ADDITIVE MANUFACTURING OF COMPONENTS FOR IN-DIE CAVITY USE, SUITABLE TO WITHSTAND ALUMINIUM HIGH PRESSURE DIE CASTING (HPDC) PROCESS CONDITIONS

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DECLARATION WITH REGARD TO INDEPENDENT WORK

I, MANUEL FILIPE VIANA TEOTONIO PEREIRA, identity number [redacted] and student number 207202850, do hereby declare that this research project submitted to the Central University of Technology, Free State for the Degree MAGISTER 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 fulfillment (or partial fulfillment) of the requirements for the attainment of any qualification.

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ABSTRACT

This research examines the suitability of Additive Manufacturing (AM) for manufacturing dies used in aluminium high pressure die casting. The study was guided by the following objectives:

- The reviews of applicable literature sources that outline technical and application aspects of AM in plastic injection moulds and the possibilities of applying it to high pressure casting die.
- To introduce AM grown die components in die manufacture. Further, to develop a methodology that will allow industry to apply AM technology to die manufacture.
- Revolutionise the way die manufacture is done. The potential for AM technologies is to deliver faster die manufacture turnaround time by requiring a drastically reduced amount of high level machining accuracy. It also reduces the number of complex mechanical material removal operations. Fewer critical steps required by suitable AM technology platforms able to grow fully dense metal components on die casting tools able to produce production runs.
- Furthermore, promising competitive advantages are anticipated on savings to be attained on the casting processing side. AM technology allows incorporation of features in a die cavity not possible to machine with current machining approaches and technology. One such example is conformal cooling or heating of die cavities. This approach was successfully used in plastic injection mould cavities resulting in savings on both the part quality as well as the reduction on cycle time required to produce it (LaserCUSING®, 2007).

AM technology has evolved to a point where as a medium for fast creation of an object, it has surpassed traditional manufacturing processes allowing for rapidly bridging the gap between ideas to part in hand. The suitability of the AM approach in accelerating the die manufacturing process sometime in the near future cannot be dismissed or ignored. The

research showed that there is promise for application of the technology in the not too distant future.

In the South African context, the current number and affordability of suitable AM platforms is one of the main stumbling blocks in effecting more widespread applied research aimed at introduction of the technology to die manufacture.

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DEFINITION OF TERMS

Definitions not referenced have been formulated by the author in order to clarify concepts.

Rapid Die Manufacture

Rapid die manufacture involves the following three complimentary activities:

(a) Creation and visualisation by computer of forms or constructions in three-dimensions;
(b) Digitising real objects and their eventual modification made possible by computer calculations, and
(c) The production of physical objects by numerically controlled machines that are used to materialise synthetic images (Lavigne, 1998).

Rapid Prototyping Technology

Rapid Prototyping Technology (RPT) is a digitally-driven, automatic additive manufacturing process that begins with the designing of a model from Computer-Aided Design (CAD) data to the eventual building of a 3D prototype.

Additive Manufacturing

Additive Manufacturing (AM) described by ASTM as a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining. Synonyms include *additive fabrication*, *additive processes*, *additive techniques*, *additive layer manufacturing*, *layer manufacturing* and *freeform fabrication*. It refers to a group of technologies used for building physical models, components, tooling and die components and finished series production parts from 3D CAD data. Unlike standard applicable mechanical machining processes, which are subtractive in nature, additive systems extract solid components through selective use of powder or liquid based materials.

ACRONYMS

.stl	Standard Triangulated Language
AM	Additive Manufacturing
CAD	Computer-Aided Design
CRPM	Centre for Rapid Prototyping and Manufacturing
CUT	Central University of Technology, Free State
DLP	Direct Light Processing
DMLS	Direct Metal Laser Sintering
DOF	Degrees of Freedom
FDM	Fused Deposition Modelling
LS	Laser Sintering
RP	Rapid Prototyping
RPT	Rapid Prototyping Technology
SLA	Stereolithography
SLM	Selective Laser Melting
HPDC	High Pressure Die Casting
CSIR	Council for Scientific and Industrial Research
MSM	Materials Science & Manufacturing
UV	Ultraviolet

STRUCTURE OF THE DISSERTATION

This dissertation is submitted via a publication output route in the form of three submitted journal articles (Chapters 4, 5 and 6) and a conference paper in Chapter 4. The results were also presented at the 2007, 2008, 2009 and 2011 annual international conferences of the Rapid Product Development Association of South Africa (RAPDASA).

The opening chapter gives an introduction and background to the work. The second chapter gives an account of the literature survey and prior art study performed prior to committing to the experimental phase. The third chapter deals with the experimental approach and methodology used for the project. Chapters 4 and 5 give an account of the experimental results obtained for various Additive Manufacturing (AM) platforms and evaluate their suitability as an emerging die manufacturing approach. Chapter 6 gives an account of the application of AM technology on an experimental die. The cores and cavities were manufactured by the EOS Direct Metal Laser Sintering (DMLS) platform at the Central University of Technology, Free State in Bloemfontein. Chapter 7 concludes with an overall discussion and recommendations related to the various chapters.

One journal article and a conference paper evaluating the selected additive manufacturing platforms are included in Chapters 4 and 5 and a second article examining the application on a die is included in Chapter 6. Five co-authors contributed to the articles, with M F V T Pereira as the primary author. The third journal article (in Chapter 7) contains the final discussion and recommendations of the work done.

CHAPTER 1

1. INTRODUCTION AND BACKGROUND TO THE STUDY

1.1 Introduction

Global issues such as energy and climate change have impacted on both the automotive and aerospace industries forcing them to adopt measures to produce products that consume fewer combustibles and emit less carbon dioxide. Making vehicles lighter is one of the logical ways of reducing fuel consumption (Uddeholm, 2007). The need for light components, able to fulfil technical and quality specifications, led to market growth for tooling that is able to mass produce parts using manufacturing processes such as aluminium and magnesium high pressure die casting. Competitive pressures to reduce the lead time required for tooling-up has also increased dramatically (Uddeholm, 2007). For this reason, research into various methods, techniques and approaches towards faster tool and die manufacture are being undertaken globally.

Aluminium high pressure die casting (HPDC) is a manufacturing process that imposes severe stresses on the dies when under processing conditions (Uddeholm, 2007). Furthermore, die manufacturing costs are a significant component of the economic feasibility of the die casting process (Uddeholm, 2007). Dies are manufactured from applicable steel materials that can withstand process conditions for an undetermined period of time; therefore the terms *die life* and *expected minimum die life prior to failure due to process induced wear and tear* are found in the industry (Yucong Wang, 1997).

The most important die wear and tear failures can be described as follows:

- **Washout damages** result from erosion and corrosion of die cavity surfaces. Corrosion takes place when the flow of molten aluminium impinges and rubs against the surfaces of the die. Erosion follows from friction wear caused when the melt solidifies around core surfaces and the casting is ejected from the die. Corrosion-erosion implies that the melt medium is corrosive to the hot work steel metal. Corrosion facilitates the erosion process. This fact distinguishes corrosion-erosion from pure erosion or mechanical wear.

- **Thermal fatigue***,* the most influential failure mode in die casting, reveals itself in two modes, namely heat checks and stress cracks. The characteristic feature of heat checks is the appearance of fine cracking lines on surfaces, which look like a spider web. Stress cracks appear mainly in corners and as individual and clearly defined cracks, sometimes filled with aluminium.

The use of technology associated initially with Rapid Prototyping Technology (RPT) for the purpose of compressing the time it takes to develop a component, is a well-established and researched approach (Gordon,1995). The approach described here is based on the substitution of masters used in gravity or low pressure metal casting processes provided by service providers, to an approach that uses RPT to directly manufacture high pressure die cast components (Karapatis, 1998). The RPT technology has evolved into a manufacturing technology, instead of only a prototyping technology, and as recently as 2010 has been referred to as Additive Manufacturing (AM). This description follows from the fact that laser and electron beam assisted technologies uses powdered metal alloys, polymers as well as ultraviolet (UV) reactive liquid polymer materials to grow CAD designed components. The novel approach researched in this study was aimed at benefiting high pressure die casting companies, by providing a faster and more economical solution for part approval for production, as well as for production batches using in-house high pressure die casting processes.

A number of AM processes can be used for this proposed rapid manufacturing tooling solution (Wohlers, 2005). However, appropriate AM processes should be able to produce cavity forming inserts with the following specifications:

- In the appropriate/correct materials, able to withstand process temperatures and pressures
- With no porosity problems
- With correct heat transfer properties
- To the required material ductility
- To the correct time scales, cost and quality

Other important advantages that this proposed approach aimed to establish were:

- Parts with mechanical properties compatible to those manufactured from die casting steels
- Repeatability and quicker turnaround times for die repair, adjustment, modifications and manufacturing
- Tooling inserts capable of producing quantities as required for prototype and production runs

The research also used accelerated testing procedures to evaluate the die material produced by the AM processes, as well as surface treatments of the selected die materials for a better resistance to washout, erosion and corrosion in a high pressure die casting environment.

Highly cracked or damaged surfaces lead to a rapid end of die life. Such dies produce ever increasing numbers of rejects due to non-compliance with dimensional and geometrical specifications.

Initial literature and internet searches were done to establish the existing knowledge in this field. From the information acquired the following deductions could be made:

- There are two major methods to produce rapid tooling (Karapatis, 1998):
  - (a) the indirect approach and
  - (b) the direct approach
- A number of successes have been achieved in the plastic injection moulding environment with rapid prototyping and tooling.
- Limited progress has been made with regards to die casting of aluminium and many possibilities for development still exist.

From the available processes a short list of potential rapid tooling processes for high pressure die casting was compiled. The short list was extracted from a number of direct processes available commercially or being commercialised. All the processes, as listed in the table below, use metal powder deposition. The direct processes are preferred due to time and cost factors. These direct processes also hold the advantage that the accuracy of the component that is manufactured is maintained because it is a single stage operation. The direct process also delivers fully dense components best suited for the die casting process.

Table 1.1 AM technologies able to produce fully dense metal components suitable for HPDC

Manufacturer	Sample System and Technology	Material (commercial name and type)	Tensile strength MPa	Tensile Modulus GPa
3D Systems	Vanguard (SLS)	LaserForm A6 (steel based)	610	138
EOS	EOSINT M250 Extended (DMLS)	Direct Steel DS20 (steel) Direct Steel DSH20 (HS steel)	600 1100	130 180
Concept Laser	M3Linear (LaserCusing)	CL 20ES (stainless steel) CL 50 WS (Hot work steel) CL 40 Ti (titanium)	650 1800 1100	145 450
LENS	750 R Alpha	H13 Hot work Steel	1 500	> 400

From the information in the table above, the following processes were selected as potentially best suited for the proposed R&D activities of the project:

Table 1.2 Selected AM platforms to produce specimens for evaluation

Number	Manufacturer	System	Materials
1	EOS	EOS M250X	DSH20 (high strength steel)
2	LENS	750/R (Alpha)	H13 Hot work steel
3	Concept Laser	M3 Linear	CL 50 WS (Hot work steel)

(a) International

- LaserCUSING® (developed by Concept Laser GmbH based on micro-welding technology).
  Service provider: Inspire AG, Institute for Rapid Product Development, Switzerland
- LENS (Laser Engineered Net Shaping),
  Service provider: Optomec, UK

(a) Local

- Direct Metal Laser Sintering (DMLS) (license agreements with 3D Systems and Fraunhofer ILT whereby EOS acquired the rights to all the relevant patents including DTM and University of Texas based on selective laser sintering)
  Service provider: CUT, Bloemfontein

A comparative experimental method was used in this study. A purpose-built rig was used to evaluate the effects of heat checking and other related aluminium melt erosion phenomena experienced by specimens grown with three AM technologies, namely EOS, LENS and LaserCUSING® in comparison with standard die material hot work steel DIN 1.2344.

The ability of a particular AM technology to produce fully dense metallic components suitable for die casting can be quickly assessed with the purpose-built experimental rig.

The assessment of damage inflicted on the cycled specimens was performed through optical microscopy of both faces and sharp corners, so as to analyse the extent of heat checking cracks, as well as the possible presence of corrosion pits. Furthermore, impact toughness and hardness values of cycled and non-cycled specimens were evaluated in order to assess the extent of material properties variation.

1.2 Problem Statement

Currently, hardened (~46HRC) hot work steels are used in HPDC die construction. The choice of materials is imposed by process conditions (die material able to keep a core strength of 1 500 MPa operating at temperatures around 600ºC), which results in the implication that die construction often is a time consuming and costly exercise.

The initial tool costs constitute a remarkable part of the production costs (3 - 5% of a productive efficiency of between 45 – 50%) and thus the economic feasibility of die casting strictly depends on a die life expectancy above 50 000 shots. Dies in general take 12-14 weeks to be manufactured with more than 60% of material removal machining activities concentrated around creating the product shape in the bolster and cavity side of the die.

1.3 Hypothesis

It is possible to develop a rapid die manufacturing methodology based on AM technology, to support companies to produce high integrity small batch cast components in a more cost- and time-effective way.

1.4 The aim of the study

The aim of this study was to establish the potential of Rapid Prototyping (RP) or Additive Manufacturing (AM) technologies to manufacture fully dense metallic components that can be used as die cavity inserts in high pressure die casting (HPDC) processes.

The research intended to develop rapid die manufacturing approaches based on AM technology. The dies manufactured following these approaches should be able to produce a minimum of 50 000 components during HPDC processes.

1.5 Importance of the study

The importance of this project resides on the fact that it impacts on two related areas of activity of the permanent die casting sector of the industry, namely the die design and manufacturing activity and the aluminium high pressure casting enterprise.

Competitive pressures to reduce the lead time and cost required for tooling-up in particular dies for HPDC leads to a constant search for new Tool and Die Manufacturing (TDM) methods. For this reason research into various methods, techniques and approaches towards faster tool and die manufacture are being undertaken globally.

One of our national imperatives is job creation and the small and medium enterprises that comprise the local casting industry and/or allied TDM‘s are supposed to contribute and play a major role towards the country‘s Gross Domestic Product (GDP).

Both the local HPDC and TDM sectors are non-competitive due to common inefficiencies such as the use of aged equipment, old technology and a lack of development of new skills on offer (FRIDGE 2005). The consequences are that these shortcomings have a significant impact on the competitiveness of local mass produced goods for the automotive, mining and packaging industries, rendering them uncompetitive (Viljoen, 2005).

This study looks at the introduction of new technologies such as AM to the TDM processes. These modern techniques applied on the die manufacturing process are believed to be well suited to circumvent and address some of the shortcomings and limitations facing the current South African HPDC and TDM companies in the short to medium time frames.

1.6 Methodology

The methodology used to achieve the objectives of the project includes the following:

(a) Develop a methodology that combines the use of AM technology with standard metal removal technologies used by industry
(b) Through comparative experimentation, evaluate and select the most suitable available AM process for die manufacturing
(c) Manufacture an experimental die using the proposed methodology
(d) Evaluate time and cost feasibility of the methodology

A diagram of the methodology used in this study is shown below.

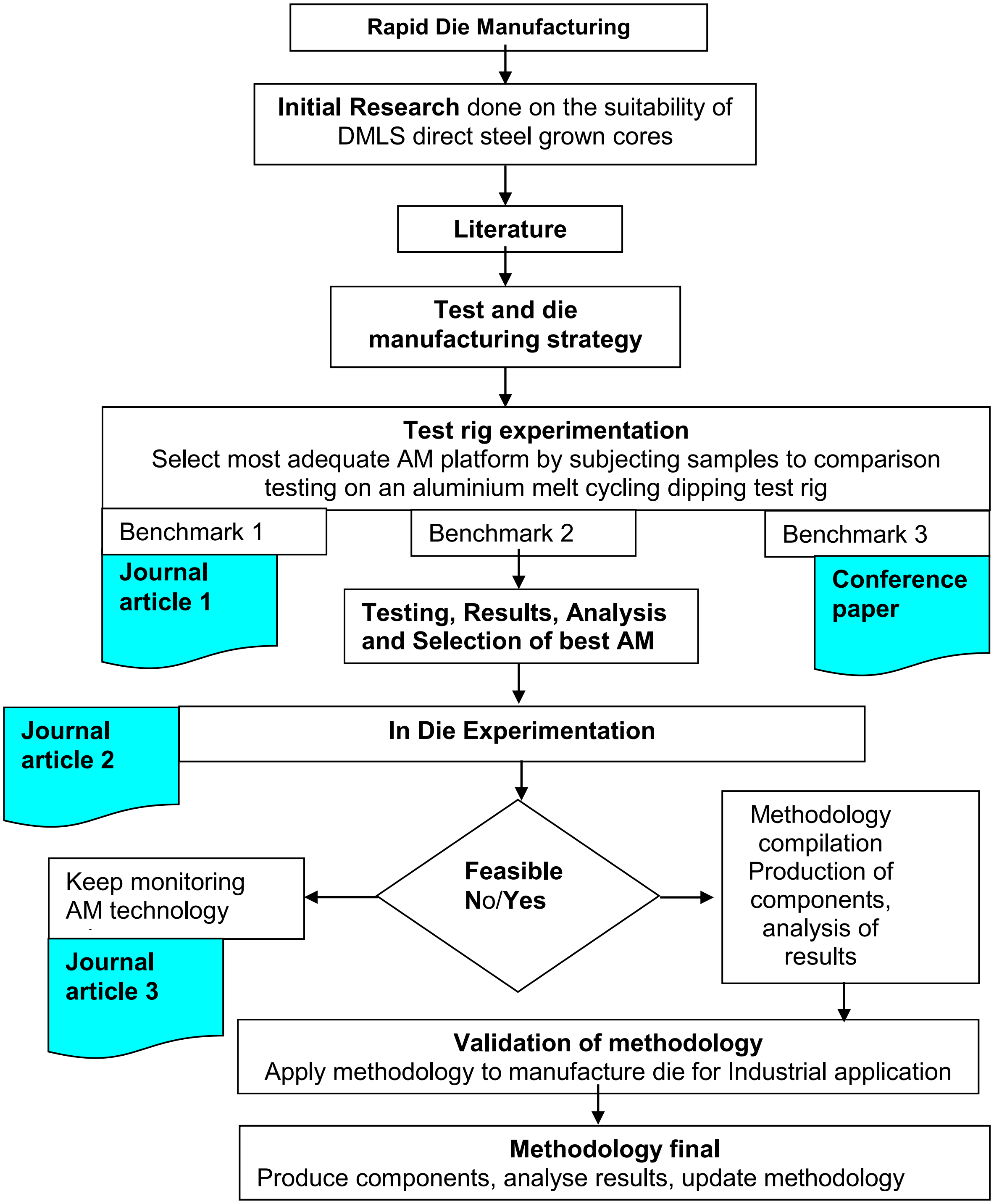

Figure 1.1 Diagram of the methodology followed in this study

1.7 Scope of the study

The current research is concerned with HPDC die design and manufacturing. Note that all the AM processes studied are now available in South Africa. Finally, standard setup parameters were used on the AM machines for the production of the experimental coupons and die cavity inserts. At this stage, no optimisation attempts were made for the manufacture of new test coupons or die cavity inserts.

1.8 Structure of the dissertation

This dissertation is submitted via the –paper format” structure. The layout adopted for the presentation of this thesis is a publication output route in the form of four publishable papers of approximately 3 000 words each which constitute the core of the thesis. Three submitted journal articles (Chapters 4, 6 and 7) and a conference paper in Chapter 5. The results were also presented at the 2007, 2008, 2009 and 2011 annual international conferences of the Rapid Product Development Association of South Africa (RAPDASA). Five co-authors contributed to the articles, with MFVT Pereira as the primary author. The structure of each paper includes the following sections:

- Abstract
- Introduction
- Experimental Approach or Methodology
- Results and discussion
- Conclusion, and
- References.

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 review or has not been submitted (prepared)

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

- Chapter 1 gives an introduction and background to the work. In this chapter the problem statement, hypothesis, the study objectives and its importance are explained
- Chapter 2 gives an account of the literature survey and prior art study performed prior to committing to the experimental phase
- Chapter 3 deals with the experimental approach and methodology used for the project
- Chapter 4 gives an account of the experimental results obtained for two AM platforms and evaluates their suitability as an emerging die manufacturing approach
- Chapter 5 is dedicated to the experimental results obtained for one other AM platform evaluating the suitability for die manufacturing
- Chapter 6 deals with the practical implementation of additive manufacturing technology on an experimental die. The cores and cavities were manufactured by the EOS DMLS platform at the Central University of Technology, Free State in Bloemfontein
- Chapter 7 concludes with an overall discussion and recommendations related to the various chapters

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CHAPTER 2

METAL ADDITIVE MANUFACTURING SYSTEMS SUITABLE FOR MOULD AND DIE MANUFACTURING

2.1 Overview

A number of literature surveys, including internet searches, were conducted in 2006, 2007, and 2009 respectively. The studies uncovered promising AM technologies that might be suitable for die manufacture. This resulted in a listing of all the AM process parameters (build speed, working envelope, materials, finish, and tolerances) of the processes deemed potentially suitable. Reports on experimental work done on selected AM technologies resultant from the literature searches can be considered as a database, as well as a repository of procedures. These procedures when applied to die manufacturing will serve as the basis for a Rapid Tooling (RT) approach to die manufacture.

A literature survey was conducted in order to establish if similar efforts are being pursued elsewhere in the world. The other primary objective of this literature search was to find AM processes, whether a single process or combinations of a few processes, able to deliver die inserts according to the requirements as listed below:

During these surveys relevant information on a number of topics were extracted, namely:

- Identification of suitable AM platforms able to produce cavity forming inserts with the following specifications:

  (a) In the correct materials
  (b) With no porosity problems
  (c) With correct heat properties
  (d) To the required material ductility
  (e) To the correct time scales, cost and quality

- Accessible service suppliers
- AM deposition capability regarding physical size limitations as well availability of suitable deposition materials able to withstand pre-determined casting process conditions
- Layer deposition routines, geometrical accuracy and mechanical characteristics of deposited materials
- Cladding, multi-material deposition capabilities (including application specifications)
- Suitable surface treatments or coatings for life and die service (including application specifications)
- Specifications for die cavity inserts suitable for aluminium die casting

The information was extracted from searches done on the internet, articles published in scientific journals and conference proceedings. From the information acquired, the following conclusions could be made:

- There are two major methods to produce rapid tooling:
  (a) the indirect approach and
  (b) the direct approach (Himmer, 2002) and (Kashka, 2000)
- A number of successes with rapid prototyping and tooling have been achieved in the plastic injection moulding environment
- Limited progress has been made with regards to metal die casting and many possibilities for development still exist

From the available processes a proposed short list of potential rapid tooling processes for metal die casting was compiled.

(a) International

- LaserCUSING^{TM} M3 Linear (developed by Concept Laser based on micro-welding technology). Service provider: Central Metallurgical Research and Development Institute (CMRDI), Egypt and the Institute for Rapid Product Development (IRPD), Inspire AG, Switzerland
- Laser Engineered Net Shaping (LENS) system provided by Optomec Inc. (Albuquerque, NM). Service provider: Optomec UK

(b) Local

- Direct Metal Laser Sintering (DMLS) (license agreements with 3D Systems and Fraunhofer ILT whereby EOS acquired the rights to all the relevant patents including DTM and University of Texas). Service provider: CUT, Bloemfontein

2.2 Additive Manufacturing platform selection

As discussed above, there are two major methods to produce rapid tooling (RT) applicable to high pressure casting, namely the indirect approach and the direct approach

The direct processes are characterised by the direct generation of the rapid tool or cavity components from the CAD models. The direct process also has the advantage that the accuracy of the component which is manufactured is maintained because it is a single stage operation. With indirect processes the component has to go through various stages in which compensation for shrinkage has to be made, which affects the accuracy of the component. Potential human error and other factors could also contribute to this accuracy problem. The most compelling argument for selecting the direct process is that it produces fully dense metallic components with mechanical strength best suited for the high pressure die casting process. Consequently, the remainder of the literature study will deal only with direct processes.

2.2.1 Direct process Additive Manufacturing platforms

All the processes listed in the tables in this section use metal powder. The direct processes are also preferred due to time and cost saving factors. Direct processes also hold the advantage that the accuracy of the manufactured component is maintained, because it is a single stage operation.

From the information in the tables below and literature surveyed the following three AM processes with potential for application in this study were identified, namely LaserCUSING^{TM}, (CUSING is made up from the words concept and fusing, describing both the process and result — the complete fusion of metallic powder), Laser Engineered Net Shaping (LENS) and Direct Metal Laser Sintering (DMLS). Only the DMLS process is available locally in South Africa and as such was selected as the basis for the research.

The following table was extracted out of the data collated on the literature survey undertaken. The information contained in the table expands the topic of direct tooling manufacturing systems to more recent commercialised or early commercialisation approaches and technologies.

Table 2.1 Early commercialisation direct tooling manufacturing processes, (© Copyright Castle Island Co., All Rights Reserved)

Direct Tooling and Manufacturing. – Processes in development or early commercialisation stages'						
Process	**STAT^{TM} [CNC machined composite]**	**Directed Metal Deposition System DMDS^{TM} [based on Sandia's LENS ®]**	**Direct Metal Deposition DMD^{TM}**	**ProMetal^{TM}**	**Electron Beam Melting (EBM)**	**Selective Laser Melting (SLM)**
Suppliers	**Catalyst PDG**	**Optomec and SB's**	**POM-Group**	**ProMetal Division of ExOne Co.**	**Arcam AB**	**MCP-HEK Tooling GmbH**
Lead time	Small parts: 6 days Medium parts: 10 days Large parts: 15 days ©	2 to 4 weeks	2 to 5 weeks (250 x 250 mm tool) to 12 to 16 weeks for larger tools	1 week	2 to 4 weeks	1 week

Direct Tooling and Manufacturing. – Processes in development or early commercialisation stages’

(Continued)

Process	**STAT™ [CNC machined composite]**	**Directed Metal Deposition System DMDS™ [based on Sandia’s LENS ®]**	**Direct Metal Deposition DMD™**	**ProMetal™**	**Electron Beam Melting (EBM)**	**Selective Laser Melting (SLM)**
Injection mould applicable quantities	Up to 1 500 or more©	10 to millions	10 to millions	100 000	Injection moulding: > 1 000 000; die casting: average 100 000	Injection moulding: 100 000 to 250 000 stampings: 3 000 die casting
Injection mould relative cost	Small parts: $3 to $6K Medium parts: $11 to $18K Large parts: $19 to $28K ©		20% more than traditional CNC			
Injection mould materials	All thermoplastics except some ultems, phenolics and silicones ©	Thermoplastics, metals	Thermoplastics, metals	Thermoplastics	Thermoplastics, metals	Thermoplastics, metals

Direct Tooling and Manufacturing. – Processes in development or early commercialisation stages' (Continued)						
Process	**STAT™** [CNC machined composite]	**Directed Metal Deposition System DMDS™** [based on Sandia's LENS ®]	**Direct Metal Deposition DMD™**	**ProMetal™**	**Electron Beam Melting (EBM)**	**Selective Laser Melting (SLM)**
Mould parameters	50 to 500 ton pressure ©	Same as typical injection moulds	Same as typical injection moulds	Up to 30K psi	Same as typical injection moulds	Same as typical injection moulds
Tolerance (mm/mm) or as designated	± 0.125 ©	X-Y: ± 0.05 in accuracy and resolution Z: ± 0.5 mm	± 0.125	± 0.125 + 0.05 mm/mm	± 0.3	± 0.025
Hardness	Rc = 44 after tempering ©	Rc = 45 to 60	Rc = 50	Rc = 30 to 35	H13 tool steel; can be hardened	See Strengths

Direct Tooling and Manufacturing. – Processes in development or early commercialisation stages'
(Continued)

Process	**STAT™** [CNC machined composite]	**Directed Metal Deposition System DMDS™** [based on Sandia's LENS ®]	**Direct Metal Deposition DMD™**	**ProMetal™**	**Electron Beam Melting (EBM)**	**Selective Laser Melting (SLM)**
Surface finish	Light texture to a mirror finish, but subject to wear ©	Requires finish machining	Requires finish machining	Requires finish machining	800 to 1 600 u microns; requires finish machining	7 to 10 u microns
Part size limitations	300 x 530 x 580mm	450 x 450 x 1 065mm	610 x 610mm	500 x 1 000 x 250mm	200 x 200 x 200mm	250 x 250 x 250mm
Strengths	Tight tolerances, lead time, choice of resins and price ©	Fully dense H-13 tool steel; mould repair possibilities: Multiple materials; conformal cooling	Cooling; repair or modify standard moulds; can be polished	60% steel / 40% bronze helps heat conformal cooling; structural mass reduction technology for improved thermal isolation; Inconel, aluminum and gold possible; 99%+ density	Fully dense parts; energy eff. process; potential for many materials; conformal cooling but powder must be removed from channels	Can use any powdered material; Supports: Same as base material; fully dense parts; conformal cooling possible but powder must be removed from channels

Direct Tooling and Manufacturing. – Processes in development or early commercialisation stages' (Continued)						
Process	**STAT^{TM}** [CNC machined composite]	**Directed Metal Deposition System DMDS^{TM}** [based on Sandia's LENS ®]	**Direct Metal Deposition DMD^{TM}**	**ProMetal^{TM}**	**Electron Beam Melting (EBM)**	**Selective Laser Melting (SLM)**
Weaknesses	Tool life, phenolic and silicone resins, single supplier	Geometric limitations on overhangs; requires finish machining	Geometric limitations on overhangs; requires finish machining	Extensive finishing required	Limited part size; slow cool-down; requires finishing	Limitations on wall thickness and overhangs

Tables 2.2 to 2.6 show the results of a benchmark exercise undertaken by Dr Abdel Ghany K. and Moustafa S. F. (Abdel Ghany (2006) of the Cairo-based Central Metallurgical Research and Development Institute on four commercially available RP metal deposition platforms.

The Egyptian work evaluates and compares the quality of four dimensionally and geometrical identical components referred as benchmarks, fabricated from metallic powders suitable for each of their four selected AM systems for metals. The evaluation considers and compares benchmark geometry, dimensional precision, material type, product strength and hardness, surface quality, building speed, materials, operation and running cost.

Table 2.2 is a summary of results extracted from industry which established rapid direct tooling manufacturing processes using polymer injection moulds as the benchmark. The aim of the study was to select and acquire the best metal AM system for the centre to be able to do research and introduce rapid tooling manufacture in Egypt.

The table summarises the initial results of a survey done by CMRDI on established direct tooling manufacturing systems and approaches used at the time of the exercise.

Table 2.2: Mature direct tooling manufacturing processes (Abdel Ghany, 2006)

Direct Tooling and Manufacturing Processes - Mature and/or More Common Technologies						
Process	**Direct AIM^{TM}**	**Space Puzzle Molding^{TM}**	**Direct Metal Laser Sintering (DMLS) (Bronze alloy)**	**CNC Al Tooling**	**SLS Tooling Direct**	**Direct Metal Laser Direct Metal Laser Sintering (DMLS) (Steel)**
Suppliers	3D Systems	Protoform	EOS GmbH	Many	3D Systems	EOS GmbH
Lead Time	1 week	2 to 4 weeks	1 to 4 weeks	4 to 16 weeks	3 to 4 days for inserts with no finishing, 5 to 10 days if finishing is required (1); 2 to 5 weeks might be typical range	1 to 2 weeks
Injection Mould Applicable Quantities	10 to 50	up to 1 000	100's to 1 000 (12)	50 to 100 000's	100's of Zn, Al, Mg die cast parts , 100 000's most plastics	100's die cast parts 100 000's most plastics

Direct Tooling and Manufacturing Processes - Mature and/or More Common Technologies

Process	**Direct AIM^{TM}**	**Space Puzzle Molding^{TM}**	**Direct Metal Laser Sintering (DMLS) (Bronze alloy)**	**CNC Al Tooling**	**SLS Tooling Direct**	**Direct Metal Laser Direct Metal Laser Sintering (DMLS) (Steel)**
Injection Mould Relative Cost	$2K to $5K	$2K to $10K; up to 50% of conventional mould cost		$4K to $25K	$4K to $10K	
Injection Mould Materials	Low temp, unfilled thermo plastics	Thermo plastics	Thermo plastics	Thermo plastics	Thermo plastics, metals	Thermo plastics, metals
Mould Parameters	May require experimentation and experience	Normal high volume moulding parameters for each plastic; up to or 700 metric ton clamping force; 140 gram shot maximum			Typical injection moulding pressure and temperature	

Direct Tooling and Manufacturing Processes - Mature and/or More Common Technologies

Process	**Direct AIM™**	**Space Puzzle Molding™**	**Direct Metal Laser Sintering (DMLS) (Bronze alloy)**	**CNC Al Tooling**	**SLS Tooling Direct**	**Direct Metal Laser Direct Metal Laser Sintering (DMLS) (Steel)**
Tolerance (mm/mm) or as designated	± 0.05	Same as standard injection molding: 0.025 to 0.05 mm with hard AL tools	± 0.07% + 0.05	± 0.025	0.08 mm layers; ± 0.08 mm, 0.005 details ; 0.125 to 0.25mm in for most dimensions	± 0.025 to 0.05 mm/mm
Hardness	N/a	Depends on material of puzzle segments			Rb 87 (D)	Brinell 60 to 80 (4)
Surface Finish		Depends on material of puzzle segments	350 u in from machine; 120 u in after shot peening		5 µm or D-3; 1 -3 µm or A-2 to A-3 after polishing	Finish Rz = 20 µm (shot peened)
Part Size Limitations		216 x 380 x 775 mm	250 x 250 x 175mm		200 x 250 x 125mm	250 x 250 x 175mm

Direct Tooling and Manufacturing Processes - Mature and/or More Common Technologies						
Process	**Direct AIM^{TM}**	**Space Puzzle Molding^{TM}**	**Direct Metal Laser Sintering (DMLS) (Bronze alloy)**	**CNC Al Tooling**	**SLS Tooling Direct**	**Direct Metal Laser Direct Metal Laser Sintering (DMLS) (Steel)**
Strengths	Direct fabrication of moulds	Can withstand high volume process moulding settings; aluminum mould segments can be made by high speed cutting, yielding 50% saving time on complex parts.	Conformal cooling; no burnout cycle; 90%+ density	Excellent accuracy and finishes; long tool life	Die casting; can take typical injection moulding pressure and temperature; Largely non attended operation; 98% density	No burnout; accuracy and surface finish is improving with new materials
Weaknesses	Severe materials and process limitations; limited availability	Manual loading and unloading and re-assembly of mould for each shot; limited to about 1 000 parts; cost per part higher than standard process	Limited tool life, lower pressures, conformal cooling channels have limitations due to required powder removal	Slow and expensive for complex parts	Requires burnout and infiltration cycle; may require finish machining; conformal cooling channels have limitations due to powder removal	May require finish machining; conformal cooling channels have limitations due to powder removal

As mentioned above, a number of tables were developed from the Egypt's Cairo-based Central Metallurgical Research and Development Institute (CMRDI) work. Their initial literature study was used to select the four most promising AM technologies suitable for the manufacture of fully dense metal components. Orders were placed with the shortlisted AM technologies service suppliers to manufacture one benchmark component (as shown in Figure 2.1) out of each of their metal powders. The results of the visual inspection of each benchmark produced can be seen in tabular form.

Figure 2.1 The tested benchmark showing different views (Abdel Ghany, 2006)

Table 2.3 Results of visual examination of a benchmark component manufactured by four different AM metal deposition systems (Abdel Ghany, 2006)

Property/BM	**1**	**2**	**3**	**4**
System	**M3 Linear** **www.concept-laser.de**	**Vanguard** **www.3dsystems.com**	**M 250 X** **www.eos.info**	**Realizer** **www.mcp-group.de**
Total shape	Complete	Complete	Missing Details	Bad/ incomplete
Dimension change	± 0.1	± 0.1	± 0.1	- 0.2
Fine details	Very accurate	Very accurate	Poor	Poor
Holes	Sharp; correct depth; near circular	Very sharp; correct depth; circular	Sharp; correct depth; near circular	Incomplete depth; near circular
Cooling tubes	Very accurate	Very accurate	Incomplete	Blocked
Sharp edges	Very sharp	Very sharp	Blunt	Blunt
Sharp corners	Very sharp	Very sharp	Blunt	Blunt

Property/BM	1	2	3	4
System	**M3 Linear www.concept-laser.de**	**Vanguard www.3dsystems.com**	**M 250 X www.eos.info**	**Realizer www.mcp-group.de**
Thin wall (1mm)	Very accurate	Very accurate	Missing	Incomplete
Surface roughness (finished surfaces)	A little rough	Smooth	Smooth	Rough
Surface roughness (1) (unfinished surfaces)	Rough	Smooth	Rough	Very rough
Layer coherence	Complete coherence (layers are not visible)	Complete coherence (layers are not visible)	Complete coherence (layers are not visible)	Not sufficient coherence (layers are visible)
Cracks	No cracks	No cracks	Internal cracks(2)	Layer separation
Examination result	Very Good	Excellent	Good	Poor

(1) Measured inside holes and grooves.

(2) Internal cracks and complete separation between the surface layer (smoothed by micro-shot peening) and the internal body was observed when slicing the benchmark.

A table with the corresponding CMRDI‘s selected AM system and corresponding metal used to build the benchmark was created.

Table 2.4 AM Metal Deposition Systems used to build the benchmark sample model (Abdel Ghany, 2006)

Number	Manufacturer	System	Materials
1	Concept Laser	M3 Linear	CL 50 WS (Hot work steel)
2	3D Systems	Vanguard HS	LaserForm A6 (steel based)
3	EOS	EOSINT M250X	DSH20 (high strength steel)
4	MCP-HEK	Realizer	Stainless steel powder

The core strength of the different materials used on the benchmark can be seen highlighted in green on the table that follows.

Table 2.5: Tensile strength of finished metallic AM products (data extracted from the vendors' internet sites)

Tensile strength of finished metallic AM products				
Manufacturer	**Sample System and Technology**	**Material (commercial name + type)**	**Tensile strength MPa**	**Tensile Modulus GPa**
3D Systems	Vanguard (SLS)	(1) LaserForm A6 (steel based)	610	138
EOS	EOSINT M250X (DMLS)	Direct Steel DS20 (steel) (1)Direct Steel DSH20 (HS steel)	600 1100	130 180

Tensile strength of finished metallic AM products				
Manufacturer	**Sample System and Technology**	**Material (commercial name + type)**	**Tensile strength MPa**	**Tensile Modulus GPa**
Concept Laser	M3 Linear (SLMW)	CL 20ES (stainless steel) (1) CL 50 WS (Hot work steel) CL 40 Ti (titanium)	650 1800 1100	145 450
MCP-HEK	MCP Realizer (SLM)	(1) Stainless Steel Commercial metallic powder Commercial ceramics powder	> 600	> 400

(1) Materials selected for benchmark.

Table 2.6 below captures most of the significant factors affecting economic feasibility of the different AM technology platforms.

Table 2.6 Parameters affecting the cost of each benchmark (Abdel Ghany, 2006)

Parameters affecting the cost of each benchmark				
Property / System BM	**1 (M3 Linear)**	**2 (Vanguard HS)**	**3 (EOSM250X)**	**4 (MCP Realizer)**
Volume (cm^3)	285.3	285.3	204.9 (1)	285.3
Weight (kg)	2.12	2.2	1.4	1.7
Layer thickness (mm)	0.03	0.08	0.02	0.05
Total process time (hrs) (2)	121	35.5	58	60
Finishing time (hrs)	1	1	1	*Not finished*
Materials cost (3) **USD / kg**	260(4)	80	180	100
Benchmark material cost	551	176	252	170

Parameters affecting the cost of each benchmark				
Property / System BM	**1 (M3 Linear)**	**2 (Vanguard HS)**	**3 (EOSM250X)**	**4 (MCP Realizer)**
Power consumption KW (5)	7.5	12.5	6	4
Average cost	High	Medium	High	Low

(1) This benchmark has different volume because the model was scaled down

(2) Processing including setup time + processing time + infiltration time (if any)

(3) Material costs were obtained from the manufacturer‘s announced price list

(4) The price of high strength tool steel is 260 USD but it is less for normal steel

(5) From the machines datasheets for the AM systems without accounting for chiller and oven wattage

The following paragraphs give a more detailed explanation of the function, operation and system specifications of the selected AM platforms.

2.3 LaserCUSING® M3 Linear

This AM platform evenly spreads fine powder layers by means of mechanical rollers, then the particles are thermally joined by a 100 or 200 watt lamp-pumped Nd:YAG laser beam moving at high speed of up to 10 m/s (Concept Laser, 2007). The AM system manufacturer, Concept Laser, claims to use a selective laser micro welding technique in which the laser beam completely "melts" the powder particles (at temperatures of 1500 – 1700°C), forming very fine molten pools which solidify to form hard and dense thin layers (20 ~ 100 µm thick) of solid metal. Because complete melting occurs, the achieved density at the end of the direct process is better than 95%, which results in components with mechanical strength close to the theoretical value of the equivalent wrought metal alloy being obtained. The system does not require an additional infiltration process. The material used in this project for die manufacture was the hot work steel alloy CL 50 WS which has high density and hardness (see Table 2.5). According to the manufacturer‘s information, many other types of metal alloy materials can be used. If contemplating using other metallic alloy powders, one must take into consideration that some process optimisation work would be required in order to obtain components with the desired properties. The most important AM machine process parameters to be optimised are the laser energy consumption, speed and shielding inert gas flow.

2.4 Direct Metal Laser Sintering (DMLS)

The technique is very similar to that used for LaserCUSING®, but one major difference is that the process uses the laser beam to "directly" sinter and join the metallic particles. Only sintering occurs, i.e. no complete melting occurs (Kruth 2004*)* and therefore the name ‗partial melting‘ is preferred. The maximum density achieved is approximately 97%. The manufacturing company, EOS, has named this processing technology "Direct Metal Laser Sintering (DMLS)". The raw material contains some chemical additives, such as phosphor, or boron and/or copper, which aid easier sintering of the metal particles at lower temperatures than those prescribed for the major base metals present in the alloy. At the end of the process, the part can be finished using a micro shot peening process and other standard die manufacturing aids.

DMLS is an advanced technology and very similar to the technology used by LaserCUSING® except that it only does –sintering”, not complete –melting”.

2.5 Laser Engineered Net Shaping (LENS)

LENS technology is utilising another approach to manufacture parts compared to a powder bed system. LENS delivers powder by nozzles directly to the point where a focused laser melts the powder, fusing it into a part line-by-line, layer-by-layer (Optomec, 2007). This process is called powder deposition and the technique typically offers larger working envelopes and the ability to either make parts or repair existing parts. One such system is LENS which has been offered commercially since 1998. LENS was originally developed at Sandia National Laboratories.

The LENS 850-R system, provided by Optomec Inc., Albuquerque, NM, offers a working envelope of 900 x 1 500 x 900mm, positional accuracy of ± 0.25 mm across the working envelope, and linear resolution of ± 0.025 mm. The included tilt-rotate table offers angular resolution of 0.01°. Spatial resolution of the features deposited using LENS can vary between 300 µm and 1 cm, depending on the laser power used. Using a 1 or 2-kW fibre laser provided by IPG Photonics (Oxford, MA) as standard equipment, it can deposit material at rates up to 200 cm^3/hr.

The LENS process is housed in a chamber purged with argon so that the oxygen level stays below 10 parts per million, to ensure there is no impurity pickup during depositions. The control head for the laser and powder metal deposition has three-axis linear X, Y, Z motion control, while a tilt-rotate table gives the system the extra two axes for five-axis control. Two additional axes are available through an optional pitch/yaw wrist control. Optomec also offers the smaller LENS 750 with a 300 x 300 x 300mm working envelope, with similar accuracy and deposition rates. LENS also provides value in repairing manufacturing defects (high value parts), thereby improving yield and reducing cost.

2.6 Conclusion

There are various types of AM tooling methods available, all classified under two groups, the direct and the indirect methods. The indirect method is an approach where a master pattern is required. However, these processes have disadvantages, because of their multi-stage process characteristics; they compromise accuracy of the component and prolong the manufacturing time. The direct methods do not require master patterns, hence are more likely to cut down on processing time as well as improving the accuracy.

From this investigation it was decided that the following processes should be evaluated for suitability in high pressure casting dies manufacture:

- LaserCUSING®, M3Linear (developed by Concept-laser based on Micro-welding technology)
- LENS (developed by Sandia National Laboratories based on delivery of powder by nozzles)
- Direct Metal Laser Sintering (DMLS) (developed by EOS based on laser sintering technology)

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CHAPTER 3

EXPERIMENTAL APPROACH AND METHODOLOGY

3.1 Overview

This chapter deals with the execution of a plan of comparative experiments used to evaluate the selected Additive Manufacturing (AM) platforms and evaluates their suitability as an emerging die manufacturing approach. As a result of this exercise, a number of articles were published and papers were delivered at conferences. Two articles were published in the *Journal for New Generation Sciences* (JNGS). One of the articles was published in the November 2009 volume 7, no 2. (Chapter 6 of this dissertation) and the other in the November 2010 volume 8, no 2 (Chapter 4 of this dissertation). A third article was published in the *South African Journal of Industrial Engineering* (SAJIE) July 2012, volume 23, no 21 (Chapter 7 of this dissertation). A paper was presented at the Rapid Product Development Association of South Africa (RAPDASA) 2009 (Chapter 5 of this disseration). The author has also presented the outcomes of this research at the Rapid Product Development Association of South Africa (RAPDASA) 2007, 2008, 2009 and 2011 Conferences.

3.2 Introduction

Aluminium high pressure die casting (HPDC) of components is a mass manufacturing process that imposes severe stresses on the dies when under processing conditions. Furthermore, die manufacturing costs are a significant component of the economic feasibility of the die casting process. Dies are manufactured out of applicable steel materials that can withstand process conditions for an undetermined period of time; therefore, the terms ―die life” and ―expected minimum die life prior to failure due to process induced wear and tear”. Die wear and tear failures are mainly ascribed to washout damage or thermal fatigue of the die cavity surfaces.

Die cavity surfaces which are highly cracked due to thermal fatigue and/or damaged surfaces due to washout lead to a rapid die end of production life. For obvious reasons, the die produces an ever increasing number of rejects due to non-compliance with dimensional and geometrical specifications.

The comparative experimental method approach was used in this study. A purpose-built experimental rig was designed and manufactured in-house. The rig was used to evaluate by comparison the effects of heat checking and other related aluminium melt erosion phenomena experienced by coupons manufactured with three AM technologies, namely EOS, LENS and LaserCUSING® in comparison with standard die material hot work steel DIN 1.2344. The approach made use of a rig able to subject the AM grown and standard steel manufactured coupons to cyclic heating and cooling following from immersion in liquid aluminium.

The ability of a particular AM technology to produce fully dense metallic components suitable for die casting could be quickly assessed with this experimental set up. Keeping economic feasibility in mind and knowing that on standard hot work steel, evidence of heat checking damage appears only after a few thousand cycles, 5 000 - 10 000 cycles were selected as experimental benchmarks.

The assessment of damage inflicted on the cycled coupons was performed through optical microscopy of both faces and sharp corners, so as to analyse the extent of heat checking cracks as well as possible presence of corrosion pits. Furthermore, impact toughness and hardness values of cycled and not cycled coupons were evaluated in order to assess the extent of material properties variation.

3.3 Experimental method

A test rig was designed and manufactured for the research. The rig is able to subject the AM and standard steel manufactured coupons to cyclic heating and cooling through immersion in liquid aluminium. The dipping cycle closely resembles the heating and cooling cycle of a typical aluminium die under casting conditions.

The initial part of the experimental plan was for each AM system supplier to fabricate four test coupons; three solid and one with an open blind-hole passage. (Refer to diagram in Figure 3.1)

3.3.1 Test coupons

The coupons were modelled with a shape suitable to perform a simple beam Charpy impact test. Initially, un-notched coupons with a length of 100mm and cross section of 10 x 10mm were machined and/or manufactured by AM technologies. The extra length of the coupon beyond the classical 55mm required for the impact test was used to hold the coupons in the test rig, described in detail in the following section. Two sets of coupons made out of three AM technology platforms and standard hot work steel were subjected to a Charpy impact test. One of the sets was first subjected to a programme of cyclic immersion in molten aluminium prior to undergoing impact testing.

Figures 3.1 and 3.2 below show the modelled coupons that were evaluated.

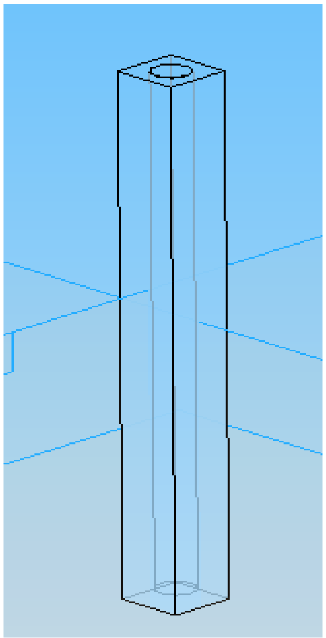


Figure 3.1 Geometrical model of test coupon with a square cross section of 10 x 10mm, length 100mm with blind hole diameter 6mm up to 2mm from the bottom.

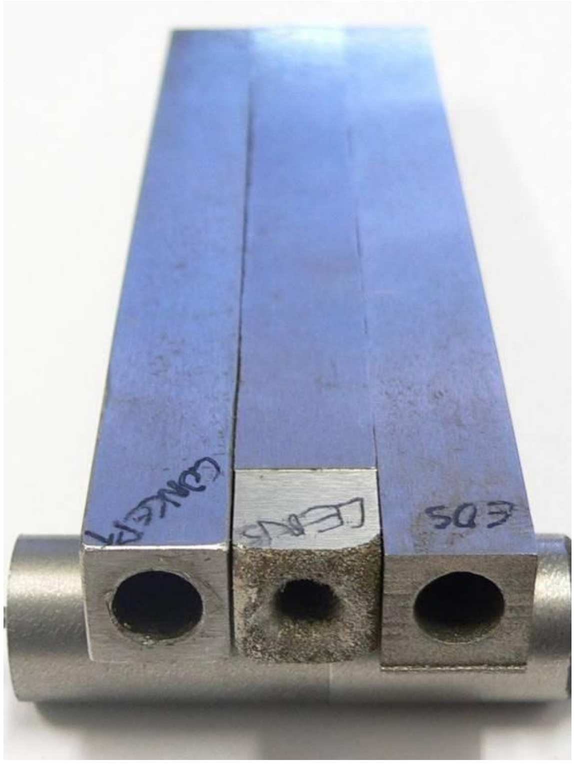


Figure 3.2 Test coupons‘ hole aspect for the three systems.

The results of initial visual and geometrical evaluation of the test coupons are shown in Table 3.1.

Table 3.1 Results of visual examination.

Results of visual examination			
Description/Benchmark	**1**	**2**	**3**
System	**Concept M3 Linear**	**LENS 750 Model**	**EOSINT M250X**
Total shape	Complete	Complete	Complete
Dimension change mm	± 0.1	± 1.5	± 0.1
Fine details	Very accurate	Poor	Very accurate
Holes	Sharp; correct depth; circular	Deformed; required 1mm per side machining	Sharp; correct depth; circular
Sharp edges	Sharp	Blunt	Sharp
Sharp corners	Sharp	Blunt	Sharp

Description/Benchmark	**1**	**2**	**3**
System	**Concept M3 Linear**	**LENS 750 Model**	**EOSINT M250X**
Surface roughness (finished surfaces)	Smooth Rą= 3.2 µm	Rough Rą= 6.4 µm	Smooth Rą= 3.2 µm
Layer coherence	Complete coherence (layers are not visible)	Complete coherence (layers are not visible)	Complete coherence (layers are not visible)
Cracks	No cracks	No cracks	Internal cracks
Examination result	Very good	Average	Good

AM coupons that underwent different heat treatments were always cycled and evaluated against heat treated standard hot work coupons. In this research, test coupons made with the materials in Table 3.2 were evaluated.

Table 3.2 Metal powders used by service providers to manufacture test coupons

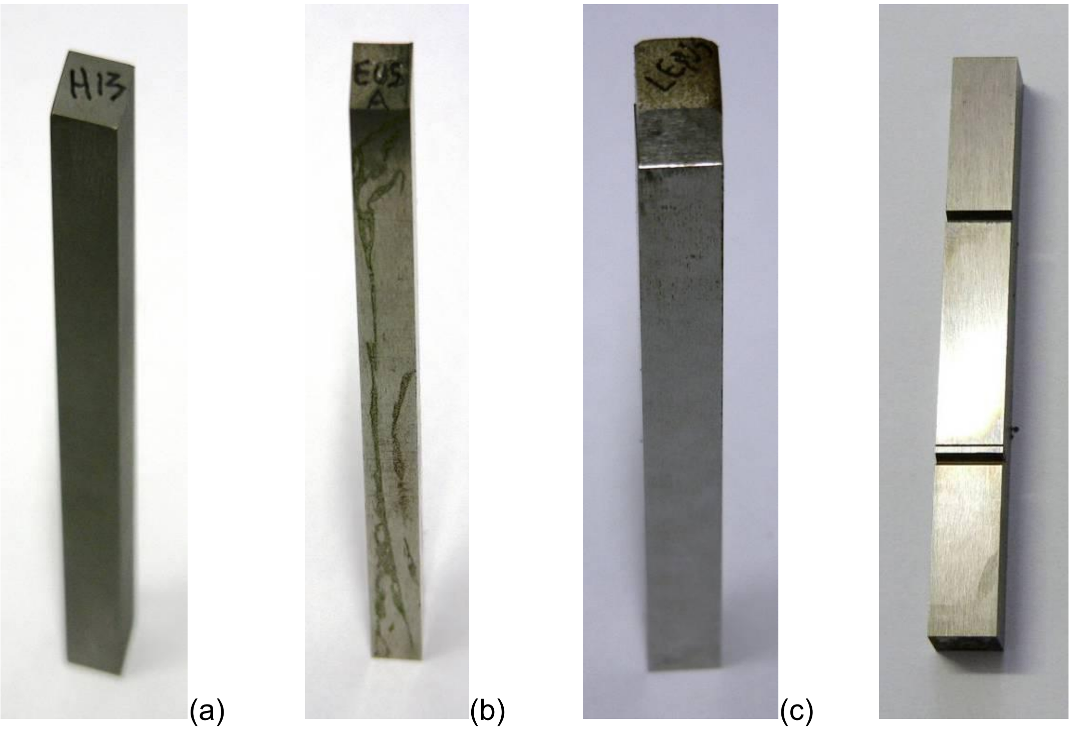
Number	Manufacturer	System	Materials
1	LaserCUSING®	M3 Linear	CL 50 WS (hot work steel)
2	LENS	Lens 750 Model	H13 (Din 1.2344 hot work steel)
3	EOS	EOSINT M250X	Direct Steel DS20 (steel)

EOS equipment suppliers were not able to provide test coupons for evaluation in more suitable material for die components.

The data captured in the manufacturing of the complete cores was evaluated and analysed. Four sets of cores were manufactured using the methods listed below:

- One following conventional die machining methods from hardened hot work steel DIN 1.2344 material
- One using the EOS process
- One using the LENS process
- One using the LaserCUSING® process

Cores manufactured with the conventional and AM methods are shown in Figure 3.3 below.



(a) (b) (c) (d)

Figure 3.3 Pictures showing the cores manufactured with the conventional and AM methods

(a) Through-hardened steel 1.2344 conventionally manufactured coupon
(b) EOS grown coupon
(c) LENS grown coupon
(d) LaserCUSING® grown coupon

3.3.2 Dipping rig for cyclic immersion in molten aluminium

The testing apparatus, as shown in Figure 3.4, was developed to simulate thermal cycling conditions that occur inside the cavity surfaces of the die in contact with the aluminium melt.

Four coupons could be mounted in this rig. The immersion cycle of the coupons closely resembles the temperature profile that cavity die components experience under high pressure casting conditions. At the same time, coupons mounted on both sides of the rotating arm were immersed either in aluminium at 660-680°C and a cooling bath at 28-30°C. Then the two opposite sides of the rotating arm were lifted and the immersion order reversed. An average cycle time of 20 seconds was achieved. The heating and cooling cycle measured on the coupons ranged between 80 and 540°C. A typical die casting thermal shock cycle experience ranges between 110 and 480°C (Ugges, 2004). This means that the coupons were subjected to a more severe heat shock deterioration cycle than when subjected to casting conditions.

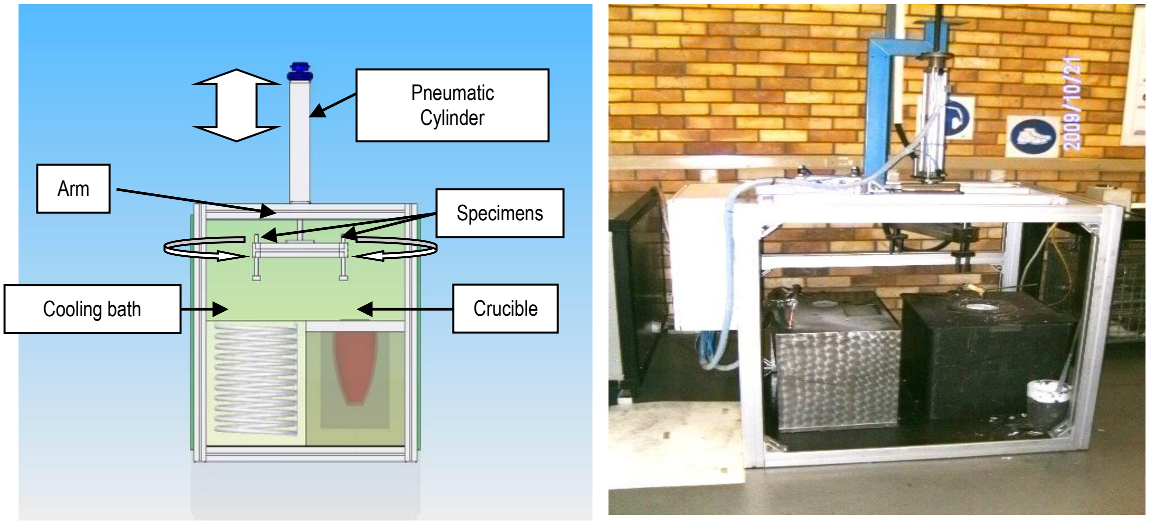


Figure 3.4 Aluminium melt cyclic dipping test rig

3.4 Density evaluation

The extent of porosity built in the manufacture of the AM coupons was done with an Ohaus density determination kit installed on a Voyager lab scale able to weigh specimens up to a weight of 210 grams and an accuracy of 0.1 mg. The density determination set up is shown in Figure 3.5 below.

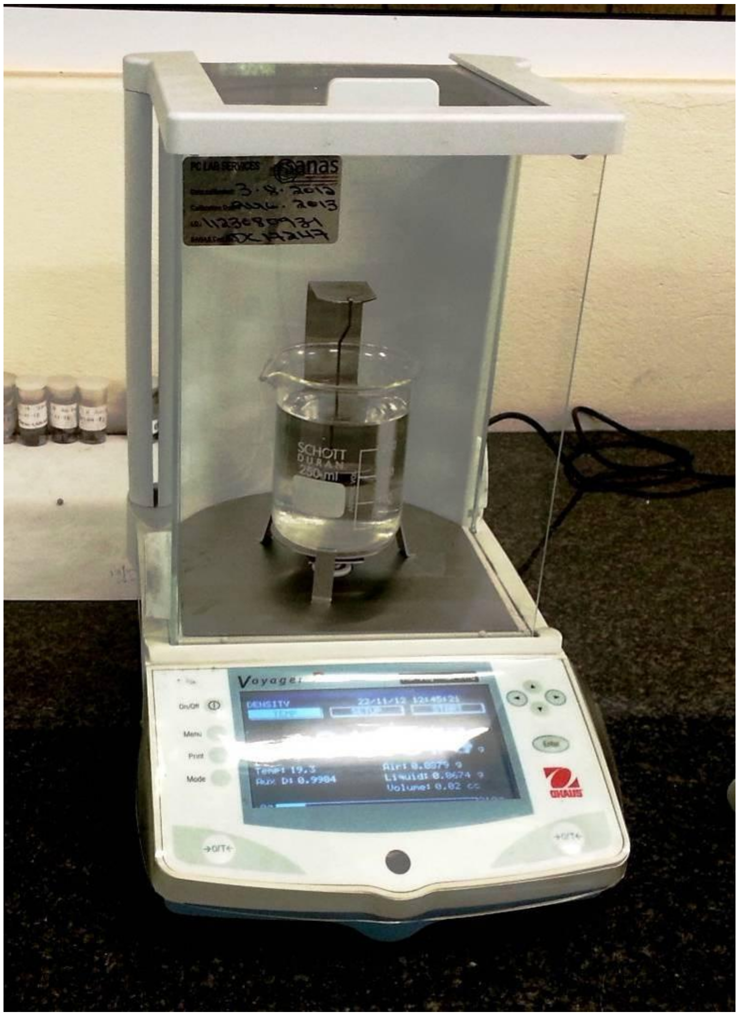


Figure 3.5 Density determination set up

The resulting average porosity of the three different AM manufactured specimens evaluated was captured on the table shown below.

Table 3.3 AM Coupons Archimedes Density

AM Technology Platform	Measured density g/cm3	Material specified density g/cm3	Porosity %
EOS	7.376	7.60	2.95
LENS	7.722	7.80	0.34
LaserCUSING	8.065	8.10	0.43

The density test results are clear evidence that EOS coupons have a significant amount of porosity compared to both LENS and Concept Laser counterparts. Further microscopy work confirmed the slightly better dense material structure characteristics of the LENS coupon in relation to the LaserCUSING® counterpart.

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CHAPTER 4

CHARACTERISATION OF METAL POWDER BASED ADDITIVE MANUFACTURED COMPONENTS WITH RESPECT TO ALUMINIUM HIGH PRESSURE DIE CASTING PROCESS CONDITIONS – SECTION A

Authors: Pereira M.F.V.T., Williams M., Du Preez W. B., 2010

Purpose

The objective of this paper is to select the more suitable Additive Manufacturing (AM) technology process between two alternatives, namely the LENS and the EOS DMLS processes. These processes are to be used to produce cavity die inserts for the manufacture of dies for aluminium HPDC.

Design/methodology/approach

An experiential comparative approach was used as the selection method. The comparative criteria used included physical metallic integrity, time taken to manufacture, surface finish, dimensional accuracy and cost.

Findings

The study indicates that AM technology has potential for significant time compression, as well as die life expectancy at established economically feasible criteria.

Originality/value

In the paper, AM technology is proposed as an alternative die manufacturing process.

Paper type: Research paper

Paper status: Published - Journal for New Generation Sciences (JNGS), Vol. 8, No. 2, pp 85-94, ISSN 1684-4998

4.1 Introduction

Aluminium high pressure die casting (HPDC) is a manufacturing process that imposes severe stresses on the dies when under processing conditions. Furthermore, die manufacturing costs are a significant component of the economic feasibility of the die casting process. Dies are manufactured out of applicable steel materials that can withstand process conditions for an undetermined period of time; therefore the terms *–die life* and *expected minimum die life prior to failure due to process induced wear and tear”* are found in the industry (Yucong Wang, 1997).

The most important die wear and tear failures are described as follows:

- **Washout damages** results from erosion and corrosion of cavity die surfaces. Erosion is attributed to the flow of molten aluminium impinging and rubbing on the surfaces. Corrosion is attributed to friction wear caused when the melt solidifies around core surfaces and the casting is ejected
- **Thermal fatigue,** the most influential failure mode in die casting, reveals itself in two modes namely heat checks and stress cracks. The characteristic feature of heat checks is the appearance of fine cracking lines on surfaces, which look like a spider web. Stress cracks appear mainly in corners and appear as individual and clearly defined cracks, sometimes filled with aluminium

Highly cracked or damaged surfaces lead to a rapid die end of life. For obvious reasons, the die produces an ever increasing number of rejects due to non-compliance with dimensional and geometrical specifications.

The use of Additive Manufacturing (AM) techniques for the purpose of compressing the time it takes to manufacture die components forms part of an ongoing research exercise. The approach described here was applied to evaluate the effects of heat checking on specimens grown with AM technology platforms, namely EOS and LENS, in comparison with standard die material hot work steel DIN 1.2344. The approach makes use of equipment able to subject the AM manufactured and standard steel manufactured specimens to cyclic heating and cooling with an immersion in liquid aluminium.

The suitability of AM technology to be able to produce fully dense metallic components suitable for die casting can be quickly assessed with the set up. With economic feasibility in mind and knowing that on standard hot work steel evidence of heat checking damage appears after a few thousand cycles - 5 000 cycles was determined as the experimental benchmark.

The assessment of damages inflicted on the cycled specimens was performed through optical microscopy of both faces and sharp corners, so as to analyse the extent of heat checking cracks as well possible presence of corrosion pits. Furthermore, impact toughness and hardness values of cycled and not cycled specimens were evaluated in order to assess the extent of material properties variation.

4.2 Experiment

The purpose of the experiment was to evaluate the performance under cyclic heating and cooling conditions of three geometrically similar components which were manufactured by different methods. Open literature revealed that similar designs of this rig are being used elsewhere in the world to perform thermal shock experiments. None of them foresaw the use for evaluation of AM manufactured specimens. A total of 5 000 shots were produced using recycled aluminium A356 material.

4.2.1 Specimens

The specimens were modelled with a shape suitable to perform a simple beam Charpy impact test. Initially, un-notched specimens with a length of 100mm and cross section 10 x 10mm were machined and/or grown. The extra length of the specimen beyond the classical 55mm required for the impact test was used to hold the specimens in the test rig described below. Two sets of specimens made out of two AM technology platforms and standard hot work steel were subjected to a Charpy impact test. One of the sets was first subjected to a programme of cyclic immersion in molten aluminium prior to undergo impact testing. Figure 4.1 shows the modelled specimens that were evaluated.

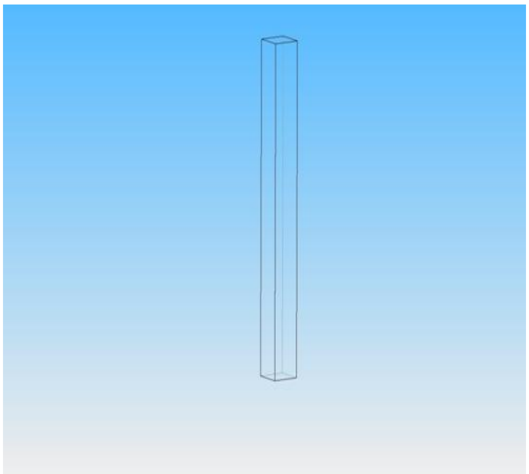


Figure 4.1 Geometrical model of test coupon with a square cross section of 10 x 10mm and length 100mm.

Figure 4.2 Manufactured and machined specimens

The material selected for a set of specimens was through-hardened and tempered hot work steel (DIN 1.2344). The alloy selected for the EOS AM process specimens was Direct Steel 20. The alloy selected for the LENS AM process specimens was equivalent to hot working steel Din 1.2344. The data captured in the manufacturing of the complete cores was evaluated and analysed

Three sets of cores were manufactured using the methods listed below:

- One following conventional die machining methods from hardened DIN 1.2344 material
- One using the EOS process
- One using the LENS process

Figure 4.3 below shows the finished manufactured and as grown cores.

(a) (b) (c)

Figure 4.3 Pictures showing the cores manufactured with the conventional and AM methods:

(a) Through- hardened steel 1.2344 conventionally manufactured specimen
(b) EOS grown coupon
(c) LENS grown coupon
(d) LaserCUSING® grown coupon

4.2.2 Dipping rig for cyclic immersion in molten aluminium

Figure 4.4 below shows the testing apparatus developed to simulate thermal cycling conditions that occur inside the cavity surfaces of the die in contact with the aluminium melt. Four specimens could be mounted in this rig; in this instance only three were evaluated. At the same time, specimens mounted on both sides of the rotating arm were immersed either in aluminium at 660-680°C and a cooling bath at 28-34°C. Then the two opposite sides of the rotating arm were lifted and the immersion order reversed. An average cycle time of 20 seconds was achieved. The heating and cooling cycle measured on the specimens ranged between 80 and 540°C. A typical die casting thermal shock cycle experience ranges between 110 and 480°C. This means that the specimens were subjected to a more severe heat shock deterioration cycle than when subjected to casting conditions.

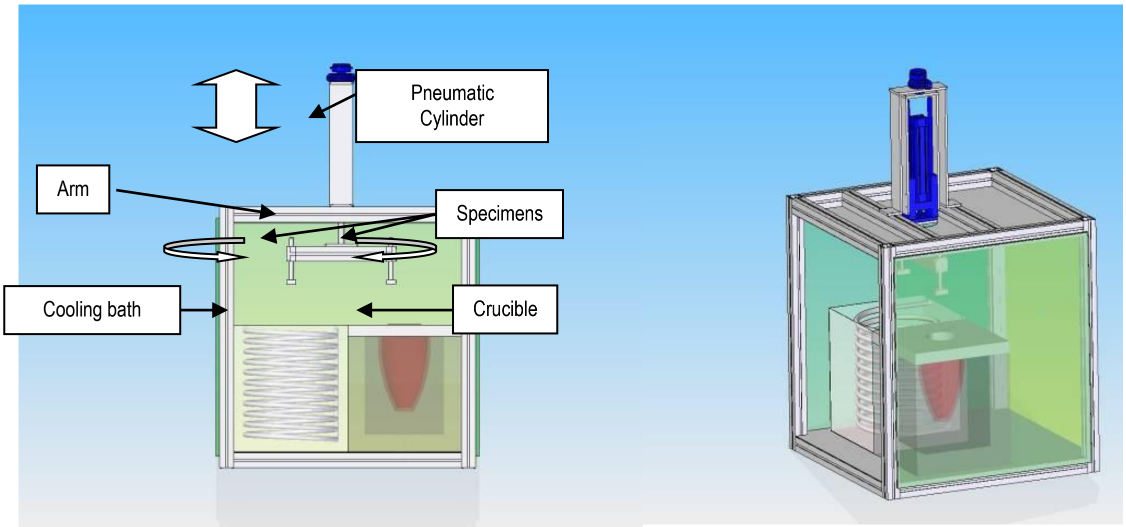


Figure 4.4 Aluminium melt cyclic dipping test rig

4.3 Experimental Results and Comparison

The data and results gathered are described, discussed and summarised in the following sections.

4.3.1 Manufacturing Time Comparison

The evaluation of the specimens manufacturing procedures are summarised in Table 4.1 below indicating the process and time taken to produce the specific specimen.

Table 4.1 Comparison of manufacturing times

Process: HWS DIN 1.2344		Process: EOS		Process: LENS	
	Time (hrs)		**Time (hrs)**		**Time (hrs)**
Milling	2.5	Laser sinter	10.5	Laser weld	2.5
Grinding	1	Grinding	1	Grinding	4
Jig bore		Jig bore		Jig bore	
Heat Treatment	4	Heat treatment		Heat treatment	
Final grinding		Final grinding		Final grinding	
Polish		Polish		Polish	
Fitting		Fitting		Fitting	
Total	**7.5**		**11.5**		**6.5**

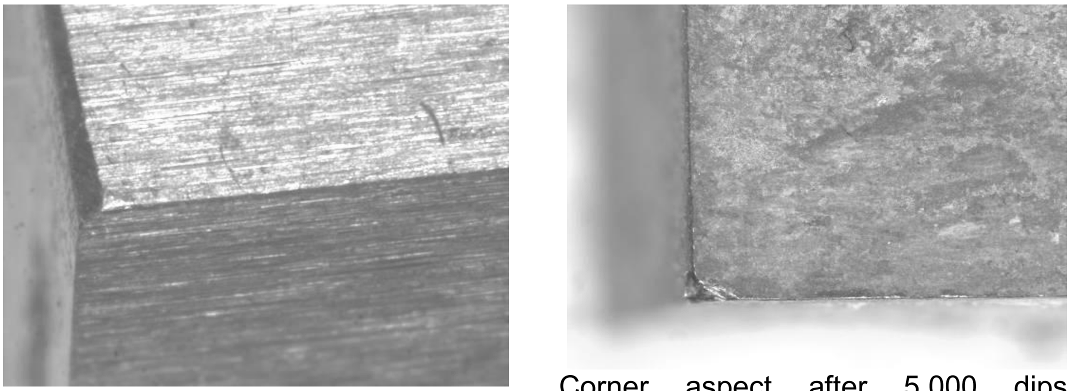
(Note: Times are based on a quantity of 4 specimens.)

4.3.2 Heat checking and corrosion checks

The results show that some aluminium welding occurred on cores grown with the EOS and LENS AM platforms and to a lesser extent on the H13 specimen (Figure 4.5). Closer investigation showed evidence of cracks and pitting occurring mainly at the corners. Washout present on the cores is on the faces opposite the gate. Figure 4.6 shows these conditions at 5x amplification on the cores.

Figure 4.5 Specimens prior to and after 5 000 aluminium melt dipping cycles

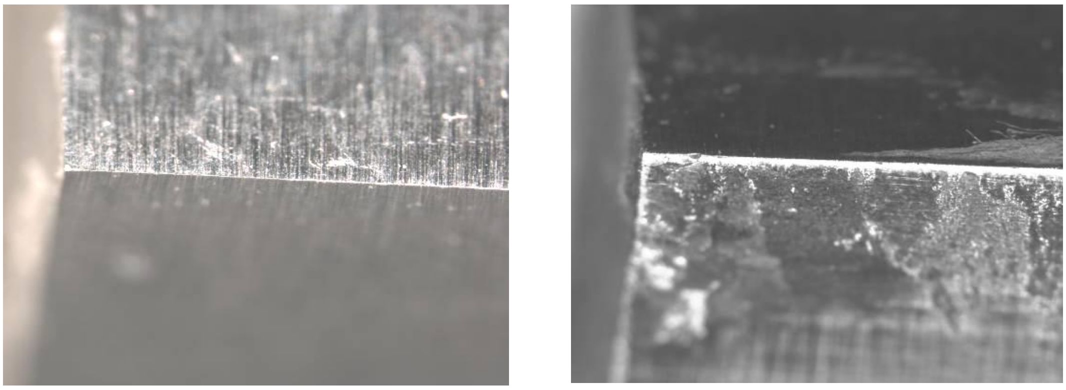
Specimen H13 **Specimen H13**



Typical corner aspect prior to dipping

Corner aspect after 5 000 dips, chipping and slight Al welding

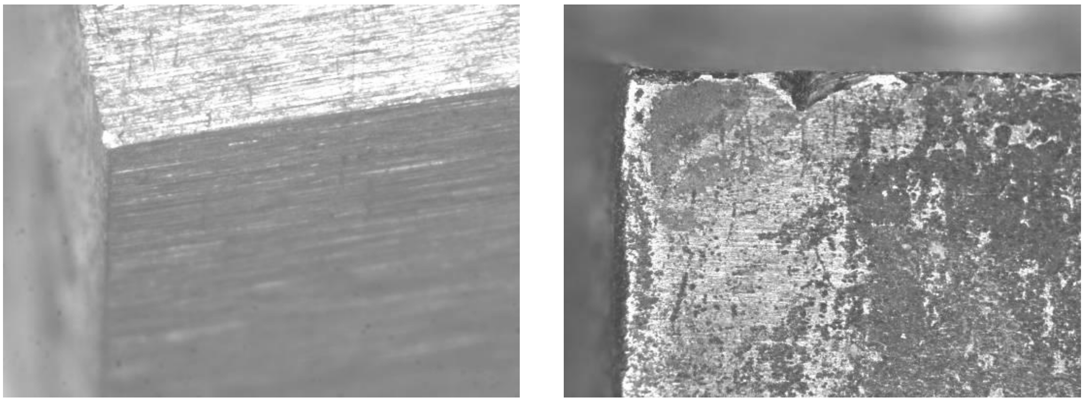
Specimen LENS **Specimen LENS**



Typical corner aspect prior to dipping

Al welding and cracks (post 5 000 dips)

Specimen EOS **Specimen EOS**



Typical corner aspect prior to dipping

Al welding, pitting and cracks (post 5 000 dips)

Figure 4.6 Photos of the specimens corners

4.3.3 Mechanical integrity and surface conditioning

The toughness and hardness of the specimens was traced prior to- and after dipping. The evaluation method of measuring the hardness of the cores was done by using a Vickers notch hardness testing machine (see Table 4.2 for results using a 20Kg and 10Kg load). A clear softening effect was noticed on all specimens but less so the effect on the already soft EOS grown specimens.

Table 4.2 Results of Vickers hardness test

Core H13 Hardness (HRC)	Core LENS Hardness (HRC)	Core EOS Hardness (Hv)
Prior 47.4-54.6	Prior 54-60.7	Prior 212.8-233.3
After 40.6-48.7	After 49.6-52.6	After 211.6-219.4

Table 4.3 below gives an idea of the impact modification experienced with the number of immersion cycles.

Table 4.3 Results of Charpy impact test

Core H13 Impact Energy (Joules)	Core LENS Impact Energy (Joules)	Core EOS Impact Energy (Joules)
Not dipped 11.8	Not dipped 7.8	Not dipped 7.8
Dipped 8.8	Dipped 8.8	Dipped 7.8

The H13 specimens showed lower impact toughness which was to be expected. Surprisingly, the LENS specimen showed a slight increase which can be attributed to the less brittle core hardness. The EOS specimen showed no change in impact toughness.

Further metallographic observation did not reveal significant microstructure modification on the LENS and H13 specimens. However, the EOS specimen clearly revealed some degree of change.

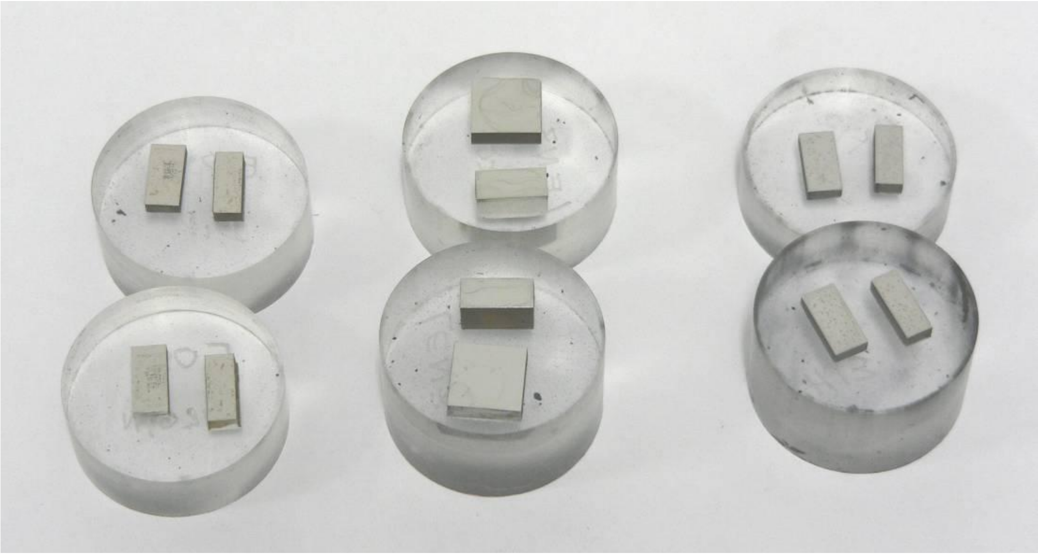
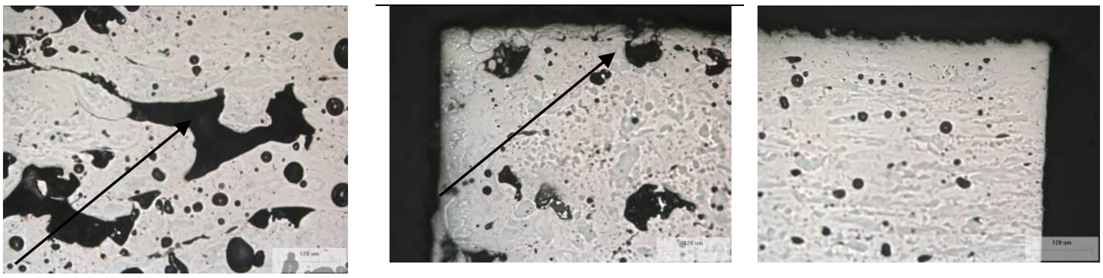


Figure 4.7 Test specimens prepared for light microscopy

The photos of the microscopic analysis of the EOS samples in Figure 4.8 indicate increased presence of gas pores accompanied by crack formation.

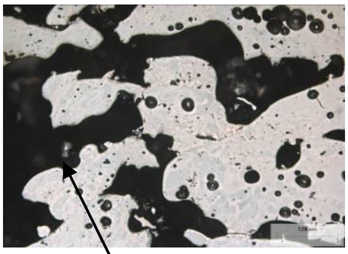


Pores on EOS specimen prior to dipping (50x)

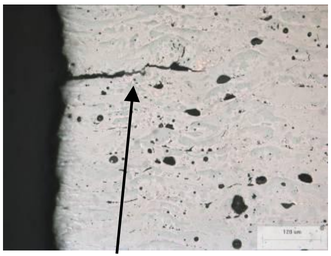
Pore area in corner conducive to crack formation in EOS specimen prior to dipping (50x)

Typical surface appearance of EOS specimen prior to dipping (20x)

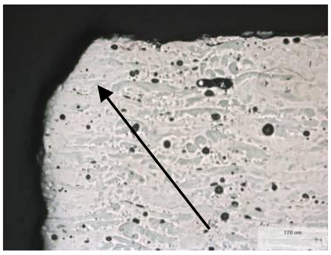
Figure 4.8 Microscope photos of EOS,H13 and LENS samples



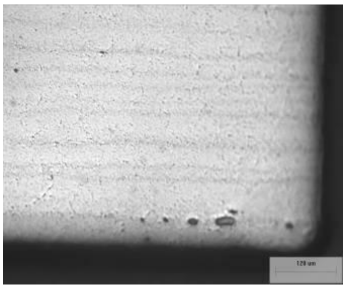
Increased and aggregated pore area of dipped EOS specimen (50x)



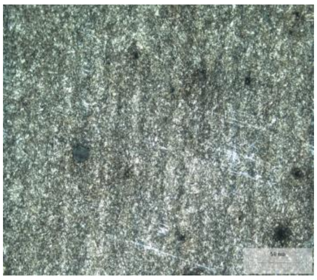
Typical crack on EOS specimen after 5 000 cyclic dip (20x)



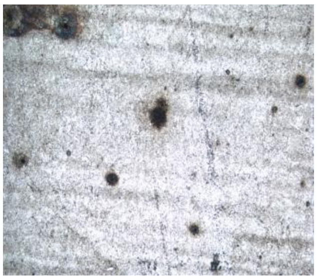
Chipped corner on dipped EOS specimen (50x)



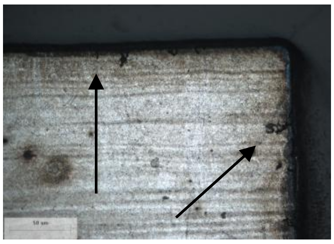
Typical aspect of sharp corner of H13 specimen prior to dipping (20x)



H13 microstructure prior to dipping (200x). Hardness = 50HRC. Even diffusion of alloying carbide elements in a ferrite matrix

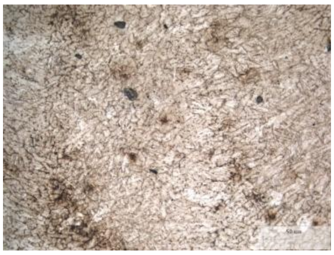


H13 microstructure after dipping (200x). Hardness = 45HRC. No significant variance on microstructure. Minor porosities and inclusions.



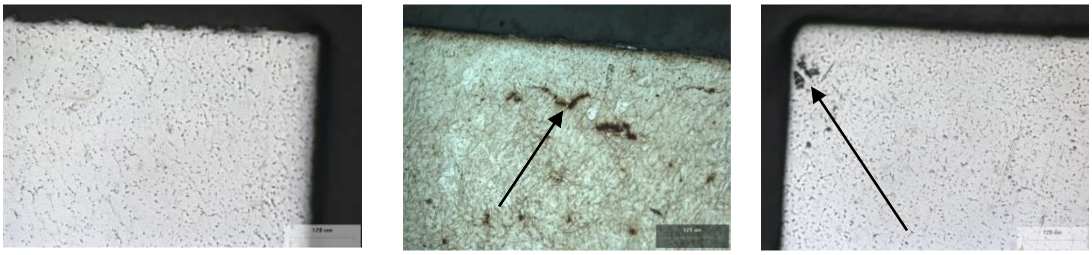
Evidence of some cracking and corrosion on dipped H13 specimen (100x)

LENS microstructure very coherent due to the complete melting of powders during processing (200x). Hardness 52 HRC



LENS specimen microstructure after dipping (200x). Hardness = 50HRC. No significant variance of matrix with minor porosities and inclusions.

Figure 4.8 Microscope photos of EOS, H13 and LENS samples (Continued)



Typical aspect of sharp corner of LENS specimen prior to dipping (20x)

Slight evidence of cracking on dipped LENS specimen

Slight evidence of corrosion on dipped LENS specimen

Figure 4.8 Microscope photos of EOS, H13 and LENS samples (Continued)

4.4 Discussion and conclusion

This paper reports both on subsequent work performed on the performance of cores manufactured through EOS DMLS as well LENS (a blown powder AM technology platform).

This reinforces previous findings around EOS grown components in that they are adequate in as far as:

- The cores will be able to withstand industrial standard HPDC processing conditions to produce small batches, i.e. < 5 000 shots. Larger batches could be produced if it is economically feasible to prepare spare cores for replacement after a predetermined number of shots
- Geometrical and surface specifications can be attained and kept under strict quality production process control that includes periodic inspection of die condition
- The time to manufacture dies can be significantly reduced if consideration is given to size and volume constraints of the AM platform
- The product development cycle of cast components can be significantly reduced where parts require alterations to the die cores

Cores grown with Direct Steel 20 have low core and surface hardness. Platform ability to grow die components with alternative powder material grades with higher wear and core strength would imply improved die life, larger batches and better economic viability.

The performance of LENS AM technology grown components under these particular experimental conditions was remarkable as far as:

- Ability to withstand industrial standard HPDC processing conditions to produce castings equivalent to standard die materials
- Time to manufacture dies can be significantly reduced, due to availability of machines with size of build envelope equivalent to NC die machining capability (motion 150cm x 90cm x 90cm (z axis)). LENS multi-nozzle capability opens opportunities for further development of:

    (a) Strategies of fast rate and lower rates of material deposition where geometrical accuracy is required
    (b) Multi-material deposition
    (c) Full die manufacture as well as dies repaired due to availability of platforms with multi-axes range of motion (up to 7)

Cores manufactured with powders equivalent to hot work steel DIN 1.2344 have core and surface hardness equivalent or higher than the standard die material. A number of die manufacturing strategies can be laid out from the research conducted:

- 3D model generation of cores prior to laser growing should include an overall surface material allowance of between 1.5 – 2.5mm
- In order to minimise deposition time, consider:

    (a) Growing the core over a compatible material substrate.
    (b) Allowing for holding and set up required by conventional machining methodologies in the design of cores and/or die structures
    (c) Designing the core hollow with the possibility to include cooling in the components

- Consider components grown at the required final hardness, free of distortion

Near net shape prototyping capabilities of powder bed AM technology makes systems such as EOS the choice for developmental, prototype and/or short run dies.

Blown powder AM processes such as LENS is the choice for full blown manufacture and repair of production dies.

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CHAPTER 5

PERFORMANCE OF LaserCUSING® METAL POWDER SPECIMENS UNDER ALUMINIUM HIGH PRESSURE DIE CASTING PROCESS CONDITIONS

Authors: MFVT Pereira, G Kunene, A. Spiering and W B du Preez, 2009

Purpose

The objective of this paper is to select the more suitable Additive Manufacturing (AM) technology process between three alternatives, namely the LENS, EOS-DMLS and LaserCUSING® process. The chosen process is to be used to produce cavity die inserts for the manufacture of dies for aluminium HPDC.

Design/methodology/approach

An experiential comparative approach was used as the selection method. The comparative criteria used included physical metallic integrity, time taken to manufacture, surface finish, dimensional accuracy and cost.

Findings

The study indicates that AM technology has the potential for significant time compression, as well as die life expectancy at established economically feasible criteria.

Originality/value In the paper, AM technology is proposed as an alternative die manufacturing process.

Paper type: Peer reviewed conference paper

Paper status: Published - 10th Annual RAPDASA International Conference, East London, South Africa

5.1 Introduction

This paper reports on experimental work performed on specimens grown by a LaserCUSING® technology platform, compared to specimens machined from standard hot work steel DIN 1.2344 or AISI H13, preferred by the die casting industry. The specimens were subjected to a programme of cyclic immersion in molten aluminium alloy and cooling in water based die release medium. The immersion cycle closely resembles the temperature profile that cavity die components experience under high pressure casting conditions. The suitability of additive manufactured components for incorporation in die manufacturing is thus evaluated.

Most of the mass market aluminium alloy components nowadays are manufactured using a production process called High Pressure Die Casting (HPDC). This particular manufacturing process imposes severe stresses on the dies when under processing conditions. Furthermore, die manufacturing costs are a significant component of the economic feasibility of the die casting process. Dies are manufactured out of applicable steel materials normally referred to as hot work steels that can withstand process conditions for an undetermined period of time; therefore the terms *die life* and *expected minimum die life prior to failure due to process induced wear and tear* are found in the industry.

The most important die wear and tear failures are classified under two categories, namely washout and thermal fatigue. *Washout damages* are a direct result of the flow of aluminium melt impinging and rubbing on the die cavity surfaces. Corrosion is attributed to friction wear caused when the melt solidifies around core surfaces and the casting is ejected. *Thermal fatigue,* the most influential failure mode in die casting reveals itself in two modes, namely heat checks and stress cracks. The characteristic feature of heat checks is the appearance of fine cracking lines on surfaces which look like a spider web. Stress cracks appear mainly in corners and appear as individual and clearly defined cracks, sometimes filled with aluminium.

Highly cracked or damaged surfaces lead to a rapid die end of life. For obvious reasons, the die produces an ever increasing number of rejects due to non-compliance with dimensional and geometrical specifications.

The use of Additive Manufacturing (AM) for the purpose of compressing the time it takes to manufacture die components forms part of an ongoing research exercise. The approach described here was applied to evaluate the effects of heat checking on specimens grown with AM technology platforms, namely LaserCUSING® in comparison with standard die material hot work steel DIN 1.2344. The approach makes use of equipment able to subject the AM grown and standard steel manufactured specimens to cyclic heating and cooling with an immersion in liquid aluminium.

The suitability of AM technology to be able to produce fully dense metallic components suitable for die casting can be quickly assessed with the set up. With economic feasibility in mind and knowing that on standard hot work steel, evidence of heat checking damage appears after a few thousand cycles, 10 000 cycles was determined as the experimental benchmark.

The assessment of damages inflicted on the cycled specimens was performed through optical microscopy of both faces and sharp corners, so as to analyse the extent of heat checking cracks as well as possible presence of corrosion pits. Furthermore, impact toughness and hardness values of cycled and not cycled specimens were evaluated in order to assess the extent of material properties variation.

5.2 Experiment

The purpose of the experiment was to evaluate the performance under cyclic heating and cooling conditions of four geometrically similar test coupons. Three AM specimens that underwent different heat treatments and one heat treated standard hot work specimen were tested. Open literature revealed that similar designs of this rig are being used elsewhere in the world to perform thermal shock experiments. None of them foresaw the use of AM grown specimens for this type of evaluation. A total of 10 000 cycles were produced using recycled aluminium A356 material.

5.2.1 Specimens

The specimens were modelled with a shape suitable to perform a simple beam Charpy impact test. Initially, notched specimens with a length of 100mm and cross section 10 x 10mm were machined and/or grown. The extra length of the specimen beyond the classical 55mm required for the impact test was used to hold the specimens in the test rig. Figure 5.1 below shows the specimens that were evaluated.

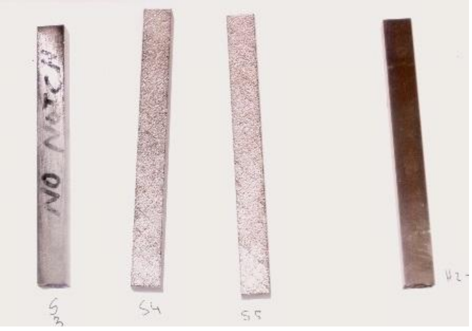
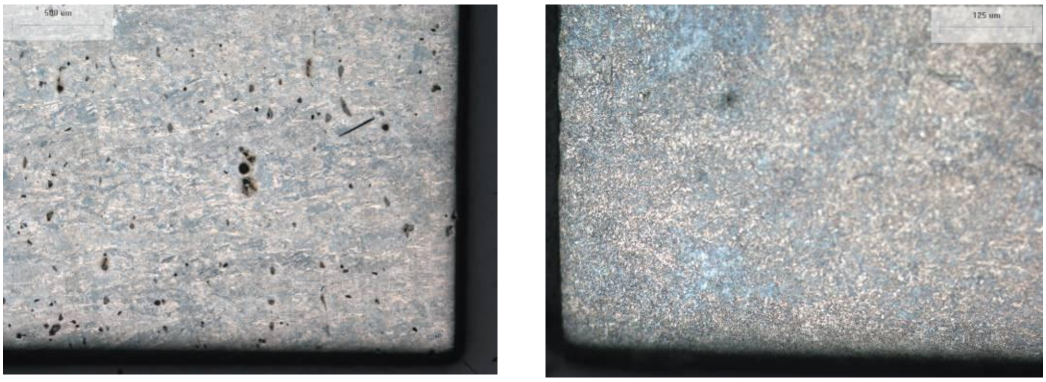


Figure 5.1 Specimens as grown and machined

The material selected for a set of specimens was through-hardened and tempered (54 HRC) hot work steel (DIN 1.2344). The alloy selected for the LaserCUSING® AM process specimens was CL50WS (equivalent to Din 1.2709). Figure 5.2 shows the etched specimens.



(a) (b)

Figure 5.2: Pictures showing typical etched specimens of cores manufactured with the AM and conventional methods

(a) CL50WS (DIN 1.2709) AM method
  - Metallographic specimen: etched with Nital 3%
  - 100 times magnification
  - Analytical observation: no metallic inclusions (mainly Oxide), almost no pores
  - Heat treatment: not hardened (Hardness 35 HRC)

(b) Standard hot work steel (DIN 1.2344)

- Metallographic specimen: etched with Nital 3%
- 100 times magnification
- Analytical observation: no metallic inclusions (mainly Oxide), no pores
- Heat treatment: hardened (Hardness 54 HRC)

The data captured in the manufacturing of the complete cores was evaluated and analysed.

The specimens were manufactured and heat treated as follows:

1. One following conventional die machining methods from hardened and tempered DIN 1.2344 material. ID marking **H1**
2. One using the LaserCUSING® process and heat treatment T2 = 490°C for 6-10hrs, ramp and controlled cooling rate of 100-150°C/h. ID marking **D1**
3. One using the LaserCUSING® process and heat treatment T2 = 540°C for 6-10hrs, ramp and cooling rate of 100-150°C/h. ID marking **D2**
4. One using the LaserCUSING® process and heat treatment, annealing 820-850 °C and T2 = 370°C for 6-10hrs, ramp and cooling rate of 100-150°C/h. ID marking **D3**

Figure 5.3 shows the finished manufactured and AM grown cores.

(H1) (D1) (D2) (D3)

Figure 5.3 Pictures showing the cores manufactured with the conventional and LaserCUSING® method
(H1) Through hardened steel 1.2344 conventional manufactured specimen
(D1), (D2), (D3) Through-hardened LaserCUSING® manufactured specimens

5.3 Dipping rig for cyclic immersion in molten aluminium

Figure 5.4 below shows the testing apparatus developed to simulate thermal cycling conditions that occur inside the cavity surfaces of the die in contact with the aluminium melt. The specimens were mounted in this rig, two in each arm end. At the same time, specimens mounted on both sides of the rotating arm were immersed either in aluminium at 630-700°C and a cooling bath at 36-45°C. Then the two opposite sides of the rotating arm were lifted and the immersion order reversed. An average cycle time of 20 seconds was achieved. The heating and cooling cycle measured on the specimens ranged between 80 and 540°C. A typical die casting thermal shock cycle experience ranges between 110 and 480°C. This means that the specimens were subjected to a more severe heat shock deterioration cycle than when subjected to casting conditions. The time immersed in either the aluminium melt or cooling medium was 5 seconds.

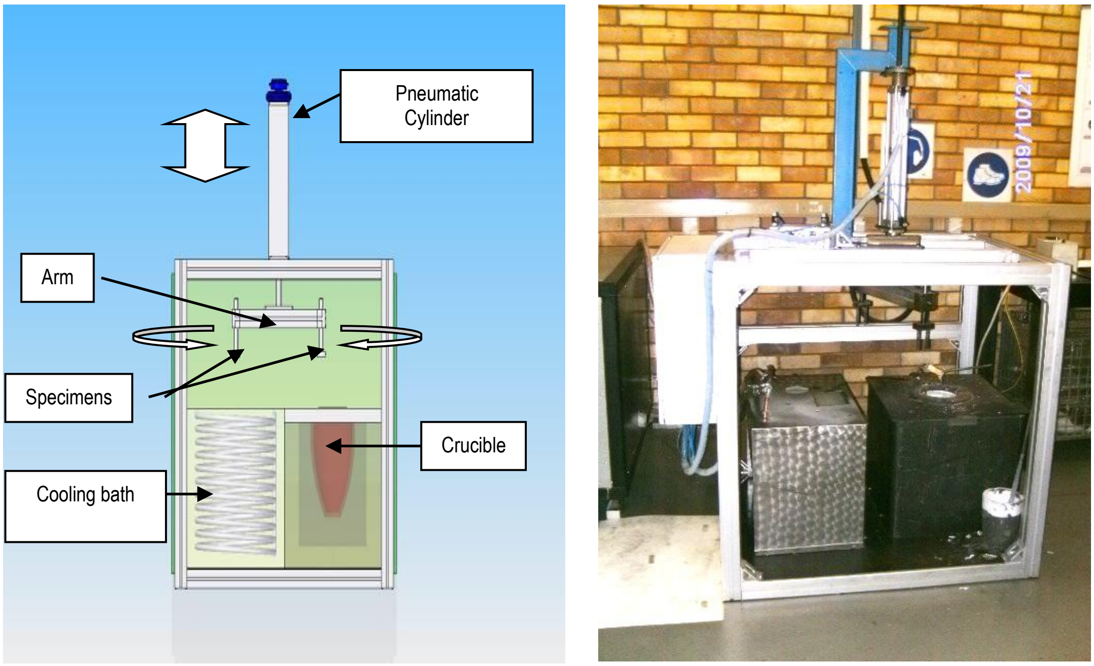


Figure 5.4 Aluminium melt cyclic dipping test rig

5.4 Experimental results and comparison

The data and results gathered are described, discussed and summarised in the following sections:

5.4.1 Specimen preparation

The AM samples used in the experiment had a measured degree of surface roughness average of R_a=3.2 μm. The preferred standard die cavity finish lies between R_a= 0.80-0.20μm. Surfaces grinding; a material removal process, was used in order to bring the finish in line with the accepted norm. The grinding operation took care of both roughness and distortion induced by heat treatment of the AM specimens. A maximum distortion of 0.2mm was measured on the specimens.

The AM samples measured between 9.98 - 10.10mm on the requested 10.0 x 10.0mm cross section dimensions. After grinding to an acceptable finish, free of distortion, the cross sections measured between 9.50 – 9.80mm. The measured deposition rate was 4cm³/hour, which translates into 2.5 hours for growing a specimen and another half an hour for removal from support plate. The evaluation of the specimens manufacturing procedures are summarised in Table 5.1 below indicating the process and time taken to produce the specific specimen.

Table 5.1 Comparison of manufacturing times

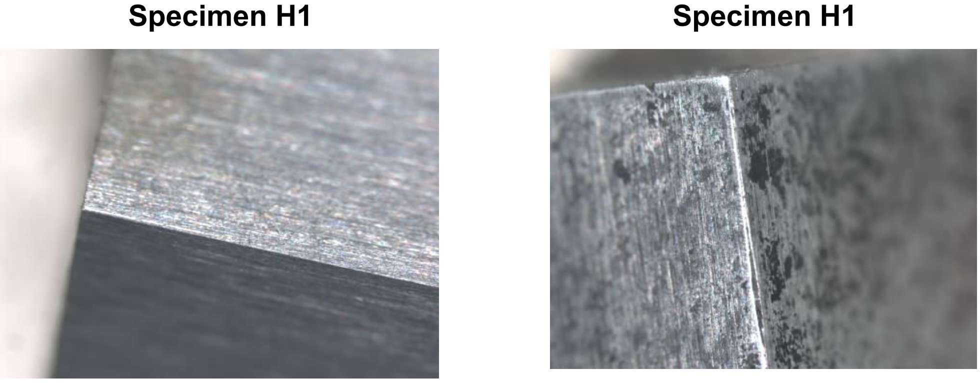
Specimen: **HWS** **Din 1.2344** **ID= H1**	**Process**	**Milling**	**Grinding**	**Jig bore**	**Heat treatment**	**Final grinding**	**Total Cost**
	Cost	R1 000.00	R400.00		R4 800.00		R6 200.00
	Hours	2.5	1		12		15.5
Specimen: **LaserCusing** **Din 1.2709** **ID= D1**	**Process**	**Laser sinter**	**Grinding**	**Jig bore**	**Heat treatment**	**Final grinding**	
	Cost						R5 600.00
	Hours	3			10	1	14
Specimen: **LaserCusing** **Din 1.2709** **ID= D2**	**Process**	**Laser sinter**	**Grinding**	**Jig bore**	**Heat treatment**	**Final grinding**	
	Cost						R5 600.00
	Hours	3			10	1	14
Specimen: **LaserCusing** **Din 1.2709** **ID= D3**	**Process**	**Laser sinter**	**Grinding**	**Jig bore**	**Heat treatment**	**Final grinding**	
	Cost						R 9 600.00
	Hours	3			20	1	24

(Note: Times are based on a quantity of 8 specimens.)

5.4.2 Heat checking and corrosion checks

The results show that some aluminium welding occurred on cores grown with the AM laser platform and to a lesser extent on the H13 specimen (Figure 5.5). Closer investigation showed evidence of cracks and pitting occurring mainly at the corners. The specimens were cleaned in an NACL solution prior to conducting closer investigation. Figure 5.6 shows these conditions at 5x amplification on the cores.

Figure 5.5 Specimens after and prior to 10 000 aluminium melt dipping cycles



Specimen H1

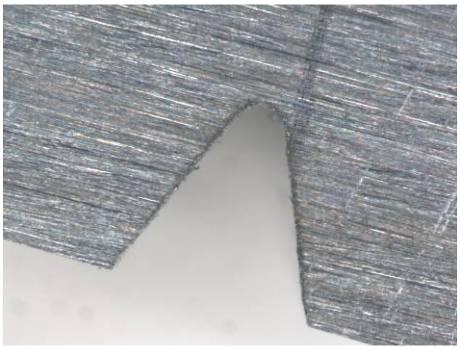
Specimen H1

Typical corner aspect prior to dipping

Corner aspect after 10 000 dips, chipping, washout, pitting & slight Al welding

Figure 5.6 Photos of the specimens corners and notch

Specimen H1

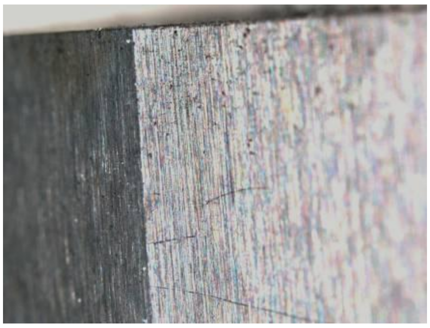


Notch prior to dipping

Specimen H1

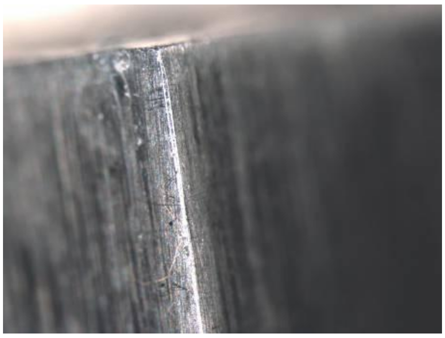
Al welding and cracks (post 10 000 dips)

Specimen D1



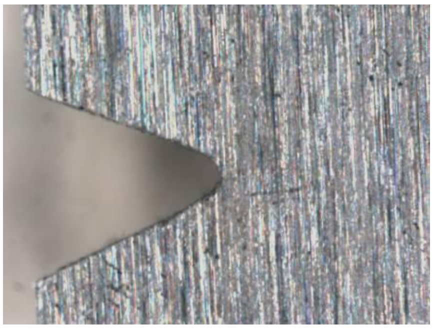
Typical corner aspect prior to dipping

Specimen D1



Al welding, pitting & wash (post 10 000 dips)

Specimen D1



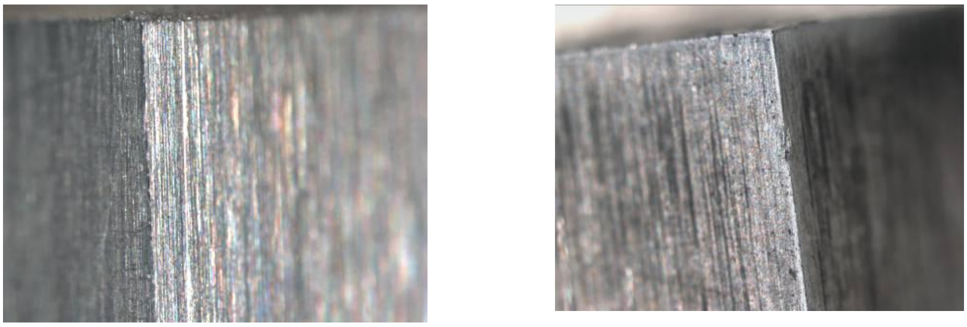
Notch prior to dipping

Specimen D1

Notch after 10 000 dips. Note chipping, crack initiation and washout

Figure 5.6 Photos of the specimens corners and notch (Continued)

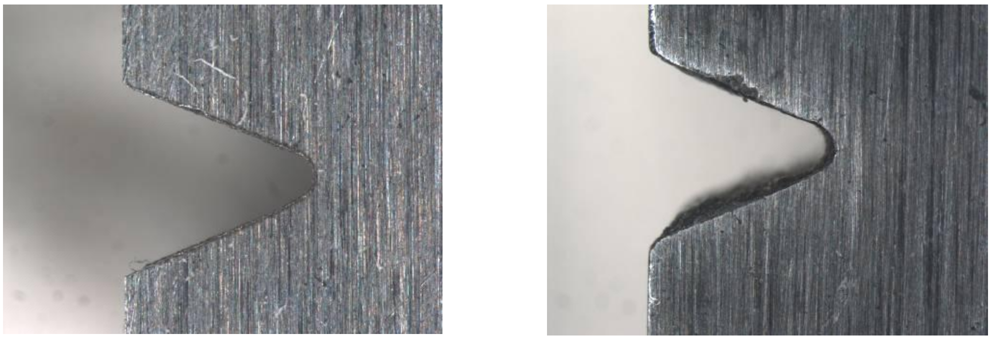
Specimen D2 **Specimen D2**



Typical corner aspect prior to dipping

Corner aspect after 10 000 dips. Note washout/crack

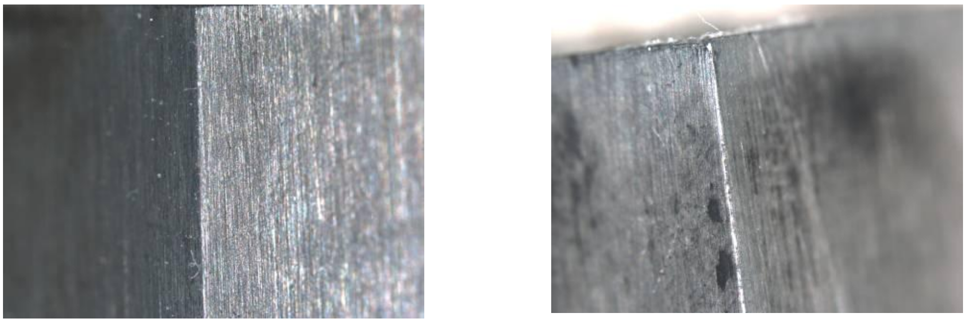
Specimen D2 **Specimen D2**



Notch prior to dipping

Notch after 10 000 dips. Note chipping, and washout

Specimen D3 **Specimen D3**

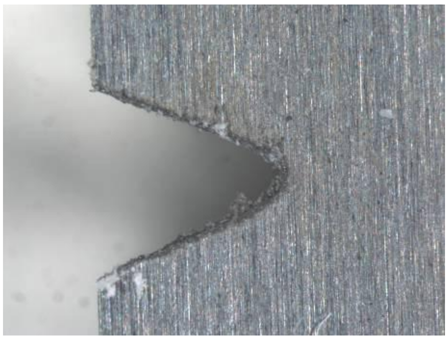


Typical corner aspect prior to dipping

Corner aspect after 10 000 dips. Note washout

Figure 5.6 Photos of the specimens corners and notch (Continued)

Specimen D3



Notch prior to dipping

Specimen D3

Notch after 10 000 dips. Not chipping, crack initiation and washout

Figure 5.6 Photos of the specimens corners and notch (Continued)

5.4.3 Mechanical integrity and microscopy

The toughness and hardness of the specimens were traced prior to- and after dipping. The evaluation method of measuring the hardness of the cores was done by using a Vickers notch hardness testing machine (see Table 5.2 for results using a 20Kg load.) A clear softening effect was noticed on all specimens.

Table 5.2 Results of Vickers hardness test

Core H13 Hardness (HRC)	**Core D1 Hardness (HRC)**	**Core D2 Hardness (HRC)**	**Core D3 Hardness (HRC)**
Prior 53.9-55.4	Prior 50.37-52.81	Prior 45.78-47.76	Prior 43.12-48.74
After 21.39-24.21	After 33.0-35.67	After 28.79-30.67	After 34.97-37.15

Table 5.3 below gives an idea of the impact modification experienced with the number of immersion cycles.

Table 5.3 Results of Charpy impact test

Core H13 Impact Energy (Joules)	Core D1 Impact Energy (Joules)	Core D2 Impact Energy (Joules)	Core D3 Impact Energy (Joules)
Not dipped 19.3	Not dipped 18.3	Not dipped 17.7	Not dipped 17.3
Dipped 13.8	Dipped 8.0	Dipped 7.8	Dipped 7.2

The H13 specimens showed lower impact toughness which was to be expected, The LaserCUSING® showed a steep decrease in toughness which can be attributed to the low elongation factor of the cores after heat treatment.

Further metallographic observation did reveal some microstructure modification on the H13 and LaserCUSING® specimens. However, the H13 specimen showed slightly less crack growth than the AM specimens which clearly revealed some degree of change. Only an extended dipping cycle (20 000 dips) will conclude if the difference of size of cracks and crack density between the test coupons is significant.

Surprising was the total loss of hardness of the Din 1.2344 test coupon with composition C= 0.4%, Si =1.0%, Cr = 5.3%, Mo =1.40%, and V = 1.0% with high red strength when compared with the Din 1.2709 powder composition C= 0.02%, Si =0.1%, Mn = 0.1%, Ni = 18.5%, Ti = 0.7%, Mo =5.0% and Co = 8.8%. The high Ni above 18% content on alloy steels normally lowers the martensite to austenite transformation temperature which tends to be lower than the Al melt temperature, which results in rapid softening of the steel. The fast softening of the Din 1.2344 specimen points to heat treatment in a non-protective atmosphere. The photos of the microscopic analysis of the samples can be seen in Figure 5.7.

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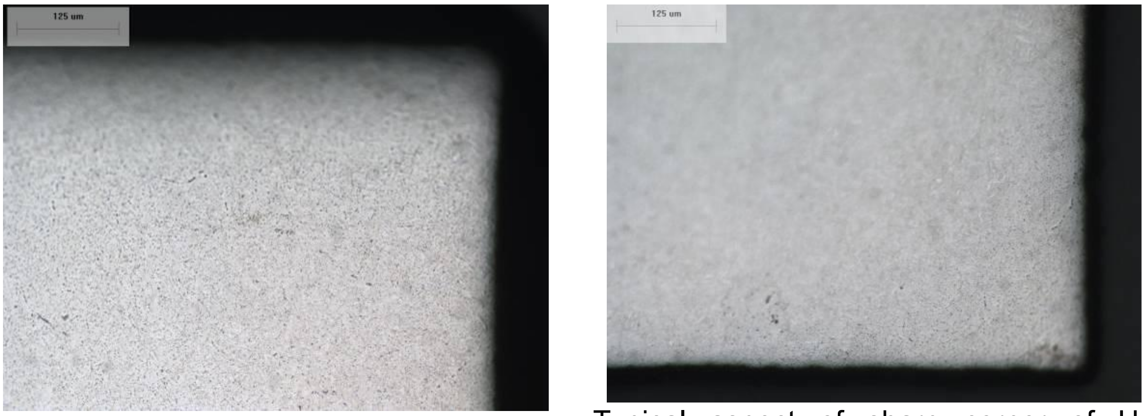
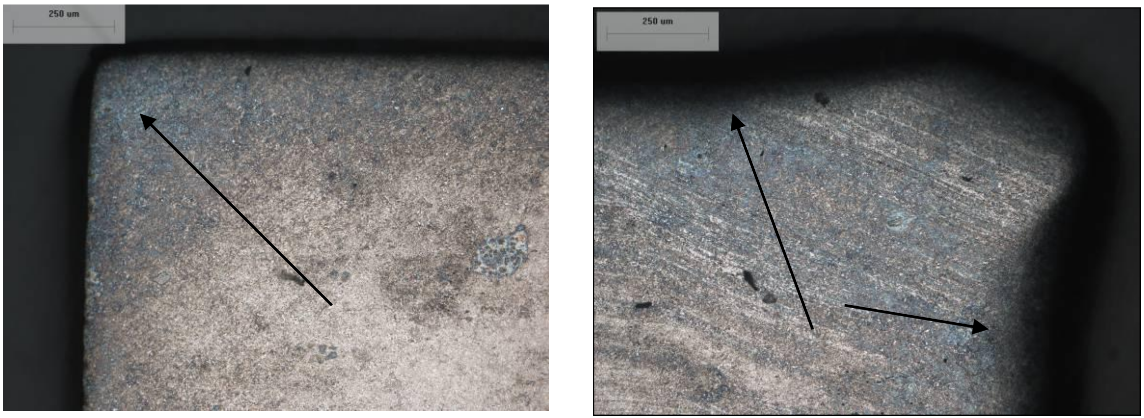


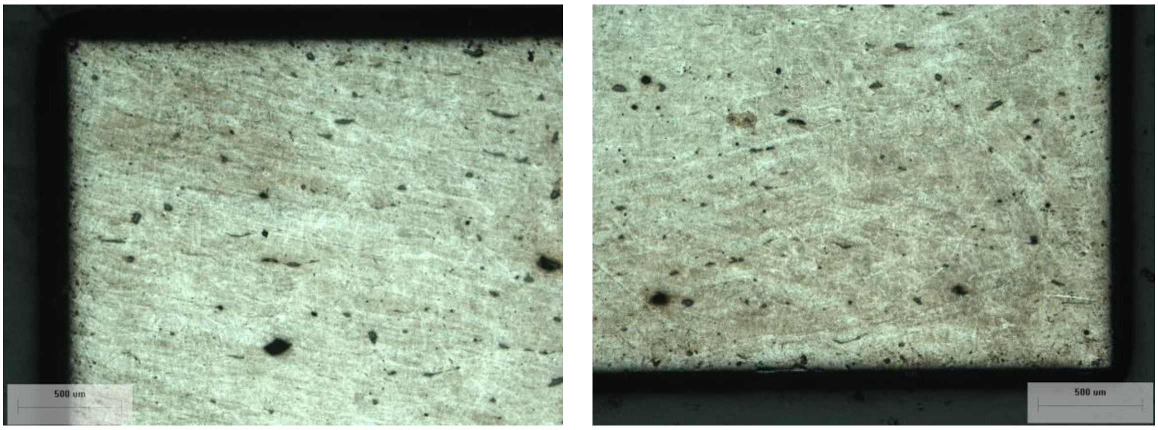
Typical aspect of sharp corner of H1 specimen prior to dipping

Typical aspect of sharp corner of H1 specimen prior to dipping



Notice oxidation emanating from corner of dipped H1 specimen due to decarburisation of the outer surfaces

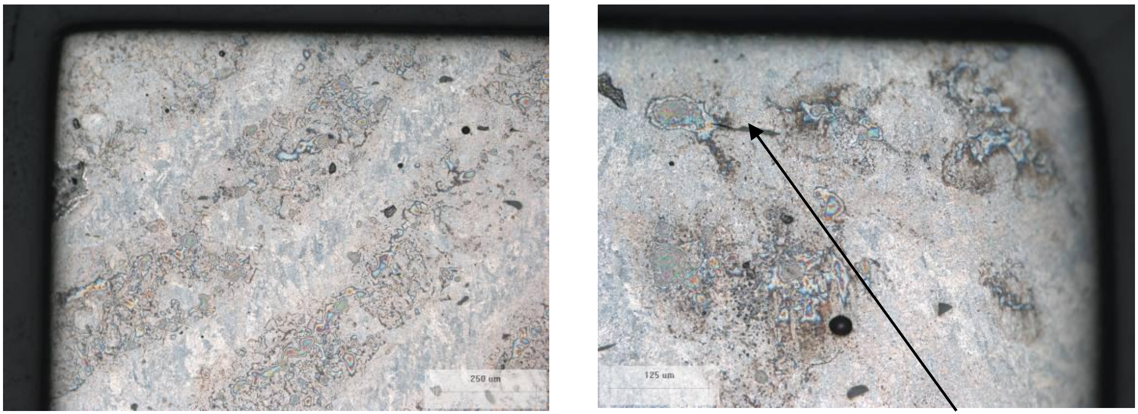
Evidence of erosion and corrosion on dipped H1 specimen



Typical aspect of a sharp corner of D1 specimen prior to dipping

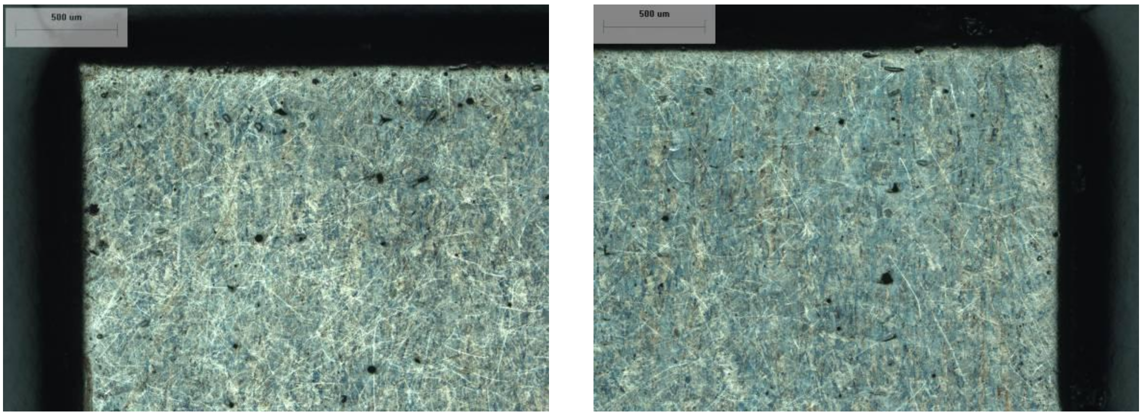
Typical aspect of a sharp corner of D1 specimen prior to dipping

Figure 5.7 Microscope photos of H13 specimen H1, and LaserCUSING® specimens D1, D2 and D3



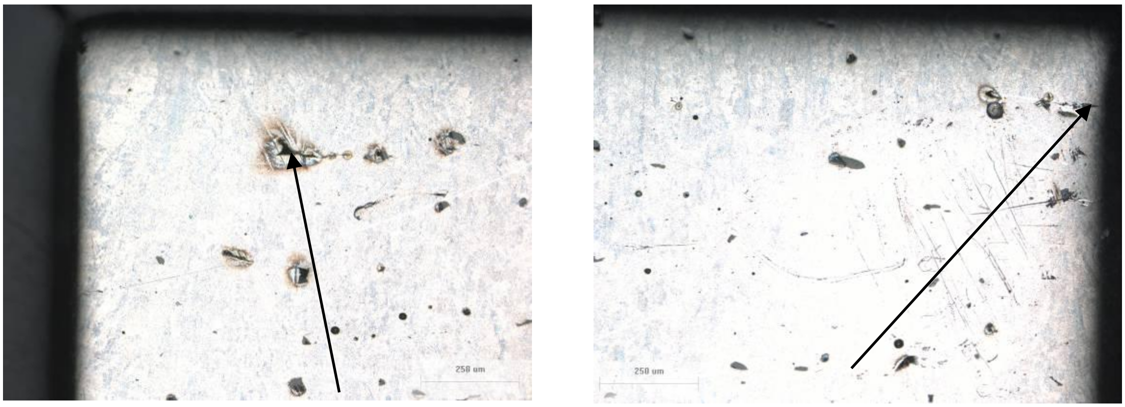
Dipped D1 specimens melt deposition tracks visible nucleation and aggregation of intermetallic alloys

D1 some crack initiation visible



Typical aspect of sharp corner of D2 specimen prior to dipping

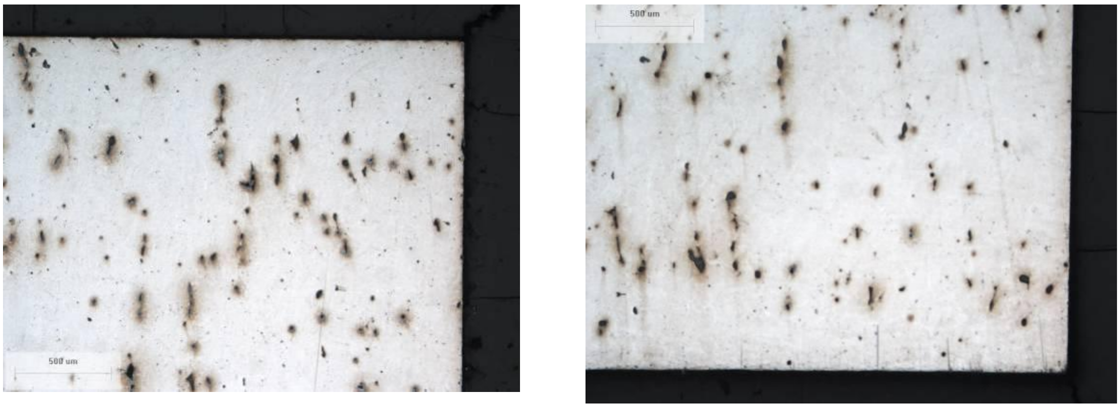
Typical aspect of sharp corner of D2 specimen prior to dipping



D2 clearly visible crack initiation

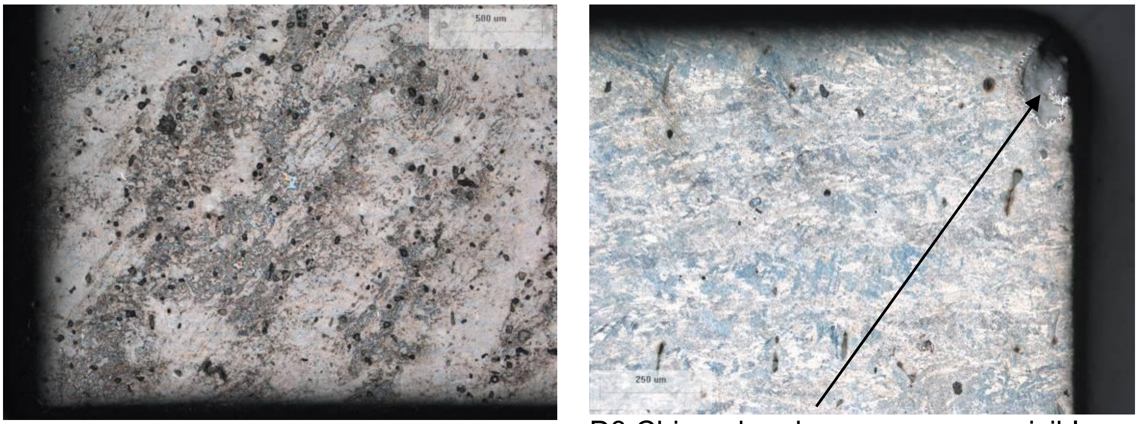
D2 small crack initiation on corner

Figure 5.7 Microscope photos of H13 specimen H1, and LaserCUSING® specimens D1, D2 and D3 (Continued)



Typical aspect of sharp corner of D3 specimen prior to dipping

Typical aspect of sharp corner of D3 specimen prior to dipping



D3 Typical deposition pattern. Note agglomeration and segregation of intermetallic alloys coupled with increased number of small pores

D3 Chipped and wear on corner visible

Figure 5.7 Microscope photos of H13 specimen H1, and LaserCUSING® specimens D1, D2 and D3 (Continued)

5.5 Conclusion

This paper reports both on subsequent work performed on the performance of cores manufactured through EOS DMLS as well LENS, a blown powder AM technology platform. Comparative analysis of the LaserCUSING® specimens described here with the standard die steel show that they would be able to fulfil very similarly functions. In order to clearly distinguish which is better will require further experimenting of the order of 20 000 dipped cycles and more.

To summarise some of the previous findings around EOS grown components, it has been established that these components are adequate in as far as:

- Suitable for time compression of product development and/or production of prototype production runs
- The cores will only be able to withstand industrial standard HPDC processing conditions to produce small batches i.e. < 5 000 shots. Larger batches could be produced, if it is economically feasible, to prepare spare cores for replacement after a predetermined number of shots
- Good near net capability able to reproduce geometry with an allowed material tolerance of 0.25mm, slow rate of deposition 2-10cm^3/hour
- The time to manufacture dies can be significantly reduced if consideration is given to size and volume constraints of the AM platform

Cores grown with Direct Steel 20 have low core and surface hardness as well some degree of porosity. The technology's ability to grow die components with alternative powder material grades with higher wear and core strength would imply improve die life, larger batches and better economic viability.

The performance of LENS grown components under these particular experimental conditions was remarkable as far as:

- Ability to withstand industrial standard HPDC processing conditions to produce castings equivalent to standard die materials
- Time to manufacture dies can be significantly reduced, due to availability of machines which size of build envelope is equivalent to NC die machining capability (motion 150cm x 90cm x 90cm (z axis)). LENS multi-nozzle capability opens opportunities for further development of:
    (a) Strategies of fast rate and lower rates of material deposition where geometrical accuracy is required
    (b) Multi-material deposition
    (c) Full die manufacture as well as dies repaired due to availability of platform with multi-axes range of motion (up to 7)
    (d) 3D model generation of cores prior to laser growing should include an overall surface material allowance of between 1.5 – 2.5mm

(e) Cores manufactured of powders equivalent to hot work steel DIN 1.2344 have core and surface hardness equivalent to the standard die material

The LaserCusing grown components performance can be considered quite remarkable as far as:

- Ability to produce die components for standard industrial production batches
- Good near net capability able to reproduce geometry with an allowed material tolerance of 0.3mm
- Reasonable turnaround time, ideal for complex geometry cavity inserts requiring integrated cooling that is particularly difficult or impossible to attain with normal mechanical removing techniques
- Availability of steel powders with similar characteristics to standard hot work steels, e.g. Din 1.2709

A number of die manufacturing strategies can be established from the research conducted:

- In order to minimise deposition and die manufacture time, consider:
    (a) Growing the core over a compatible material substrate
    (b) Allowing for holding and set up required by conventional machining methodologies in the design of cores and/or die structures
    (c) Designing the core hollow with the possibility to include cooling in the components
- Growing components at the required final hardness, free of distortion

Near net shape prototyping capability of powder bed AM technology makes systems such as EOS the choice for developmental, prototype and or short run dies. Concept LaserCUSING technology is a good choice for complex small to medium die inserts able to withstand standard aluminium production rates.

Blown powder AM processes, such as LENS, is the choice for the manufacturing of larger dies and/or repair of production dies. More extensive finishing operations will be required when compared with the powder bed technology AM platforms.

AM technology has matured enough for widespread use by industry. Economic feasibility is the key for a more rapid or slow adoption. The range of applications stand to multiply exponentially if the gap is reduced between the cost of AM platforms and steel powders versus allied conventional removal technologies and wrought steels.

Acknowledgement

Professor Gideon Levy and Inspire Institute for Rapid Product Development Switzerland for providing the LaserCUSING specimens used in this experiment.

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3. Pereira M.F.V.T., Williams M., Bruwer R., 2009, Rapid die manufacturing using Direct Laser Metal Deposition. *Journal for New Generation Sciences (JNGS),* Vol. 7, No. 3, pages 58 – 69, ISSN 1684-4998.

4. Pereira M.F.V.T., Williams M., Du Preez W. B. 2010, Characterization of metal powder based rapid prototyping components with respect to aluminium high pressure die casting process conditions, *Journal for New Generation Sciences (JNGS),* Vol. 8, No. 2, pp 85 – 94, ISSN 1684-4998.

CHAPTER 6

CHARACTERISATION OF METAL POWDER BASED ADDITIVE MANUFACTURED COMPONENTS WITH RESPECT TO ALUMINIUM HIGH PRESSURE DIE CASTING PROCESS CONDITIONS – SECTION B

Authors: Pereira M.F.V.T., Williams M., Bruwer R., 2009

Purpose

The objective of this paper is to apply the EOS Direct Metal Laser Sintering (DMLS), Additive Manufacturing (AM) technology process to manufacture cavity die inserts for the manufacture of dies for aluminium HPDC.

Design/methodology/approach

Experiments and criteria for determining suitability were developed and evaluated which included time, cost and life expectancy. Accelerated testing procedures to evaluate the die inserts manufactured using the AM technique were created. The resistance of the AM produced inserts was measured against washout, erosion, heat checking and corrosion in a high pressure die casting environment.

Findings

The study indicates that AM technology has potential for significant time compression, as well as die life expectancy at established economically feasible criteria.

Originality/value

In the paper, AM technology is proposed as an alternative die manufacturing process.

Paper type: Research paper

Paper status: Published - Journal for New Generation Sciences (JNGS), Vol. 7, No. 3, pp 58–69, ISSN 1684-4998

6.1 Introduction

This article explores the use of technology associated with Additive Manufacturing (AM) for the purpose of reducing the time it takes to develop core and cavity components to be incorporated in a High Pressure Die Casting (HPDC) die able to produce aluminium parts. This direct approach is a well-established and researched manufacturing method (Gordon, 1995).

Global issues such as energy and climate changes have impacted on both the automotive and aerospace industries forcing them to adopt measures to produce products that consume fewer combustibles and emit less carbon dioxide. Making vehicles lighter is one of the logical ways of reducing fuel consumption. The need for light components, able to fulfil technical and quality specifications, led to market growth for tooling that is able to mass produce parts using manufacturing processes such as high pressure die casting. Competitive pressures to reduce the lead time required to manufacture tooling has also increased dramatically. For this reason research into various methods, techniques and approaches to tool manufacture are being undertaken globally.

Light alloy components produced using HPDC or related processes pose a particular challenge as far as AM is concerned. Die manufacturers still associate AM with producing non-functional prototypes, due to lack of information about materials and selected AM technology platforms able to manufacture components with process suitable properties. When it is imperative to test functional prototypes it becomes evident that direct manufacturing is time consuming/expensive and requires equipment that is not always readably available. Some leading edge manufacturers use AM technologies to create masters that are used in sand and lost wax centrifugal casting processes to produce a limited number of metallic prototypes (Karapatis, 1998).

The end result is a shorter delivery time of parts approved for production. Evidently, the costs associated with producing prototypes and pre-series are high. The approach described here is based on the substitution of masters used in gravity or low pressure processes (provided by service providers) to an approach that uses AM to directly manufacture HPDC die components. This approach aims at benefiting HPDC companies with a faster and more economical solution for part approval for production as well as for small batches using their in-house installed high pressure die casting processes.

A number of AM processes can be used for this proposed rapid manufacturing tooling solution (Wohlers, 2005), notwithstanding that they should be able to produce cavity forming inserts with the following specifications:

- In the appropriate/correct material
- With no porosity problems
- With correct heat transfer properties
- To the required material ductility and
- To the correct time scales, cost and quality

Other important advantages that this solution aims to establish are:

- Parts with compatible mechanical properties to those manufactured from die casting steels
- Repeatability and quick turnaround times for die repair, adjustment, modifications and manufacturing
- Tooling inserts capable of producing component quantities for short runs, i.e. < 5 000 components

A project plan was developed in order to expedite the described Rapid Tooling (RT) approach and a number of tasks were planned including:

- Conducting a literature search on various AM technologies
- Developing a plan of experiments and testing criteria
- Executing the plan of experiments
- Analysis and comparison of results and
- Reporting and recommendations

The research used accelerated testing procedures to evaluate the available AM die material, surface coatings and treatments of die materials for their resistance to washout, erosion and corrosion in a high pressure die casting environment.

6.2 Additive Manufacturing platform selection

A literature survey was conducted in order to extract relevant information and identify promising technologies for application in Rapid Tooling (RT) (applicable to high pressure casting) (Himmer, 2002) and (Kashaka, 2000). From the information acquired it was deducted that there were two major methods to produce RT:

- The indirect approach and
- The direct approach

The direct processes are characterised by the direct generation of the rapid tool or cavity components from the computer aided design (CAD) models. The direct process also holds the advantage in that the accuracy of the component that is grown is maintained because it is a single stage operation. With indirect processes the component has to go through various stages in which compensation for shrinkage has to be made, which affects the accuracy of the component. Potential human error and other factors will also contribute to this accuracy problem. The most compelling argument for selecting the direct process is that it produces fully dense metallic components with the mechanical strength best suited for the high pressure die casting process.

A number of AM processes with potential for application were identified namely Direct Metal Forming (DMF) or Direct Metal Deposition (DMD), Electron Beam Melting (EBM), Laser Engineered Net Shaping (LENS) and Direct Metal Laser Sintering (DMLS). Of these, only DMLS was available locally in South Africa and as such was selected as the basis for the research.

6.3 Plan of experiments

The primary objective of this research was to use accelerated testing procedures to evaluate die materials produced by AM techniques, potential surface coatings and other treatments of die materials to improve their resistance to washout, erosion and corrosion in high pressure casting environments (Holler, 2000).

Besides the primary direct metal fully dense growing process, the other envisaged processes to be considered were:

- Heat treatment
- Surface treatments
- Cladding and/or joining fully dense grown areas to support bases or substrate structures

The aim of the experiment was to evaluate the performance of two geometrically similar components which were manufactured by different methods, namely the direct rapid prototyping method compared to conventional die manufacturing (Schorn, 2004). The High Pressure Die Casting (HPDC) process was selected as the process for evaluation and accelerated casting conditions were used:

- Melt temperature: 700 – 750 ºC
- Gate speed: 40 m/s
- Die temperature: 200 – 230 ºC

A total of 1 000 shots were produced using recycled aluminium A356 material. Every 100th shot was evaluated and the rest of the parts were reprocessed.

6.4 Part and die components design

A part was modelled with a core shape, complex enough to compare cost, time and quality of the manufacturing process. The die catered for four cavities, therefore, it was possible to gather a comprehensive amount of comparative information about the different cores‘ performances. The material feeding system (runner and gate inserts) were redesigned together with the cavity and core holding inserts. After all these modifications were carried out, the shot weight was calculated. Figure 6.1 below shows the designed cavity inserts and core components that were evaluated.

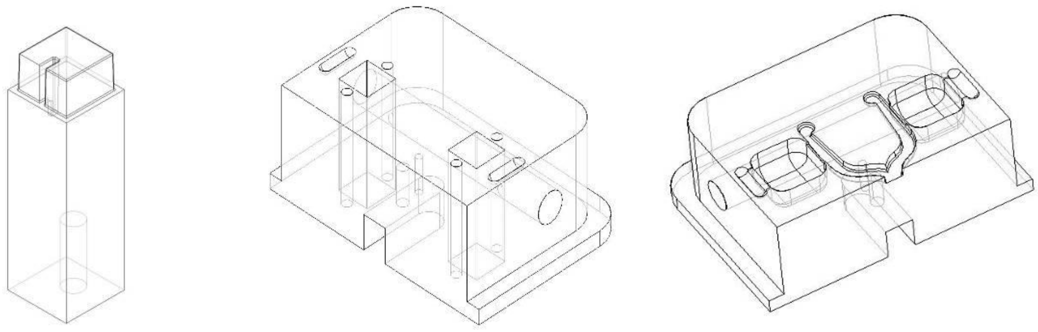

(a) (b) (c)

Figure 6.1 3D models of the core (a), core holding inserts (b) and new cavity (c)

6.5 Manufacturing, assembly and try-outs

The material selected for the die cavities, runner, gate and core support inserts was through-hardened and tempered hot work steel (DIN 1.2344). The alloy selected for the AM process cores was Direct Steel 20. The data captured in the manufacturing of the complete cores was evaluated and analysed, which included assessing the work required to obtain acceptable fitting tolerances for high pressure casting dies.

Four cores were manufactured using the methods listed below:

- One following conventional die machining methods from hardened DIN 1.2344 material
- One using the DMLS process
- One using the DMLS process combined with surface treatment (plasma nitriding)
- One using the DMLS process with special heat treatment application (Toyota Diffusion (TD) coating). However, premature failure of the coating was experienced (see Section 6.5)

Figure 6.2 below shows the finished manufactured and as grown cores.

(a) (b) (c) (d)

Figure 6.2 Pictures showing the cores manufactured with the conventional and RT methods

(a) Through-hardened steel 1.2344 conventional manufactured core marked 0
(b) Plasma nitrided AM grown core marked with 1 dot
(c) AM grown core ready to be assembled marked with 2 dots
(d) AM grown core ready for assembly marked with 3 dots

Figure 6.3 shows an example of a shot produced during the trial runs and the die mounted on the HPDC machine. A total of 1 000 shots were completed during the sample runs (in batches of 100 before analysis and inspection). An average cycle time of 30 seconds were achieved from pouring metal to extracting components.

Figure 6.3 Example of a typical shot (left) and die installed on casting machine (right)

6.6 Experimental results and comparison

The data and results gathered are described, discussed and summarised in the following sections.

6.6.1 Manufacturing time comparison

The evaluation of the manufacturing procedures are summarised in Table 6.1 below indicating the process and time taken to produce the specific core.

Table 6.1 Comparison of manufacturing times

Core 1 ID (0)		**Core 2 ID (.)**		**Core 3 ID (..)**		**Core 4 ID (…)**	
Process	**Time (hrs)**	**Process**	**Time (hrs)**	**Process**	**Time (hrs)**	**Process**	**Time (hrs)**
Milling	2.5	DMLS	13.5	DMLS	13.5	DMLS	13.5
Grinding	2	Grinding		Grinding		Grinding	
Jig bore		Jig bore		Jig bore		Jig bore	
Heat Treatment	1	Heat Treatment	1	Heat Treatment		Heat Treatment	
Finish grind	4	Finish grind	3	Finish grind	3	Finish grind	3
Spark Erosion	7						
Polish	2	Polish	1	Polish	1	Polish	1
Fitting	3	Fitting	3	Fitting	3	Fitting	3
Electrode Manuf.	4						
Total	**25.5**		**21.5**		**20.5**		**20.5**

(Note: Times are based on a quantity of 3 cores and the DMLS growing time is the worst case scenario)

6.6.2 Dimensional and surface quality checks

After the production of the 1 000 experimental shots, the geometrical dimensions of the cores were verified and compared to the as-manufactured dimensions. Some predetermined core dimensions were taken for comparison using a digital vernier calliper and micrometer. A 2D core drawing with the dimensions is shown in Figure 6.4. Table 6.2 shows the results of the measurements taken.

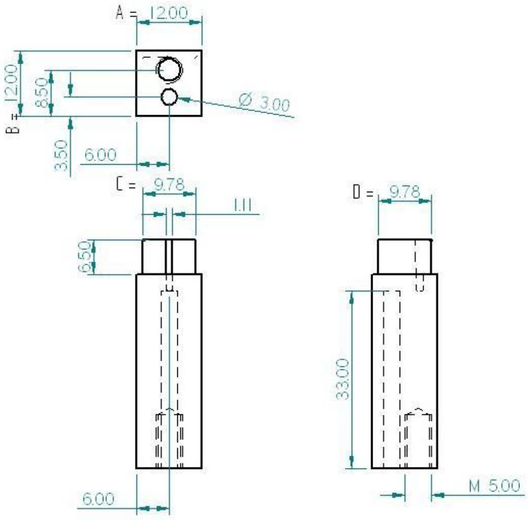
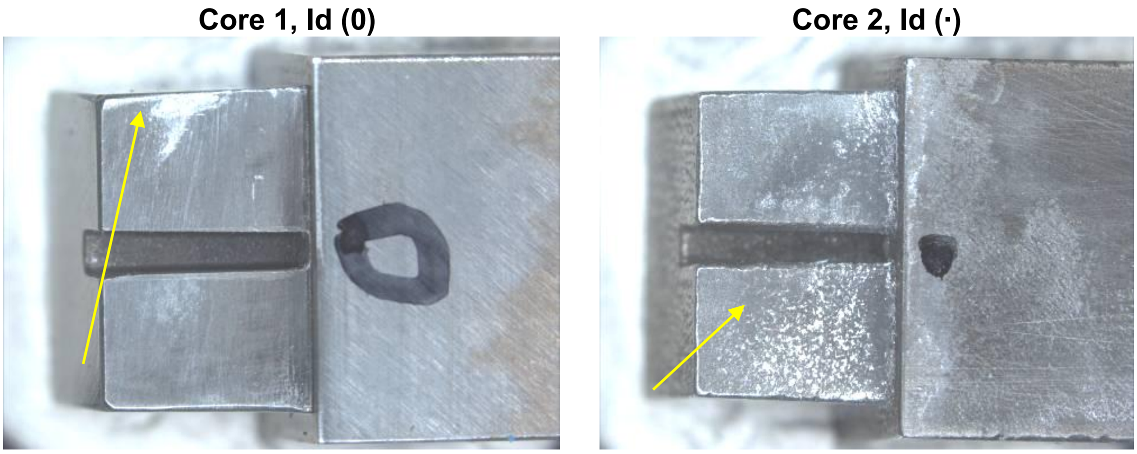


Figure 6.4 Dimensioned core drawing

Table 6.2 Geometrical dimensions verification

Core 1-ID (0)			Core 2-ID (·)			Core 3-ID (··)			Core 4-ID (···)		
	Pre (mm)	**Post (mm)**		**Pre (mm)**	**Post (mm)**		**Pre (mm)**	**Post (mm)**		**Pre (mm)**	**Post (mm)**
A	12.005	12.005	**A**	12.01	12.01	**A**	12.005	12.005	**A**	12.008	12.008
B	12.00	12.00	**B**	12.005	12.005	**B**	12.00	12.00	**B**	12.00	12.005
C	10.075	10.075	**C**	9.90	9.84	**C**	9.9	9.815	**C**	9.95	9.82
D	10.07	10.075	**D**	9.90	9.9	**D**	9.90	9.81	**D**	9.96	9.80

The results show that some distortion occurred on cores 2, 3 and 4. Closer investigation showed evidence of cracks and pitting occurring mainly at the corners. Washout present on the cores occurs on the faces opposite the gate. Figure 6.5 show these conditions at 5x amplification on the various cores.

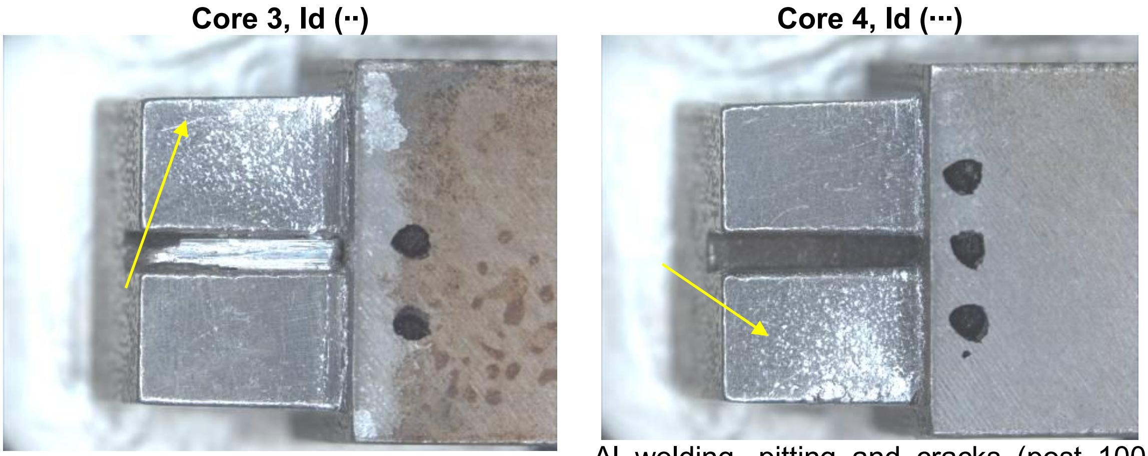


Core 1, Id (0)

Core 2, Id (·)

Initial aluminium welding (post 100 shots)

Initial Al welding and pitting (post 100 shots)



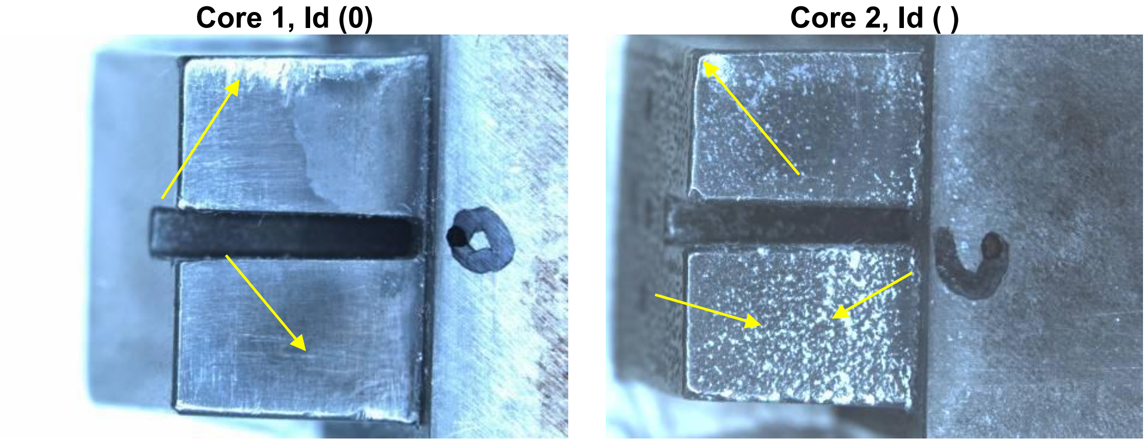
Core 3, Id (··)

Core 4, Id (···)

Initial Al welding and pitting (post 100 shots)

Al welding, pitting and cracks (post 100 shots)

Figure 6.5 Photos of the cores‘ faces opposite the gate

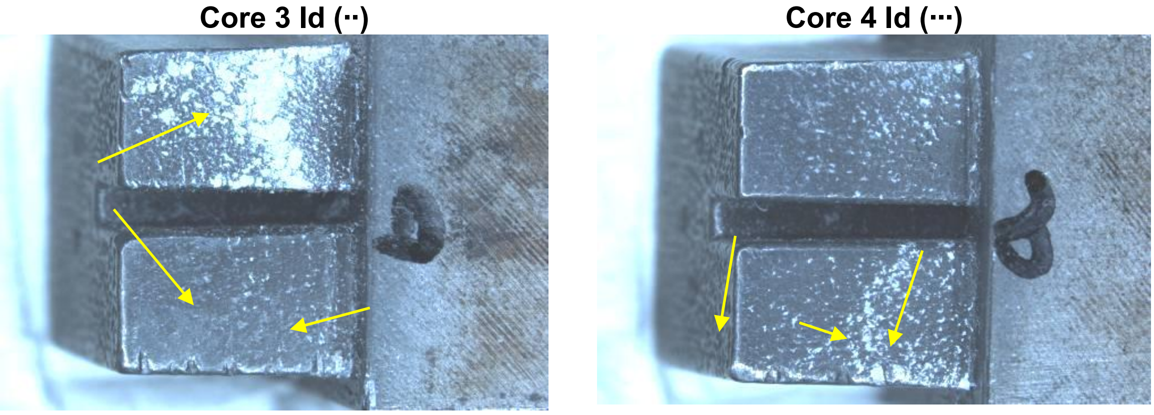


Core 1, Id (0)

Core 2, Id ( )

Al welding and cracks appeared (post 1 000 shots)

Al welding, pitting & cracks (post 1 000 shots)



Core 3 Id (··)

Core 4 Id (···)

Al welding, pitting and cracks (post 1 000 shots)

Al welding, pitting and cracks (post 1 000 shots)

Figure 6.5 Photos of the cores‘ faces opposite the gate (Continued)

The part quality was evaluated using visual inspection techniques on the areas of the component in contact with the cores at the start of the trial and after 100 shots. Figure 6.6 shows the quality deterioration of the components in the areas formed by the cores.

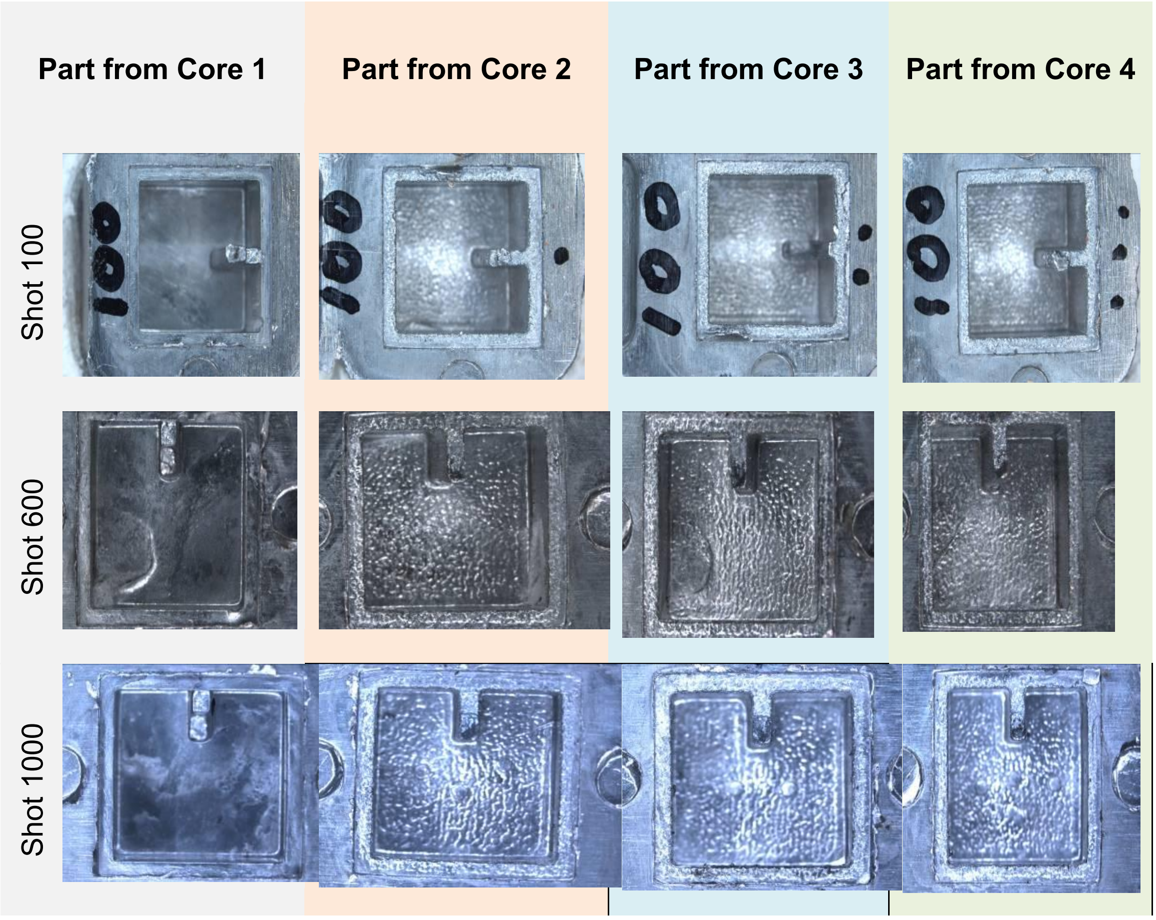


Figure 6.6 Comparative photos of area formed by cores on cast component

No drastic quality deterioration (>0.1mm deviation on radius size at the corners) was evident or surface finish anomalies were noticed.

6.6.3 Wash out effect

All the cores were weighed in order to establish any core material washout from the aluminium melt when filling the cavity. Results are shown in Table 6.3 below.

Table 6.3 Weights of cores

Core description	Pre	Post 100	700 shots	1000 shots
Core 1 Weight (g)	43.3371	43.34	43.344	43.3766 (+0.09%)
Core 2 Weight (g)	41.3538	41.138	41.1204	41.1594 (-0.47%)
Core 3 Weight (g)	41.209	41.2137	41.1652	41.1619 (-0.11%)
Core 4 Weight (g)	41.3433	41.23	41.2178	41.2325 (-0.27%)

The following observations were noted at 100 shots:

- Core 1 increased in weight due to aluminium welding on to the core
- Core 3 increased in weight due to a piece of aluminium breaking off in the rib area of the part
- Core 2 and 4 decreased in weight due to washout

The following observations were noted at 1 000 shots:

- Core 1 increased in weight due to further metal welding
- Core 2 increased in weight due to metal welding
- Core 3 decreased in weight due to an increase in crack size
- Core 4 decreased in weight due to an increase in the number of cracks appearing in the corner

6.6.4 Heat dissipation

Temperature measurements of the various cores were taken after about 50 shots with a handheld touch probe. The readings were taken 15 seconds after the melt was introduced in the cavities. Table 6.4 below show the results.

Table 6.4 Temperature measurements on cores

Shot No	Melt Temperature (°C)	Core 1 (°C)	Core 2 (°C)	Core 3 (°C)	Core 4 (°C)
11	648.5	159	149	148	150
56	648	163	147	146	152
100	684.5	168	152	150	160

The results reveal that the AM cores dissipate heat at a faster rate than the conventional 1.2344 core.

6.7 Heat treatment and surface conditioning

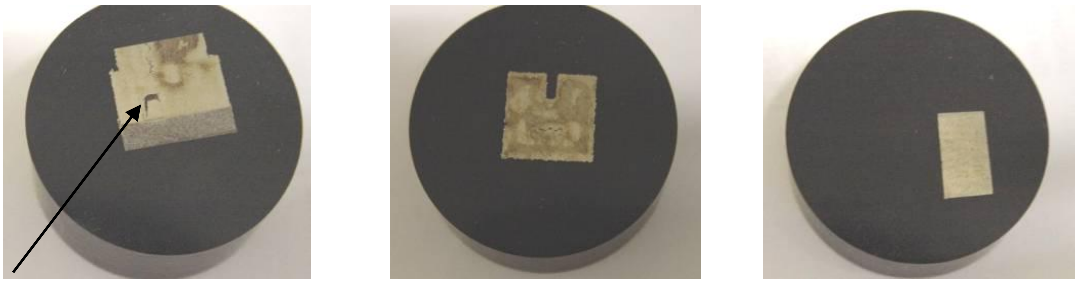
Core life extension strategies were taken into consideration that included exploring the possibilities of subjecting the cores to through-hardening and surface treatment processes. The test pieces were subjected to treatments such as plasma nitriding and the Toyota Diffusion (TD®) coating process and the results evaluated. The evaluation method consisted of measuring the hardness of the cores by using a Vickers notch hardness testing machine (see Table 6.5 for results using a 500 gram load), microscopic analysis of the coating and surface hardness depth.

Table 6.5 Results of Vickers hardness test

Core 1 1.2344 Hardness (Hv)	Core 2 Direct steel 20 Nitrided Hardness (Hv)	Core 3 Direct steel 20 Hardness (Hv)	Core 4 Direct steel 20 Hardness (Hv)
737-812	***240-276**	**260-312**	**205-234**

(*) Core 2‘s hardness readings were below expectation and further microscopic analysis revealed that the penetration of the hard surface layer was less than 5µm.

TD® coating on the AM test piece failed as blistering occurred even on previously polished outer surface areas. Further microscopic investigation revealed that the AM laser melting process induces the creation of gas pores, which, when subjected to temperatures around 900°C, results in blistering and crack forming. The test samples that were prepared for microscopic evaluation can be seen in Figure 6.7 below.



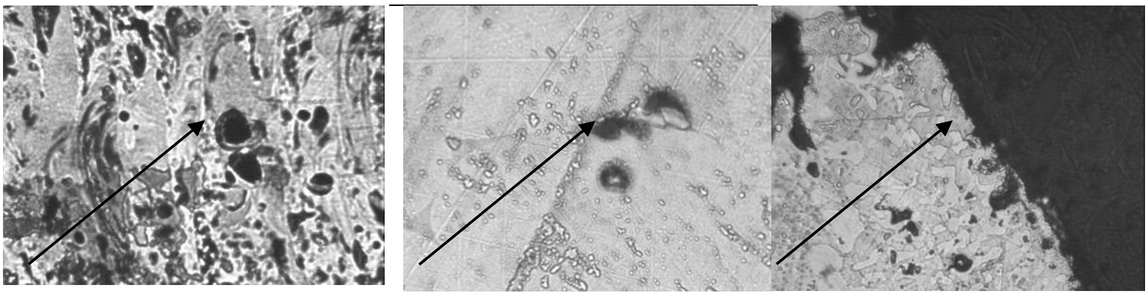
TD coating specimen crack cut transversely

TD coating specimen cut longitudinally

Plasma nitriding specimen

Figure 6.7 Test specimens prepared to study TD coating and plasma nitriding effects

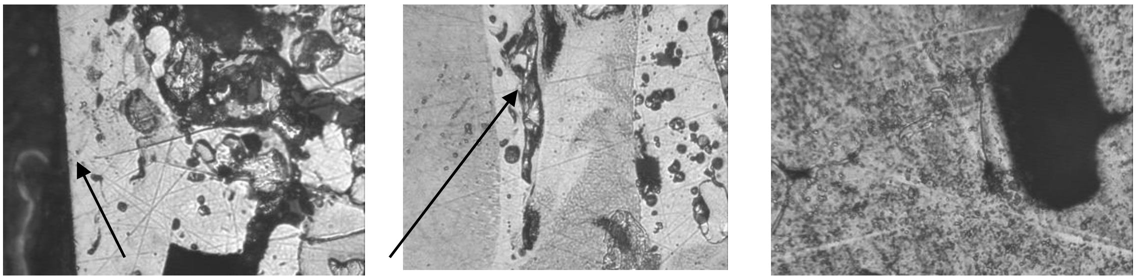
The photos of the microscopic analysis of the samples in Figure 6.8 indicates the presence of gas pores, crack formation and the depth of the surface treatment present on the TD® and plasma nitrided samples (viewed with magnifications 10X and 50X).



Pores on TD coated sample (50x)

Crack formation in TD sample (10x)

120 µm Edge depth on TD sample (50X)



5µm Edge on plasma nitride sample (50x)

Pore agglomeration in plasma nitrided sample (10x)

Pore 80µm average size (50x)

Figure 6.8 Microscope photos of TD® and plasma nitrided samples (Continued)

6.8 Conclusion

The research performed revealed that the performance of the three cores manufactured through DMLS, using Direct Steel 20 powders, was adequate for the set project objectives in as far as:

- The cores manufactured through DMLS will be able to withstand industrial standard HPDC processing conditions to produce small batches of cast components
- Geometrical and surface specifications can be attained and kept
- The time to manufacture dies can be significantly reduced if consideration is given to size and volume constraints of the AM platform
- The product development cycle of cast components can be significantly reduced where parts require alterations to the die cores

It was established that the AM cores portray a better resistance to aluminium welding than conventional hot work steels and have a faster heat dissipation rate, which opens possibilities for significant savings in processing cycle times.

The results are also encouraging due to the ability to produce large batches of castings using cores grown with this type of AM technology. The production of large batches will then include the costs associated with a die core replacement strategy based on a predetermined number of cycles.

The cores grown with Direct Steel 20 have low core and surface hardness, allowing for ease of finishing operations and the attaining of tight dimensional tolerances in a much faster time than conventional methods.

The foundation of a number of basic rules and die manufacturing strategies can be laid out from the research conducted:

- 3D model generation of cores prior to laser growing should include an overall surface material allowance of between 0.1 - 0.2mm
- In order to minimise the core volume, consider:

    (a) Growing the core over a compatible material substrate
    (b) Take into consideration designing the supports for the growing platform of the cores and the interface between the grown core and fitment area into the die
    (c) Consider other joining techniques such as cements and welding
    (d) Designing the core hollow with the possibility to include cooling in the component

- Consider using powder material grades with higher wear and core strength in die areas subjected to high friction and wear such as the gate and in areas perpendicular to the melt front

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CHAPTER 7

APPLICATION OF LASER ADDITIVE MANUFACTURING TO PRODUCE DIES FOR ALUMINIUM HIGH PRESSURE DIE CASTING

Authors: Pereira M.F.V.T., Williams M., Du Preez W. B. 2010

Purpose

The objectives of this paper is to discuss the outcomes of work done on a number of Additive Manufacturing (AM) technologies to produce fully dense metal components suitable for use as High Pressure Die Casting (HPDC) die cavity inserts.

Design/methodology/approach

Three AM technology platforms were selected and underwent evaluation of their suitability as die cavity inserts in the manufacture of High Pressure Die Casting (HPDC) dies. Apart from comparing the different manufactured AM inserts with one another, their performance was also compared with components manufactured in standard hot work steel Din 1.2344.

Findings

The study indicates that AM technology has potential for application in aluminium HPDC die manufacture and also proposes a methodology and procedure for applying AM technology in die manufacture. Recommendations done for the application of AM to produce die cavities are primarily based on economic feasibility.

Originality/value

In the paper, AM technology is proposed as an alternative die manufacturing process.

Paper type: Review paper

Paper status: Published - South African Journal of Industrial Engineering (SAJIE), Vol. 23, No. 2, pp 147-158, ISSN 1012-277X

7.1 Introduction

Aluminium alloy components for a number of automotive applications are mass produced using a production process called High Pressure Die Casting (HPDC). This manufacturing process imposes severe stresses on the forming dies during processing. These stresses are caused when molten aluminium is injected at high pressure into the die cavities to fill them and then solidify. Furthermore, the die manufacturing cost is a significant component determining the economic feasibility of the die casting process. Dies are manufactured from applicable steel materials normally referred to as hot work steels that can withstand the process conditions for an undetermined period of time. The terms *die life* and *expected minimum die life prior to failure* follows from the process induced wear and tear. Dies must be able to repetitively produce components with prescribed dimensions and good surface finish to specification. After some use, die cavity wear and tear is noticeable to such an extent that eventually a new die is required to be able to meet dimensional and surface requirements of the component being produced.

The most important die wear and tear failures are classified under two categories, namely washout and thermal fatigue. *Washout damages* are a direct result of the flow of the aluminium melt impinging on and rubbing against the die cavity surfaces. Corrosion is attributed to friction wear caused when the melt solidifies around core surfaces and the casting is ejected. *Thermal fatigue,* the most influential failure mode in die casting, reveals itself in two modes, namely heat checks and stress cracks. Thermal fatigue cracks occur as the die cavity surfaces are placed under tension when the cold (~25°C) water-based release agent impinges on the hot surfaces previously exposed to the aluminium melt. The cooling effect of the die lubricant spray on the underlying hot material causes a tensile stress in the hot die surface, resulting in surface cracks. This cycle is repeated each time a casting is made. The characteristic feature of heat checks is the appearance of fine cracking lines on surfaces which look like a spider web. Stress cracks appear mainly in corners and appear as individual and clearly defined cracks, sometimes filled with aluminium.

The use of Laser Additive Manufacturing (AM) for the purpose of compressing the time it takes to manufacture die components formed part of an ongoing research project. The research evaluated the effects of heat checking on specimens grown with the AM technology platforms LaserCUSING®, EOS and LENS.

7.2 Laser Additive manufacturing technologies investigated

In this research, two types of AM technologies that are suitable for the manufacture of die components, were investigated. One of the types uses the technology commonly referred as Powder Bed Layer Deposition with two leading technology providers, namely EOS and Concept Laser. Another approach to building a part from layers of material in a powder bed is to deliver powder by nozzles directly to the point where a focused laser melts the powder, fusing it into a part line-by-line, layer-by-layer. This technique, called Powder Deposition, (Wohlers, 2003) typically offers larger working envelopes and the ability to either make parts or repair existing parts. A leading service provider of this technology and test coupons for experimentation is LENS.

In this research test coupons made with the materials in Table 7.1 were evaluated.

Table 7.1 Metal powders used by service providers to manufacture test coupons

Number	Manufacturer	System	Materials
1	Concept Laser	M3 Linear	CL 50 WS (Hot work steel)
2	LENS	LENS 750 Model	H13 (Din 1.2344 Hot work steel)
3	EOS	EOSINT M250X	Direct Steel DS20 (steel)*

* EOS equipment suppliers were not able to provide test coupons for evaluation in more suitable material for die components.

7.3 Experimental method

A test rig was designed and manufactured for the research. The rig is able to subject the AM grown and standard steel manufactured specimens to cyclic heating and cooling with an immersion in liquid aluminium. The dipping cycle closely resembles the heating and cooling cycle of a typical aluminium die under casting conditions.

The suitability of any AM technology able to produce fully dense metallic components acceptable for die casting can be quickly assessed with the test rig. With economic feasibility in mind and knowing that on standard hot work steel, evidence of heat checking damage appear after a few thousand cycles, 10 000 cycles was set as the experimental benchmark.

The assessment of damages inflicted on the cycled specimens was performed through optical microscopy of both faces and sharp corners, so as to analyse the extent of heat checking cracks, as well as the possible presence of corrosion pits. Furthermore, impact toughness and hardness values of cycled and non-cycled specimens were evaluated in order to assess the extent of material property variation.

The objective of the initial experimental plan was for each AM system supplier to fabricate four test coupons; three solids and one with an open blind-hole passage. (Refer to diagram in Figure 7.1)

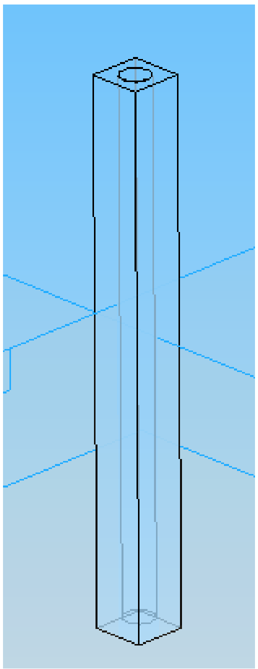


Figure 7.1 Test coupon with a square cross section of 10mm x 10mm, length 100mm with blind hole diameter 6mm up to 2mm from the bottom

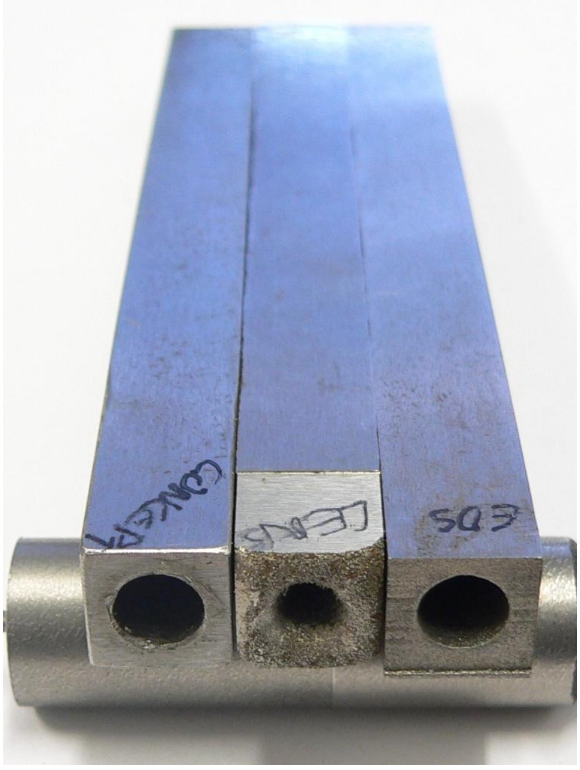


Figure 7.2 Test coupon hole aspect for the three systems

The results of the initial visual and geometrical evaluation of the test coupons are shown in Table 7.2.

Table 7.2 Results of visual examination (Abdel Ghany, 2006)

Description	**1**	**2**	**3**
System	**Concept M3 Linear**	**LENS 750 Model**	**EOS M 250 X**
Total shape	Complete	Complete	Complete
Dimension change in mm	± 0.1	± 1.5	± 0.1
Fine details	Very accurate	Poor	Very accurate
Holes	Sharp, correct depth, circular	Deformed, required 1mm per side machining	Sharp, correct depth, circular
Sharp edges	Sharp	Blunt	Sharp
Sharp corners	Sharp	Blunt	Sharp
Surface roughness (finished surfaces)	Smooth Rą=3.2 μm	Rough Rą=6.4 μm	Smooth Rą=3.2 μm
Layer coherence	Complete coherence (Layers are not visible)	Complete coherence (Layers are not visible)	Complete coherence (Layers are not visible)

Description	**1**	**2**	**3**
System	**Concept M3 Linear**	**LENS 750 Model**	**EOS M 250 X**
Cracks	No cracks	No cracks	Internal cracks(2)
Examination result	Very Good	Average	Good

Evaluation of costs and finishing are shown in Table 7.3.

Table 7.3 Processing and finishing costs of test coupons

Description	**1**	**2**	**3** (1)
System	**Concept M3 Linear**	**LENS 750 Model**	**EOS M 250 X**
Layer thickness (mm)	0.03	0.08	0.02
Total process time (hrs)	3.5	2.5	10.5
Finishing time (hrs)	1 (heat treatment)	4	1
Materials cost USD/kg	260	80	180
Coupon benchmark cost vs wrought manufactured	5.2	1,7	2. 2
Average cost	Very high	Medium	High

7.3.1 Cyclic Immersion in molten aluminium

Figure 7.3 below shows the testing apparatus developed to simulate thermal cycling conditions that occur inside the cavity surfaces of the die when in contact with the aluminium melt. The specimens were mounted in this rig, two in each arm end. At the same time, specimens mounted on both sides of the rotating arm were immersed either in aluminium at 630-700°C or a cooling bath at 36-45°C. Then the two opposite sides of the rotating arm were lifted and the immersion order reversed. An average cycle time of 20 seconds was achieved. The heating and cooling cycle measured on the specimens ranged between 80 and 540°C. A typical die casting thermal shock cycle experience ranges between 110 and 480°C. This means that the specimens were subjected to an even more severe heat shock cycle than when subjected to casting conditions. The time of immersion in either aluminium melt or cooling medium was 5 seconds.

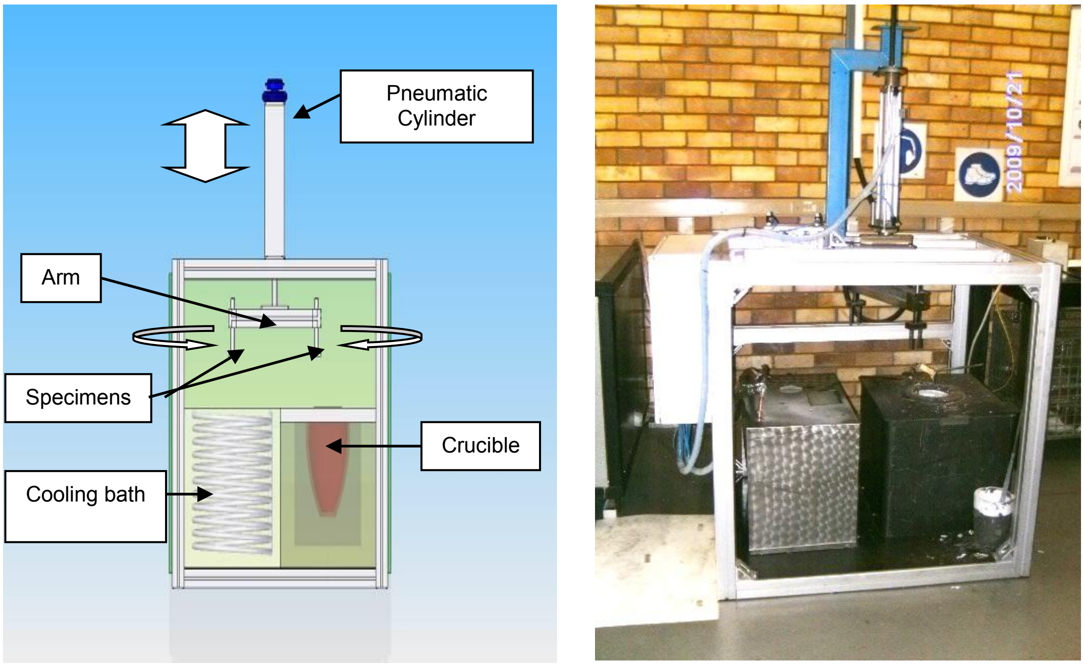


Figure 7.3 Aluminium melt cyclic dipping test rig

7.4 Experimental results and discussion

The data and results obtained are described, discussed and summarised in the following sections.

7.4.1 Specimen preparation

The AM samples used in the experiment had a measured degree of surface roughness average of Rą=3.2 µm; the preferred standard die cavity finish lies between Rą=0.80-0.20µm. Surface grinding, a material removal process, was used in order to bring the finish in line with the accepted norm. The grinding operation took care of both roughness and distortion induced by heat treatment of the AM specimens. A maximum distortion of 0.2mm was measured on the specimens.

The AM samples measured between 9.98 - 10.10mm on the requested 10.0 x 10.0mm cross section dimensions. After grinding to an acceptable finish free of distortion the cross sections measured between 9.50 – 9.80mm. The LENS AM grown test coupon measured deposition rate was 4cm^3/h, which translates into 2.5h for growing a specimen and another half an hour for removal from the support plate.

Table 7.4 Comparison of manufacturing times

Specimens HWS DIN 1.2344		Specimens EOS		Specimens LENS		Specimens Concept	
Process	**Time (h)**	**Process**	**Time (h)**	**Process**	**Time (h)**	**Process**	**Time (h)**
Milling	2.5	Laser sinter	10.5	Laser weld	2.5	Laser weld	12
Grinding	1	Grinding	1	Grinding	4	Grinding	1
Jig bore		Jig bore		Jig bore		Jig bore	
Heat treatment	4	Heat treatment		Heat treatment	4	Heat treatment	4
Finishing grind		Finishing grind		Finishing grind		Finishing grind	
Polish		Polish		Polish		Polish	
Fitting		Fitting		Fitting		Fitting	
Total	**7.5**		**11.5**		**10.5**		**17**

(Note: Times are based on a quantity of 4 specimens.)

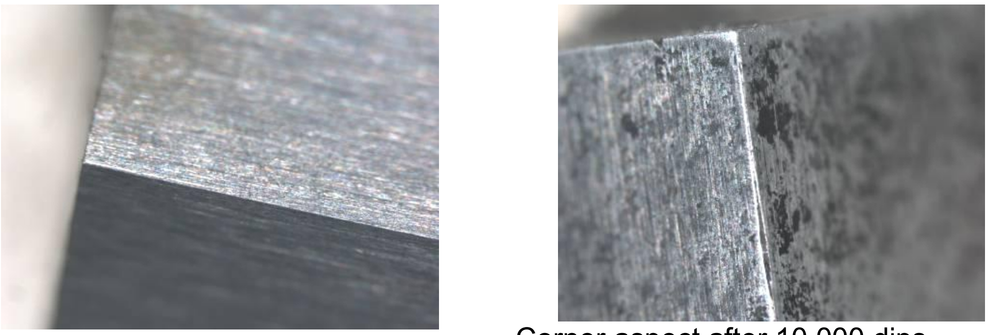
7.4.2 Heat checking and corrosion checks

The results show that some aluminium welding occurred on cores grown with the AM laser platform and to a lesser extent on the H13 specimen (Figure 7.4). Closer investigation showed evidence of cracks and pitting occurring mainly at the corners. The specimens were cleaned in an NaCl solution prior to conducting closer investigation.

Figure 7.4 Specimens prior and after 10 000 aluminium melt dipping cycles

Figure 7.5 shows images at 5x amplification of the manufactured cores.

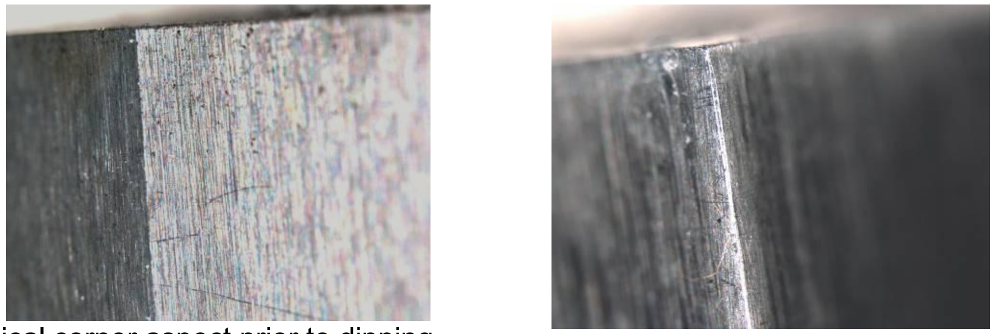
Specimen H13 **Specimen H13**



Typical corner aspect prior to dipping

Corner aspect after 10 000 dips, showing chipping washout, pitting and slight Al welding

Specimen Concept **Specimen Concept**

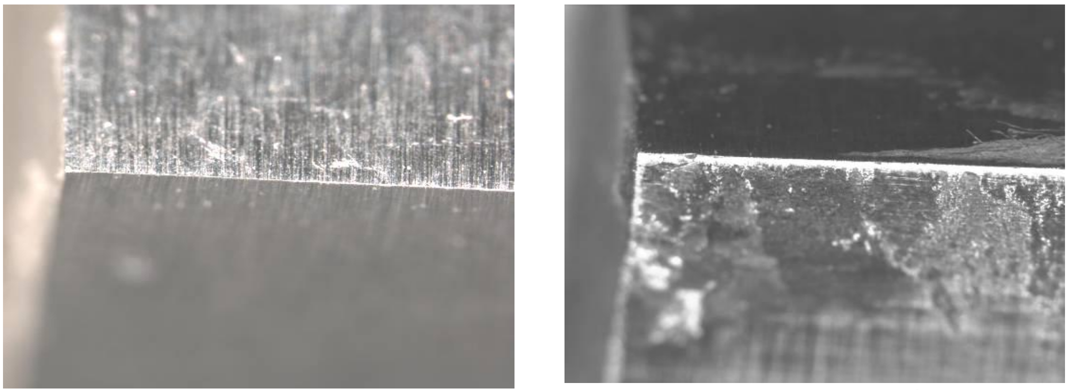


Typical corner aspect prior to dipping

Al welding, pitting & wash (post 10 000 dips)

Figure 7.5 Optical micrographs of the specimen corners and notches at 5x magnification

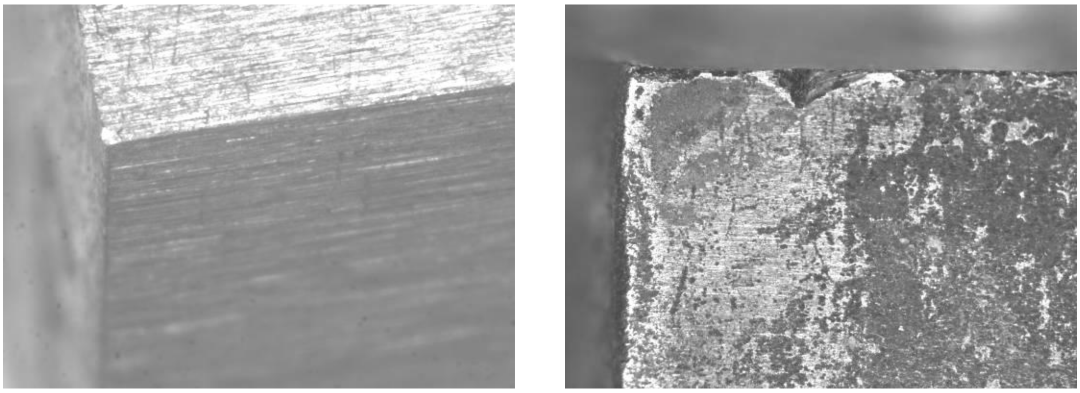
Specimen LENS **Specimen LENS**



Typical corner aspect prior to dipping

Al welding, and cracks (post 5 000 dips)

Specimen EOS **Specimen EOS**



Typical corner aspect prior to dipping

Al welding, pitting and cracks (post 5 000 dips)

Figure 7.5 Optical micrographs of the specimen corners and notches at 5x magnification (Continued)

7.4.3 Mechanical integrity and microscopy

The toughness and hardness of the specimens were determined prior to dipping and thereafter. A Vickers and Rockwell notch hardness testing machine was used to measure the hardness of the cores. Table 7.5 gives the results, using a 20kg and 10kg load. A clear softening effect was noticed on all specimens. It was less pronounced on the already soft EOS grown specimens.

Table 7.5 Results of Vickers hardness test

Core H13 Hardness (HRC) (20kg)	Core LENS Hardness (HRC) (20kg)	Core EOS Hardness (HV) (10kg)	Core Concept Hardness (HRC) (20kg)
Prior: 47.4-54.6	Prior: 54-60.7	Prior: 212.8-233.3	Prior: 50.37-52.81
After: 40.6-48.7	After: 49.6-52.6	After: 211.6-219.4	After: 33.0-35.67

Table 7.6 shows the changes in impact toughness found with the number of immersion cycles.

Table 7.6 Results of Charpy impact tests

Core H13 (Din1.2344) Impact Energy (Joules)	Core LENS Impact Energy (Joules)	Core EOS Impact Energy (Joules)	Core Concept Impact Energy (Joules)
Not dipped 11.8	Not dipped 7.8	Not dipped 7.8	Not dipped 18.3
Dipped 8.8	Dipped 8.8	Dipped 7.8	Dipped 8.0

The H13 specimens showed a decline in impact toughness, which was the result of the annealing effect experienced during the heat cyclic dipping. Surprisingly, the LENS specimens showed a slight increase, which can be attributed to a less brittle, more tempered core after experiencing the heat cycling like heat treatment. The EOS specimens showed no change in impact toughness.

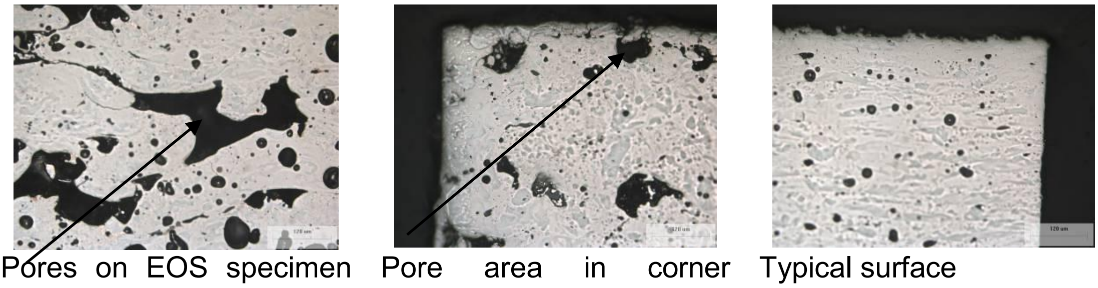
The Concept LaserCUSING® specimens showed a steep decrease in toughness, which can be attributed to the fast annealing accompanied with loss of ductility or lower elongation properties of the cores when compared with the condition prior to cycle dipping.

Further metallographic observation did reveal some microstructure modification on the H13 and LaserCUSING® specimens. However, the H13 specimen showed slightly less crack growth than the AM specimens which clearly revealed some degree of change. Only an extended dipping cycle experiment (20 000 dips) will conclude if the difference of size of cracks and crack density between the test coupons is significant.

Surprising was the partial loss of hardness of the H13 (Din 1.2344) test coupon with composition C = 0.4%, Si = 0%, Cr = 5.3%, Mo =1.40%, and V = 1.0% with high red strength, when compared with the Concept CL 50 WS equivalent to Din 1.2709 powder composition C = 0.02%, Si =0.1%, Mn = 0.1%, Ni = 18.5%, Ti = 0.7%, Mo =5.0% and Co = 8.8%. The greater loss of hardness can be attributed to the high Ni (above 18%) content of the Concept alloy. Ni content on alloy steels normally lowers the martensite to austenite transformation temperature, which tends to be lower than the Al melt temperature, resulting in rapid softening of the steel.

The slower softening rate of the conventional (H13) and LENS Din 1.2344 specimens clearly indicate that the heat treatments were done in a non-protective atmosphere.

Further metallographic observation did not reveal significant microstructure changes in the Concept, LENS and H13 specimens. However, the EOS specimen clearly revealed some degree of change. The micrographs of the microscopic analysis of the EOS specimens in Figure 7.6 indicate an increased presence of gas pores, accompanied by crack formation.

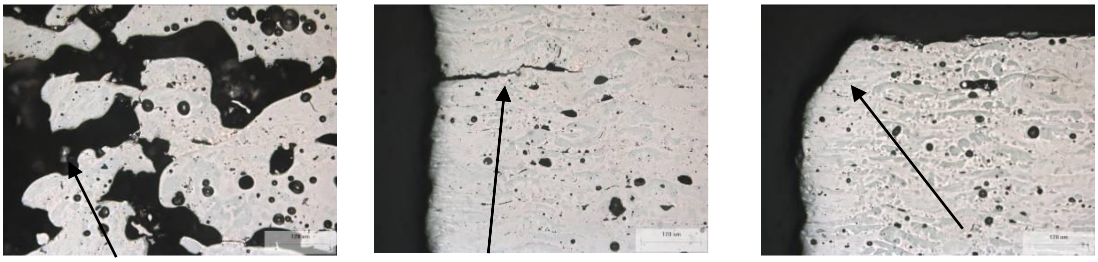


Pores on EOS specimen prior to dipping (50x)

Pore area in corner conducive to crack formation in EOS specimen prior to dipping (50x)

Typical surface appearance of EOS specimen prior to dipping (20x)

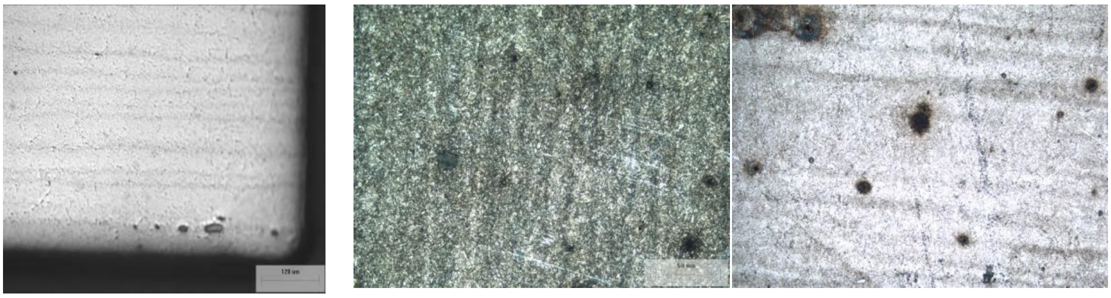
Figure 7.6 Optical micrographs of EOS,H13, LENS and Concept samples



Increased and aggregated pore area of dipped EOS specimen (50x)

Typical crack on EOS specimen after 5 000 cyclic dips (20x)

Chipped corner on dipped EOS specimen (50x)



Typical aspect of sharp corner of H13 specimen prior to dipping (20x)

H13 microstructure prior to dipping (100x).
Hardness= 50HRC.
Even diffusion of alloying carbide elements in a ferrite matrix

H13 microstructure after dipping (200x).
Hardness= 45HRC.
No significant variance on microstructure. Very few porosities and inclusions.

Evidence of some cracking and corrosion on dipped H13 specimen (100x)

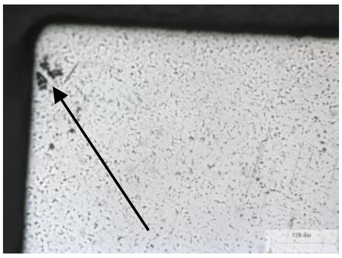
LENS microstructure very coherent due to the complete melting of powders during processing (200x).
Hardness= 52 HRC

LENS specimen microstructure after dipping (200x).
Hardness= 50HRC.
No significant variance of matrix with very few porosities and inclusions.

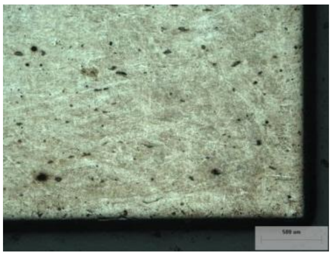
Figure 7.6 Optical micrographs of EOS,H13, LENS and Concept samples (Continued)

Typical aspect of sharp corner of LENS specimen prior to dipping (20x)

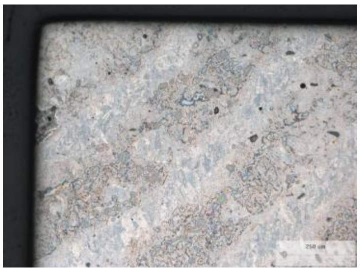
Slight evidence of cracking on dipped LENS specimen (100x)



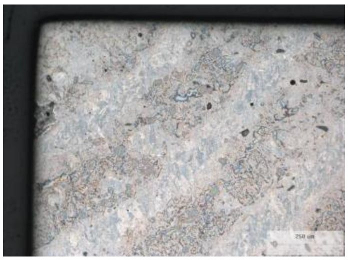
Slight evidence of corrosion on dipped LENS specimen (20x)



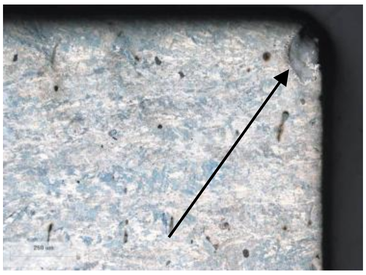
Typical aspect of sharp corner of Concept specimen prior to dipping (20x)



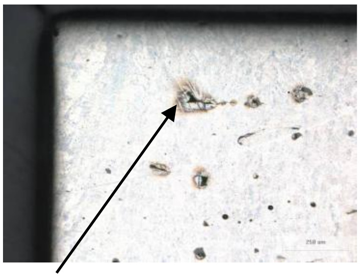
Concept specimen melt deposition tracks visible - nucleation and aggregation of intermetallic alloys (100x)



Concept coupon prior to dipping. Small number of pores visible (100x)



Concept coupon after dipping - chipped and wear on corner visible (100x)



Concept coupon after dipping - clearly visible crack initiation (100x)

Concept coupon after dipping. Note agglomeration and segregation of intermetallic alloys coupled with increased number of small pores (200x).

Figure 7.6 Optical micrographs of EOS, H13, LENS and Concept samples (Continued)

7.5 Conclusion

This paper reports the work performed on the performance of cores manufactured through EOS DMLS, Concept LaserCUSING® and LENS (a blown powder AM technology platform). Comparative analyses of both the LaserCUSING® and LENS specimens with the standard die steel show that they would be able to fulfil similar functions. In order to clearly distinguish which is better, will require further experimentation with 20 000 cycles and more.

Recapping our findings around EOS grown components (Pereira, 2009), (Pereira, 2008), it was found that they are adequate in as far as:

- Good candidate for time compression of product development and/or production of prototype production runs
- The cores will only be able to withstand industrial standard HPDC processing conditions to produce small batches i. e. <5 000 shots. Larger batches could be produced if it is economically feasible to prepare spare cores for replacement after a predetermined number of shots
- Good near net capability able to reproduce geometry with an allowed material tolerance of 0.25mm, slow rate of deposition 2-10cm^3/hour
- The time to manufacture dies can be significantly reduced if consideration is given to size and volume constraints of the AM platform

Cores grown with Direct Steel 20 have low core and surface hardness, as well as some degree of porosity. EOS-marketed AM technology platform‘s ability to grow die components with alternative powder material grades with higher wear and core strength would certainly imply the ability to grow die components with an improved die life, larger production batches and better economic viability.

The performance of the LENS AM technology grown components (Pereira, 2010) under these particular experimental conditions was remarkable as far as:

- Ability to withstand industrial standard HPDC processing conditions to produce castings equivalent to standard die materials.

- Time to manufacture dies can be significantly reduced due to availability of machines which size of build envelope is equivalent to NC die machining capability (motion 150cm x 90cm x 90cm (z axis)). LENS multi-nozzle capability opens opportunities for further development of:

  (a) Faster build rates generally, and lower rates of material deposition where geometrical accuracy is required.
  (b) Multi-material deposition
  (c) Full die manufacture as well as die repair due to the availability of platforms with multi axes range of motion (up to 7)

    (i) 3D model generation of cores prior to laser growing should include an overall surface material allowance of between 1.5 – 2.5mm
    (ii) Cores manufactured from powders equivalent to hot work steel DIN 1.2344 have core and surface hardness equivalent to the standard die material

The LaserCusing AM technology grown components‘ performance (Pereira, 2009) can be considered quite remarkable as far as:

- Ability to produce die components for standard industrial production batches
- Good near net capability able to reproduce geometry with an allowed material tolerance of 0.3mm
- Reasonable turnaround time, ideal for complex geometry cavity inserts requiring integrated cooling that is particularly difficult or impossible to attain with normal mechanical metal removal techniques
- Availability of steel powders with similar characteristics to standard used hot work steels, e.g. Din 1.2709

Feasibility for adoption of AM in die component manufacturing should be determined once more advantages are found.

The following arguments are suggested:

- Component geometry is very complex. In order to be manufactured, multiple material removal technologies are required, i.e. EDM, milling and grinding, to mention a few.
- Hot work steel is deposited with acceptable quality.
- Cost is competitive. A rule of thumb that can be utilised is to look at the amount of material that needs to be removed from a billet or piece of wrought material to manufacture a die cavity. If the amount of material to be removed is above 75%, there is a good likelihood that the component is a good candidate for AM.

A number of die manufacturing strategies can be laid out from the research conducted:

- In order to minimise deposition and die manufacture time, consider:

    (a) Growing the core over a compatible material substrate
    (b) Allowing for holding and set up required by conventional machining methodologies in the design of cores and/or die structures
    (c) Designing the core hollow with the possibility to include cooling in the components

- Consider components grown at the required final hardness, free of distortion.

Near net shape manufacturing capability of powder bed AM technology makes systems such as EOS the choice for developmental, prototype and/or short run dies. Concept LaserCUSING technology is a good choice for complex small to medium die inserts able to withstand standard aluminium production rates.

Blown powder AM processes, such as LENS, is the choice for the manufacturing of larger dies and/or repair of production dies. More extensive finishing operations (conventional machining) will be required when compared with the powder bed technology AM platforms.

AM technology has matured enough for widespread use by industry. Economic feasibility will be the key for a more rapid or slower adoption of the technology by industry. The range of applications stands to multiply exponentially if the gap is reduced between the cost of AM machines and steel powders versus conventional machining technologies and wrought steels.

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