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Development of Complex Patterns: Scope and Benefits of Rapid Prototyping in Foundries

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***Abstract*— The quality through frugal engineering concepts has gained prime importance to the foundries around the world. Although simulation packages have been used as a tool to achieve quality and productivity, the use of Rapid Prototyping (RP) is not yet fully practiced in foundries in this concern. This paper provides a detailed study of the fabrication of a complex master pattern (impeller casting) using rapid prototyping technique besides presenting its scope and benefits compared to the current practices. The main objective of this work is to enlighten the foundry engineers to make use of rapid prototyping technology (fused deposition modeling) to eliminate the material wastage in pattern production, reduce the cost and lead-time in the production of accurate complex castings of an acceptable surface quality.**

Index Terms—**Complex Pattern, Rapid Prototyping, Fused Deposition Modeling, Sand Casting.**

I. INTRODUCTION

The competitive market has always given a prime importance to minimize the production cost, lead time and deliver good quality products at an affordable price. Casting is generally justifiable only when it is produced in large volumes due to the high cost of tooling for pattern/die making. Rapid Prototyping (RP) has been introduced to the industries to facilitate reverse engineering and to produce castings even when the order quantity is as low as unity. RP has simplified pattern making which was hitherto a skilled job and depended on artisans. Over the years, there have been many developments in RP technologies to favor casting process [1,2].Patterns made from Laminated Object Manufacturing (LOM), Fused Deposition Modeling (FDM) and Selective Laser Sintering (SLS) are strong enough to replace the traditional wooden patterns [3]. Recently, SLS processing is used to manufacture silica sand patterns which may be used as sand cores too [4]. Today, foundry engineers are much aware of the benefits of using computer aided design and simulation packages to evaluate defects and ensure the quality and productivity. However, the removal of defects generated from master patterns such as dimensional inaccuracy, surface quality, parting line mismatches etc. have remained as a few challenges to metal casting industries. Design and fabrication of master pattern is an important pre-casting activity in casting process planning. Though there are several advantages of using RP in the production of master patterns, the use of RP is not yet fully practiced in foundries. Hence, the main objective of this work is to enlighten the foundry engineers to make use of RP technology (fused deposition modeling) to eliminate the material wastage in pattern production, reduce the cost and lead-time in the production of accurate complex castings of an acceptable surface quality. In this concern, the discussion is made on the development of impeller casting using aluminum alloy, both by conventional as well as RP processing route.

II. DESIGN AND FABRICATION OF COMPLEX MASTER PATTERNS

The cost of any casting increases in direct proportion to the preciseness of its dimensional tolerance requirements and also the surface finish. Approximate values of surface roughness (generally specified by ISO number, N1 to N12) and tolerance on dimensions typically obtained with different manufacturing processes is shown in Figure 1. Casting process, especially the investment casting process is one of the near-net shape manufacturing processes, designed to minimize the cost of producing close tolerance parts. Maintaining close dimensional tolerance in a casting is affected by many factors. Most of these factors can be controlled in the foundry, although minor variations can occur among each batch of productions due to uncontrollable factors.

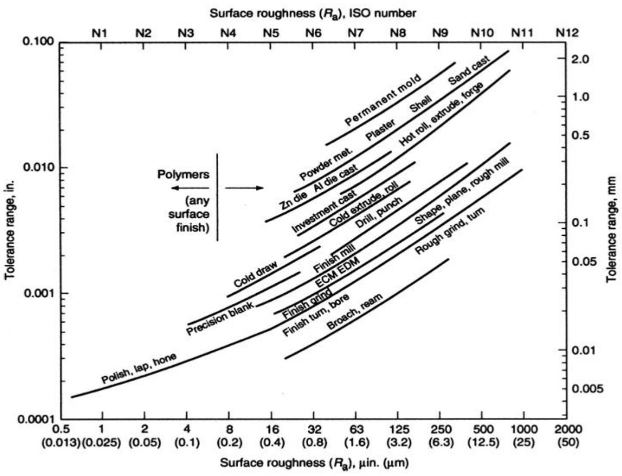

Fig.1 Approximate values of surface roughness and tolerance on dimensions typically obtained with different manufacturing processes [5].

The consistency of casting dimensions depends on the casting process used and the degree of process control achieved in the foundry. The system of dimensional tolerances which is applicable to the dimensions of cast metals and their alloys produced by sand molding, gravity die casting, low pressure die casting, high pressure die casting and investment casting is well documented in the

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international standard ISO 8062–1994. The equivalent British Standard BS6615:1996 and German Standards DIN 1680/DIN1688 can also be referred for more details. The tolerance capability of the value added castings is controlled by six main parameters [6]. These parameters according to their preference are as follows:

1. Molding process.
2. Casting weight and longest dimension.
3. Mould degrees of freedom.
4. Draft on mold, patterns and cores
5. Patternmaker's contraction.
6. Cleaning and heat treating.

Based on the casting processes, the engineer should take care of additional parameters too. For example, in the case of investment casting process, the factors that affect casting tolerance are: (i) wax or plastic temperature (ii) firing temperature (iii) die temperature (iv) shell composition (v) pressure of injection (vi) rate of cooling. The dimensional or shape variations caused by these factors can be addressed by [7]:

- Linear tolerance which is normally applied to the features such as length, concentricity, fillet radii, holes, flatness, straightness, corner radii, and curved holes.
- Geometric tolerance which is normally applied to the features such as profiles & true positioning, parallelism, contours, radii, roundness, perpendicularity, tapered holes, and cam profiles.

Most of the above features are explained in US military standard (MIL –STD-8); however, the method of measuring these features can be specified by the casting purchaser. As explained, the accurate and sound castings of specified tolerance and surface finish depend on the quality of complex master pattern used in the production process. Hence, to manufacture different grades of castings, the specified tolerance and surface roughness grades should be achieved accurately on the shape and geometric features of master patterns. Generally in the foundries, the master patterns are made using plywood, wood (Teak, Neem, Mango etc.) and hard boards. These patterns have many limitations such as difficulty in fabrication to achieve the exact shapes, may require assembly of parts, are susceptible to absorption of moisture, fungus attack, shrinkage and may require special coating to increase the shelf life. To overcome these difficulties, patterns made of light alloys are also used. However, the cost, the size limitation and the easiness in molding process are some of the limitations of metal/alloy patterns. Recently, all these limitations are surmounted by the introduction of polymer (thermoplastics and photopolymers) patterns such as ABS (Acrylonitrile-Butadiene-Styrene), PC (polycarbonate), ULTEM, PPS (Polyphenylsulfone) etc. which can be easily fabricated by RP machines. The usage of polymer/plastic patterns have several advantages such as enhanced pattern life in product cycle, great dimensional accuracy, reduction in inspection and rework and also the reusability. Table 1 shows the properties of ABS-M30 and Teak wood used in the present study. Patterns made of ABS are dense, rigid, can serve at higher temperature and has lower shrinkage compared to that of Teak patterns.

Table 1: Properties of ABS-M30 and Teak wood

Properties	ABS-M30	Teak
Ultimate tensile strength	40	95 - 155
Compressive strength	42	48 - 91
Coef. of thermal	10×10^{-5}	---
Thermal conductivity	0.2	0.19 -
Poisson's ratio	0.35	0.42
Operating Temperature	60	30
Density (kg/m3)	1024	630-720
Shrinkage (%)	0.1	0.6 - 0.6

Rapid prototyping is an automatic production of physical objects using additive manufacturing technology in which the model is built layer by layer. RP takes virtual designs from Computer Aided Design (CAD) or animation modeling software, transforms them into thin, virtual, horizontal cross-sections (generally in STL file format standardized by rapid prototyping industries) and then creates successive layers until the model is completed. In this study fused deposition modeling (FDM) is used to fabricate the complex master pattern. A strategic approach to achieve complex master pattern using FDM defines the specifications, plans, parameters, activities, processes and constraints. Compared to other RP technologies such as 3D print, SLS, SLA and Polyjet, FDM requires 6 slices of 0.178 mm to complete 1 mm thickness of the parts. Figure 2 shows a conventionally made (wooden) pattern and the pattern (ABS) fabricated through RP technology (fused deposition modeling).

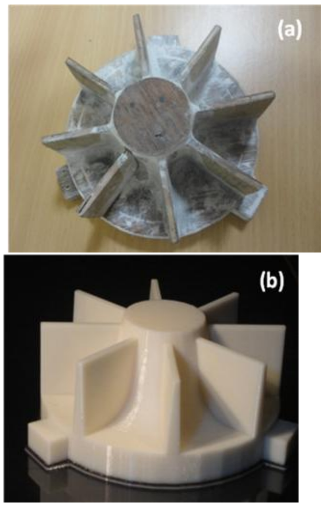

Fig. 2 Master Pattern of Impeller Casting (a) wooden material (b) ABS material.

In the current study, STRATASYS FORTUS 400mc RP machine was used to fabricate pattern of impeller casting. The general methodology of making this ABS pattern involves following steps:-

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1. Creation of CAD models of all components
2. Conversion of CAD models to STL format
3. Slicing of STL file into thin cross-sectional layers
4. Layer by layer construction of the models
5. Cleaning and finishing of the RP models

The CAD models made in Solid Edge software is optimally (to approximate exact surfaces) converted to STL format (which represents a 3D surface to an assembly of planar triangles). The individual model in STL format is then pre-processed in INSIGHT program to adjust the size, location and orientation of the model within the RP machine. Slicing of the model (which can vary from 0.01 mm to 0.7mm) also is done to fix a deposition thickness of 0.124 mm. Tool path generation, support material (SR-30) generation, assigning of material (ABS-M30) for building, are the other pre-processing steps done in INSIGHT. The time taken to build the parts and the amount of building material and the support material required for the parts can be obtained from the software. Patterns thus built are removed from the machine. Support material is cleaned and the edges may be finished by filing if required.

III. DISCUSSION

Conventionally, impeller pattern is manufactured based on the dimensions and specifications in blue prints (2D drawings). Conventional method of making patterns is a tedious task, since it includes the usage of hand cutting tools such as chisel, different sizes of saw etc. and requires an exact sequence of the tasks to form the complex master pattern. On the other hand, pattern production using RP technology is computer automated which provides accurate shape and dimensions and avoids the need of joining individual blades.

Table 2: Lead time and cost comparison for conventional method with RP method

Production Details	Conventional Method	Rapid Prototyping
Design time (hrs)	4	4
Fabrication time (hrs)	18	2.25
Man Hours required (hrs)	16	8
Total time (hrs)	22	6.25
Number of castings/patterns	40 – 60	300 - 450
Total cost (INR)	300	600

Lead time comparison of the fabrication of master patterns through conventional method and rapid prototyping technology is showed in Table 2. A reduced lead time of 65 -70 % can be obtained using RP method in addition to the reduction in manpower in the production of master patterns. Although the total cost involved in RP method is twice that of conventional method, considering the number of castings which can be obtained using master patterns, four times reduction in production cost per ABS master pattern is achieved. There are several advantages of using RP technology in foundries. Compared to conventional method and CNC machining process, RP technology is fast accurate and manufactures the pattern without any material wastage. Since RP technology integrates numerical control, it does not require any special tools, jigs and fixtures and secondary operation to build the master patterns. Since the technology is highly automated risk factor/errors is comparatively less and has an ability to create any shape and geometrical features. In addition to this, patterns can be made hallow which is difficult in conventional and CNC fabrication. A detailed comparison between conventional, CNC and RP fabrication methods to obtain master patterns is shown in Table 3.

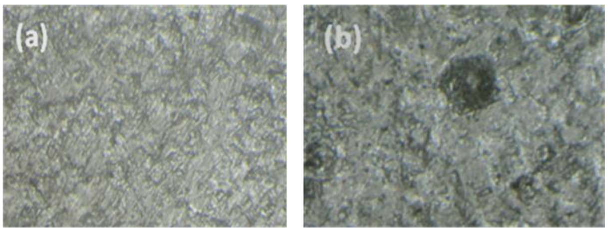

Fig. 3 Photo micrographs obtained at 4X magnification (a) ABS master pattern (b) wooden pattern.

The dimensions of the fabricated wooden master pattern and ABS master pattern with respect to their aluminum castings were observed. Based on these observations, it is understood that there was a normal deviation on the dimensions in both the castings due to the shrinkage of aluminum alloy. However, it is observed that the contours of casting (the edge of blades) made using wooden patterns were not sharp enough or accurate compared to that of casting made using ABS pattern. A microscopic observation was also made to understand the surface quality of the castings obtained using master patterns made of wood and ABS. Photo micrographs obtained at 4X magnification (Figure 3) shows smooth surface finish of ABS master pattern compared to the wooden pattern. An increased adherence of sand particles to the wooden master pattern can cause surface irregularities at a length scale of sand grains. Based on the visual comparison, it can be suggested that the roughness of the impeller casting can be reduced from RMS 125 to RMS 60 by replacing wooden master pattern to ABS master pattern.

IV. CONCLUSION

The results of this study indicate significant advantages in employing rapid prototyping technology in the production of master patterns. These advantages include substantial cost and lead-time savings with minimal material wastage. In addition to this, the accurate dimensions and enhanced surface quality of castings (better than ISO N10 specification) obtained using ABS patterns eliminated secondary post-processing steps. The higher density and the rigidity of ABS patterns may also increase the pattern life which in turn contributes to more number of castings per pattern and reduction in the total production cost. These benefits clearly indicate a wide scope for RP technology in foundries. Though this technology has welcomed by foundries in the production of value added castings, the usage of RP technology in small and medium scale foundries is still in infancy stage due to high initial cost and the higher material cost. But, RP technology can be economical by making hollow patterns and opting for mass customization through rapid manufacturing. It is envisaged that the introduction of economically viable materials and advanced additive manufacturing technology will potentially change the production volume of the castings, meeting the customer requirements.

Table 3 Comparisons between conventional, CNC and RP fabrication methods to obtain complex master patterns

Variables	Conventional	CNC Machining	Rapid Prototyping
Forming process	Subtractive manufacturing process which requires skills, various tools, jigs & fixtures	Subtractive manufacturing process which may also require programming skills	Additive manufacturing process without much human intervention or tooling
Operations	Single operation only can be performed at a time	Simultaneous operations on the pattern are restricted	Multiple operations are integrated in the pattern building process
Post-Operations	Secondary or tertiary machining operations are required depending on the complexity of the pattern	Secondary machining operations may be required to complete a pattern fabrication.	Secondary operations are not required, as fine shaped pattern is obtained.
Tools	Different types of cutting and finishing tools are required to form specific features and profiles on the pattern	Different types of cutting and finishing tools are required to form specific features and profiles on the pattern	No special tools are required
CAD data	CAD model is not required	CNC tool path generation based o on CAD data requires more time to generate a program	Time required to process a CAD data (STL format) for pattern building is very nominal
Risk factor/error	very high risk factor since there can be manual errors	high risk factor while machining the pattern	Risk factor during pattern building, is very less
Integral Features	Integral features within the pattern cannot be built	Forming integral features within the pattern are limited	Integral features within the pattern can be easily built
End product	Single pattern at a time	Single pattern at a time	Multiple patterns at a time
Operator	Compulsory until the completion of job	Required for programming & feeding the parts to CNC machine	May not be required, best suited for web based manufacturing
Nature of the product	Generally solid pattern can only be obtained	solid & hollow (depending on wall thickness) pattern can be made	Solid and hollow (depending on wall thickness) patterns can be obtained

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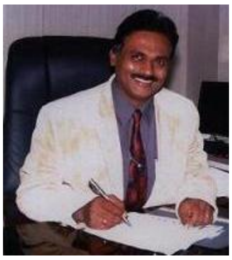

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