than Z-Cast process with regard to their application for RCT (Nyembwe et al., 2011). According to this study, tools obtained from DCCP moulds would have better surface finish and dimensional accuracy. On the other hand, tools produced by the Z-Cast process would be cost efficient and quicker to produce. The study was based on results of several benchmarking studies (Pham & Gault, 1998; Dimitrov et al., 2003; Dimitrov et al., 2005; Kim et al., 2008) in which parts from various RP processes were compared on characteristics such as surface finish, dimensional accuracy, manufacturing time and cost amongst others.

However, at this stage it is not known how RCT tools will score in practice based on the above tool characteristics. It is also important to investigate the effects of the various RCT steps on these characteristics. In this paper, only the surface finish and dimensional accuracy of RCT tools are examined with the aid of a case study. These tool characteristics are amongst the most crucial with regard to tool usability.

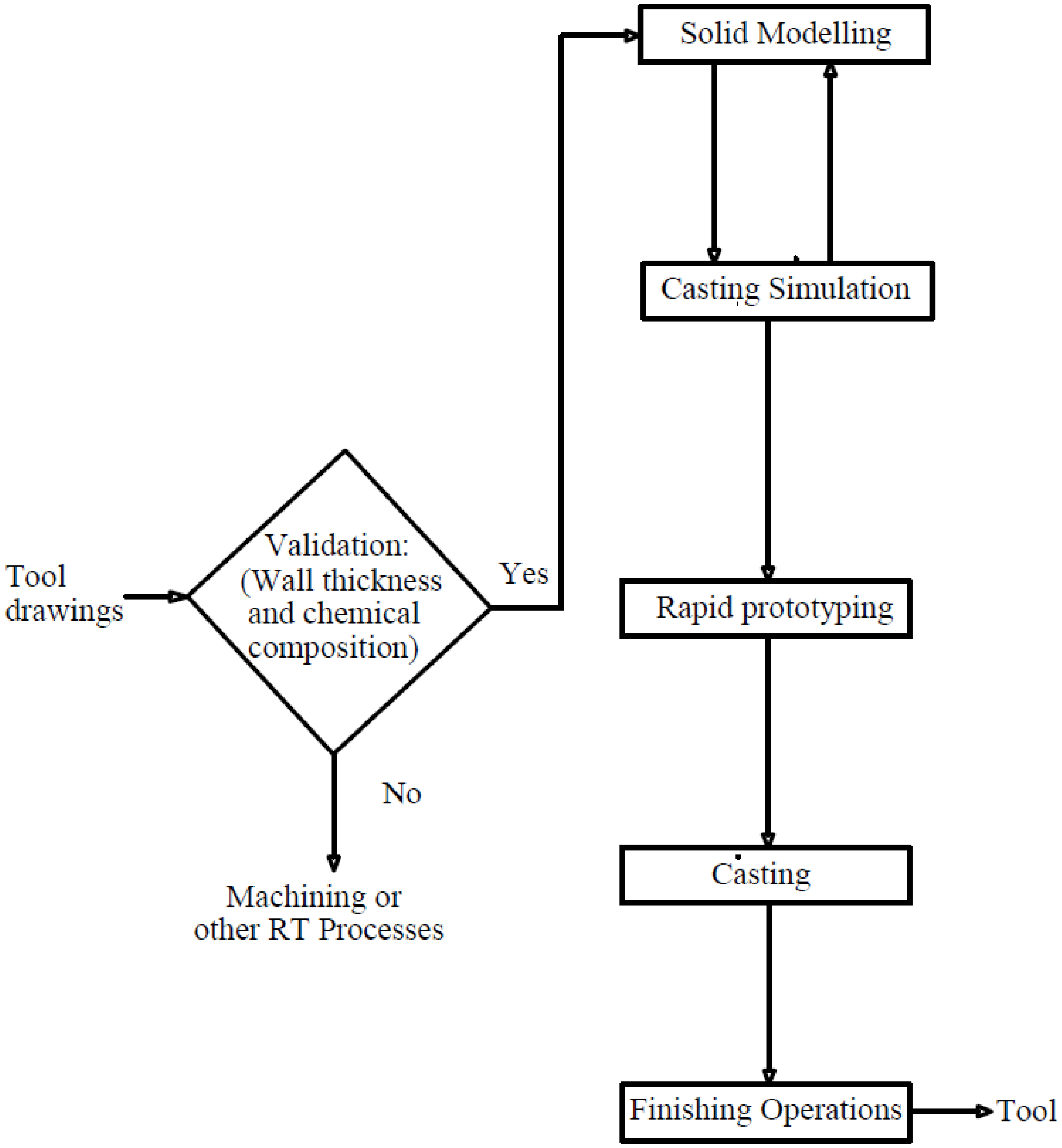


Figure 8.1 *RCT process chain (Nyembwe* et al., *2010*)

8.2 Methodology

The study methodology consists of three elements namely:

i. The manufacturing of tools by casting in RP sand moulds
ii. The measurement of the mould and tool surface finish
iii. The assessment of the mould and tool dimensional accuracy

8.2.1 Manufacturing of tools by casting in rapid prototyping sand moulds

The tool that was manufactured in this investigation was an aluminium die for the production of wax patterns used in the investment casting of a steel bracket. The 2D drawings of this steel component are shown in Appendix 1. The die parts were produced following the RCT process chain as shown in Figure 8.1. The casting modelling of sand moulds were done using Pro-Engineering software. A snapshot of the 3D model of the bottom part of the die is shown in Figure 8.2 (a). Magmasoft software was used to conduct a casting simulation of the part to be cast. The objective of casting simulation was to produce a defect free casting and in particular to prevent metal oxidation during mould filling due to poor gating system. A top gating system through a Foseco Kalpur device was used. An EOSINT S 700 RP machine was used to grow the sand mould for cast dies shown in Figure 8.2 (b). This machine is based on LS of foundry sand. One of the sand moulds produced was brush coated with Foseco's ISOMOL 185. ISOMOL coatings are flammable, solvent-based mold and core coatings. The principle refractory medium contained in these coatings is a high-purity zircon. ISOMOL coatings are recommended for use in the casting of iron, steel and non-ferrous alloys amongst them aluminium alloys. These coatings can be used through a wide range of metal casting sections. ISOMOL coatings provide excellent casting surface quality (Foseco, 2005). Gravity casting was used to produce the final tool. Aluminium silicon alloy (LM4) was melted in an electric furnace at 750^0 C and the liquid metal degassed prior to casting. The final cast die components are shown in Figure 8.2 (c).

(a)

(b)

(c)

Figure 8.2 *(a) CAD of the lower part of the die, (b) DCP mould, (c) RCT die as-cast before finishing operations*

8.2.2 Measurement of the mould and tool surface roughness

The surface finish or surface roughness was determined using a portable surface roughness tester (TIME model TR 110). This instrument provides two roughness parameters namely the

Arithmetic Average Roughness (Ra) and the Mean Average Roughness (Rz) that characterise the surface profile of the mould and casting. Ra reflects the average height of irregularities of the component from a mean line. Rz, on the other hand, is the average distance between the highest peak and the deepest valley in five sampling lengths, or cutoffs. Rz is in general more sensitive then Ra to changes in surface finish because maximum profile heights, and not the averages, are examined. Schematic representations of Ra and Rz are shown in Figure 8.3. The mould surface roughness was obtained as the average of the surface roughness of 18 points, shown in Figure 8.4. Corresponding points on the cast die were considered to determine its overall surface finish.

Surface roughness was measured on the following:

i. Uncoated RP mould
ii. Coated RP mould
iii. Casting produced from uncoated mould
iv. Casting produced from coated mould

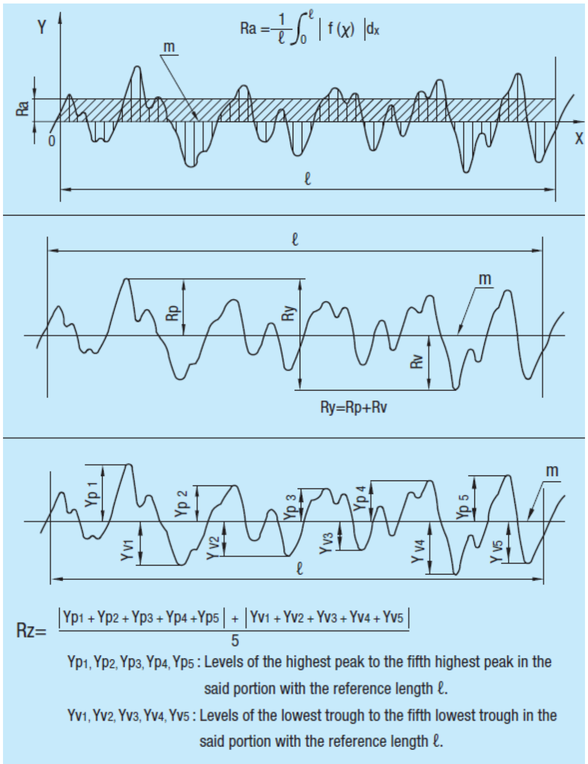


Figure 8.3 *Variety of surface roughness indicators and typical calculations (JISB0031, 1994)*

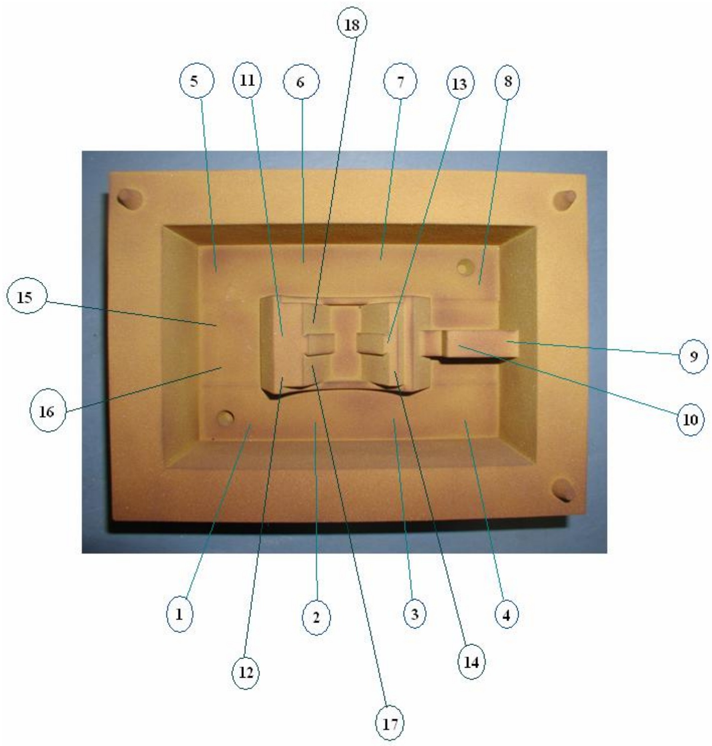


Figure 8.4 *Points used to determine average surface roughness of the mould*

8.2.3 Assessment of the mould and tool dimensional accuracy

A two-step process, shown in Figure 8.5 was followed to measure and assess the dimensional accuracy of moulds and cast tools. A VIVID 910 3D non-contact digitizer from Konica Minolta was used to produce the 3-D scanned data from the parts. The 3-D scanned data were then compared to the original CAD data during the merging step using Geomagic Qualify software. Dimensional accuracy results consist of 3-D comparison and deviation distribution of dimensions. Table 8.1 shows the dimensional tolerances used for the merging of sand moulds and castings. These tolerances have been informed by literature reporting on the dimensional accuracy of LS and shell casting processes (Groover, 2006; Kim et al., 2008).

The dimensional accuracy was determined for the following objects:

i. Uncoated RP mould
ii. Coated RP mould
iii. Casting produced from uncoated mould

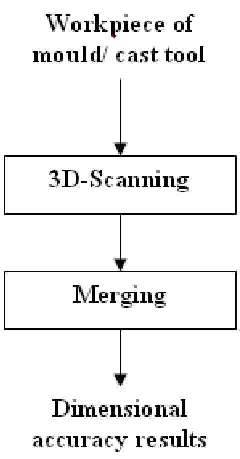


Figure 8.5 *Process flow diagram for the assessment of dimensional accuracy*

Table 8. 1Tolerance used in the merging process

Tolerances [mm]	Sand Mould	Cast tool
Max. Critical	2.0	2.0
Max. Nominal	0.2	0.5
Min. Nominal	-0.2	-0.5
Min. Critical	-2.0	-2.0

8.3 Results

8.3.1 Surface roughness

Figure 8.6 shows the average values of surface roughness for the various parts. The coated mould has a better surface finish than the uncoated mould. The difference in roughness shown by the Ra and Rz parameters of the uncoated mould were respectively 2.5 and 1.8 times larger than the same parameters for the coated mould. On the other hand, the RCT tool obtained from the coated mould had an overall smoother surface finish than the cast tool produced from the uncoated mould. The best surface finish obtained for the cast die had Ra and Rz equal to 3.23 µm and 11.38 µm respectively.

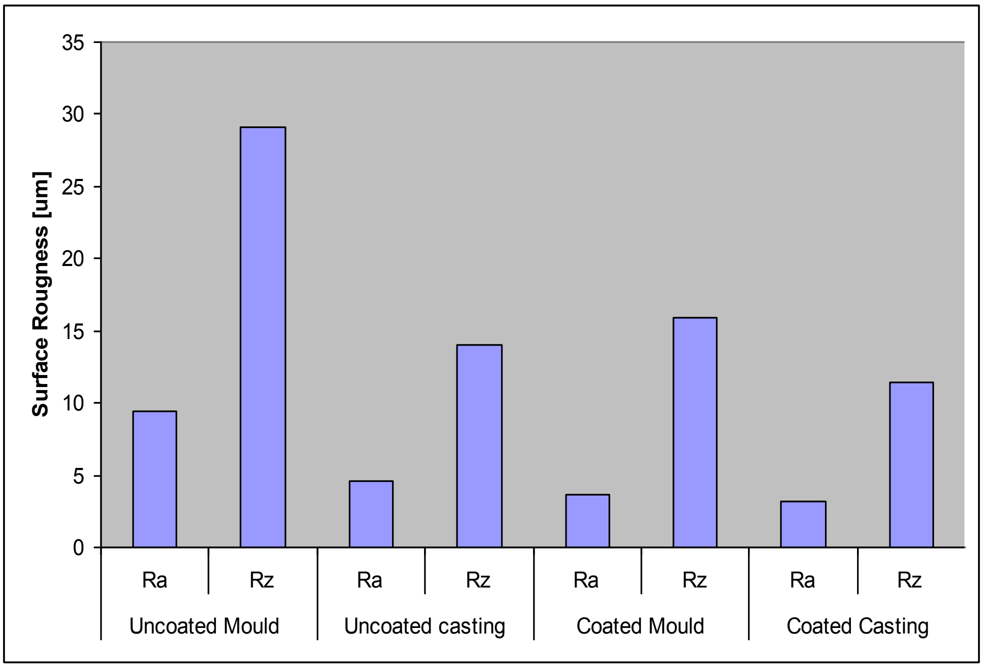


Figure 8.6 *Average roughness for the RP moulds and the RCT tool*

8.3.2 Dimensional accuracy

8.3.2.1 3-D comparison

The 3-D comparisons of scanned data with reference CAD data are shown in Figure 8.7. The green areas represent points that have dimensions within the nominal tolerances defined in Table 8.1. The blue areas represent points below the dimensions of the reference part. The yellow and red areas represent points above the dimensions of the reference part. It appears that the coated mould has a better overall dimensional accuracy than the uncoated mould and the cast die from the coated mould.

Figure 8.8 represents the quantified geometric and dimensional accuracy obtained after merging. About 82% accuracy was achieved for the cast die within the nominal tolerances of ±0.5 mm. The coated mould appears to exhibit a better accuracy than the uncoated mould with 90% point clouds coinciding with the original CAD data within an error range of ±0.2 mm in the former case compared to 82% in the latter case.

8.3.2.2 Deviation distribution of dimensions

The deviation distribution graphs from the comparison of scanned data with reference CAD data are shown in Figure 8.9. The following general observations can be made from these graphs:

i. Data are missing in the central part of the graphs.
ii. 70 to 80% of the points lie on the right hand side of the graphs.
iii. A pattern emerges as one progress from Figure 8.9 (a) to Figure 8.9(d). The left-hand side bars are continuously truncated, while the right-hand bars increase in heights. Figure 8.10 conveys the same message.

8.4 Discussion

8.4.1 Surface finish

The coated mould exhibited a better surface finish compared to the uncoated mould (Figure 8.6). The coating applied on the mould before casting, filled up the interstices of the uncoated mould's surface created by the granular structure of the sand grains and the layer-by-layer manufacturing of the mould. This improvement in surface finish on the coated mould was transferred to the cast tool. The RCT tool produced from the coated mould had an overall better surface finish than the one produced from an uncoated mould. However, the difference of tool surface roughness between the casting from the uncoated mould and the one from the coated mould was not very significant since Ra and Rz parameters were close. Possible reasons include the particle size of the moulding sand, the pouring temperature of the cast alloy and the wetting properties of the aluminium-silicon alloy.

The LS process for the sand mould is similar to the Shell sand process characterised by the use of very fine sand with an AFS number higher than 60 in order to improve the surface finish of a casting (Beeley, 2001). It appears that in this instance, the application of a coating had a reduced effect in improving the casting surface finish. The other possible reason is the relatively low pouring temperature of 750^0C of the cast alloy used in this investigation in comparison with the sintering temperature of silica sand of 1450^0 C. At this temperature it is unlikely that sand-burn defect can occur, thus explaining the limited effect of the coating in improving the surface finish. Finally if the alloy does not sufficiently wet the mould surface then its irregularities will not be transmitted to the casting.

The average Ra and Rz for the cast tool produced from the coated mould were respectively 3.23 and 11.38 μm. These values are still much higher than those of machined part with values of Ra between 1.6 and 0.1 μm (Dergarmo et al., 2003). This confirms the need for light machining as the final operation steps of the RCT in order for RCT tools to meet the standard specification of tools for surface finish.

8.4.2 Dimensional accuracy

The application of a coating layer to the sand mould cavity seemed to have compensated for the errors of the uncoated mould, thus making the coated mould appearing to have a better overall geometric and dimensional accuracy of the moulds. Considering the RCT steps, the most probable source of the dimensional errors on the uncoated mould would be the AM step by laser sintering. This step involves the layer-by-layer growing of the mould followed by strengthening by means of curing in an oven at 220^0C for 200 minutes. It is possible that during curing mould expansion and deformation occur. This phenomenon was observed with larger RP mould and still has to be fully investigated.

On the other hand, the cast die seemed to have lost the dimensional accuracy of the coated sand mould as shown in Figure 8.8. Figures 8.7(c) and 8.9(c) suggest that the cast die had expanded as shown by dimensions. The expansion could be attributed to mould wall movement during casting. The displacement of sand mould walls is generally caused by the metallostatic pressure exercised on the walls by the molten metal entering the mould cavity. Factors such as the low strength of the mould and the loose closing of the mould accentuate the mould wall movements to the extent that the expansion of the casting might possibly surpass the contraction associated with the casting solidification, resulting in loss of dimensional accuracy. Figures 8.7 (e) and 8.9 (e) corroborates the explanation of possible mould wall movement during casting

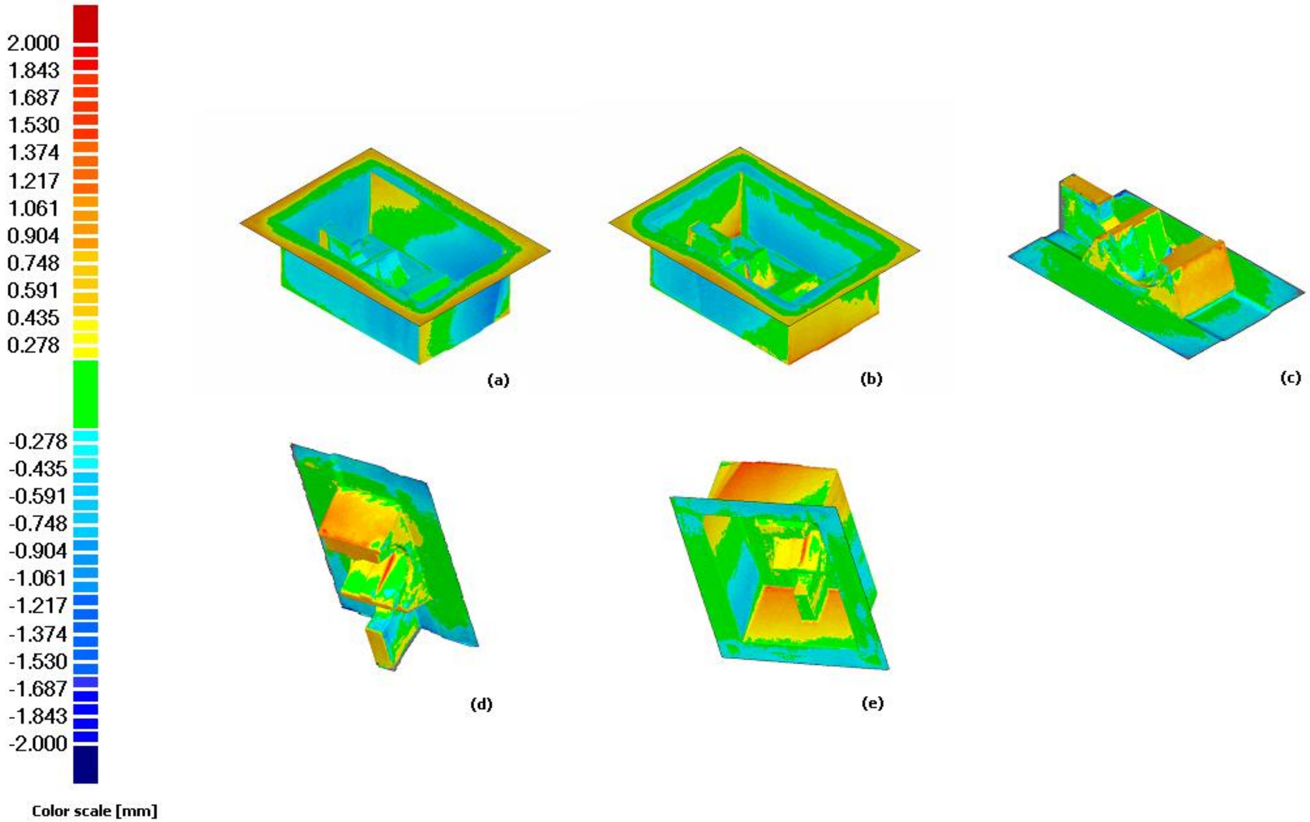


Figure 8.7 *3D comparison of scanned parts with original CAD data. (a) Uncoated mould, (b) coated mould, (c) coated casting, (d) coated casting vs. coated mould, (e) Coated mould vs. uncoated mould*

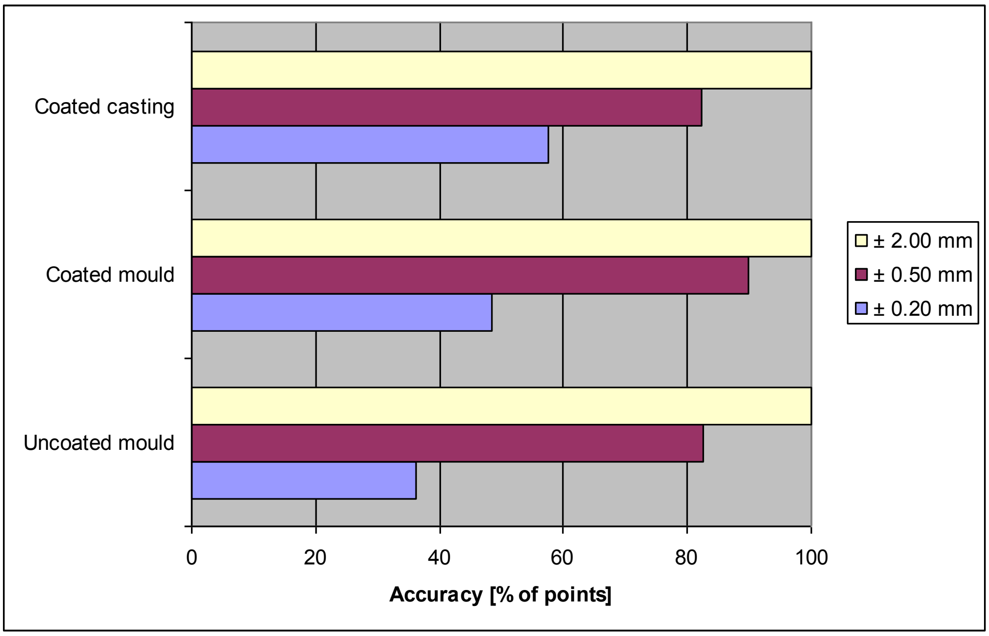


Figure 8.8 *Geometric and dimensional accuracy of RP moulds and cast die*

Two phenomena, including sagging during mould curing and mould wall movement during casting could be at play in determining the final dimensional accuracy of the RCT tools. It appears that the most important step resulting in the loss of dimensional accuracy was Rapid Prototyping.

8.5 Conclusion

In this study an initial assessment of the surface finish and dimensional accuracy of RCT tools was conducted. The investigation showed that mould coating contributes slightly to the improvement of the cast tool surface finish. With regard to the dimensional accuracy of the cast tool, incremental contribution of the RP step and metal casting led to the final cast die being larger than what was aimed for during the casting modelling. The biggest contributor to the loss of dimensional accuracy was the RP stage, possibly during the post treatment of the mould by curing in a furnace. Because of the above, machining will always be required to improved the surface finish and the dimensional accuracy of the cast tool.

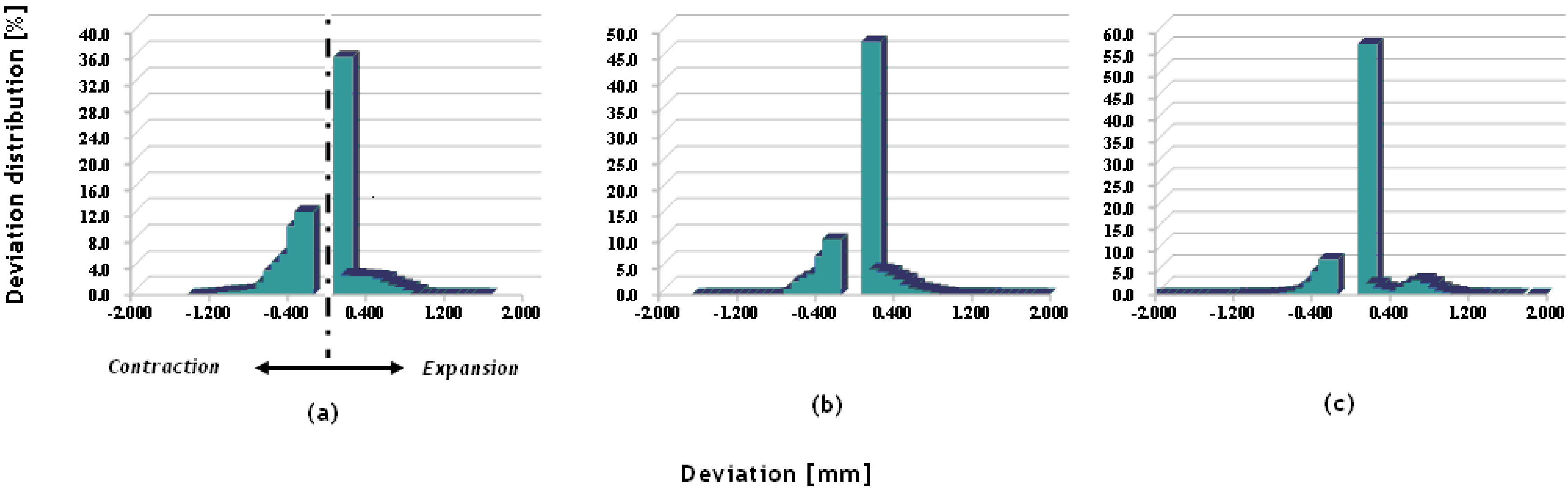


Figure 8.9 *Deviation distributions. (a) Uncoated mould, (b) coated mould, (c) coated casting*

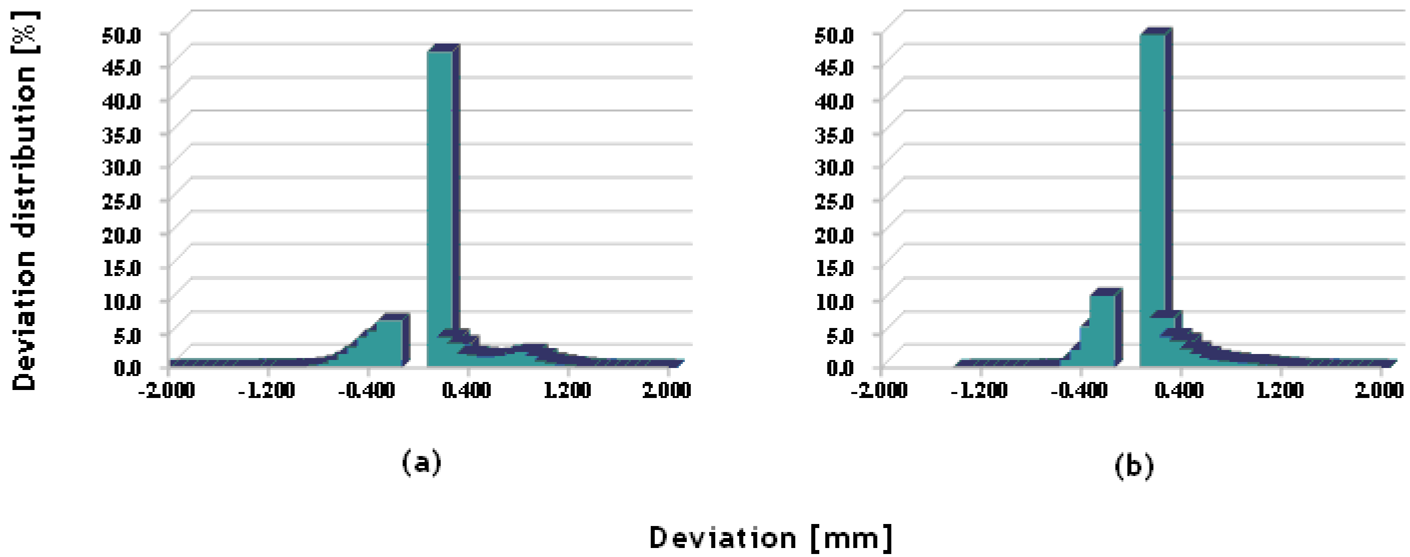


Figure 8 10 *Deviation distributions. (a) coated casting vs. coated mould, (b) Coated mould vs. uncoated mould*

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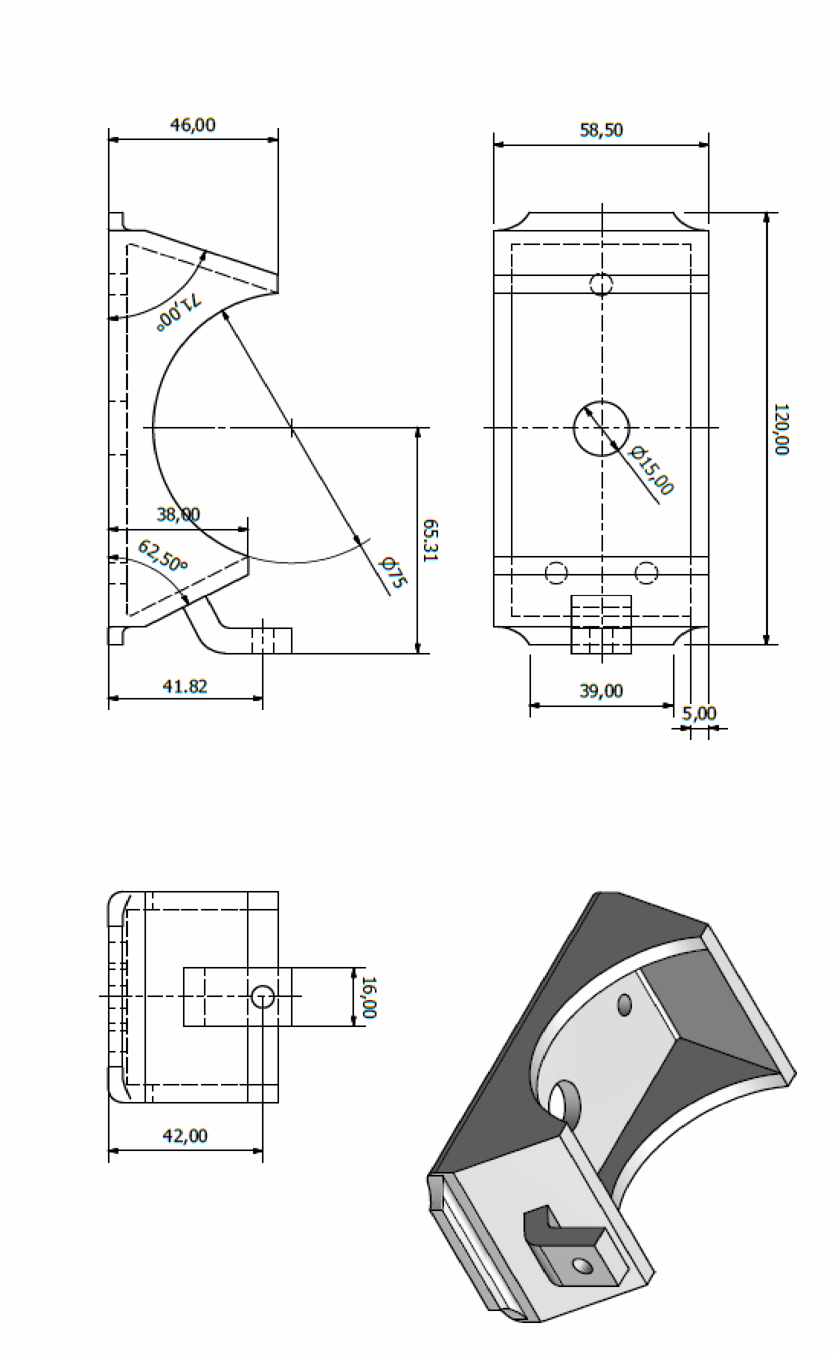
Appendix

Appendix 8.1 2 D drawings of steel bracket



CHAPTER 9

COMPARISON OF ADDITIVE MANUFACTURING PROCESSES FOR RAPID CASTING FOR TOOLING APPLICATION USING THE ANALYTIC HIERARCHY PROCESS (AHP)

ABSTRACT

Purpose – This paper has two objectives. Firstly the durability of cast tools produced in Additive Manufacturing (AM) sand moulds is assessed. Secondly cast tools obtained from sand moulds produced by Direct Croning (DC) and Z-Cast processes are compared. The comparison takes into account the tool durability characteristic in addition to previously considered criteria such as manufacturing time and cost, surface finish and dimensional accuracy of cast tools.

Design/ methodology/approach – The tool durability is empirically inferred from the mechanical properties and metallographic analysis of castings. The comparison of cast tools obtained in various AM sand moulds is conducted using the Analytic Hierarchy Process (AHP).

Findings – Merit of durability figures of 0.048 to 0.152 were obtained for the cast tools. It was found that tools obtained from DC moulds have merit of durability figures three times higher than the tools produced from Z-Cast moulds. The application of AHP mathematical calculation resulted in a 52% preference for the DC versus 48% preference for Z-Cast thus indicating a marginal superiority of the Laser Sintering process compared to the Three Dimensional process.

Originality/ Value – In this study experimental data of cast tool characteristics are used to conduct an investigation on the preference of existing AM processes for the production of sand moulds using a multi-dimensional criteria analysis technique.

Key Words – Additive Manufacturing; Analytic Hierarchy Process; Direct Croning Process; Durability; Z-Cast Process

Paper type - Research paper

Paper status: Published

9.1 Introduction

Rapid Casting for Tooling (RCT) has been proposed as tool and die manufacturing method (Nyembwe, et al, 2010). Through RCT, tools and dies are essentially produced by metal casting in sand moulds obtained by Additive Manufacturing (AM) processes. Figure 9.1 illustrates the RCT process chain that comprises five steps and a validation stage to determine if a tool can be manufactured by RCT. The AM processes that can be used include the Direct Croning (DC) and Z-Cast processes.

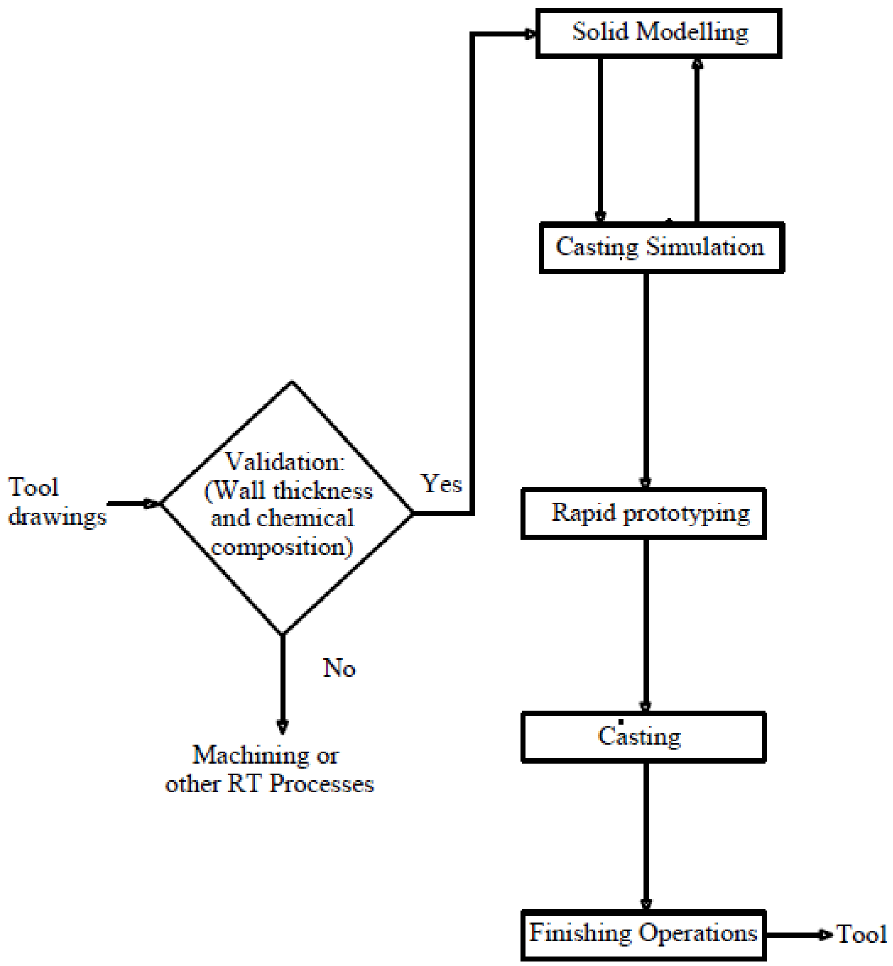


Figure 9.1 *RCT process chain (Nyembwe* et al, *2010*)

The DC process is based on the Laser Sintering (LS) process. In this instance, a laser beam is used to selectively fuse pre-coated foundry sand particles into a solid part that will become a component of the sand mould (Chua et al, 2010). On the other hand the Z-Cast process is based on three dimensional printing (3DP) technique. In this case, an ink-jet head selectively deposits or “prints” resin binder fluid that glues the sand particles together to form a mould that can be used for metal casting (Palm, 2002).

LS and 3DP have been compared in several investigations (Pham et al, 1998; Dimitrov et al, 2003; Dimitrov et al, 2005; Kim et al, 2008) From these studies, it transpire that LS provides parts with better surface finish and dimensional accuracy compared to 3DP that excels with regards to manufacturing speed and cost efficiency. Although the parts were not sand mould components to use for metal casting, it is generally accepted that the results obtained from the benchmark studies will apply to the DC and Z-Cast processes.

A recent theoretical study (Nyembwe et al, 2012) focused on the selection of the most suitable AM process between DC and Z-Cast specifically for RCT applications using the Analytic Hierarchy Process (AHP). AHP is well a known multi-dimensional criteria analysis that uses intensities assigned to comparison criteria and alternatives to derive mathematically overall preferences of alternatives. The study indicated that the DC process was better than the Z-Cast process. The DC and Z-Cast processes were respectively implemented by using EOSINT S 700 and Z-Corporation 510 Spectrum machines. The overall preferences for these two alternatives were respectively calculated at 73% and 27%.

Although the above study provided valuable understanding on the overall performance of DC and Z-cast with regards to the manufacturing of sand moulds for RCT applications, it had two quite relevant limitations:

i. Theoretical pairwise comparisons of AM processes were based on the results of general benchmark studies on LS and Three Dimensional Printing (3DP) (Pham et al, 1998; Dimitrov et al, 2003; Dimitrov et al, 2005; Kim et al, 2008). No experimental work using DC and Z-Cast was carried out to generate specific data for the allocation of AHP intensities required in such an endeavour.
ii. The durability of cast tools was not considered amongst the selection criteria that included the manufacturing time and cost, surface finish and dimensional accuracy. It was assumed that the durability was independent of the AM process used to produce sand moulds.

Broadly speaking, the durability of a tool represents its resistance to abrasion wear during normal service conditions. It is an important characteristic since it determines the tool life based essentially on the criterion of dimensional degradation. Tool durability generally depends on metallurgical factors such as the alloy type, composition and microstructure. The latter factor is a function of the tool solidification mode. Thus, the different AM moulds in terms of their refractory base sand types could possibly impact on the RCT tool solidification mode and consequently the tool durability.

In the present work, DC and Z-Cast processes are compared using AHP with regards to the production of RCT tools. The comparison criteria include the manufacturing time and cost, surface finish, dimensional accuracy and durability of tools. Experimental results on DC and Z-Cast tools are used for the pairwise comparison of the two AM processes and the determination of intensities. The aim of this study is to assess the influence of using a comprehensive set of experimental data of tool characteristics on the overall preferences of DC and Z-Cast for RCT application.

9.2 Methodology

A three steps methodology was followed in the present investigation:

i. Production of RCT tools using DC and Z-Cast processes for the production of sand moulds
ii. Characterisation of RCT tools
iii. Application of AHP

9.2.1 Production of RCT Tools

A case study consisting of the manufacturing of an A356.0 aluminium alloy die to be used for the lost wax casting of a steel bracket shown in Figure 9.2 was used in this undertaking. RCT experimental conditions are summarised in Appendix 1. It can be noted that DC and Z-Cast are the two types of AM processes used in this study. At the time of conducting this work, these were the only two types of AM processes locally available for the production of sand moulds. Figure 9.3 illustrates the CAD of the lower part of the die, the LS mould components as well as the as-cast RCT die.

At the end of this step, the manufacturing time and cost of cast dies were determined. The tool manufacturing time represents the sum of actual working times devoted to each RCT step. Likewise the tool manufacturing cost represents the total of partial costs of each RCT step.

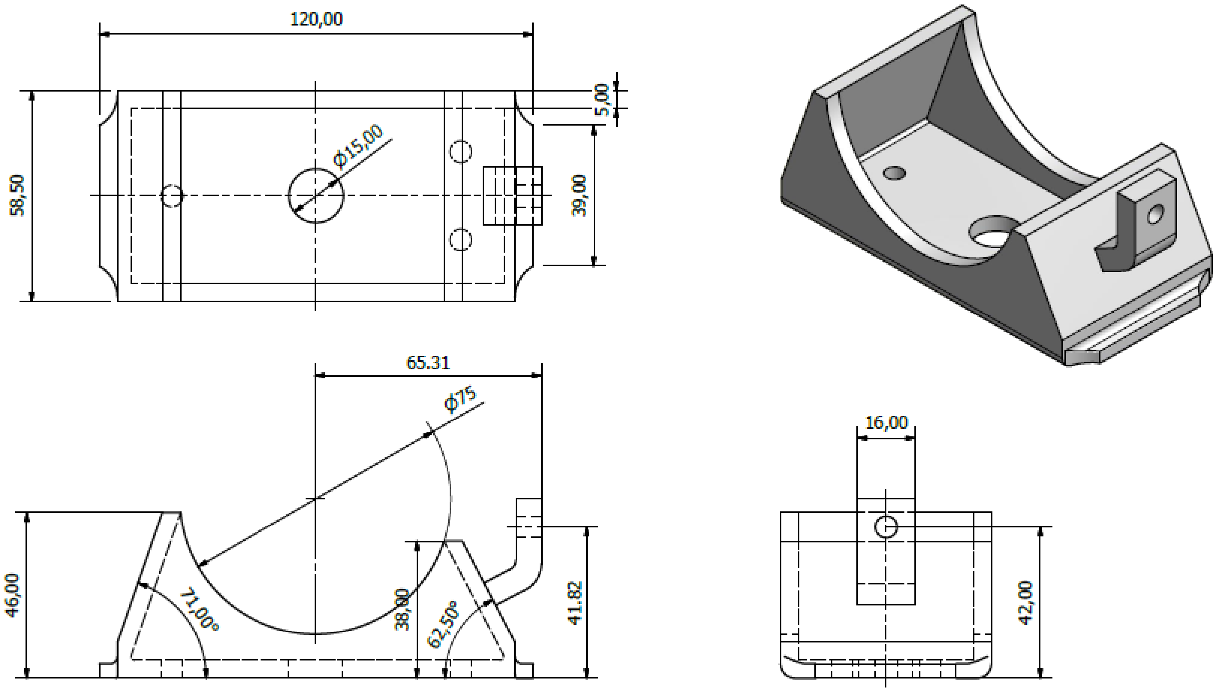
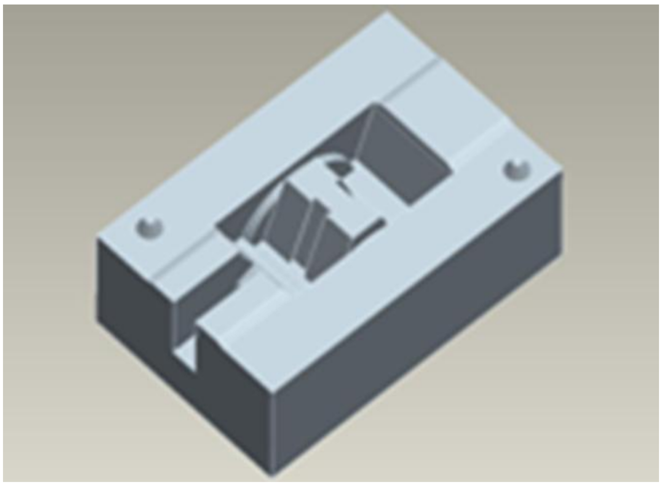
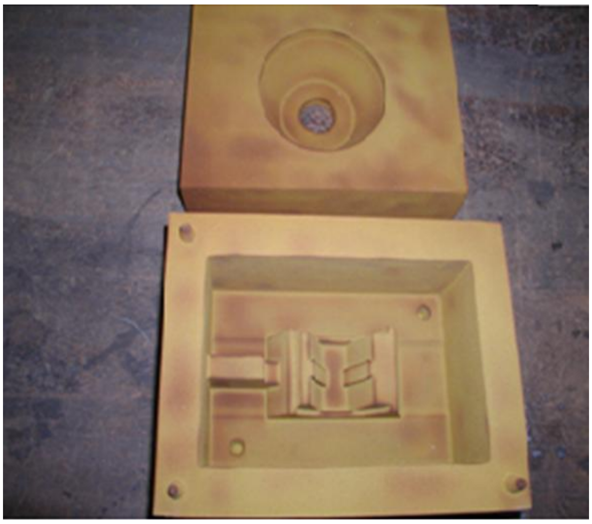


Figure 9.2 *2D drawing and 3D view of the steel bracket*

(a)



(b)



(c)

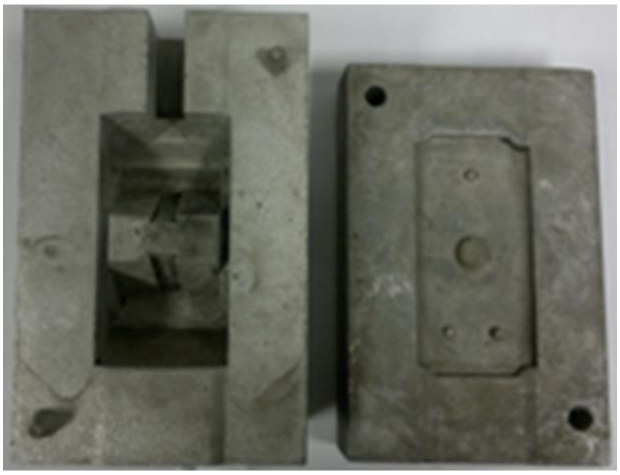


Figure 9.3 *(a) CAD of the lower part of the die, (b) DC mould, (c) RCT die before finishing operations*

9.2.2 Characterisation of tools

The cast dies were characterised in terms of dimensional accuracy, surface finish and durability.

9.2.2.1 Dimensional accuracy

Three dimensional scanning of RCT tools was performed using a VIVID 910 3D non-contact digitizer from Konica Minolta. The scan data were then compared to the ones of the CAD die to generate deviation distribution curves. Geomagic Qualify software was used for the merging process of these various data. Table 9.1 shows the dimensional tolerances used for the merging of sand moulds and castings (Groover, 2006; Kim et al, 2008).

Table 9. 1 Tolerance used in the merging process

Tolerances [mm]	Sand Mould	Cast tool
Max. Critical	2.0	2.0
Max. Nominal	0.2	0.5
Min. Nominal	-0.2	-0.5
Min. Critical	-2.0	-2.0

9.2.2.2 Surface finish

The arithmetic average roughness (Ra) and mean average roughness (Rz) of the RCT die surfaces were measured using a portable surface roughness tester type TIME model TR 110.

9.2.2.3 Durability

Referring essentially to the dimensional degradation as failure criterion, the durability of a RCT tool could be reflected by its resistance to abrasion wear. Considering such durability metric for the RCT tool, it has to be stressed that abrasion wear can be expressed quantitatively by Eq (1) (Rabinowicz, 1965).

$$V = \frac{k_w F_n L_s}{H} \qquad \textbf{(1)}$$

where V is the volume of tool material worn away, k_w the wear coefficient, F_n the force normal to the sliding interface, L_s the distance slid, and H the hardness of the tool.

The resistance of a tool material to abrasion wear is likely to increase with hardness. However, if its surface finish is not free from imperfections and irregularities such as microcracks, scratches, dents etc., from which cracks can originate, this influence of high hardness on resistance to abrasion wear might not be effective. This influence of high hardness on resistance to abrasion wear would also not be effective if inter-grain bonding is weak (Xiao, 1990).

Furthermore, the resistance of a tool material to abrasion wear can be improved by reducing its grain size. It can also be improved by inducing residual compressive stresses in the top layers during the final step of manufacturing (Tonshoff, 1991).

Based on the details above mentioned, the following figure of merit (Eq. (2)) was used to measure the durability of RCT tools.

$$D = \frac{K_{CV}.H}{d.R_z} \qquad \textbf{(2)}$$

where D is the figure of merit of durability of the RCT tool, K_{CV}, H and d respectively the impact toughness, hardness and grain size of the tool material, and Rz the surface finish (mean average roughness) of the RCT tool.

Thus, the durability of RCT tools was determined from the measurements of impact toughness, hardness, grain size (primary dendrite spacing) of the tool material and surface finish of the RCT tool.

The impact toughness was measured with a Tinius Olsen pendulum impact tester. The hardness was measured with a Zwick/Roell Indentec ZHV Vickers hardness tester under a load of 1 kg and a dwell time of 10 s. The grain size was measured from Scanning Electron Microscope (SEM) micrographs using Analysis5® image analysis software. A Tescan Vega3M SEM was used for the acquisition of SEM images in back scattered electron (BSE) imaging mode. The measurement of the mean average roughness was described earlier in the section.

9.2.3 Application of AHP

The AHP hierarchy has been implemented as follows:

i. The goal: Determination of the most suitable AM process for RCT application between the DC and Z-Cast process.
ii. The five AHP criteria included manufacturing time and manufacturing cost, dimensional accuracy, surface finish and durability.
iii. The two alternative AM processes were DC and Z-Cast.
iv. Results obtained in Section 2.1 and 2.2 were used to allocate the various intensities during the pairwise comparisons of criteria and alternatives. Table 9.2 shows the fundamental scale for pairwise comparison used in this study.

Table 9.2 The fundamental scale for pairwise comparisons

Intensity of Importance	Definition	Explanation
1	Equal importance	Two elements are equal with regards to the objectives
3	Moderate importance	One element is slightly preferred over another
5	Strong importance	One element is strongly prefer over another
7	Very strong importance	One element is preferred very strongly over another.
9	Extreme importance	One element is dominantly preferred over another
Intensities of 2, 4, 6 and 8 can be used to express intermediate values		

9.3 Results

9.3.1 Manufacturing time and cost

Table 9.3 presents the results of manufacturing time for the dies obtained from DC and Z-cast moulds. It emerges that AM is the time-determining step. It can also been seen that the RCT process chain using Z-cast was 28 % faster than RCT using DC.

Table 9.4 presents the results of manufacturing cost for the dies obtained from DC and Z-cast moulds. It emerges once again that RP is the cost-determining step. In addition it transpires from the table that RCT using the Z-cast process was 23% cheaper than RCT using DC.

Table 9.3 Manufacturing time

RCT Tool	Time [hour]					
	CAD Modelling	Casting Simulation	AM	Casting	Finishing Operation	Total
DC	5.5	5	24	1	1	36.5
Z-Cast	5.5	5	16	1	1	28.5

Table 9.4 Experimental manufacturing cost

RCT Tool	Cost [Rand]				
	CAD Modelling	Casting Simulation	AM	Casting	Total
DCP	790	2280	12000	2000	17070
Z-Cast	790	2280	8000	2000	13070

9.3.2 RCT tool characteristics

9.3.2.1 Dimensional Accuracy

Figure 9.4 shows the deviation distributions of dies obtained from DC and Z-Cast moulds. It appears that the Z-Cast die exhibits a better dimensional accuracy than the DC die. In the case of the Z-Cast die, close to 88% of points were found to be in tolerances [-0.5 to +0.5 mm] compared to only 80% in the case of the DC die.

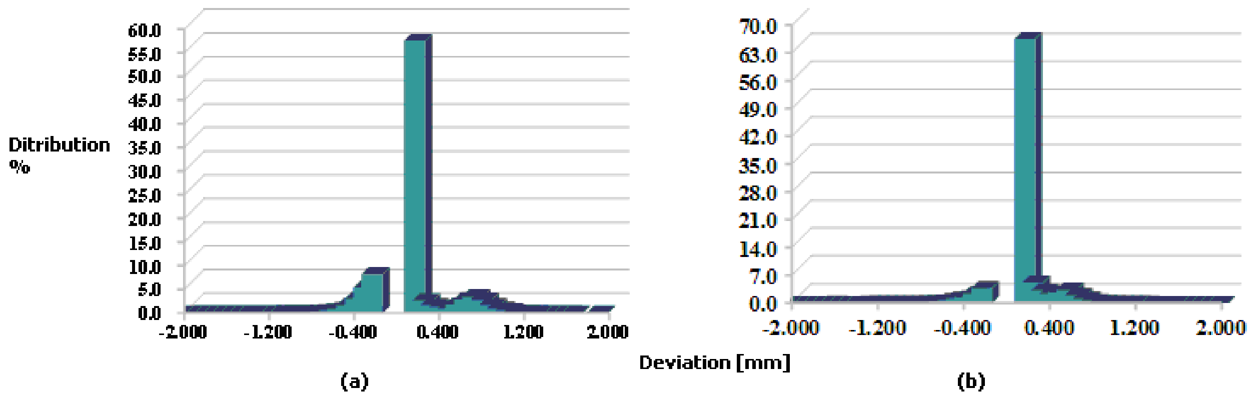


Figure 9.4 *Deviation distributions (a) Die from DC mould, (b) Die from Z-Cast mould*

9.3.2.2 Surface Finish

Figure 9.5 presents the surface roughness values for the dies obtained from two types of moulds. It emerges that the DC- RCT die had a better surface finish as the corresponding values of Ra and Rz were the lowest.

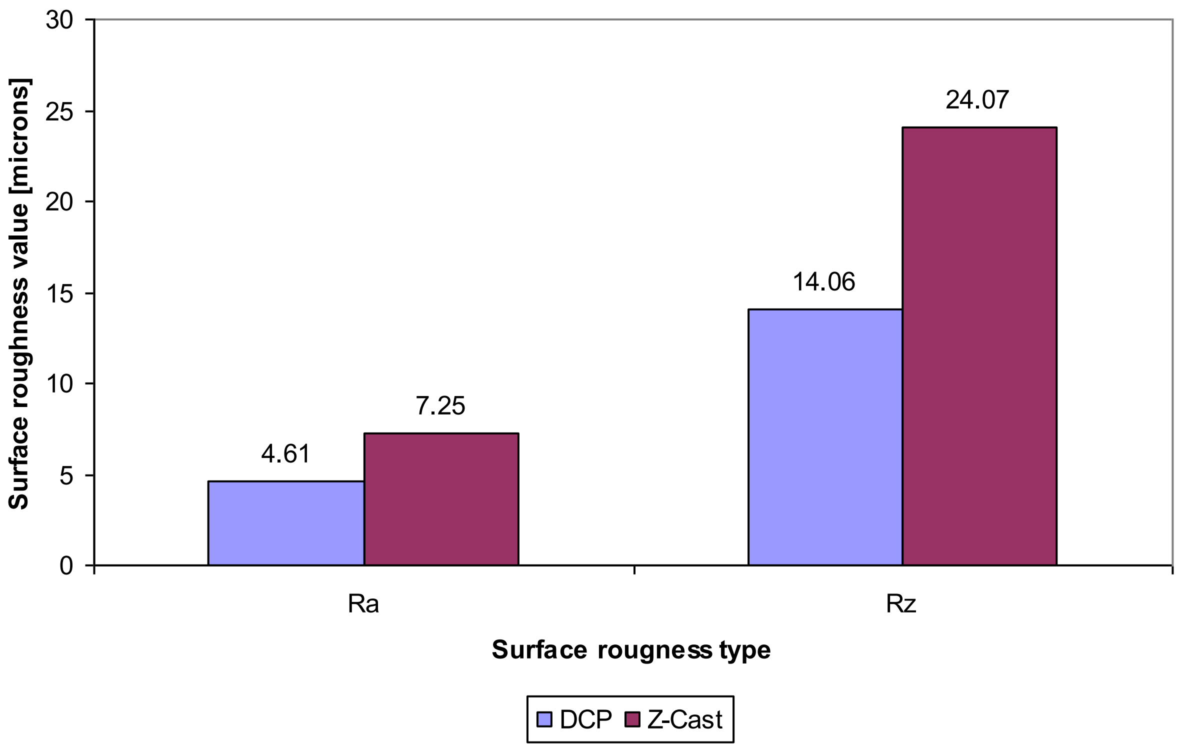


Figure 9.5 *Surface Roughness*

9.3.2.3 Durability

The typical microstructures of the RCT tools for which the chemical composition is presented in Table 9.5, are shown in Figure 9.6. The impact toughness, Vickers hardness, grain size and mean average roughness of the RCT tools as well as the figure of merit of durability derived thereof are presented in Table 9.6. LS RCT tools appeared to be slightly tougher and stronger than 3DP RCT tools. However, it emerged that the surface finish was the parameter which impacted the most on the difference of durability between LS and 3DP RCT tools. LS RCT tool emerged as more durable.

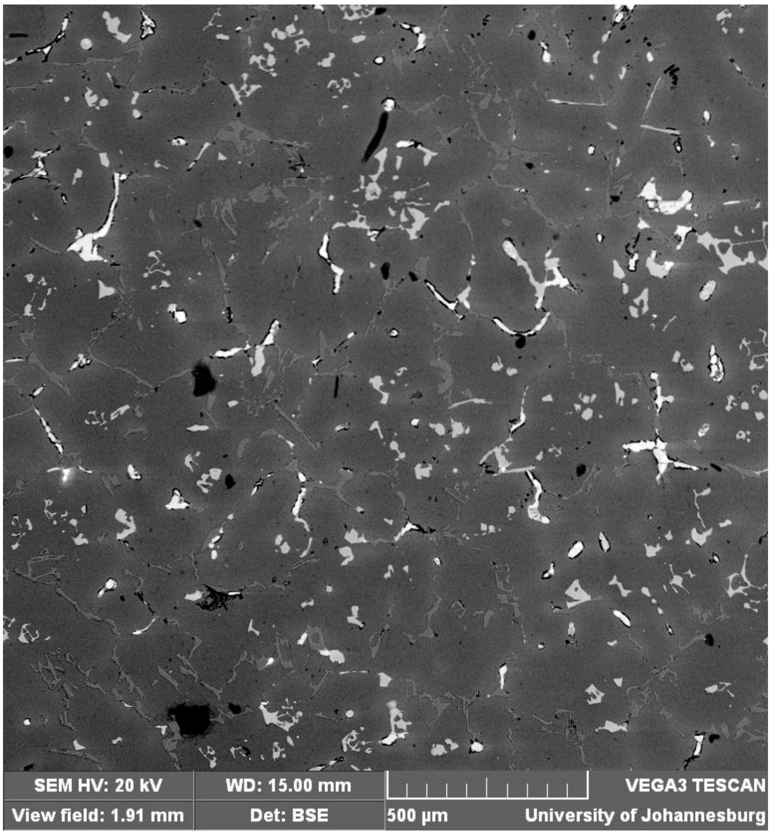
Table 9.5 Chemical composition of the RCT tool material

Element	Si	Fe	Cu	Mn	Mg	Zn	Pb	Sr	Al
Weight %	5.965	1.126	3.068	0.379	0.143	0.445	0.05	0.0010	Balance

Table 9.6 Impact toughness, Vickers hardness, grain size and mean average roughness of the RCT tools as well as the figure of merit of durability derived thereof

RCT Tool	**K_{CV}, [J]**	**HV_1**	**d, [μm]**	**R_z, [μm]**	**D**
LS	2	78.2	141.74	7.25	0.152
3DP	1.83	74	116.80	24.07	0.048

(a)



(b)

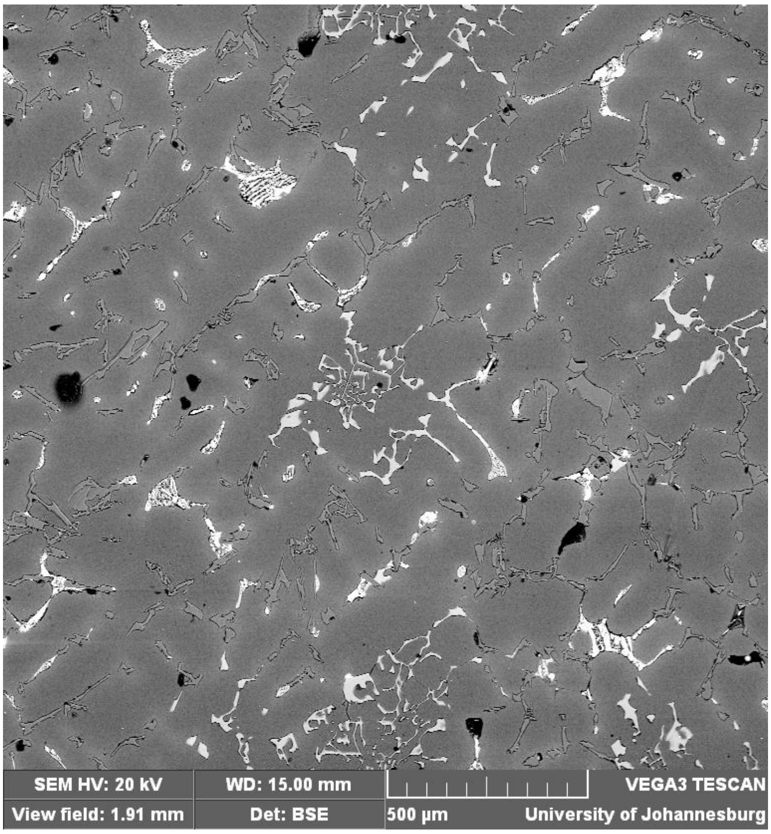


Figure 9.6 *Microstructure of the RCT tools, 0.1 g/l NaOH etching, BSE, SEM image, (a) LS tool (b) 3DP tool*

9.3.3 AHP Results

Table 9.7 shows the results of pair wise comparison of the five criteria with the corresponding intensity allocations. In terms of criteria importance, the following hierarchy was adopted: Surface finish and dimensional accuracy followed by durability followed by manufacturing time followed by manufacturing cost. It is crucial that the die first meets the quality requirements in terms of dimensional accuracy and surface finish that will be transferred to the final production part. The RCT tool should have a high durability figure of merit in order to last in service. Moreover, the RCT die should also be quickly delivered. A premium price would therefore have to be paid to meet all the above conditions.

Table 9.7 Pairwise comparison of criteria

Criteria A	B	**More Important**	**Intensity**
Surface finish	Dimensional accuracy	A= B	1
Surface finish	Manufacturing cost	A	7
Surface finish	Manufacturing time	A	5
Surface Finish	Durability	A	4
Dimensional accuracy	Manufacturing cost	A	7
Dimensional accuracy	Manufacturing time	A	5
Dimensional Accuracy	Durability	A	4
Manufacturing cost	Manufacturing time	B	3
Manufacturing cost	Durability	B	5
Durability	Manufacturing Time	A	3

Table 9.8 shows the weights of the five criteria considered using the intensity allocations of Table 9.7 (Appendix 9.2). The consistency factor was found to be equal to 2.8%

Table 9.8 Criterion weights

	A	**B**	**C**	**D**	E
Weights	0.37	0.37	0.08	0.04	0.14

A = Surface finish

B = Dimensional accuracy

C = Manufacturing time

D = Manufacturing cost

E = Durability

Table 9.9 shows the pairwise comparison between the DC and Z-Cast processes with regard to each criterion. Results obtained in Section 3.1 and 3.2 have been used to allocate the intensities. These data suggest that for the surface finish and durability, the superiority of the LS process is very strong justifying intensities of 7. On the other hand for the dimensional accuracy, manufacturing time and cost the superiority of the 3DP process is stronger hence intensities of 5 and 7 have been allocated.

Table 9.9 Pairwise comparison of alternative with respect to each criterion

Criteria	**Better Process**		**Intensity**
	DC	Z-Cast	
Surface Finish	X		7
Dimensional Accuracy		X	5
Manufacturing Time		X	7
Manufacturing Cost		X	7
Durability	X		7

Table 9.10 shows the resulting weight of alternative AM processes with regards to the various criteria (Appendix 9.3). From Tables 9.8 and 9.9, the overall preferences of the two AM processes were determined and found to be equal to 52% for DC and 48 % for Z-Cast (Appendix 9.4). Compared to the previous comparison study mentioned in Section 1, the preference for LS process decreased while the one for the 3DP process increased by 21 % point.

Table 9.10 Weights of alternatives

	DC	**Z-Cast**
Surface Finish	0.88	0.13
Dimensional Accuracy	0.17	0.83
Manufacturing cost	0.13	0.88
Manufacturing time	0.13	0.88
Durability	0.88	0.13

9.4 Discussion

9.4.1 Manufacturing time and cost, RCT tool characteristics

The experimental results obtained on the surface finish, manufacturing time and cost confirmed the trends obtained in the previous benchmark studies that compared LS machines with 3DP machines ((Pham et al, 1998; Dimitrov et al, 2003; Dimitrov et al, 2005; Kim et al, 2008). The 3DP process is known to be faster and more cost efficient compared to the LS process. From the experimental results, an intensity of 7 was used to indicate the superiority of Z-Cast compared to DC.

With regards to the dimensional accuracy, the experimental results obtained contradicted the previous benchmark study results (Pham et al, 1998; Dimitrov et al, 2003; Dimitrov et al, 2005; Kim et al, 2008). It was found that the Z-Cast die was geometrically and dimensionally more accurate compared to the DC die. A possible explanation to this disagreement of results is that in the previous benchmark studies, the accuracy measurements were performed from the parts produced by LS and 3DP processes not from the castings obtained from LS and 3DP moulds. During metal casting several phenomenon take place including mould-metal interactions, solidification, and contraction that could have impacted on the final results of dimensional accuracy. In addition, the refractory powders (Z501 and silica sand) used in this study are different from the ones used in the previous benchmark studies.

Incidentally the durability figure of merit (Eq (2)), the DC process was also found to be superior to the Z-Cast process with regards to the durability of the tools produced from the respective moulds. The difference between the durability of two AM processes could possibly be due to the effect of the mould material that influence metal mould reactions, surface finish and casting cooling. Shell moulds produced in the DC process are made of silica sand while Z-Cast moulds produced on the Spectrum 510 are made of proprietary synthetic sand (Z Cast 501). These materials have different thermal conductivity, fineness and chemical reactivity with the aluminium alloy leading to marked different durability of the cast dies and therefore justifying the allocation of an intensity of 7 during the pairwise comparison of the DC to the Z-cast process.

9.4.2 AHP results

Overall the two processes seem to reach equilibrium. The DC is superior on to two criteria that ranked very high in importance while the Z-Cast is better with regard to the other three criteria that ranked slighter lower in importance. Applying AHP mathematical calculation results in a 52 % preference for DC versus 48% preference for Z-Cast.

9.5 Conclusion

Merit of durability figures were inferred by mechanical properties and SEM analysis indicate that DC tools have a better wear resistance than Z-Cast tools in their applications for mass production processes such as sand casting or injection moulding. The use of experimental data of manufacturing time and cost and various tool characteristics including surface finish, dimensional accuracy and durability has allowed the authors to reliably allocate priorities and intensities during the comparison of DC and Z-Cast for RCT application using the AHP technique. New preference values different from the ones obtained in previous studies were obtained for the LS and 3DP processes. They show that DC is marginally more suitable than Z-Cast for RCT application.

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Appendices

Appendix 9 1Technical characteristics of RCT steps during die manufacturing trials

RCT Steps	Experimental conditions
CAD Modelling (Pro Engineering software: wildfire II)	- Filleting of designs - Al contractions added - 1mm machining allowance added
Casting simulation (Magmasoft software)	**Aluminium die:** - Objectives: minimise shrinkage and oxidation during filling - Iterations: 5
Rapid Prototyping (LS EOSINT S 700 and 3DP Spectrum 510 RP machines)	**DCP: EOSINT S700:** - Standard operating parameters - Curing of mould parts at 750 ^{0}C - Shell sand (silica)
	Z-Cast: Spectrum 510: - Standard operating parameters - No curing of moulds
Metal Casting (Gravity casting)	**Aluminium die:** - Charge: LM 4 - Resistance furnace - Nitrogen degassing - Pouring temperature: 750^0 C - Kalpur direct pouring device
Finishing operation	As Cast

Appendix 9.2 Determination of criterion weights

Table 9.2.1 Preference on criteria

	Surface finish	**Dimensional accuracy**	**Manufacturing time**	**Manufacturing cost**	**Durability**
Surface finish	1	1	5	7	4
Dimensional accuracy	1	1	5	7	4
Manufacturing time	1/5	1/5	1	3	1/3
Manufacturing cost	1/7	1/7	1/3	1	1/3
Durability	1/4	1/4	3	5	1

Table 9.2.2 Weights on criteria

	Surface finish	**Dimensional accuracy**	**Manufacturing time**	**Manufacturing cost**	**Durability**	**Average**
Surface finish	0.39	0.39	0.35	0.30	0.41	0.37
Dimensional accuracy	0.39	0.39	0.35	0.30	0.41	0.37
Manufacturing time	0.08	0.08	0.07	0.13	0.03	0.08
Manufacturing cost	0.06	0.06	0.02	0.02	0.03	0.04
Durability	0.10	0.10	0.21	0.22	0.10	0.14

Each element in Table 9.2.2 is obtained by dividing the entry in Table 9.2.1 by the sum of the column it appears in. For instance the (manufacturing time, manufacturing cost) element in Table 9.2.2 is calculated as: 3/ (7+7+3+1+5) = 0.13. Values in the Average column are obtained by averaging values in the different rows. The Average column represents the weights of criteria.

Appendix 9.3 Determination of alternative weights

Step 1: Weights of alternatives with regards to each criterion

Table 9.3.1.1 Comparison of RP processes on surface finish/ durability

	EOSINT	Z510 Spectrum
EOSINT	1	7
Z510 Spectrum	1/7	1

Table 9.3.1.2. Weights of alternatives with regards to surface finish/ durability

	EOSINT	Z510 Spectrum	Average
EOSINT	0.88	0.88	0.88
Z510 Spectrum	0.13	0.13	0.13

Table 9.3.1.3. Comparison of RP processes on dimensional accuracy

	EOSINT	Z510 Spectrum
EOSINT	1	1/5
Z510 Spectrum	5	1

Table 9.3.1.4 Weights of alternatives with regards to dimensional accuracy

	EOSINT	Z510 Spectrum	Average
EOSINT	0.17	0.17	0.17
Z510 Spectrum	0.83	0.83	0.83

Table 9.3.1.5 Comparison of RP processes on manufacturing time/ manufacturing cost

	EOSINT	**Z510 Spectrum**
EOSINT	1	1/7
Z510 Spectrum	7	1

Table 9.3.1.6 Weights of alternatives with regards to manufacturing time/ manufacturing cost

	EOSINT	**Z510 Spectrum**	**Average**
EOSINT	0.13	0.13	0.13
Z510 Spectrum	0.88	0.88	0.88

Step 2 Weights of alternatives

Table 9.3.2.1 Weights of Alternatives*

	EOSINT	**Z510 Spectrum**
Surface Finish	0.88	0.13
Dimensional Accuracy	0.17	0.83
Manufacturing cost	0.13	0.88
Manufacturing time	0.13	0.88
Durability	0.88	0.13

* Values in Table 9.3.2.1 rows are obtained from Average column in tables above

Appendix 9.4 Determination of overall weights

Table 9.4.1 Determination of overall weights of alternatives

Appendix 9.1 data	**Appendix 9.2 data**				
A	**B**	**C**	**D**	**E**	**F**
Criterion Weights	**Alternative Weights**				
		EOSINT	**Z510 Spectrum**	**EOSINT**	**Z510 Spectrum**
0.37	Surface Finish	0.88	0.13	0.32	0.05
0.37	Dimensional Accuracy	0.17	0.83	0.06	0.31
0.08	Manufacturing cost	0.13	0.88	0.01	0.07
0.04	Manufacturing time	0.13	0.88	0.01	0.04
0.14	Durability	0.88	0.13	0.13	0.02
				0.52	**0.47**

The results of columns E and F are obtained by multiplying A by C and A by D respectively. The overall weights are summing values in columns E and F

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

This study investigated the possibilities of manufacturing tools by metal casting in sand moulds essentially produced by Additive Manufacturing (AM) processes. Several features of this attempt were examined in order to gain an integrated understanding of this manufacturing route in terms of its relevance and performance. The following conclusions emerged from this endeavor:

i. Rapid Tooling (RT) processes are leading the group of tool manufacturing processes that could be suggested as alternatives to the traditional machining.
ii. Modern developments and trends of AM processes for the production of sand moulds make it possible to revisit metal casting as a viable route for tool manufacturing among the indirect RT processes existing so far.
iii. By combining modern metal casting processes and design tools together with AM of sand moulds, it is possible to develop a process chain that optimises the production of cast tools.
iv. The Analytic Hierarchy Process has proven to be an effective method for the selection of the most suitable AM processes to be implemented in the Rapid Casting for Tooling (RCT) process chain. Using such a multi-dimensional criteria analysis technique, the overall difference between EOS laser sintering and Z-Corporation three dimensional printing was quantified in the particular context of RCT. It was shown that laser sintering was the more suitable AM process for RCT compared to three dimensional printing.
v. The success of the practical implementation of RCT and the related known-how are dependent on the casting simulation step on one hand and the elimination of exogenous factors linked to workmanship on the other hand.
vi. The AM of sand moulds is the cost driver as well as the rate determining step of RCT. Controlling this step will go a long way in making the RCT process chain more competitive compared to machining.

vii. Overall, the manufacturing of metallic tooling by casting in sand moulds produced by AM processes is a viable alternative. The method presents benefits of lower manufacturing cost and shorter processing time. However the as cast tool quality with regard to dimensional accuracy and surface finish are still not comparable to machining. RCT will inevitably require some minimal machining.

viii. RCT tools obtained from DC moulds will resist better to abrasion wear than the ones produced from Z-Cast moulds with regards to their applications for mass production processes such as sand casting or injection moulding.

10.2 Recommendations

New challenges were encountered during the undertaking of this project and need to be addressed together with some others features which were not covered in the current study. In this regards future work may include:

i. The broadening of RCT applications to the manufacturing of tooling used in other mass production processes such as injection molding, die casting and forging.

ii. An in depth investigation of tool design, material and geometry suitable for RCT.

iii. The economic and quality assessment of RCT tools that have been subjected to finishing operations such as machining and heat treatment.

iv. A study of RCT process learning curve and acceptance by local tool rooms as an alternative method for practical use

v. An investigation of centralized procurement of manufacturing technology to obviate the high capital cost by an individual foundry.