COMBINING ADDITIVE FABRICATION AND CONVENTIONAL MACHINING TECHNOLOGIES TO DEVELOP A HYBRID TOOLING APPROACH

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ABSTRACT

South Africa is constantly loosing contracts for the manufacturing of innovative projects to the East, due to its non-competitive mould-making industry. The paper will report on progress made in a specific focus area in mould-making, namely Hybrid Moulds for injection moulding. Hybrid Moulds refers to a hybrid between Additive Fabrication and conventional methods through the use of amongst others, Direct Metal Laser Sintering techniques, combined with conventional CNC machining (High Speed) techniques. Although the emphasis is on an economically viable process for limited production runs, once the moulds have been developed, it normally is pushed to its limits to realize production quantities. One of the competitive edges is the cutting of lead-times, which obviously impacts on production costs. Another aspect is the ability to manufacture short runs of injection moulded parts in the required engineering material Realising that Laser Sintering of metals is an expensive manufacturing process, a concurrent manufacturing process was developed. Intricate mould details, which normally are time-consuming to manufacture through EDM processes, were grown as inserts, while the less-complex parts of the mould is machined in Aluminium through 3 and 5 Axis High Speed CNC Machining. Using a 3-axis CNC wire cutter, pockets will be created where the more complex Laser Sintered Metal inserts will be fitted. One of the competitive edges is the cutting of lead-times, which obviously impacts on production costs. Another aspect is the ability to manufacture short runs of injection moulded parts in the required engineering material.

Keywords: Direct Metal Sintering, Conventional CNC machining, Injection Moulding

1. INTRODUCTION

In supporting potential customers to bring new products to the market, they must be assisted to convert their idea, concept product or final design into a physical model at a desirable price, without sacrificing quality. Various Rapid Prototyping (RP) systems make it possible to produce prototype models quickly, but these prototypes are still not produced in the end-use material which will be used during the final production process. Product developers require prototypes in the end material as verification prior to commencing production. Next, the innovator or company has to make the crucial decision to go to the final step of production tooling, trust that the decision was correct and that the product can justify the expenses.

The major expenses associated with new product development, is usually a function of tool making, which in turn is a function of the time taken (by highly skilled artisans) to produce the tooling. Producing injection moulding tools can be slow and expensive due to the intensive labour required when using conventional tooling methods. The number of skilled toolmakers in South Africa is declining; the time-to-market of products is shorter and part complexity is increasing.

It is clear that any process that can provide a faster mould production method and can cut back on labour time, whilst simultaneously producing models in the end-use material, will be beneficial. The risk involved in new product development, associated with conventional tooling, is in many cases no longer an issue, as Rapid Tooling (RT) has developed into a capable technology giving the option of an intermediate (bridge tooling) or even a final tool (dependent on the number of products (injection shots) needed to be manufactured in the moulds). However, RT has to be available at an affordable price - otherwise it will not serve the purpose.

Conclusions made from experimental results proved that in order to find the most economic and appropriate manufacturing solution, it is sometimes necessary to combine conventional mould making techniques with RT techniques to develop so-called "hybrid" moulds. "Hybrid" moulds refers to moulds of which certain parts of the tooling is grown using Direct Metal Laser-Sintering (DMLS), and inserted into/onto parts machined with conventional techniques. This approach will be determined by the tool-geometry [1].

2. EXPLAINING THE PROCESSES

2.1 Direct Metal Laser Sintering

The Direct Metal Laser-Sintering (DMLS) process on EOSINT M systems is suitable to manufacture moulds and tool inserts, using the Direct Tool process, and functional prototypes, using the Direct Part process. Powdered metal with a grain size of less than 20 microns are sintered together by a high power laser. No infiltration or secondary post processing is required after the growing process as the models are fully dense. The Direct Metal 20 and Direct Steel 20 materials were developed and optimised especially for the DMLS process. Fig. 1 explains the working principle of the DMLS process.

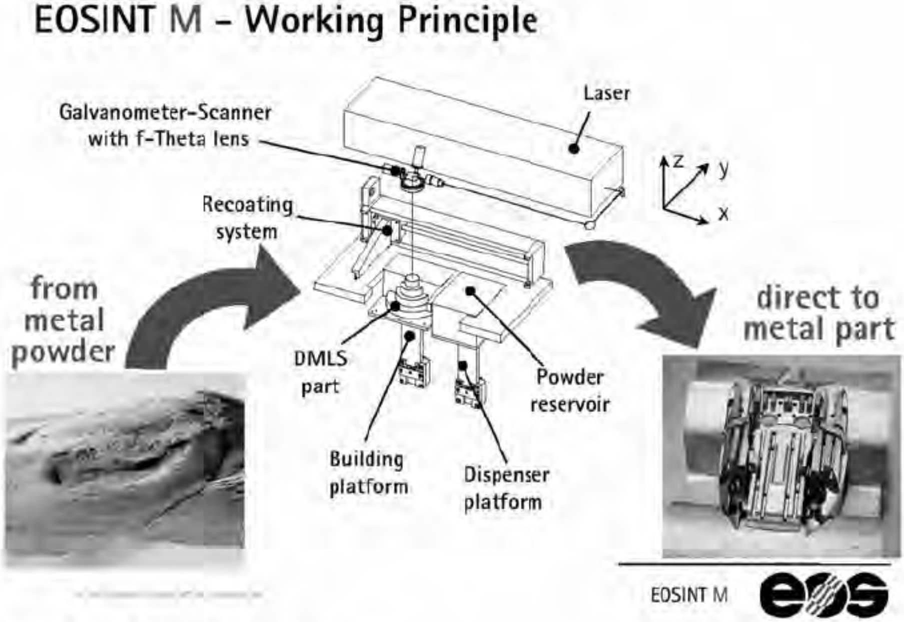

Fig. 1. DMLS working principle

EOS introduced the EOS M250 as the first metal sintering system. At that stage the system used a CO2 laser to sinter Direct Steel 20 and Direct Metal 20 material. With newer laser technology available, EOS developed the M270 machine which processes newer materials with a solid state laser. Table 1 explains the difference between the EOS M250 and M270 machine. Table 2 shows the commercially available that can be processed using DMLS technology.

EOSINT M 250 Xtended	EOSINT M 270
	
□ all-round system for Direct Metal and Direct Steel materials	□ top-end system for all DMLS materials in best quality
□ build volume 250 • 250 • 200 mm (including thickness of building platform)	□ build volume 250 • 250 • 215 mm (including thickness of building platform)
□ CO2 laser, 200 Watt	□ solid state laser, 200 Watt □ dual focus

Table 1. Difference between EOSINT M250 and EOSINT M270 [4]

Material Name	Material Type	Typical Applications
Direct Metal 20	Bronze-based mixture	Injection moulding tooling; functional prototypes
Direct Steel 20	Steel-based mixture	Injection moulding tooling; functional prototypes
Direct Steel H20	Steel-based mixture	Injection moulding tooling; functional prototypes
EOS Stainless Steel 17- 4	Stainless steel 17-4 PH / 1.4542	Functional prototypes and series parts; engineering and medical
EOS Cobalt Chrome MP1	CoCrMo super alloy	Functional prototypes and series parts; engineering, medical and dental
EOS Titanium Ti64	Ti6Al4V light alloy	Functional prototypes and series parts; aerospace, motor sport etc.
EOS Titanium CP	Pure titanium	Functional prototypes and series parts; medical and dental

Table 2. Commercially available DMLS materials [3]

Direct Metal 20, Direct Steel 20 and Titanium Ti64 are available at the Centre for Rapid Prototyping & Manufacturing (CRPM).

2.2 Conventional Tooling

Injection moulds are made conventionally by various processes such as EDM (Electric Discharge Machining), CNC milling and wire cutting, as well as combinations of these processes. However, constructing a mould using these processes can be a time/labour intensive exercise. As shown in Fig. 2, steel cavities appear to be more expensive than those made in other materials. In spite of this, steel cavities are normally the preferred option, due to the longer service life of the mould.

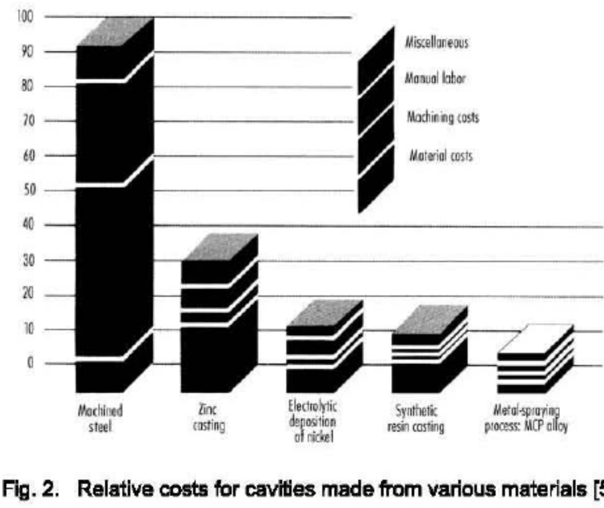

Fig. 2. Relative costs for cavities made from various materials [5]

In order for the tool-making industry to keep up with the shorter time-to-market of new products, it is clear that only up-to-date equipment, such as CNC controlled wire cutters and five axes CNC controlled milling machines, are used in modern tool rooms. In spite of this equipment, some new products need an even faster turnaround time and conventional tooling cannot fulfil this expectation.

2.3 Comparison of CNC lead-times to RP

The total lead-time from data receipt to part delivery can be divided into three stages, namely pre-processing, construction time and post-processing. When evaluating RP within these parameters, it is found that most of the process is performed with no supervision, which means that RP is not labour intensive. Only pre-processing and post-processing needs human intervention. Therefore, RP systems can produce prototypes for 24 hours of the day and throughout weekends, which gives RP a tremendous advantage, when compared to CNC operations that require staffing as seen from the Table 3.

Theoretically, RP systems could produce prototypes:	Realistically, RP systems could produce prototypes:	Three axis CNC systems working a three-shift operation:
8760 hours a year	7000 hours per year	6025 hours (excluding weekends and holidays)

Table 3. Utilisation of machine hours per year for a RP system compared to a CNC system [6]

3. RESEARCH AIMS

The research aims were firstly to evaluate the effectiveness of "hybrid" tooling in injection moulding of plastic articles and secondly to identify which parts of the tooling can be grown, and inserted into/onto parts machined with conventional techniques to minimise the cost of tooling for injection moulding.

4. CASE STUDIES

4.1 Case study 1: Spear gun handles

A customer approached our product development centre (CRPM) to assist in the manufacturing of 1000 spear gun handles. The previous quotes that the customer received were too expensive and the product could not be manufactured using conventional methods. It was decided to use the "Hybrid" approach, in which conventional machining was combined with the DMLS process. The core and cavity inserts were machined in Aluminium, but the sliding core parts, used to make the hollow features, were grown in Direct Metal 20 material. Fig. 3 to 8 show the tool design, manufacturing and optimising designs

Fig. 3. Injection moulded part

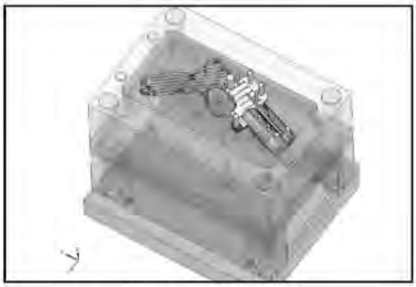

Fig. 4. Tool design

Fig. 5. Grown inserts in Direct Metal 20

Fig. 6. Aluminium machined inserts

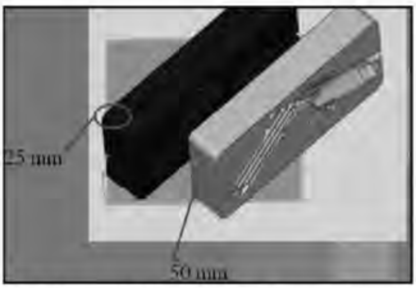

Fig. 7. Optimised design to reduce growing volume

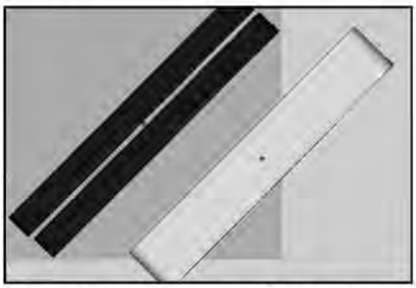

Fig. 8. Part placement on M250 platform

It was decided to optimise the design to determine whether it will improve the cost to produce the two cavities at a reduced height of 25 mm. The height of the original insert design was 50 mm and had too much extra material at the back of the insert. To produce the inserts using conventional CNC or DMLS process, a minimum of 8 mm is required as extra material from the deepest part of the cavity to the back part of the insert. Table 4, 5 and 6 shows the different calculation options and from the data it is clear that the DMLS process, using the 0.02 or 0.06 mm layer thickness option, is not suited for prototypes of this size geometry. It was decided to CNC machine the two cavities with 50 mm thickness as an available bolster to be used had the 50 mm pockets already machined into it and there was no significant difference in the cost.

	Aluminium machined inserts with 50 mm thickness	Aluminium machined inserts with reduced 22 mm thickness
Material cost	€ 180	€ 80
Machining time	58 hrs	57 hrs
Machining cost	€ 1160	€ 1140
Total cost	€ 1340	€ 1220

Table 4. Cost to CNC machine two Aluminium cavities of the design showed in Fig. 6

	DMLS inserts (0.02mm) with 50 mm thickness	**DMLS inserts (0.02mm) with reduced 22 mm thickness**
Material cost	€ 8155	€ 3352
Growing time	232 hrs	130 hrs
Growing cost	€ 7540	€ 4225
Total cost	€ 15695	€ 7577

Table 5. Cost to produce (0.02 mm layer thickness) two cavities of the design showed in Fig. 6 using the DMLS process

	DMLS inserts (0.06mm) with 50 mm thickness	**DMLS inserts (0.06mm) with reduced 22 mm thickness**
Material cost	€ 6779	€ 3024
Growing time	117 hrs	59 hrs
Growing cost	€ 3803	€ 1918
Total cost	€ 10582	€ 4942

Table 6. Cost to produce (0.06 mm layer thickness) two cavities of the design showed in Fig. 6 using the DMLS process

DMLS cores (0.02mm)
Material cost = € 84
Growing time = 9 hrs
Growing cost = € 281
Total cost = € 365

Table 7. Cost to produce three cores using the DMLS process

The mould was assembled and the first 250 handles were produced in glass filled nylon for client approval. Another two cavities were machined in Aluminium without any cores needed to produce the blue rubber over mould grip (showed in Fig. 3). The order of a thousand moulds was completed and the client could use these parts to source more funding to make production tools.

4.2 Case study 2: The secure airway clamp project

A local anaesthetist made an enquiry to develop a device that could secure the ET (Endo-tracheal) tube better than conventional methods. When a patient is intubated during anaesthesia it is very important that the ET tube remains in the correct place. If the tube deviates from the correct position it can cause one or both lungs to collapse which can be fatal. The idea behind the product was to design and manufacture a product that holds an ET tube in place in a more secure manner than the current normal plaster. This project has a worldwide patent registered. The secure airway clamp is a two-component part with an inner hard nylon part which ensures the stability of the product, and with a soft 60 Shore A rubber that is over- moulded on the nylon part to ensure that the mouthpiece does not hurt the patient's mouth

It was decided to CNC machine the cavities (as shown in Fig. 10) to produce the inner part in Aluminium because of its simple geometry. The cavities were machined in two days. The over mould cavities (as shown in Fig. 11) were grown on the DMLS process (0.02 mm layers) in 53 hours at a cost of € 2646. The conventional price for the tooling to produce the two component Secure Airway clamp is approximately € 10 000 and will take 6-8 weeks to manufacture.

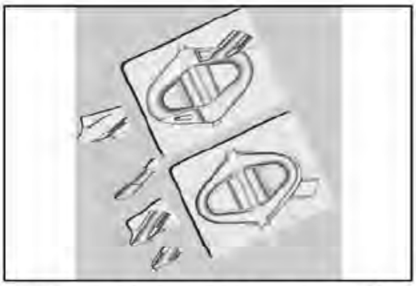

Fig.9. Design of inserts to be grown in Direct Metal 20 material using the DMLS process

Fig.10. Cavities were machined but the small bronze insert was grown and fitted inside the mould.

Fig.11. Grown inserts in Direct Metal 20 material using the DMLS process

A dual advantage is achieved by this "Hybrid" approach, as time to market is significantly shortened and as a result of the money saved, it is possible to identify and correct design mistakes without considerable financial losses.

4.3 Case study 3 - The flag holder project

The CRPM assisted a start up company to develop a flag holder device (seen in Fig. 12 and 13) to attach a supporter's flag to a car. The flag holder consists of a top, bottom cover, internal lock part, gasket and a vacuum suction cup.

Fig. 12. Flag holder design

Fig. 13. Enlarged view of the design

After the design was completed it was decided to manufacture a nylon prototype, as shown in Fig. 14, using the Laser Sintering process and PA2200 polyamide material. The rubber suction cup and gasket was vacuum cast to simulate the 60 Shore A material. This prototype was tested at 120 km/h with a one by two meter flag.


Fig. 14. Rapid prototype fitted onto a car

After approval by the client, designs were made of all the cores and cavities to manufacture the different components using the injection moulding process. The top, bottom cover and internal lock part was to be made in glass filled nylon and the gasket and a vacuum suction cup out of 60 Shore A rubber. The cavities for the internal lock, gasket and suction cup were machined in Aluminium due to its simple geometry. It took approximately 10 days to machine the cavities.

The cores (as shown in Fig. 15, 16 and 17) of the top and bottom covers were grown in DMLS (0.02mm layers) in Direct Metal 20 material. Part of the core design was a conformal cooling design. The cooling design was very intricate and close to the surface and the only way to construct the cooling lines was by using DMLS process. The two core inserts were grown in 60 hours at a cost of € 2791.

Fig. 15. Design of bottom cover core

Fig 16. Design of top cover core with conformal cooling lines

The two cavities (as seen in Fig. 18) were machined in Aluminium at UV Tooling (Cape Town). This injection moulding firm also did the assembly of the two cores and two cavities and performed the trial runs. UV Tooling was very impressed by the quality especially on the shut off areas as it was not necessary to trim the injection moulded parts.

Fig. 15. Design of bottom cover core

Fig 16. Design of top cover core with conformal cooling lines

4.4 Case study 4: The SIMpill project

The SIMpill® Medication Adherence System is aimed at monitoring the patient's medication schedule and intake of medication. This system reminds patients and caregivers, as necessary, by sending a text message to the patient's and/or caregiver's mobile phone if the patient does not take their medication as prescribed. All monitoring and reminders happen in real-time. Fig. 19 shows the design of the SIMpill device and the middle part with the compartments needed to be injection moulded. Fig. 20 shows the completed product and the white part was injection moulded by using the Rapid Tooling approach.

Fig 19. Design of SIMpill product

Fig. 20. Injection moulded part

The client needed 250 injection moulded parts within two weeks when he approached us. The part was produced with rapid prototyping. The client however needed a medical grade ABS part for the pills to be stored in. After design approval the inserts design were made by a local injection moulding firm. It was decided to use a bolster that was already used for another project as the time frame was very short. The core and cavity was grown in Direct Metal 20 on a metal base using the DMLS process, as seen in Fig. 21. The inserts were machined/fitted inside the bolster within approximately seven days including the polishing of the inserts as shown in Fig. 22. The production of the first 150 parts took one day to complete. The client was satisfied with the quality and fitment of the products.

Fig. 21. Grown core and cavity using DMLS process

Fig. 22. Polished core with ejector pins fitted

The significance of this project was that it took 12 days from design to final parts. Compared to the six weeks quoted (as seen in Table 7) to manufacture these inserts conventionally there is a huge saving in time which means faster time to market.

	DMLS Produced inserts	Conventional Produced Inserts
Cost to produce inserts	**€ 1800**	**€7500 (quoted)**
Fitment of inserts	**€ 1500**	**Included in quoted price**
Time to produce + fitment	**12 days**	**6 weeks (quoted)**

Table 7. Cost and time comparison

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5. CONCLUSIONS

Larger, less complex inserts are better suited to be manufactured by normal CNC milling. To attain fine features inside a complex insert, like thread or fine writing, the EDM process was conventionally required. However, the disadvantage of EDM is that it is a time-consuming process and such inserts will save time and money when grown with the DMLS process. Each injection moulding tool must be evaluated to determine whether it has large areas that can be CNC-machined or fine thread or detail that can be grown directly with the DMLS process.

The following conclusions can be drawn from these case studies:

- In Case study 1 the production of the conventional tooling inserts was faster than the DMLS produced inserts, but growing the cores using the DMLS process was more cost effective.
- The DMLS process is better suited to smaller inserts with more detail and that requires extensive EDM work.
- The parts must be grown in the correct axis, to achieve a better surface finish and better accuracy, and to ensure good shut-offs on the sliding cores. Critical surfaces and holes need to be orientated in the direction (parallel) of the laser to minimise the stair-stepping effect through that surface
- On the design files extra stock can be placed on critical surfaces which can then be cleaned off by CNC milling.
- A combination between the conventional and additive fabrication process can be more suitable for some projects but other projects may only require one of these processes. Deciding between the processes will be lead by the geometry of the insert to be produced.

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