

# RAPID DIE MANUFACTURING USING DIRECT LASER METAL DEPOSITION

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## ABSTRACT

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 for tooling-up has also increased dramatically. For this reason research into various methods, techniques and approaches to tool manufacture is being undertaken globally. This paper highlights the work undertaken at the CSIR on the issue of rapid die manufacturing through the application and evaluation of a rapid prototyping technique and coating technologies applied to die components of a high pressure casting die for the production of aluminium components. Criteria for determining suitability were developed against which the technique was evaluated that included time, cost and life-expectancy. Results of accelerated testing procedures to evaluate the die material produced by the rapid prototyping technique and surface coatings and treatments of die materials for their resistance to washout, erosion, heat checking and corrosion in a high pressure die casting environment, are presented. The outcomes of this research will be used for further development and application of specific techniques, design principles and criteria for this approach.

**Keywords:** Rapid Tooling, Rapid Prototyping Techniques, High Pressure Die Casting, Die Manufacture

## 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. The need for light components able to fulfil technical and quality specifications has 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 for tooling-up has also increased dramatically. For this reason research into various methods, techniques and approaches to tool manufacture is being undertaken globally.

The use of Rapid Prototyping Techniques (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). This approach aims at benefiting high pressure casting companies with a faster and more economical solution for part approval for production as well as for small batches using in-house high pressure die casting processes.

A number of RPT processes can be used for this proposed rapid manufacturing tooling solution (Wohlers, 2000), notwithstanding that they should be able to produce cavity-forming inserts with the following specifications:

- In the appropriate/correct materials
- 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 solution aims to establish are:

- parts with mechanical properties compatible to those manufactured from die casting steels;
- repeatability and quicker turnaround times for die repair, adjustment, modifications and manufacturing; and
- tooling inserts capable of producing quantities as required for prototype or short runs.

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

## **2. RAPID PROTOTYPING 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; Kashka, 2000). From the information acquired it was deduced 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 must 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 to the high pressure die casting process.

Three RP processes with potential for application were identified, namely Direct Metal Forming (DMF) or Direct Metal Deposition (DMD), Electron Beam Melting (EBM) and Direct Metal Laser Sintering (DMLS). Of these three, only DMLS is available locally in South Africa and as such was selected as the basis for the research.

### **3. PLAN OF EXPERIMENTS**

The primary objective of this research was to use accelerated testing procedures to evaluate die materials produced by RP 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°C
- gate speed: 40 m/s
- die temperature: 200 230°C

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

### 3.1 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 performance of the various cores. The material feeding system (runner and gate inserts) were redesigned together with the cavity and core holding inserts. After all these modifications the shot weight was calculated.

Figure 1: below shows the designed cavity inserts and core components that were evaluated.

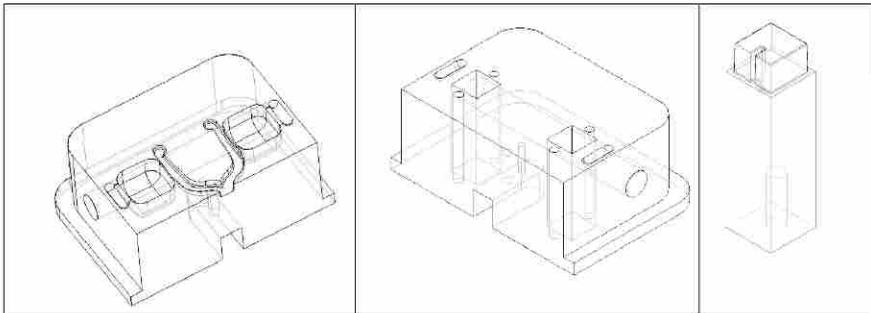


Figure 1: 3D models of the core, new cavity and core holding inserts

### 3.2 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 RP 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 4.5).

Figure 2 below shows the finished manufactured and as grown cores.

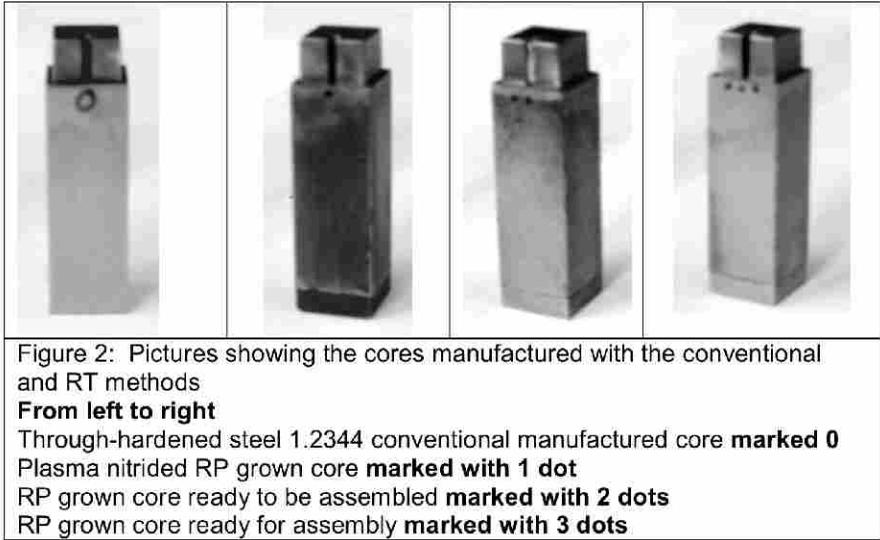
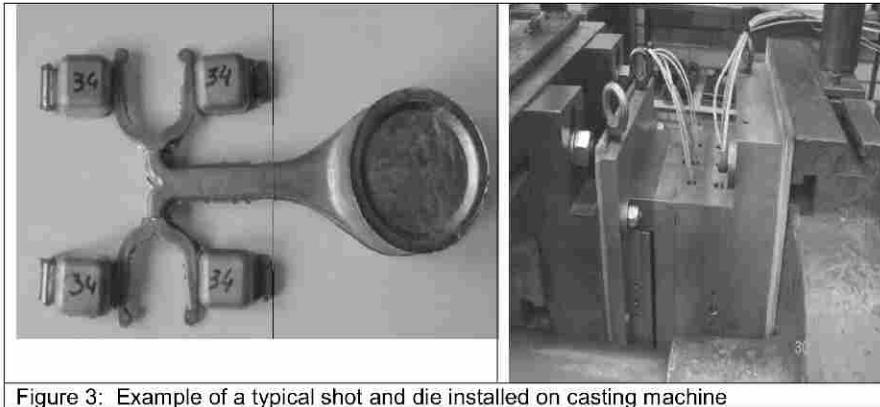


Figure 3 below shows an example of a shot produced during the trial runs and the die mounted on the HPDC machine. A total of 1 000 shots were completed during the sample runs (in batches of 100 before analysis and inspection). An average cycle time of 30 seconds were achieved from pouring metal to extracting components.



#### 4. EXPERIMENTAL RESULTS AND COMPARISON

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

## 4.1 Manufacturing Time Comparison

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

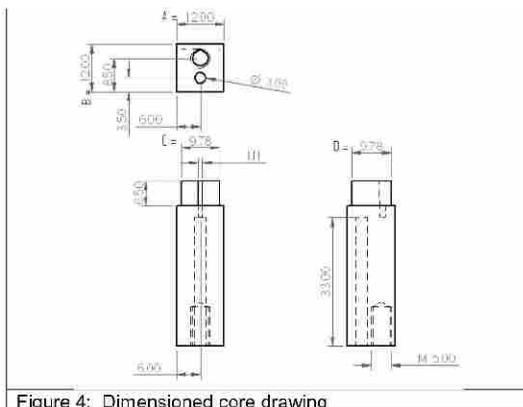
**Table 1:** Comparison of manufacturing times

| Core 1<br>ID (0)    |               | Core 2<br>ID (.) |               | Core 3<br>ID (..) |               | Core 4<br>ID (...) |               |
|---------------------|---------------|------------------|---------------|-------------------|---------------|--------------------|---------------|
| Process             | Time<br>(hrs) | Process          | Time<br>(hrs) | Process           | Time<br>(hrs) | Process            | Time<br>(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     |               |
| F grind             | 4             | F grind          | 3             | F grind           | 3             | F grind            | 3             |
| Spark erosion       | 7             |                  |               |                   |               |                    |               |
| Polish              | 2             | Polish           | 1             | Polish            | 1             | Polish             | 1             |
| Fitting             | 3             | Fitting          | 3             | Fitting           | 3             | Fitting            | 3             |
| Electrode<br>Manuf. | 4             |                  |               |                   |               |                    |               |
| <b>Total</b>        | <b>25.5</b>   |                  | <b>21.5</b>   |                   | <b>20.5</b>   |                    | <b>20.5</b>   |

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

## 4.2 Dimensional and surface quality checks

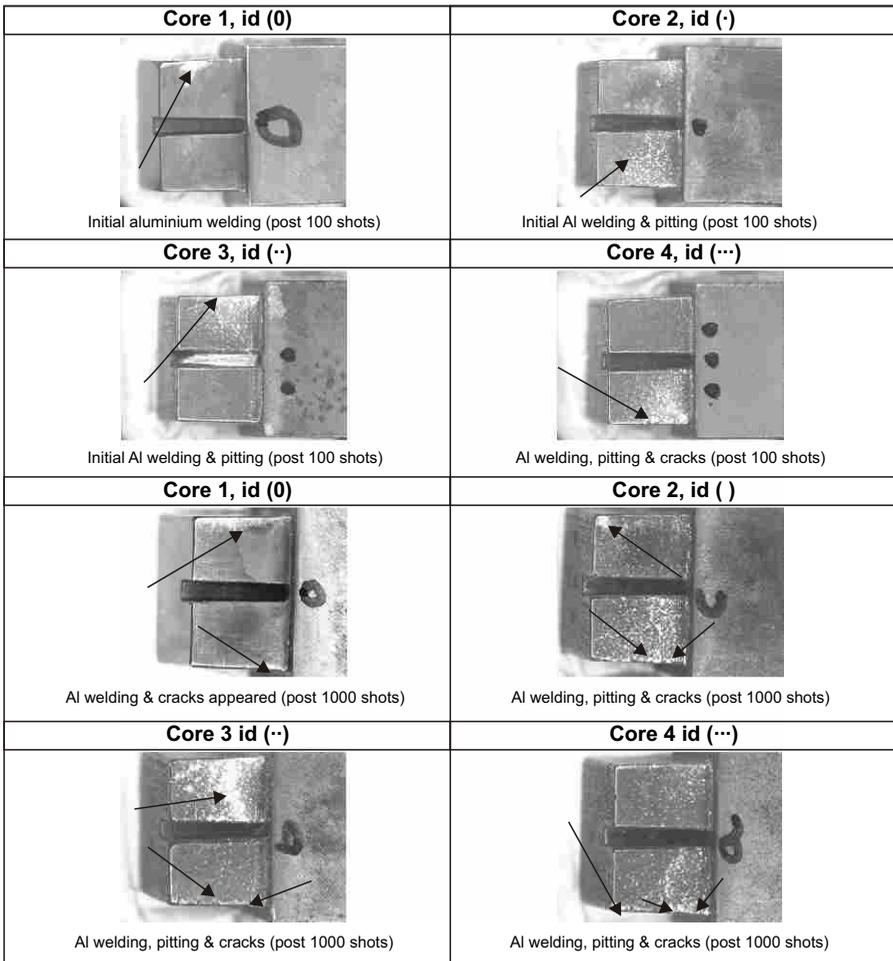
After the production of the 1000 experimental shots, the geometrical dimensions of the cores were verified and compared to the as-manufactured dimensions. Some predetermined core dimensions were taken for comparison using a digital vernier calliper and micrometer. A 2D core drawing with the dimensions is shown in Figure 4. Table 2 shows the results of the measurements taken.



**Table 2:** Geometrical dimensions verification

|   | Core 1-ID (0) |           | Core 2-ID (-) |           | Core 3-ID (-) |           | Core 4-ID (-) |           |   |        |        |
|---|---------------|-----------|---------------|-----------|---------------|-----------|---------------|-----------|---|--------|--------|
|   | 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 is on the faces opposite the gate. Figure 5 shows these conditions at 5x amplification on the various cores.



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 shows the quality deterioration of the components in the areas formed by the cores.

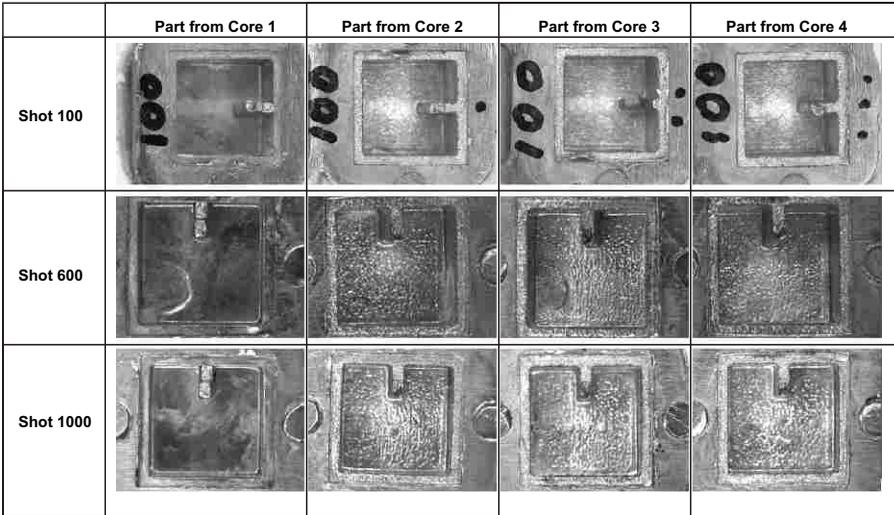


Figure 6: Comparative photos of area formed by cores on cast component

No drastic quality deterioration ( $>0.1\text{mm}$  deviation on radius size at the corners) or surface finish anomalies were noticed.

### 4.3 Washout 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 3 below.

Table 3: Weights of cores

|                   | 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 2 increased in weight due to a piece of aluminium breaking off in the rib area of the part.

- Core 3 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.

#### 4.4 Heat dissipation

Temperature measurements of the various cores were taken after about 50 shots with a hand-held touch probe. The readings were taken 15 seconds after the melt was introduced in the cavities. Table 4 below shows the results.

**Table 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 RP cores dissipate heat at a faster rate than the conventional 1.2344 core.

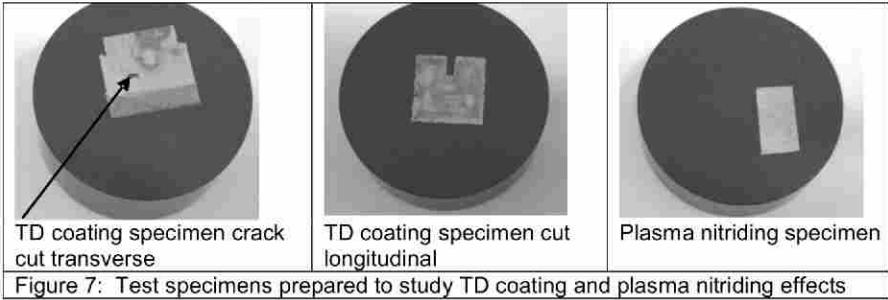
#### 4.5 Heat treatment and surface conditioning

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 5 for results using a 500 gram load, microscopic analysis of the coating and surface hardness depth).

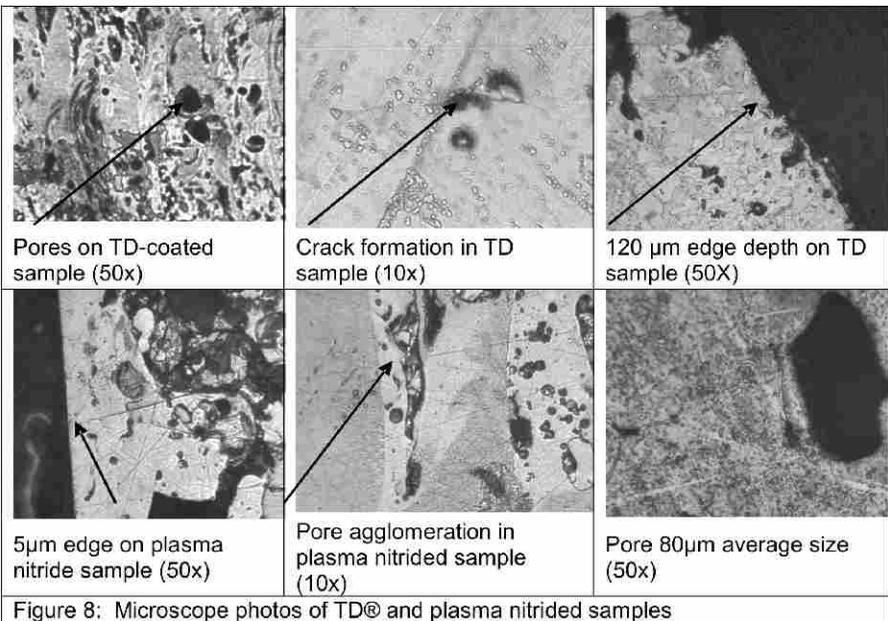
**Table 5:** Results of Vickers hardness test

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

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



The photos of the microscopic analysis of the samples in Figure 8 indicate 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.



## 5. CONCLUSIONS

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 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.

It was established that the RP cores portrayed a better resistance to aluminium welding than conventional hot work steels and they 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 RP 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 determined 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:
  - growing the core over a compatible material substrate;
  - 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;
  - consider other joining techniques such as cements and welding;
  - design core hollowing and the possibility of including 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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