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Investigations for deducing wall thickness of aluminium shell casting using three dimensional printing

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Analysis and modelling

ABSTRACT

Purpose: of the present study is to verify the feasibility of decreasing the shell thickness in rapid shell casting based upon 'three dimensional printing' technology in order to evaluate the dimensional accuracy for aluminum castings. Rapid prototyping has been in evidence for the past twenty years and is being widely used in diverse areas, from the building of aesthetic and functional prototypes to the production of tools and moulds for technological prototypes

Design/methodology/approach: Further consistency with the tolerance grades of the castings has been checked as per IT grades along with mechanical properties of the aluminium castings. Starting from the identification of component/ 87benchmark, technological prototypes are produced with different shell thicknesses. Measurements on a coordinate measuring machine allowed calculating the dimensional tolerances of the castings produced.

Findings: The research proved that the shell thickness having value less than the recommended one is more suitable from dimensional accuracy and economic point of view. The result indicates that at 5 mm shell thickness, hardness of the casting is improved by 3.79%. Further production cost and production time has been reduced by 54.6% and 55.4% respectively in comparison to 12 mm recommended shell thickness.

Practical implications: The analysis procedure is better for proof of concept and for the new product, for which the cost of production for dies and other tooling is more.

Originality/value: The 3DP technique at different shell thicknesses (12 mm to 2 mm) provided satisfactory results, limited at present to the field of light alloys. This process ensures rapid production of pre-series technological prototypes and proof of concept at less production cost and time.

Keywords: Rapid prototyping; 3D printing; Commercial aluminium alloy; CMM; Dimensional tolerance

1. Introduction

Rapid prototyping has been in evidence for the past twenty years and this RP industry is experiencing impressive growth. So far, research has been done about prototype making. Due to these investigations, various techniques (stereolithography, selective laser sintering, three dimensional printing etc.) and machines have been developed. [16] observed that with the use of this technology, astounding reductions in design & prototyping cycles and tangible improvements in new product quality can be obtained. The three dimensional printing (3DP) based on the MIT's (Massachusetts Institute of Technology) ink jet technology under U.S. patent no. US005340656 [11] and utilized by Z-Corporation in a variety of printers is considered to be one of the most future oriented rapid prototyping (RP) systems. It is classified as a typical 'concept modeler', a low-end system, and represents the fastest RP-process. Figure 1 shows the basic 3DP process. This 3DP technique based on layer by layer manufacturing is extending their fields of application, far beyond the original idea of generating design iterations. The applications have been extended from the building of aesthetic and functional prototypes to the production of tools and moulds for techological prototypes or pre-series. In particular, layer by layer construction applied to the tool and dies making, directly from virtual designs (from computer aided design (CAD) or from animation modelling software), is defined as rapid tooling (RT). Manufacturers are increasingly looking towards RT, especially for short production runs which do not justify the investment required for conventional hard tooling [12]. A variety of tooling can currently be produced using different RP technologies. For the purpose of classification, tooling is divided into direct or indirect tooling [6]. In direct tooling, the tool or the die is created directly by the RP process. In the second method which is used in the present research work i.e. indirect tooling, only the master is created using the RP technology. From this master, a mould is made out of a material such as silicon rubber, epoxy resin, soft metal, or ceramic. Most rapid tooling today is indirect. RP parts are used as patterns for making moulds and dies. Patterns, cores and cavities for metal castings can be obtained through these rapid casting (RC) techniques [4,10,13]. By using 3D printing, to produce the ceramic shells with integral cores directly from the CAD model, a number of disadvantages of the traditional process are avoided. Most significant is that the metal dies are typically expensive and time consuming to produce, with lead times ranging from two to six months. For relatively small and complex parts, the benefits of additive manufacturing can be significant [2, 9].

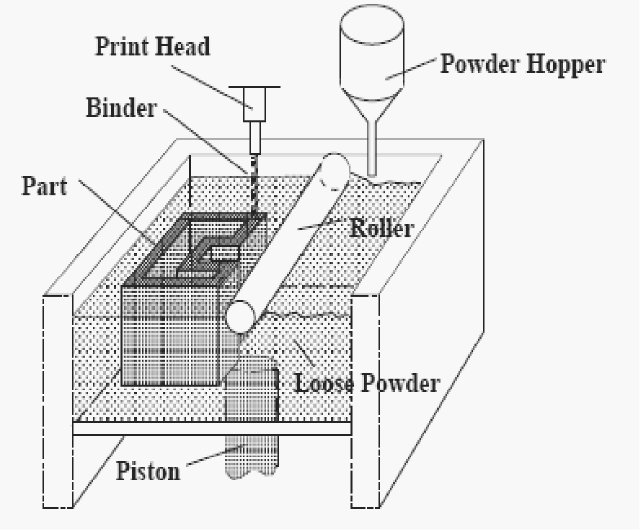

Fig. 1. 3D printing process

In this field, innovative solutions are now available based on 3D printing process, which can extend RC possibilities thanks to the lower costs with respect to previous technologies such as selective laser sintering of sand [7]. One such technological solution is the Zcast process, in which 3D-printing technology with the use of a ceramic material allows the production of complex cavities and cores, suitable for casting light alloys. Components can be made by depositing a first layer of powder material in a confined region and then depositing a binder material to selected regions of the layers of the powder material to produce a layer of bonded powder material at selected regions. Such steps are repeated for selected number of times to produce successive layers of selected regions of bonded powder material so as to form the desired component. The unbounded powder material is then removed.

The present research aims at using the 3DP technology as rapid shell casting to make the shell moulds. A ‘RP’ shell model was used as the positive pattern around which the sand is filled in a moulding box. An effort has been made through experiments, to study the feasibility of decreasing the shell wall thickness from the recommended one (12mm), in order to reduce the cost of production and time as well as to evaluate the dimensional accuracy, mechanical properties of the Al castings obtained for assembly purpose. The consistency of the tolerance grades of the obtained castings (IT grades) as per allowed IS standards for casting process were checked. Experimental studies regarding this solution are lacking in literature, in particular the technological feasibility in the case of thin-walled parts needs to be assessed and the dimensional tolerances calculated. Bassoli et al. [3] conducted studies for two technological solutions in this field and this study aims at evaluating the dimensional accuracy of two rapid casting (RC) solutions based on 3D printing technology: investment casting starting from 3D-printed starch patterns and the Z Cast process for the production of cavities for light-alloys castings. Wang [15] and Ramos [9] also proposed similar studies with regard to different solutions for the production of technological prototype. The present research regarded the concurrent product process development and production of series of technological metal prototypes by means of rapid casting (RC) process. Following are the objectives of study:

- To find the best settings of the 3DP machine in terms of the layer thickness, part orientation and post curing time to make the RP shell moulds.
- To verify the feasibility of decreasing the shell thickness from recommended one in order to reduce the production cost and time.
- To evaluate the dimensional accuracy of the Al castings obtained and to check the consistency of the tolerance grades of the castings (IT grades) as per allowed IS standards for casting process.
- Proof of concept, to present the concept in physical form with minimum cost by avoiding the cost of making dies and other fixtures for a new concept.

2. Experimental plan

For the desired objectives, an aluminium alloy component was chosen as a benchmark, representative of the automobile field, where the applications of the RT and RC technologies are particularly relevant. The experimental procedure started with the CAD modelling of the benchmark (figure 2) having total volume of 20483.83mm^3 and surface area of 9225.79mm^2. To obtain best settings of the 3DP machine in terms of layer thickness, part orientation and post curing time, upper and lower shell prototypes were produced by using RC solution based on the 3DP technology (Figure 3).

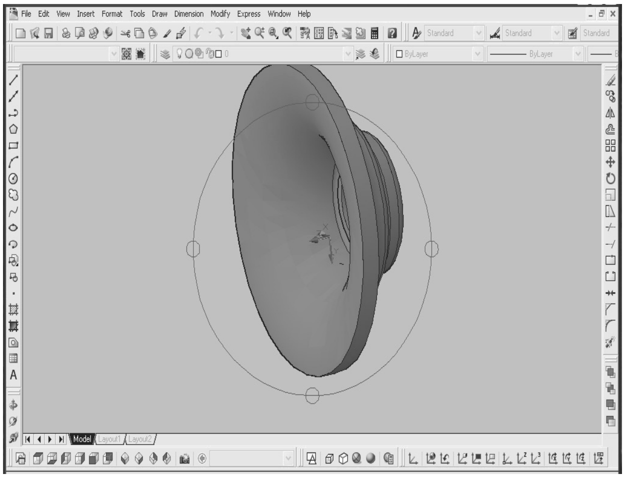

Fig. 2. CAD model of the benchmark

A number of experiments were conducted for the possible outcomes of the 3DP machine with objective function of minimizing the production cost, production time and improvement in dimensional as well as mechanical properties. Post treatment for parts was chosen as standard specifications (6h isothermal at 200°C heating ramp of 1.5°C). Four permutations were established for remaining two machine parameters- layer thickness and part orientation. So for these four permutations, four sets of experiments were conducted with the planning of following phases.

- The analysis of benchmark leads to definition of the feeding system and riser in a concurrent product process development [8].
- CAD modeling of Upper and lower shells and these parts were manufactured by 3D printing technique
- The inner surfaces of the cavity were air-blown and treated by foundry painting to improve the molten metal flow. Parts were assembled for co linearity of axes in both the planes and a commercial cast Aluminium alloy (333.0) was poured to obtain the technological prototype.
- The results of the pilot study are shown in Table 1 and leads to the selection of layer thickness as 0.127 mm and horizontal part orientation for the final experimentation.

2.1. Prototype development for diffirent shell thicknesses and casting production

Starting from the CAD model of the component, shells were modelled for different shell wall thicknesses. From the analysis of geometry and volume of benchmark, single feeder and riser system was designed for pouring the molten metal. RP shell models are used as positive patterns around which the sand is filled in a moulding box. Commercial cast aluminium alloy 333.0 was used for casting.

2.2. Measurement results

The measurement paths for the internal and the external surfaces of the benchmark have been generated through the measurement software of the DEA Iota 0101 CMM [1,17]. The different dimensions measured with CMM are outer diameter, curve radius and component thickness. Outer diameter was measured as ten (10) circles mean diameter at different points. The curve radius was measured by scanning the inner and outer curve surfaces. The results of the dimensional measurements have been used to evaluate the tolerance unit (n) that derives starting from the standard tolerance factor i, defined in standard UNI EN 20286-1 (1995). The values of standard tolerances corresponding to IT5-IT18 grades, for nominal sizes up to 500mm, are evaluated considering the standard tolerance factor i (in micrometers) indicated by the following formula, where D is the geometric mean of the range of nominal sizes in millimeters.

$$\text{Tolerance factor } i = 0.45\,(D)^{1/3} + 0.001D, \qquad (1)$$

In fact, the standard tolerances are not evaluated separately for each nominal size, but for a range of nominal sizes. For a generic nominal dimension D_{JN}, the number of the tolerance units ‘n’ is evaluated as follows:

$$n = 1000(D_{JN} - D_{JM}) / i, \qquad (2)$$

Where D_{JM} is a measured dimension.

The tolerance is expressed as a multiple of i: for example, IT14 corresponds to 400i with n= 400. The results of dimensional measurements are used to evaluate the tolerance grades. The obtained tolerance grades are IT14 and IT15. It is important to notice that the tolerance grades calculated for the considered RC techniques are consistent with the values allowed for casting operations, between IT11 and IT18 [5]. Since the technological prototypes lies in the range of IT11 to IT18, thus are completely acceptable at all shell thicknesses. However better dimensional accuracy is obtained at 5 mm shell wall thickness (Ref. table2).

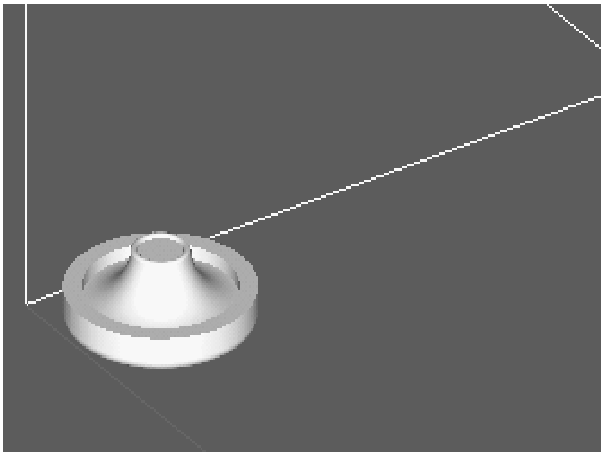

Fig. 3. Model of shell

Table 1.
Observations of pilot experimentation.

Layer thickness (mm)	Part orientation	Post curing time	Observation				
			Production cost (Rs)	Production time	Vickers hardness no.	Avg. Surface Roughness	Avg. outer diameter (mm)
0.101	Horizontal	60 minutes	850	85 min	94	6.89	49.151
0.127			681	65 min	94	6.88	49.152
0.101	Vertical		1800	180 min	94	6.83	49.149
0.127			1420	150 min	94	6.85	49.15

Table 2.
Observations of Final Experimentation

Exp. No	Shell Thickness (mm)	Avg. Outer Diameter	Avg. Specimen thickness	Avg. Curve Radius	Avg. VHN	Avg. Surface Roughness
1	12	49.151	3.477	14.549	94	6.88
2	9	49.022	3.341	15.21	89	6.79
3	7	49.154	3.6	14.374	94	6.89
4	6	49.169	3.294	14.347	93	6.87
5	5	49.189	3.45	14.828	98	6.82
6	4	49.112	3.212	14.751	94	6.66
7	3	49.016	3.163	13.847	93	6.7
8	2	48.986	3.15	13.822	92	6.8
9	1	Broken Due to Molten metal Pressure				

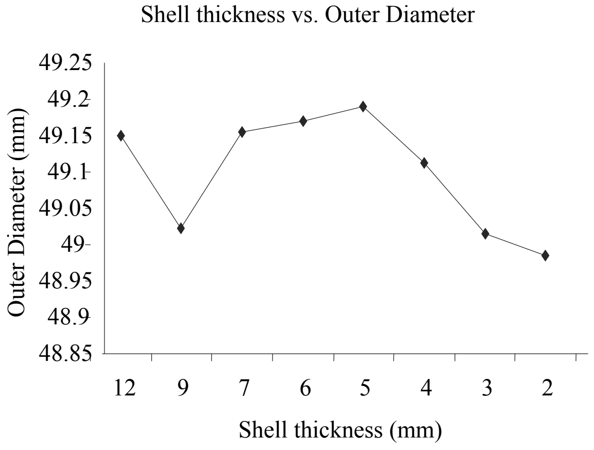

Fig. 4. Effect of shell wall thickness on outer diameter

Surface hardness of the castings obtained was measured on Vickers's scale and shown in table 2. The Micro-Vickers Hardness Tester (Model No. MBK-H2) was used for measurements. The results of dimensional measurements, surface hardness, surface roughness, Production cost and time are shown in tables 2 and figures-4-5.

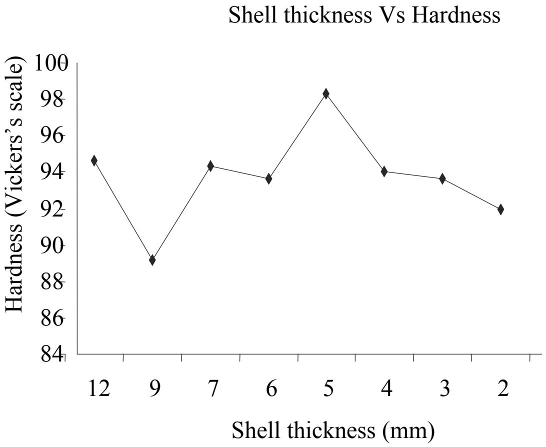

Fig. 5. Effect of shell wall thickness on surface hardness

3. Conclusions

The 3DP technique at different shell thicknesses (12 mm to 2 mm) provided satisfactory results, limited at present to the field of light alloys. With respect to traditional sand casting, this process ensures rapid production of pre-series technological prototypes and proof of concept at less production cost and time. On the basis of experimental observations made on the aluminium castings obtained from different shell wall thicknesses, the following conclusions can be drawn:

- It is feasible to reduce the shell thickness from the recommended value of 12mm to 2mm. The tolerance grades of the castings produced from different thicknesses were consistent with the permissible range of tolerance grades (IT grades) as per standard UNI EN 20286-I (1995).
- The Hardness (on Vickers scale) obtained with 5mm thickness was better. However marginal improvement in dimensional accuracy has been observed.
- The adopted procedure is better for proof of concept and for the new product, for which the cost of production for dies and other tooling is more.
- The results indicates that at the 5mm shell thickness, hardness of the castings was improved by 3.79%, The production cost and production time was 54.6% and 55.4% less in comparison to 12 mm recommended shell thickness.

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