# Some recent developments and experiences with Rapid Manufacturing by indirect means

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## Abstract

*Rapid Manufacturing is defined as the use of a Computer Aided Design (CAD) based automated additive manufacturing process to construct parts that are used directly as finished products and components. While material and cost constraints still remain as the main limitations, some of the rapid prototyping technologies have overcome these shortcomings, and gradually progressed towards making rapid manufacturing a reality. Alternatively, rapid manufacturing was also made possible by the use of one of the additive manufacturing processes in expediting certain stages of some traditional processing methods. While literature presents ample examples of successful implementation of both methods, the present paper focuses on the indirect means of achieving rapid manufacturing. A critical review of some of the latest developments will be presented, followed by an evaluation of some of the recent experimental investigations carried out as part of the research activities at the Centre for Rapid Product Development, AUT University, Auckland, New Zealand.*

***Keywords***: *Rapid prototyping, manufacturing and casting, cost and quality considerations*

## 1 Introduction

Rapid prototyping processes have gone through many stages of development, involving improvement of constituent materials and their characteristics as well as invention of new processes. The very basic approach of being able to produce 3D shapes directly from CAD files allowed researchers to initiate novel methods of extending the application of these techniques in different other processes. The overall aim was to develop methods and means for the rapid manufacturing of products allowing the production of end use parts directly from CAD files, without the use of any complex tooling. While Selective Laser Sintering (SLS) scores the best in terms of producing functional parts directly from a wide variety of materials including polymers, and metals such as steel, aluminium and titanium. There were initial concerns regarding the part density and porosity, considering the point-by point processing, however, the recent machines are reported to be able to achieve much better results.

These new manufacturing techniques thus provide a means of being able to produce rapidly, and will also allow rapid changes in design or product variety. All these aspect being of paramount importance considering the competitive nature of current global markets, there has been a considerable amount of importance given to these new and relatively recent developments.

There are however, more indirect influences of these developments on a variety of other activities such as rapid production of tooling for some of the traditional processes. Being termed as the rapid tooling, these approaches pave way for the elimination of the time consuming stages of building production tooling. While replacement of wax patterns by the prototyped polymer patterns for investment casting [1-4] was one of the early developments, direct production of sand moulds either by SLS or 3D printing [ 5-8 ] and construction of EDM tools by electroplating RP patterns [17-21] were some of the examples of these approaches. This paper reviews current status of some of these indirect approaches towards rapid manufacturing and also talks about some experiences of the authors while investigating in these lines as part of the research activity at the Centre for Rapid Product Development of AUT University, Auckland, New Zealand.

## 2 Pattern making through RP

The pattern making process was one of the first to be influenced by the RP technologies, since their inception in the late 80s, in terms of either replacing wax patterns by polymer prototypes or layered manufacturing of reusable patterns. Layered Object Manufacturing (LOM) allows fabrication of complex patterns from CAD files, by adding a special paper layer over layer and laser cutting of each layer to confirm to the shape of the section. Majority of RP applications in casting however were in the use of RP patterns for investment casting, targeting the elimination of human skills and reduction in time and production costs.

Stereo lithography was used to produce sacrificial patterns for the investment casting process [1] and the cast products were reported to have good surface finishes. Further extension of the technique using other RP processes like SLS and Fused Deposition Modelling (FDM) was attempted by Pham and Dimov [2]. There were issues however with the burning out and removal of the RP pattern and the consequent cracking of shell moulds. Dickens et al [3] took this lead and investigated the pattern and casting qualities while using RP prototypes made of LOM, SLA and FDM. While significant time reductions were reported, the dimensional quality seemed to be inadequate and there was the question of whether the time savings could really offset the cost savings, considering the additional initial investments.

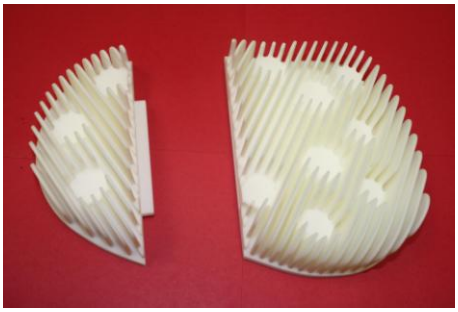
A benchmark model consisting of common shapes and profiles was created to assess the effectiveness of the FDM process for indirect IC mould production with sacrificial RP patterns [4] and found that the thermal expansion problems associated with earlier materials were eliminated. There were issues however, of the ABS polymer chemically reacting with the ceramic mould wall surface due to corrosive degradation during the burnout process that could be overcome by printing hollow patterns. Thermo gravimetric analysis results show the residual ash content as 2.218% for the FDM patterns, as against 0.04 % for the traditional foundry wax patterns. Surface roughness analysis of aluminium castings produced both from IC moulds produced using ABS patterns and indirectly through silicon rubber moulds averaged at around 5 µm. While dimensional accuracy was acceptable, production costs were halved and overall, hard tooling was eliminated with the use of RP patterns, leading to significant time savings.

Overall, the use of RP parts as sacrificial patterns for investment casting was successful, considering the time savings achieved, without sacrificing on the quality. There are other approaches in which RP can be effectively used in reducing the time for casting. One of the methods the authors tired was to produce entire patterns for complex parts to be used for the production of sand and ceramic moulds. While LOM is a process that was basically intended for use in the pattern making for sand casting, there are limitations of this to be used as a general purpose machine. This would mean a lot of investment on a machine that can only be used for one type of applications. A better alternative then is to try and use other RP processes for making large patterns, for use in the sand casting process. While SLA, SLS and FDM are candidate processes with capabilities to produce patterns in a variety of plastics, FDM is selected in the current study, as the machine is readily available for the research.

FDM produces solid 3D parts making use of a filament form of ABS polymer. While the mechanical characteristics of the printed parts are inferior relative to the actual ABS polymer parts produced through traditional injection moulding processes, the final performance characteristics of the parts would also depend on whether processed in solid or sparse options and the part shape. The following are some of the problems anticipated while using FDM parts as sand casting patterns:

- Dimensional instability
- Possible distortion during the filling up of sand around patterns due to the relatively lower strength of parts
- Thin sections getting distorted and displaced
- Distortion of moulds and patterns while withdrawing
- Easy wear and tare and short life of patterns

A typical industrial product requiring a single solid pattern and at the same time having complex detail was required to be selected for the purpose of assessing the validity of the approach. At the same time, there was a need to produce a cylinder head for an old motor cycle engine, as part of a student project, and the opportunity was used to investigate the usefulness of the FDM patterns for the production of sand moulds and subsequent casting of the part with complex fin structure using a casting grade aluminium alloy. The overall size of the pattern being larger than the maximum allowable size on the FDM machine currently available for use at AUT, it was split and printed in two parts as shown in figure 1, with a boss and a corresponding recess created for easy assembly at the end.



*(a) ABS pattern printed in two parts*

*(b) Pattern assembled and ready to use*

**Figure 1**: The ABS pattern

The pattern was then used to produce the aluminium casting as shown in figure 2, at one of the local foundries. Some preliminary dimensional and surface quality analyses conducted are suggestive that the overall quality is within the normal limits and the pattern is sufficiently strong and easily withstood the process conditions and has a promising life for quite a few more castings. Considering again a preliminary cost analysis, the pattern making process involved materials worth almost NZ $ 800. While this is a major expense, a complex and critical part of an outdated machine could be produced within three days, without any inventory or supply chain support system. Though the material cost of the pattern is still a big concern, it could be argued that the labour and time required to make the same pattern using traditional mehods would have been far in excess of that occurred in this project. As research in alternative materials progresses, and the technologies become more widely used, cheaper alternatives will become available and rapid manufacturing by indirect means becomes more and more of a practicval solution in specific manufacturing systuations.

**Figure 2**: Engine head cast using aluminium

There were some issues in terms of the strength of the pattern while withdrawing from the sand mould, and an additional bottom board was necessary to be placed at the flat bottom for easy withdrawal. However, the thin fins did not pose any serious problems such as bending or breaking apart and the mould prepared was crisp and conforming to the shape. A detailed dimensional analysis and tolerance aspects of pattern and the final casting are yet to be undertaken, but the results of these preliminary investigations are promising and dimensional variation if any from the solid model to the pattern and then to the actual casting is believed to be easy to control by considering appropriate compensation procedures.

## 3 SLS and 3D printing for sand casting

A more direct method of applying the developments in RP to save tooling time in casting is to directly produce sand moulds from CAD files. Early attempts in this direction were centred around the application of SLS for printing 3D moulds from CAD files, by fusing either sand grains directly or polymer coated sand grains. The castings produced from these moulds were found to be accurate and repeatable but the surface roughness seemed to be adversely affected due to the stair-step effects resulting from the slicing and layered processing [1, 2]. Nevertheless, the moulds and cores produced by laser sintering Zircon sand and silica sand materials on an

SLS SandForm machine were found to be as good as those form traditional casting processes.

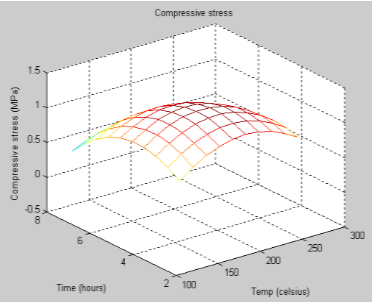
Gibbons [6] used an EOSint S700 SLS machine to produce moulds of the intake manifold of a KTM 525 cc single cylinder engine by sintering phenolic resin coated silica croning sand. The castings produced were reported to be adequate, with considerable amount of time savings, with the mould produced within 33 hours, as against several days required in the traditional route. While investigating the solidification mechanisms of sintered sand moulds, Tang et al [7] linked the bonding mechanism to the easy melting of boundary surfaces of sand particles due to the presence of inclusions such as $Al_2O_3$, that create a salt like eutectic. The compressive strength and surface roughness were found to be proportional to the laser power and inversely proportional to the scanning speed. Casalino et al [8] used Taguchi methods to investigate into the effects of various process parameters such as speed and laser power on principal mould material responses; permeability and compressive strength. The results indicated suitability of SLS moulds for casting both ferrous and nonferrous metals, exhibiting recommended permeability and strength values.

It is evident that SLS produces moulds suitable for casting all metals and provide means of getting quick castings without the need for any pattern and also with the obvious advantage of unlimited design freedom leading to the production of complex castings. However, the SLS machines are expensive and processing costs are also high. A feasible alternative is to use 3D printing for the production of sand moulds. While Zcorporation comes up with materials suitable for casting non-ferrous metals, currently there is no 3D printing material suitable for casting ferrous metals. It is however, a far cheaper solution for the rapid production of non-ferrous castings, and the current research in this direction is now reviewed, followed by a discussion on the experiences of the authors with rapid casting using 3D printing technology.

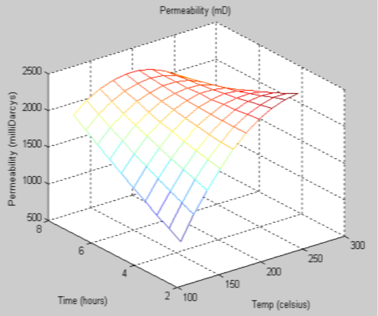
Initial research using 3D printing for producing ceramic shell moulds was found to be less time consuming, as the sacrificial pattern making stages were eliminated [5]. Kochan [9] while examining the effectiveness of various RP processes notes that 3D printing, though effective in producing pattern less moulds, would take more time as the printing process in itself being slow and there are further limitations on the maximum size of moulds that can be printed.

Direct production of sand moulds by 3D printing was found to be superior compared to the use of other RP techniques by Bak [10] in facilitating short run production. While geometrical tolerances and surface finishes were competitive, the breakeven point was achieved with fewer than 50 units. Thermal Distortion testing was used by Rebros et al [11] to evaluate changes resulting from thermo mechanical reactions in 3D printed moulds produced using a ProMetal printer. Mass loss and surface cracking were observed in printed moulds, due to uneven expansion and contraction of differentials in the sand composite, but these changes were also found to be present in the sand chemically bonded by the Phenolic-Urethane Cold Box Process. Dimitrov et al [12-14] in a series of publications evaluated the 3D printing process in comparison with other approaches such as investment casting using starch patterns and also by analysing the dimensional qualities of parts produced. Results showed suitable IT grades as well as acceptable surface roughness values for the cast parts.

While 3D printing appears to be a cheaper alternative to SLS in quickly producing pattern less moulds for use in the production of one of parts or small run jobs, there are several aspects that still require answers. Some work was done at the Centre for Rapid Product Development of AUT University investigating into the mould material as well as casting characteristics while using 3D printed moulds for casting both aluminium and magnesium. One of the early experimental investigations resulted in the following response surfaces as shown in figure 3 for the ZCAST 501 material for the post baking compressive strength and permeability variation. It may be readily observed, that experimental factors have definite effects on the responses, and there are optimum points for both sets of experiments. All these results are more elaborately discussed elsewhere [15].



*(a) Comp. strength vs baking parameters*



*(b) Permability vs baking parameters*

**Figure 3**: ZCAST 501: Moulding characteristics

ZCAST 501 is the material recommended by the ZCorporation to be used on their printers for producing sand moulds for casting non-ferrous metals and alloys. However, during these initial trials using different material options, it was found that the other material supplied by ZCorporation, ZP131, though meant to be used mainly for normal prototypes, works equally good for casting light metals and in fact, gives better results in terms of surface roughness and sharpness of parts produced, considering the relatively smaller grain size. In a subsequent experiment, the authors also investigated the moulding characteristics of this material also through a statistical design of experiment. Similar response surfaces are obtained in this case also. The response surface for the compressive strength suggests that the best response is attained while baking at a lower temperature for a long time. On the other hand, the best permeability was attained when both baking time and temperature were kept low. Possible reasons for these variations and the conditions for optimum properties are still under investigation, using SEM studies.

Further experimental work was conducted on the characteristics of castings produced using both mould materials. The optimum baking conditions were employed and further factors such as mould coatings and pouring temperatures were investigated while casting different light metal alloys. While the results of these experiments can not be presented and discussed here at length as they are currently under consideration for a journal publication, the overall results were encouraging. The combination of ZP131 and MAGCOAT as the mould coating was found to be working the best in terms of casting strengths, and other essential characteristics for both A356 and AZ91HP. More importantly, the ultimate tensile strength, surface roughness and percent elongation values obtained under optimum conditions were found to be either equal to or even better than those from traditional sand casting processes.

While this proves the suitability of 3D printed RP moulds for casting light metals with no major losses in the casting characteristics, there is however, the issue of not being able fill these moulds under pressure due to practical difficulties. The lower pressures resulting from gravity filling would lead to mis-runs and the limitations on the minimum thickness of constituent parts. The use of centrifugal casting process was thought to be a suitable approach for overcoming this limitation. However, the ability of the moulds to withstand the higher pressures, and the problems of mould erosion under the action of the more turbulent liquid metal were required to be investigated. Further experimental trials involving the use of centrifugal casting in 3D printed moulds proved to be successful, and the conditions for the best performance of 3D printed moulds in centrifugal casting were identified.

Overall, SLS seems to be the best option when non-ferrous metals are required to be rapidly cast into RP moulds. A cheaper alternative is 3D printing, but currently suitable only for light metals and alloys. Best mould material characteristics can be obtained by using optimum baking time and temperature, and the best combination of mould materials and coatings give rise to more favourable casting responses

## 4 Electroplated RP tools for EDM

Electrical Discharge Machining (EDM) is one of the most commonly used non-conventional machining methods and has unique characteristics in that it is basically a non-contact type thermal machining process and can be equally effective, irrespective of the hardness of the work material [16, 17]. The process is based on material removal through a series of electrical discharges between the electrode and the work piece [17]. The basic EDM system consists of a shaped electrode tool and the work piece connected to a DC power supply and placed in a dielectric fluid [18]. When the potential difference between the tool and the work piece is sufficiently high, a spark discharges through the fluid, removing a very small amount of material from both the tool and the work piece. The electrode tool and the work piece never actually make direct contact, thus eliminating mechanical stresses, chatter and vibration problems [16].

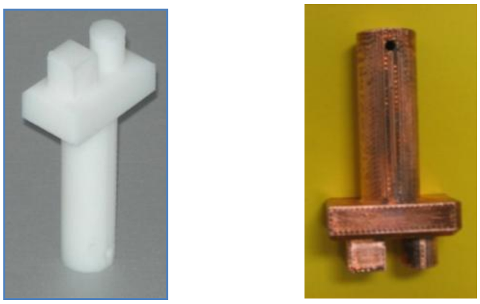
Injection moulding dies and tooling for other similar purposes are common examples where EDM finds its application. The other method of producing such tools is possible use of CNC systems involving 3 to 5 axes, however with certain limitations. While EDM is a probable solution where CNC machining fails, the production of the EDM tools still remains a challenge, and would again require multi-axis CNC machining, thus resulting in a kind of a circular argument. When the shapes are too complex to be achieved by direct machining, the whole process is usually broken into several stages, involving use of EDM tools of different shapes. All these aspects adversely affect the production time, with typical lead times for specific injection moulding dies varying between 4 and 12 weeks [19].

With the global competition driving manufacturing systems towards the least possible product lead times, there have been attempts in the direction of improving the processing of EDM electrodes with conductive materials. Samuel and Philip [20] attempted a powder metallurgy solution, by sintering tungsten in copper matrix for producing EDM tools. It was demonstrated that it was possible to combine desired properties of different materials by altering physical properties through compacting pressure and sintering temperature.

Several attempts have also been made attempting to use one or the other of the RP processes either directly or indirectly in the processing of EDM tools. Electroforming is one of the techniques mostly attempted, which involves developing a thin conductive coating over a non-conductive part by electroplating. A fine layer of conductive paint is used first either by brush or by spray painting followed by a thick coating of copper by electroplating. Allan et al [19] produced thin walled copper electroforms backed-up with low melting fillers and successfully used them as EDM electrodes. The basic form of the electrode was produced by printing SLA parts from CAD models. While the experimental investigations proved the possibility to use filled thin walled electroforms as EDM electrodes, the depth of erosion achieved was reported to be related to the wall thickness of the leading faces adjacent to the primary sparking corners and edges of the electrode. A minimum face thickness of 0.6 mm was found to achieve an erosion depth of more than 6 mm. Narrow internal cavities were not plated to the critical thickness within reasonable timescales and the low current densities employed.

EDM Tools were produced both by copper coating STL models and by copper coating of direct metal laser sintered bronze models [21]. The amount of copper deposited on both electrode models proved problematic as the electroplating process was unable to deposit enough copper in the inner cavities of the electrodes, with very gradual reduction in copper layer thickness from the outer faces or surface to virtually no deposition in the inner walls and bottom face. Consequently, the electrodes were considered unsuitable for the envisaged EDM process, but this appeared to be jumping to a quick conclusion, while methods of improving electroplated copper thickness could have been attempted.

Electrodes printed in ABS using the FDM process were electroplated and used as EDM tools for machining a steel specimen as part of the research at AUT on the indirect means of achieving rapid manufacturing. The printed ABS electrode and the copper coated electrode are shown in figure 4 Typical thicknesses used for the coatings range from 100-700 µm.



*(a) ABS form* *(b) After electroplating*

**Figure 4**: EDM Electrode

The coated electrodes are tested by machining a hardened steel piece on the EDM machine available in the workshop of AUT University. The total depth of machined hole up to the point of failure is the main response measured in each case, in order to establish the effectiveness of the process. Around ten tools with varying thickness of copper coating are used. While the life of a tool seems to have a direct bearing on the coating thickness, the failure modes of tools are quite similar in all the cases. While tools with low shell thickness failed quickly, the life of tools has increased with coating thickness

The total depth of cut before failure of the tool is measured in each case and there is almost a linear relationship between the coating thickness and the depth of cut as shown in figure 5, for most part of the range of coating thicknesses used. The depth of cut increases with increasing shell thickness, but all tools finally failed at spots where the shell thickness was the minimum. This was attributed to an inherent weakness of the electroplating process, and subsequent experimental work involving agitated electrolytic bath and shaped electrodes were found to improve the coating thickness.

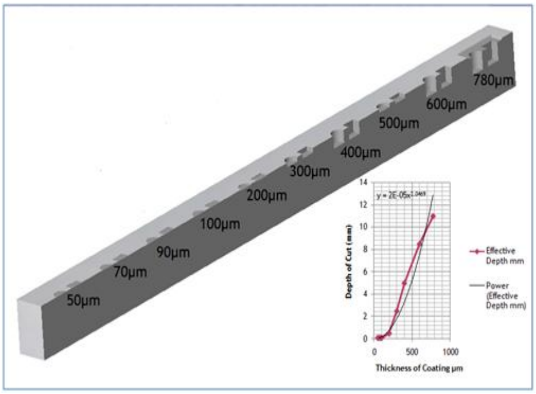


**Figure 5**: Depth of cut vs coating thickness

## 5 Conclusions

It is understood, rapid manufacturing is possible through the use of RP indirectly in some traditional processes. Experiences at AUT with pattern and mould making using FDM and 3D printing gave promising results in terms of time saved. Rapid production of EDM tools by electroplating FDM parts was also successful, but critical areas need improved electroplating methods for achieving a more uniform coating.

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