SUITABILITY OF LAYER MANUFACTURING TECHNOLOGIES FOR RAPID TOOLING DEVELOPMENT IN INVESTMENT CASTING OF LIGHT METALS

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ABSTRACT

Rapid tooling (RT) in the context of this research presents the possibility of improving the traditional investment casting process by shortening lead times while still maintaining affordable costs and required quality. Various rapid prototyping processes are available that can be used to create direct metal, polymer or wooden dies for this casting technology. This paper presents results gained in an AMTS project, focusing on RT development for investment casting of light metals. One of the most widely used layer manufacturing processes available in South Africa is selective laser sintering. A machine produced by the German manufacturer EOS (process known as laser sintering) utilising this technology was selected for the study. Two of the materials that are suitable for rapid die making are used, which in turn reflects different mechanical properties and process economics. A standard benchmark part was used as a study base. Two dies were built, one in alumide and one in polyamide. A comprehensive measurement programme was conducted, followed by an appropriate statistical analysis and evaluation regarding accuracy and surface finish. A number of wax patterns were produced. The best wax patterns from each die were selected and evaluated. The subsequently produced castings in Al, Mg and TI were further examined and evaluated.

Various issues concerning the reinforcement, wax injection, pattern removal, accuracy and surface finish of the dies are discussed in the paper. The research concludes that rapid tooling techniques can be successfully used for creating accurate dies in order to shorten lead times in the investment casting process chain.

Keywords: investment casting, rapid prototyping, rapid tooling, layer manufacturing

1. INTRODUCTION

This paper investigates the utilisation of rapid prototyping (RP) in the process chain of investment casting (IC), together known as rapid investment casting (RIC). RIC can be divided into three main areas namely *pattern making*, *die making* and *shell making*. Rapid prototyping, also known as an additive or layer manufacturing technology, can be used in each of these three areas with varying results.

Rapid tooling (RT) involves the use of additive technologies to manufacture tooling and tooling inserts [1]. Investment casting has many benefits. Some of them are design flexibility, the processing of a wide choice of alloys, reduced production costs, fewer assembly operations, reproduction of fine details, high dimensional accuracy for light and heavy parts, elimination of certain tooling when using rapid tooling techniques etc. A wide variety of ferrous and nonferrous alloys can be used in the investment casting process [2]. Multiple parts can be produced as a single part and costly machining and assembly operations can be reduced or eliminated.

The objective of the study is to explore the applicability of layer manufacturing methods for rapid tooling development so that complex, near-net shape, high value components can be produced. Table 1 lists the various LM processes and their applicability to investment casting.

Figure 1 shows the rapid prototyping and rapid tooling processes used in RIC.

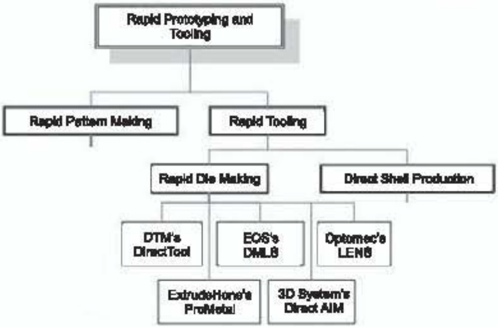


Figure 1: Rapid prototyping and tooling processes [3]

Table 1: LM processes applicability to investment casting [1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12]

Process		Applicability to Investment Casting		
		Patterns	Dies	Shells
1	SLA	X	-	-
2	SLS (and LS)	X	X	X
3	FDM	X	-	-
4	LOM	X	X	-
5	3DP (MM2)	X	-	-
6	3DP (ThermoJet)	X	-	-
7	3DP	X	X	X
8	LENS	-	X	-
9	Direct Metal Deposition	-	X	-
10	EBM	-	X	-
11	DMLS	-	X	-
12	SLM	-	X	-

Each kind of process technology has its unique area of relevance for investment casting, as well as its own set of advantages and disadvantages. Careful thought must be given when selecting a specific process, because there are numerous factors that should be taken into consideration. For example, certain processes are better known for their use in creating patterns, dies or shells, as indicated in Table 1.

In this paper the capabilities of two materials processed by the EOS laser sintering machine are compared through a comprehensive benchmark study. Conclusions are drawn in terms of accuracy and surface finish.

2. PROCESS CHAINS FOR RAPID INVESTMENT CASTING

There are a number of process chains that can be followed to develop patterns, dies and shells for investment casting using rapid prototyping and rapid tooling techniques.

The conventional IC process can be summarized in the eight steps as illustrated in Figure 2. The direct-die-fabrication process chain looks similar to the conventional process chain, the only difference being the method of die fabrication. Rapid tooling allows for the shortening of lead times.

2.1. Direct die fabrication

After a die has been designed, it must be cut from wood or some other material such as steel or aluminium. This process can be performed by hand (manually) or by using a specific cutting technology like CNC cutting. Rapid investment casting involves directly manufacturing the die in metal or some specific polymer by applying a layer manufacturing process such as 3DP, SLS, SLM, DMD or EBM.

Conventional Investment Casting Process Chain

Direct Die Fabrication

Figure 2: Process chains [3]

2.1. Indirect tool fabrication

Dies may also be indirectly manufactured. First a master pattern is produced by using certain layer manufacturing processes. The die is then manufactured from this master pattern using rapid tooling technologies as applicable.

Indirect tooling can be split into two categories namely soft-tooling and hard-tooling. The difference between the two is the method and material used to manufacture the die. Soft-tooling is used for small production quantities, and hard-tooling for larger production quantities. Processes for soft-tooling include epoxy resins and silicone rubbers. Processes for hard-tooling include metal spraying, 3D Keltool and cast metal [3].

3. METHODOLOGY

A standard benchmark part is used. Two measuring programmes are carried out on each part, comparing the part to the original CAD model, using a CMM. The first programme measures various coordinate points (deviations) which are used to carry out a statistical analysis. The second programme measures various geometric and dimensional tolerances. The tolerances are used to calculate a dimensional accuracy index (DAI) for each part. The statistical values and DAI are used for evaluation and comparison.

3.1. Benchmarking part

The part used for benchmarking can be seen in Figure 3. It was designed within tooling projects from the FP6 Framework of the European Commission EC and used for similar studies [13]. The dies represent an exact negative of the pattern and include a shrinkage allowance for the investment casting wax used.

Each feature incorporated on the benchmark part has a certain purpose for the benchmarking process and is used to measure specific tolerances. Table 2 lists the various features on the benchmark part and the purposes of each of them.

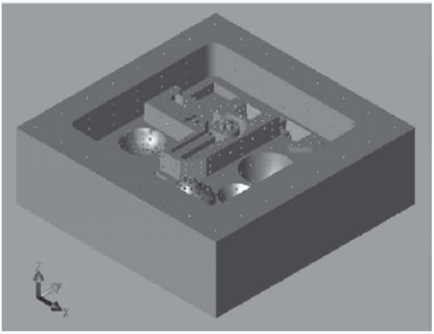


Figure 3: Benchmark part

Table 2: Purpose of each feature

Feature	Purpose	Quantity and Nominal size
Cubes	Straightness, repeatability, linear accuracy	2 (8 x 8 x 8 mm) 2 (8 x 8 x 4 mm) (Half-Cube)
Rectangular protrusion	Perpendicularity, linear accuracy	1 (25 x 8 x 8 mm)
Pyramid	Angularity, accuracy	1 (12 x 17 x 20 mm)
Sphere (half)	Symmetry, repeatability of a constantly changing sloping profile, axial runout, radial runout	1 (ø35 mm)
Cone	Constant sloping profile, taper, axial runout, radial runout, symmetry	1 (ø30 x 26 mm)
Free-form (conical)	Non-constant sloping profile, axial runout, radial runout, symmetry	1 (ø40 x 30 mm)
Free-form (sinkhole)	Non-constant sloping profile, axial runout, radial runout, symmetry	1 (ø30 x 20 mm)
Wedges	Angularity	(X direction 20 x 20 mm) (Y direction 20 x 25 mm)
Rectangular Hole	Perpendicularity,	1 (25 x 8 x 5 mm)
Cylindrical Hole/ Hollow Cylinder	Concentricity, circularity, accuracy	1 (ø30 x ø20 x 27 mm)
Triangular Hole	Angularity, perpendicularity	1 (10 x 8 x 4 mm)
Flat Thin Walls	Parallelism , thickness	1 (35 x 27 x 5 mm) 1 (35 x 27 x 3 mm)
Square base	Flatness, straightness, parallelism	1 (150 x 150 mm)
Mechanical Features	Competence of machine to build particular features (Visual Inspection)	Free-form, Chamfer, Fillet
Yes/No Features	Machines ability to build certain features (Visual Inspection)	Small triangular hole, Small cross-shaped hole, Thin walls

4. SUITABILITY OF LAYER MANUFACTURED DIES FOR INVESTMENT CASTING

4.1. Rapid die making

More than six commercialised systems are available that allow direct metal die production. Direct metal tooling has drastically improved the lead time and reduced the cost for producing prototype and production tooling [3].

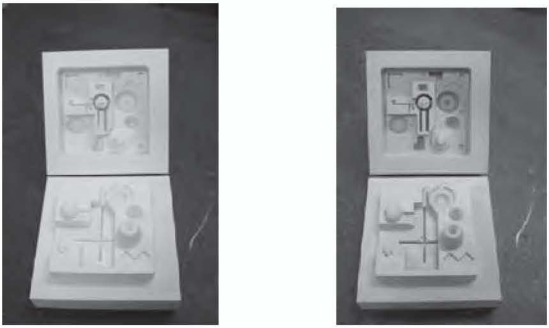
A die consists of at least two parts, namely a core and a cavity. Conventional dies are machined from aluminium or steel. The investment casting process is able to produce very complex parts and therefore dies are often required to split into multiple parts. This complexity may sometimes require a number of loose inserts to be incorporated in the die. The degree of complexity is directly proportional to the costs induced. This means that cost and lead time will increase with the increase in complexity of the die. However, complex dies can easily be built with RP machines, which in turn reduce the cost and lead time, especially for low volume production.

4.2. Building the dies

Two dies of different materials, namely alumide and polyamide, were built on an EOS P385 LS machine. A 0.8 % shrinkage factor was added to the dies for wax shrinkage and release angles of 1˚ to 2˚ were added to certain surfaces for ease of pattern removal from the dies. Due to the high cost of materials, the core and cavity of each die were built hollow (5mm shell), except for the alumide core which was built as a solid (Figure 4). Building hollow dies is standard practice to keep costs down and allow for reinforcement. Hollow dies also allow for inclusion of cooling channels. The LS dies are more rigid due to the graphite in the materials used, which prevents problematic sagging during part removal and oven curing [14]. The statistical results are shown in Table 3.

Table 3: Statistical results

Descriptive statistics	Alumide die	Polyamide die	Wax pattern (Alumide)	Wax pattern (Polyamide)
Mean	-0.0188	0.0648	0.0068	-0.0537
Standard error	0.0055	0.0085	0.0154	0.0103
Median	-0.0330	0.0120	-0.0090	-0.0400
Mode	0.0320	-0.0670	-0.1940	0.0110
Standard deviation	0.1371	0.2122	0.3522	0.2345
Sample variance	0.0188	0.0450	0.1241	0.0550
Kurtosis	1.2294	-0.8667	0.6394	0.8502
Skewness	0.6803	0.4397	-0.0119	-0.3391
Range	0.8880	0.9970	2.6270	1.5930
Minimum	-0.4020	-0.3560	-1.5210	-0.8770
Maximum	0.4860	0.6410	1.1060	0.7160
Sum	-11.691	40.373	3.539	-28.104
Count	623	623	523	523
Largest(1)	0.4860	0.6410	1.1060	0.7160
Smallest(1)	-0.4020	-0.3560	-1.5210	-0.8770
Confidence level (95.0%)	0.0108	0.0167	0.0303	0.0201
Dimensional accuracy index (DAI)	90.70%	93.02%	64.66%	65.52%
Surface finish *Ra (µm)*	15.785	15.703	4.273	6.128
Lead Time (days)	3	3	1	1
Cost	R16845	R10160	R250	R250
Material	Alumide	Polyamide	Green wax	Green wax



a. Polyamide die set **b.** Alumide die set

Figure 4: Polyamide and alumide die sets

5. SUITABILITY OF WAX PATTERNS FROM LAYER MANUFACTURED DIES FOR INVESTMENT CASTING

5.1. Preparation of dies for wax injection

The dies are very fragile and cannot withstand the clamping force of a wax injection machine during injection. For this reason MCP F18 resin is used to fill the hollow cavities and hollow polyamide core. The cavities and cores are each reinforced with a 10 mm aluminum plate (fixed to the dies with M8 bolts), and machined flat on their backs to allow for even clamping by the wax injection machine. A guiding/location plate is added to each side of each die. A 10 mm runner is machined along the splitting line of each die. Figure 5a show the reinforced dies.

5.2. The wax injection process

A Schott 20 ton injection machine is used for wax injection. The type of wax used is 289B Green wax [15]. The following machine variables can be controlled: injection time, dwell time, cooling time, wax filling, injection pressure, dwell pressure, wax temperature and clamping force.

a. Reinforced dies b. Melted with butane flame c. Pattern stuck to die

Figure 5: Patterns stuck to dies

The first injection for each die was disastrous, because the patterns stuck to the cavity of each die. A butane flame had to be used to melt the wax out of the alumide cavity, taking care that the surface was not damaged (Figure 5b). Trichloroethylene was used as a cleaning solvent to remove the wax from the surfaces.

The dies are porous and were absorbing the releasing agent before injection could take place. Releasing agent was sprayed multiple times until it seemed that the surfaces had become saturated. A few of the surfaces were lightly sanded to help ease ejection of patterns from the cavities.

a. Wax part broke off **b.** Poor solidification **c.** Wax pushed into surface

Figure 6: Poor solidification of wax pattern

a. Thick wax layer forming **b.** Small cracks forming **c.** Core sagging under ruler

Figure 7: Polyamide core compressing

The alumide core was compressing due to its porosity. The pattern part of the core was literally sagging into the solid base (Figures 7a, 7b and 7c). Small cracks were also forming between the core and its base (Figure 7b).

5.1. Surface roughness of dies and wax patterns

Die surface roughness measurements were taken before any release agent was applied. The results indicate that there is a very small difference in the surface roughness of the two dies: a difference of only 0.082 μm. The reason for such a close value can be explained by the fact that both materials have an average grain size of 60 μm.

The alumide wax pattern has a better surface finish value than the polyamide pattern with values of 4.273 μm and 6.128 μm respectively. The patterns have better surface finishes than the dies. This is due to the excessive use of release agent and slight sanding of surfaces to help pattern removal from dies.

5.2. Economics of the process

Figure 8 and Figure 9 illustrate the tooling cost and lead time for different tooling. A tool for the benchmark part is not that complex and therefore not that expensive, but for a very complex die the cost can easily increase to R150 000 or more, also depending on the die material used. Only small pattern quantities can be produced with RP dies and they are therefore meant for rapid product development purposes.

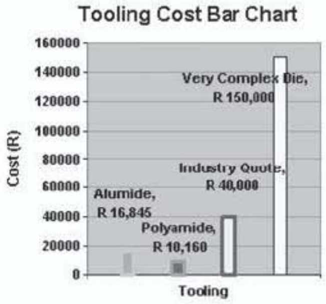


Figure 8: Cost comparison of tooling (dies)

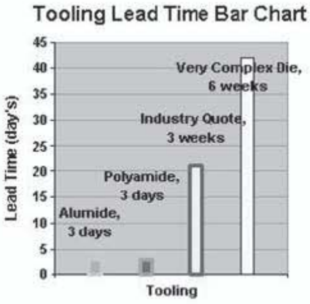


Figure 9: Lead time comparison of tooling (dies)

The results of the statistical analysis of the wax patterns are shown in Table 3.

6. CONCLUSIONS

Rapid dies

Both die cavities demonstrate very good dimensional and geometric accuracy with very few values and features out of tolerance. This indicates that both materials could provide very accurate dies for the creation of wax patterns for investment casting. The DAI is only an estimation method and there is little difference between the two values. However, an ANOVA analysis concludes that there is still a significant difference in accuracy between the dies.

Based on the statistical analysis, it can be concluded that the alumide die is more accurate than the polyamide die (Table 3), although both dies provided good features with adequate definition.

Wax injection

The dies are very fragile and porous and reinforcement is a definite requirement when wax injection is used. Proper alignment of the dies using guide pins or plates is necessary to prevent the core from bumping against the cavity and causing damage to the surface and features of the die.

Continuous layers of silicone release agent must be applied until the porous dies become saturated in order to obtain a first pattern. The excess amounts of release agent influence the surface quality of the wax patterns. Excessive scraping and heat (butane flame) used to remove wax from dies causes damage to the surface finish and die definition. Wax dissolving solvents (trichloroethylene) should be used for cleaning or removing wax from surfaces. Light sanding of the inner side walls of the die is necessary for easy pattern removal.

Poor heat-transferring properties of the dies limit the number of continuous injections. Dies become too warm and wax does not solidify at thick sections. This is a clear indication that cooling channels will be needed to reduce injection cycle times. Increasing dwell times allows for better solidification of wax, but only until die temperatures become too high. Water cooling channels could easily have been included in the die cavities by inserting copper pipes in the back of the hollow dies before filling them with resin.

Die porosity allows for wax penetration in areas experiencing continuous high wax pressure. This complicates pattern removal from dies. Slight buckling of the patterns is caused by the removal process, but this can be reduced or eliminated by the use of ejector pins.

The alumide core was compacted by the pressure of the wax injection. The pattern thickness nearly doubled after a dozen injection cycles. The compacting is due to the porosity of the dies. There was so much sagging of the core that fine cracks started forming. Therefore it can be concluded that RP dies are mechanically weaker than conventional dies due to their porosity; however they are strong enough for prototyping purposes. Building hollow dies and reinforcing them with resin can reduce the overall compacting effect.

Wax patterns

The measurements show that the wax pattern from the polyamide die is slightly more accurate than the wax pattern from the alumide die.

The deformation of the dies under the pressure of multiple injection cycles might be the cause of some of the far out-of-tolerance deviations on the patterns.

There is little difference between the DAI values, concluding that the accuracy of the patterns is comparable. However, the ANOVA analysis indicates that there is still a significant difference in accuracy between the wax patterns. It can be concluded that the wax pattern from the polyamide die is statistically more accurate than the one from the alumide die.

Die and wax pattern surface roughness

Surface roughness only differs by a fraction between the two dies. Results show that the wax patterns from the alumide die have a better surface than ones from the polyamide die.

Process economics

Material cost is still one of the most influential factors on the final expenditure for dies. Manufacturing time and post-processing also have a slight influence on the price.

The LS powders and reinforcement materials used for the dies are expensive and the total cost can be anything from ten to twenty thousand rand to produce the first benchmark pattern from an LS die made of alumide or polyamide. It is expensive, but compared to conventional tooling for the production of only one or a few patterns it is a fully acceptable price. The dies were grown with a 5 mm wall thickness; if the dies were grown solid the cost would have been more than double for each of them. The higher cost of the alumide die is not justified when accuracy and surface finish are taken into account. However, the better tool life might justify the higher cost depending on the number of patterns required.

Suppliers can produce and deliver a die in roughly a week. The reinforcement of the die and injection will take a further two or three days before delivery of the first pattern. Producing more patterns from each die will drastically cut the cost per pattern. It can be concluded that direct die fabrication is a feasible approach for small production runs, especially for components with a complex geometry.

7. ACKNOWLEDGEMENTS

AMTS Economic support
CSIR Collaborations
CUT Collaborations
TUT Collaborations
CastCo Cooperation and continuous efforts

8. REFERENCES

[1] Levy G.N., Schindel R., Kruth J.P. (2003) Rapid Manufacturing and Rapid Tooling with Layer Manufacturing technologies, State of the Art and Future Perspectives. *Annals of the CIRP*, Vol. 52, No. 2, pp. 1-21

[2] AMTS - Project Consortium. (2006) Investment Casting Capabilities for Light Metal Alloys. Project Plan, Automotive and Aerospace Industry Sectors, CSIR, South Africa

[3] Cheah, C.M., Chua, C.K., Lee, C.W., Feng, C., Totong, K. (2005) Rapid prototyping and tooling techniques: a review of applications for rapid investment casting. *The International Journal of Advanced Manufacturing Technology,* Vol. 25, No. 1-2, pp. 308320

[4] Wohlers, T. (2007) *Wohlers Report, Rapid Prototyping, Tooling & Manufacturing, State of the Industry*, Annual Worldwide Progress Report, Fort Collins, Colorado

[5] *Different Print Processes*, Castle Islands world wide guide to rapid prototyping, URL: http://home.att.net/~castleisland/, Accessed 12 Aug 2006

[6] EOS Website, URL: http://www.eos.info/products.html?L=1, Accessed 5 December 2007

[7] Dimitrov, D., Schreve K., De Beer, N., Christiane P.J. (2008) Three Dimensional Printing In South African Industrial Environment. *SA Journal of Industrial Engineering*, Vol. 19, No. 1

[8] Stratasys Website, URL: http://intl.stratasys.com/default.aspx. Accessed 5 December 2007

[9] Blake P., Fodran E., Koch M., Menon U., Priedeman B., Sharp S. (1997) *FDM of ABS patterns for investment casting.* Proc Solid Freeform Fabrication Symposium, Austin, TX, 1113 August, pp. 195202

[10] POM Group Website, URL:http://www.pomgroup.com/tool_reconfiguration1.asp. Accessed 14 September 2007

[11] Electron Beam Melting, URL:http://en.wikipedia.org/wiki/Electron_Beam_Melting. Accessed 14 September 2007

[12] ARCAM Website, URL: http://www.arcam.se/technology/index.asp. Accessed 14 September 2007

[13] Euro Tooling 21, IP Project, *Sixth Framework programme (FP6)*, European Commission, 2003

[14] Booysen, G. (2007) Researcher, Central University of Technology, Free State, January 2008, Personal Conversation

[15] Rossouw, P. (2007) Senior Researcher, Metals and Metals Processes, CSIR Materials Science and Manufacturing, December 2007, Personal Conversation