CHARACTERIZATION OF METAL POWDER BASED RAPID PROTOTYPING COMPONENTS WITH RESPECT TO ALUMINIUM HIGH PRESSURE DIE CASTING PROCESS CONDITIONS

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ABSTRACT

This paper is based on tests performed on die component specimens manufactured by EOS-DMLS (direct metal laser sintering) and LENS (laser engineered net shape) RP (rapid prototyping) technology platforms, as well as manufactured specimens machined out of preferred standard hot work steel DIN 1.2344. These specimens resemble typical components used in metal high pressure die casting toolsets. The specimens were subjected to a programme of cyclic immersion in molten aluminium alloy and cooling in water-based die release medium. The heat checking and soldering phenomena were analyzed through periodic inspections, monitoring crack formation and evidence of surface washout. At the end of the thermal tests, mechanical strength and hardness tests were performed to assess toughness and core resistance variations in relation to the initial conditions. Finally metallographic investigations were performed through optical microscopy on all the specimens considered.

The outcomes of this research will be presented and used by the CSIR for further development and application of the assessed EOS-DMLS and LENS rapid prototyping technologies in rapid die manufacturing techniques and die design principles, including time and economic feasibility criteria to be applied when considering rapid die manufacture.

Keywords: rapid tooling, rapid prototyping techniques, high pressure die casting, die manufacture, die life, thermal fatigue, DMLS, LENS

1. INTRODUCTION

Aluminium high pressure die casting (HPDC) is a manufacturing process that imposes severe stresses on the dies during processing. Furthermore, die manufacturing cost forms a significant component of the economic feasibility of the die casting process. Dies are manufactured from suitable steel materials that can withstand process conditions for an undetermined period of time; thus the terms *die life* and *expected minimum die life prior to failure* due to process induced wear and tear.

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

- *Washout damage,* resulting 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 from there.

- *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 looking like a spider's web. Stress cracks appear mainly in corners as individual and clearly defined cracks, occasionally filled with aluminium.

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

The use of rapid prototyping (RP) techniques for the purpose of significantly reducing the time it takes to manufacture die components, forms part of an ongoing research programme. The approach described here was applied to evaluate the effects of heat checking on specimens grown with RP technology platforms namely EOS-DMLS and LENS in comparison with standard die material hot work steel DIN 1.2344 (equivalent to AISI H13). This approach makes use of equipment able to subject the RP grown and standard steel manufactured specimens to cyclic heating and cooling with an immersion in liquid aluminium.

The suitability of RP technology able to produce fully dense metallic components suitable for die casting can be quickly assessed with the setup. 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 were determined as the experimental benchmark. Assessment of damage inflicted on the cycled specimens was performed through optical microscopy of both faces and sharp corners, to analyze 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 variation in material properties.

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. (1,2) None of them envisaged the use of the equipment for evaluation of RP grown specimens.

A total of 5 000 shots was produced using recycled A356 aluminium material.

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 of 10x10mm were machined and grown by the selected RP techniques. The extra length of the specimen beyond the classic 55mm required for the impact test was used to hold the specimens in the test rig described below. Two sets of specimens produced on two RP technology platforms and standard hot work steel were subjected to Charpy impact tests. One of the sets was first subjected to a programme of cyclic immersion in molten aluminium prior to undergoing impact testing.

Figure 1 below shows the modelled and actual specimens that were evaluated.

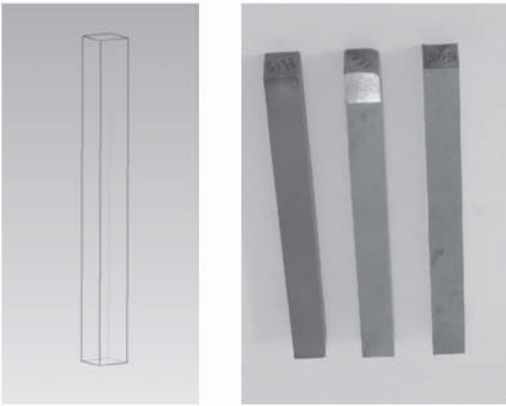


Figure 1: 3D model of the specimens, and the EOS-DMLS, LENS and machined specimens

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-DMLS RP process specimens was Direct Steel 20. The alloy selected for the LENS RP 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:

1. One following conventional die machining methods from hardened DIN 1.2344/H13 material
2. One using the EOS-DMLS process
3. One using the LENS process

Figure 2 below shows the finished manufactured and EOS-DMLS, LENS grown cores.

Figure 2: Pictures showing the cores manufactured with the conventional and RP methods. From left to right: Through-hardened steel H13 conventional manufactured specimen, EOS-DMLS grown specimen, LENS grown specimen

2.2. Dipping rig for cyclic immersion in molten aluminium

Figure 3 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 or in a cooling bath at 28-34°C. Subsequently, 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°C and 540°C. A typical die casting thermal shock cycle experience ranges between 110°C and 480°C. This means that the specimens were subjected to a more severe heat shock deterioration cycle than when subjected to normal die casting conditions.

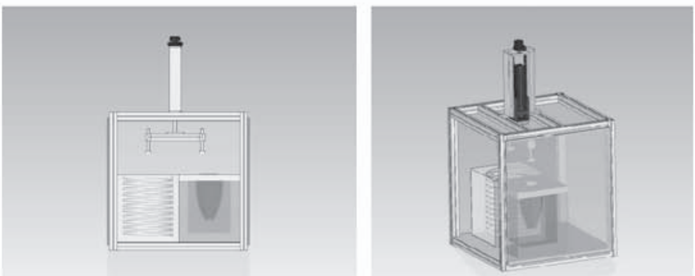


Figure 3: Aluminium melt cyclic dipping test rig

3. EXPERIMENTAL RESULTS AND COMPARISONS

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

3.1. Manufacturing time comparison

The evaluation of the specimen's manufacturing procedures are summarised in Table 1 below, indicating the process and time taken to produce each specific specimen.

Table 1: Comparison of manufacturing times

Specimen HWS H13		Specimen EOS-DMLS		Specimen LENS	
Process	Time (h)	Process	Time (h)	Process	Time (h)
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	
F grind		F grind		F grind	
Polish		Polish		Polish	
Fitting		Fitting		Fitting	
Total	**7.5**		**11.5**		**6.5**

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

3.2 Heat checking and corrosion checks

The results showed that some aluminium welding occurred on cores grown with the EOS-DMLS and LENS RP platforms and to a lesser extent on the H13 specimen (Figure 4). 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 5 shows these conditions at x5 magnification of the cores.

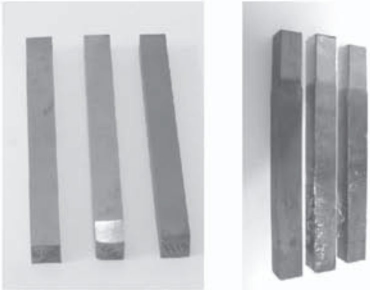


Figure 4: Specimens prior to and after 5000 aluminium melt dipping cycles

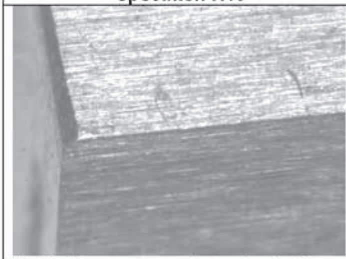
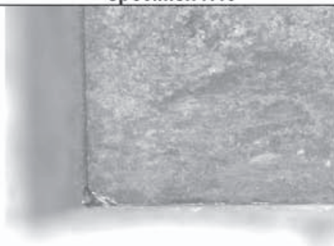
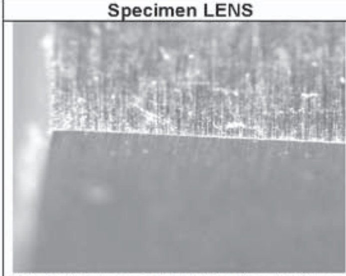
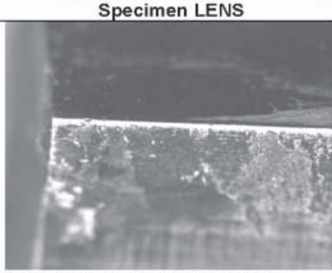
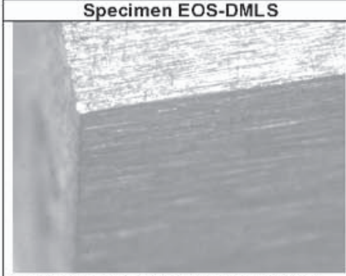
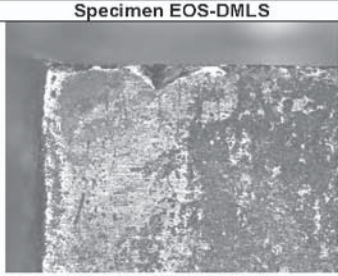
Specimen H13	Specimen H13
 Typical corner aspect prior to dipping	 Corner aspect after 5 000 dips, showing chipping and slight Al welding
Specimen LENS	**Specimen LENS**
 Typical corner aspect prior to dipping	 Al welding and cracks seen after 5 000 dips
Specimen EOS-DMLS	**Specimen EOS-DMLS**
 Typical corner aspect prior to dipping	 Al welding, pitting and cracks seen after 5000 dips

Figure 5: Photos of the specimens' corners

3.3 Mechanical integrity and surface conditioning

The toughness and hardness of the specimens were traced both prior to and after dipping. The evaluation method used for measuring the hardness of the cores was Vickers notch hardness testing (see Table 2 for results using a 20kg and 10kg load.) A clear softening effect was noticed on all specimens, but less so on the already soft EOS-DMLS grown specimens.

Table 2: Results of Vickers hardness test

Core H13 Hardness (HRC)	Core LENS Hardness (HRC)	Core EOS-DMLS 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 3 below gives an idea of the impact modification experienced with the number of immersion cycles.

Table 3: Results of Charpy impact test

Core H13 Impact energy (Joules)	Core LENS Impact energy (Joules)	Core EOS-DMLS 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 a decrease in impact toughness, which was to be expected. Surprisingly, however, the **LENS** parts showed a slight increase which can be attributed to the less brittle core hardness. The EOS-DMLS manufactured 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-DMLS manufactured specimen clearly revealed some degree of change.

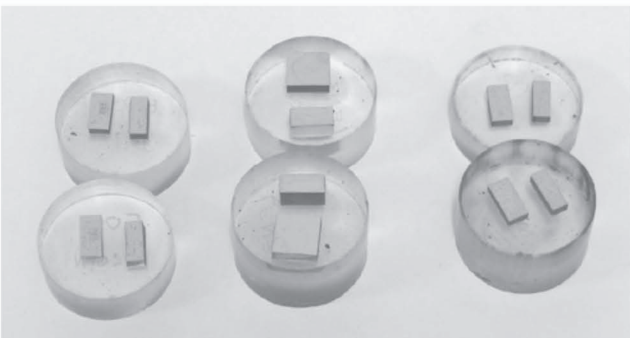


Figure 6: Test specimens prepared for light microscopy

The micrographs of the microscopic analysis of the EOS-DMLS samples in Figure 7 indicate increased presence of gas pores accompanied by crack formation.

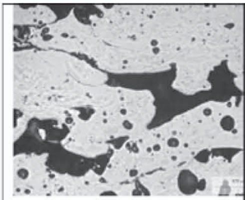
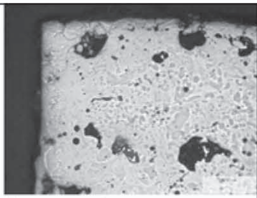
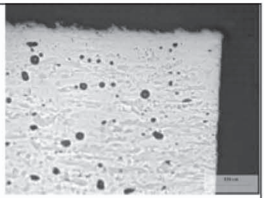
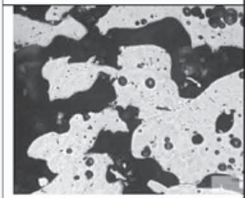
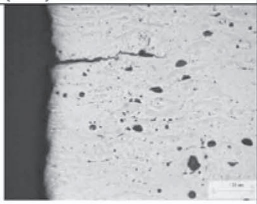
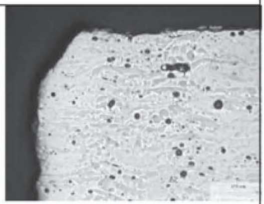
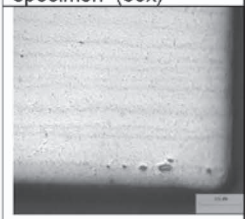
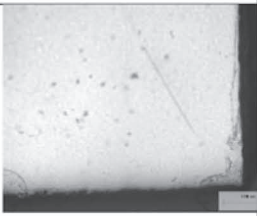
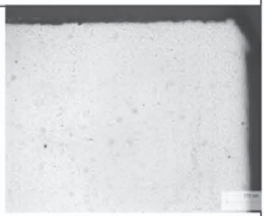
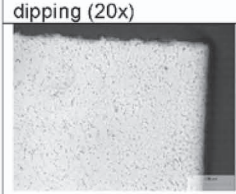
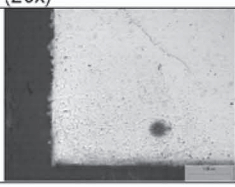
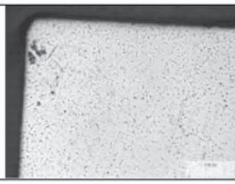
		
Pores in EOS-DMLS specimen prior to dipping (50x)	Pore area in corner conducive to crack formation in EOS-DMLS specimen prior to dipping (50x)	Typical surface appearance of EOS-DMLS specimen prior to dipping (20x)
		
Increased and aggregated pore area of dipped EOS-DMLS specimen (50x)	Typical crack on EOS-DMLS specimen after 5 000 cyclic dip (20x)	Chipped corner on dipped EOS-DMLS specimen (50x)
		
Typical aspect of sharp corner of H13 specimen prior to dipping (20x)	Evidence of some cracking and corrosion on dipped H13 specimen (20x)	Further evidence of corner chipping on dipped H13 specimen (20x)
		
Typical aspect of sharp corner of LENS specimen prior to dipping (20x)	Very little evidence of corrosion or cracking on dipped LENS specimen	Slight evidence of corrosion on dipped LENS specimen

Figure 7: Optical micrographs of H13, LENS and EOS-DMLS samples

4. DISCUSSION AND CONCLUSIONS

This paper reports on previous work done on the performance of cores manufactured through EOS-DMLS (3), and also on LENS blown powder RP technology.

The current results reinforce previous findings regarding EOS grown components, namely 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 production process quality control that includes periodic inspection of die condition;
- the time to manufacture dies can be significantly reduced if due consideration is given to size and volume constraints of the RP 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 RP technology grown components under these particular experimental conditions was remarkable in terms of:

- ability to withstand industrial standard HPDC processing conditions to produce castings equivalent to standard die materials;
- time to manufacture dies, which can be significantly reduced due to availability of machines of which size of build envelope is equivalent to NC die machining capability (motion150cm x 90cm x 90cm (z axis)). LENS Multi nozzle capability opens opportunities for further development of:
  - strategies of fast rate and lower rates of material deposition where geometrical accuracy is required;
  - multi material deposition; and
  - full die manufacture as well as die repairs due to availability of platform with multi axes range of motion (up to 7).

Cores manufactured from powders equivalent to hot work steel DIN 1.2344 have core and surface hardness equivalent to 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:
  - o growing the core over a compatible material substrate;
  - o allowing in the design of cores and/or die structures for holding and set up required by conventional machining methodologies;
  - o designing core hollowing and the possibility of including cooling in the components.
- Consider components grown at the required final hardness, free of distortion.

Dimensional and geometrical accuracy of EOS-DMLS type of powder bed RP technology makes such systems the choice for developmental, prototype and/or short run dies. Blown powder RP processes, such as LENS, would be the choice for full blown manufacture and repair of production dies.

5. REFERENCES

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