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Effect of moulding sand on statistically controlled hybrid rapid casting solution for zinc alloys †

Rupinder Singh*

Department of Production Engineering, Guru Nanak Dev Engineering College, Ludhiana, 141-006, India

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Abstract

The purpose of the present investigations is to study the effect of moulding sand on decreasing shell wall thickness of mould cavities for economical and statistically controlled hybrid rapid casting solutions (combination of three dimensional printing and conventional sand casting) for zinc alloys. Starting from the identification of component/ benchmark, technological prototypes were produced at different shell wall thicknesses supported by three different types of sands (namely: dry, green and molasses). Prototypes prepared by the proposed process are for assembly check purpose and not for functional validation of the parts. The study suggested that a shell wall with a less than recommended thickness (12mm) is more suitable for dimensional accuracy. The best dimensional accuracy was obtained at 3mm shell wall thickness with green sand. The process was found to be under statistical control.

Keywords: Moulding sand; Statistically controlled; Hybrid rapid casting; Dimensional accuracy; Zinc alloys; Hardness

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1. Introduction

Rapid Prototyping (RP) is a method used to fabricate physical objects through layer-by-layer deposition of material under computer control [1]. It is an additive production process unlike subtractive or formative processes. Objects are fabricated in RP by deposition of layers contoured in a (x-y) plane two dimensionally, while the third dimension (z) results from the stacking of layers [2]. Fig. 1 shows the basic concept of RP.

Three-dimensional printing (3DP) is a relatively new form of RP. The process of 3DP was patented in 1994 by Sachs et al. under U.S. patent number 005340656 [3]. It was developed at Massachusetts Institute of Technology (MIT) and licensed to Soligen Corporation, Extrude Hone and Z Corporation of Burlington [1, 3]. Fig. 2 shows a schematic of the 3DP process. Application of layer-by-layer manufacturing technique is growing from building of aesthetic and functional prototypes to the production of tools and moulds for technological prototypes [4]. In particular, additive construction applied to the production of dies and electrodes, directly from digital data, is defined as rapid tooling (RT) [5]. Patterns, cores and cavities for metal castings can be obtained through rapid casting (RC) techniques. In both cases, since the tooling phase is highly time-consuming, great competitive advantages can be achieved.

Moreover, RT and RC processes allow the simultaneous development and validation of the product and of the manufacturing process [6]. Technological prototypes can constitute a strategic means, not only for functional and assembly testing or to obtain the customer's approval, but mainly to outline eventual critical points in the production process [7]. The immediate relevance of RC techniques consists, above all, for parts availability [8]. Traditionally, in order to produce cast prototypes, a model and eventual cores have to be created, requiring time and costs that hardly match the rules of the competitive market. For this reason, functional tests are typically performed on prototypes obtained by metal cutting, which are not effective in outlining issues related to the manufacturing process. The possibility to verify the usefulness of a technological solution, in early stages of the product development, ensures a 'concurrent engineering' approach and minimizes the risk of late modifications of the definitive production tools. The initial cost increase can thus be recovered through a reduction of costs and time for the following phases of development, engineering and production, as well as through non-monetary advantages [9]. In particular, for relatively small and complex parts, the benefits of additive construction can be significant [10]. In this field, innovative solutions based on 3DP processes can extend RC possibilities due to the lower costs with respect to previous technologies (such as laminated object manufacturing of sand casting). One such

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* Corresponding author. Tel.: +91 98722 57575, Fax: +91161 2502700
E-mail address: rupindersingh78@yahoo.com

Fig. 1. RP concept [2].

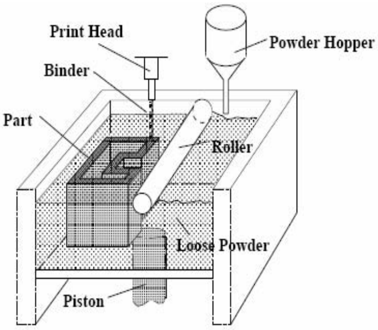

Fig. 2. Schematic of 3DP process [2].

Table 1. Mechanical and thermal properties of zinc alloy casting.

Mechanical properties	
Hardness	Vickers 30
Tensile Strength	Ultimate 37MPa
Modulus of Elasticity	96.5 GPa
Thermal properties	
Melting Point	419.58^{0}C
Physical properties	
Density	7.10 gm/cm^3

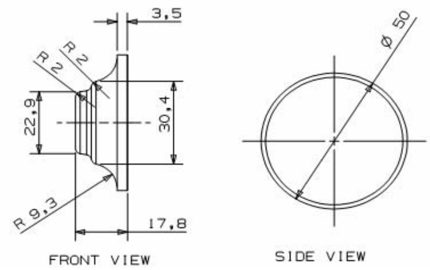

Fig. 3. Benchmark dimensions.

technological solution in shell casting uses starch patterns produced on 3DP conceptual modelers [11]. A second 3DP technology using ceramic material allows the production of complex cavities and cores, suitable for casting light alloys [12].

A key issue regarding the shell casting process is the production of a pattern in the case of a prototype casting, for which the traditional die casting is uneconomical. RP techniques can meet this requirement, producing a single or few parts in a short amount of time without tooling costs [13, 14]. The present research regards shell patterns obtained by 3DP on which the ceramic shell can be built and then joined (as in the conventional process) to obtain the cavity for pouring metal. There is a lack of experimental studies regarding this solution in literature; In particular, the technological feasibility in the case of thin-walled parts needs to be assessed [15, 16].

In this work, the 3DP technology has been used as rapid shell casting to make the shell moulds for zinc alloy. An effort has been made through experiments; to study the feasibility of decreasing the shell wall thickness from what is recommended (12mm), in order to evaluate the dimensional accuracy of zinc alloy castings obtained, for assembly purposes. It should be noted that as per Zcast 3DP process, by selecting the shell wall thickness as 12mm there is no need for backing or supporting shells while pouring the molten metal [17-20]. Now, since 3DP is a patented technology, there is a high cost involved in making the shells upto 12mm in thickness [21]. To make the 3DP process cost effective an effort has been made by some of the researchers to support the shell wall with loose sand from the outside [20, 21]. In the current work, three different types of sand (namely dry, green and molasses) have been used for supporting shells of different thicknesses prepared by 3DP in order to ascertain the best properties for a hybrid casting solution. The following objectives have been set for the present experimental study:

To evaluate the dimensional accuracy and consistency of the tolerance grades of the castings (IT grades) as per allowed IS standards for shell castings prepared by a hybrid rapid casting technique (combination of 3DP and conventional sand casting) and supported with different types of sand (namely dry, green and molasses).

To study the feasibility of decreasing the shell thickness from what is recommended (12mm) for statistically controlled rapid casting of zinc alloy.

2. Experimentation

In order to accomplish the above objectives, 'zinc alloy casting' has been chosen as a benchmark. Table 1 shows the mechanical, thermal and physical properties of zinc alloy used in the present study. The component selected for the present study is shown in Fig. 3. The experimental procedure started with drafting and model creation using AutoCAD software.

For rapid casting based on 3DP, the following phases were planned:

After the selection of the benchmark, the component to be built was modelled using a CAD (Fig. 4). The CAD software used for the modelling was UNIGRAPHICS Ver. NX 5.

The shells of the pattern were made at different shell thicknesses. The thickness values for shells were 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2 and 1mm. Moulds were manufactured in 3DP (Z Print machine, Model Z 510) with Z Cast 501 powder, and parts were heat-treated at a temperature of 110^{0}C for 1 hour. The shells prepared were supported by different types of sands (dry, green and molasses), and zinc alloy was poured to obtain the technological prototype. Figs. 5, 6 and 7 show printed and

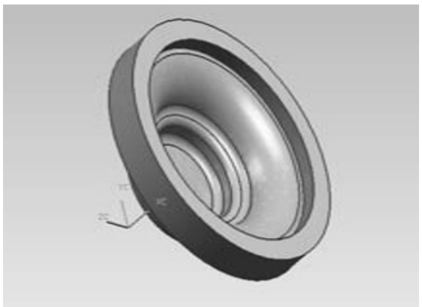

Fig. 4. CAD model of benchmark.

Fig. 5. Printed and cleaned shells.

Fig. 6. Post curing of shells by heating at 110^{0}C for 1 hour.

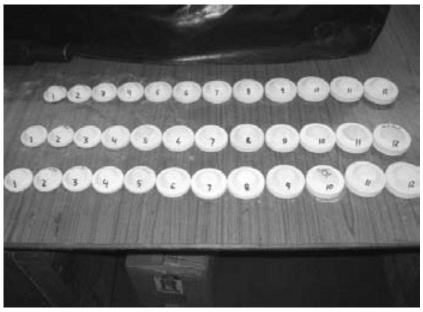

Fig. 7. Printed and cured shells ready for hybrid casting.

Fig. 8. Shells supported with dry sand.

Fig. 9. Controlled pouring of molten Zn.

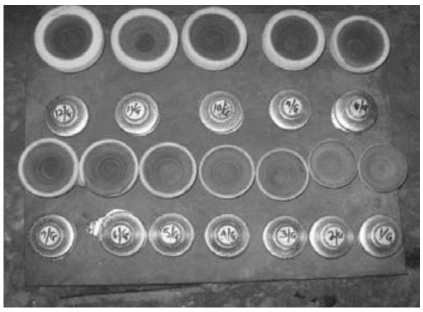

Fig. 10. Hybrid Zn casting.

cleaned shells, post-curing of shells, and cured shells ready for hybrid casting, respectively. In the present study, the process of hybrid shell casting has been divided into three steps:

Hybrid shell casting with dry sand

Hybrid shell casting with green sand

Hybrid shell casting with molasses sand

For experimentation 36 (12×3) cleaned and cured shells of thicknesses 12mm to 1mm were used in the casting process. Each set of 12 mould cavities was supported with dry, green and molasses sand, respectively, in individual moulding boxes for hybrid shell casting. Fig. 8 shows shells supported with dry/green/molasses sand. Fig. 9 and 10 shows controlled pouring of molten Zn and hybrid Zn casting, respectively.

3. Results and discussion

The measurement paths for the internal and the external surfaces of the benchmark have been generated through the measurement software of the 'GEOPAK v2.4.R10' coordinate measuring machine (CMM). These paths direct the movements of the CMM probe along trajectories normal to the parts surface. About 70 points have been measured on the external surface. For each point the machine software evaluates the deviations between the measured positions and the theoretical ones for the X, Y, and Z coordinates (Fig. 11). Table 2 shows variation in measured dimension (D_{JM}) of the outer diameter, with respect to the nominal dimension (D_{JN} = Φ50mm), of

Table 2. IT grades for outer diameter (D_{JM}) supported by different types of sand.

Shell mould thickness in mm	Green sand supported shells Tolerance factor i =1.56 (μm)		Dry sand supported shells Tolerance factor i =1.56 (μm)		Molasses sand supported shells Tolerance factor i =1.56 (μm)	
	Measured diameter of component in mm for dry sand D_{JM}	IT grade	Measured diameter of component in mm for dry sand D_{JM}	IT Grade	Measured diameter of component in mm for dry sand D_{JM}	IT grad e
12	49.475	IT13	49.760	IT11	49.520	IT13
11	49.580	IT13	49.780	IT11	49.730	IT12
10	49.465	IT13	49.545	IT13	49.740	IT12
9	49.380	IT14	49.710	IT12	49.535	IT13
8	49.680	IT12	49.610	IT12	49.655	IT12
7	49.820	IT11	49.710	IT12	49.505	IT13
6	49.475	IT13	49.665	IT12	49.440	IT13
5	49.595	IT13	49.625	IT12	49.445	IT13
4	49.330	IT14	49.615	IT12	49.400	IT13
3	49.802	IT11	49.575	IT13	49.405	IT13
2	49.480	IT13	49.710	IT12	49.355	IT14
1	49.460	IT13	49.570	IT13	49.400	IT13

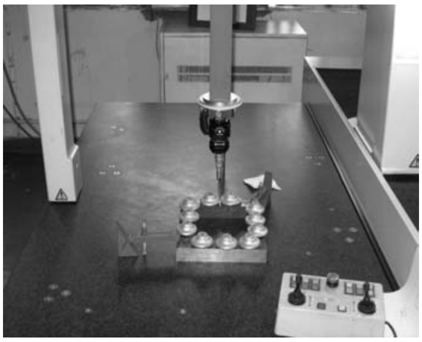

Fig. 11. CMM probe measuring dimensions of components.

castings prepared at different shell thicknesses (mm) supported by three different types of sand (dry, green and molasses) [22].

As observed from Table 2, the castings were successfully produced at all shell wall thickness from 12mm to 1mm. However, the best IT grades was IT11, which has been obtained at 7mm and 3mm shell wall thicknesses with green sand supported shells. Similar results are obtained using dry sand support and shells with 12mm and 11mm wall thickness. This means there is a strong relation between the shell wall thickness and the measured diameter for the same type of sand. This may be because different combinations of Z Cast powder and sand supported shells have different rates of heat transfer, which affects the final physical and mechanical properties of the castings. Since a small shell wall thickness value represents cost effectiveness (in terms of less quantity of powder and binder material used) [21], the shell wall thickness of

Table 3. Bench mark dimensional value for 3mm shell thickness.

S.No	Observation	Mean	Above or below mean	Up or Down
1	49.752	49.80433	B	
2	49.802	49.80433	B	U
3	49.796	49.80433	A	B
4	49.813	49.80433	A	U
5	49.823	49.80433	A	U
6	49.84	49.80433	A	U
Mean	49.80433		$E_{AB=1}$	$E_{UD=2}$

A=above the mean, B=below the mean, U=Up from previous reading, D=Down from previous reading

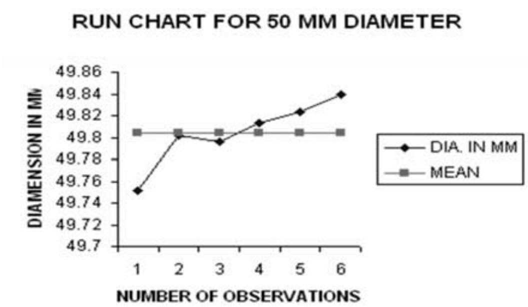

Fig. 12. Run-chart of the measured values of outer diameter (benchmark).

3mm supported by green sand is recommended. As the shells have to be used only once for generating the prototype, the life of the shells was not affected by reduction in shell wall thickness. The surface finish of castings obtained is in the range of 6.5 to 7.0μm. Since the component in the study is not a functional part, there will not be any problems involving mechanical.

The component selected in the present study is actually used in the suspension systems of automobiles. An outer diameter of 50mm was chosen because it is an actual functional dimension in assembly. It should be noted that the results are based upon study done on a simple geometry (Fig. 3), but the same results are applicable to any complex geometry of similar volume since the solidification time depends on the ratio of volume to surface area [21]. There is not any specific environmental requirement for the pouring process of molten zinc alloys in shell castings prepared by 3DP.

Furthermore (based upon observations in Table 2), to understand whether the process is statistically controlled, six samples of zinc alloy were cast for optimum shell thickness value of 3mm, supported with green sand. The dimensions of the outer diameters measured by CMM are shown in Table 3. Based upon Table 3, Fig. 12 shows a run-chart of the measured outer diameter values (benchmark).

Now, if the mean and standard of population having a normal distribution is μ and σ respectively then for variable data, X, the standard normal deviate, Z, is defined as:

$$Z = \frac{(Xi - \mu)}{\sigma} \tag{1}$$

were X_i is the variable data obtained, μ is the mean of the data and σ is the standard deviation [23].

3.1 Calculation for Z (standard normal deviate) above and below

$$E(\text{run})_{\text{AB}} = \left(\frac{N}{2} + 1\right) \tag{2}$$

where N is the number of observations and E $(\text{run})_{AB}$ is the expected number of run above and below

$$E(\text{run})_{\text{AB}} = \left(\frac{6}{2} + 1\right) = 4 \tag{3}$$

$$\sigma_{\text{AB}} = \sqrt{N - \frac{1}{4}} \tag{4}$$

where σ_{AB} is the standard deviation of above and below

$$\sigma_{\text{AB}} = \sqrt{6 - \frac{1}{4}} = 1.118 \tag{5}$$

$$Z_{\text{AB}} = \{\text{RUN}_{\text{AB}} - E(\text{run})_{\text{AB}}\} / \sigma_{\text{AB}} \tag{6}$$

where RUN_{AB} is the actual number of run obtained above and below

$$Z_{\text{AB}} = \frac{(1-4)}{1.118} = -2.6834 \tag{7}$$

P_{AB} = NORMSDIST (Z) when the value of Z is negative (using Microsoft excel software)

P = 0.003645

For up and down calculations:

$$E(\text{run})_{\text{UD}} = 2N - \frac{1}{3} \tag{8}$$

Where N is the number of observations and E $(\text{run})_{UD}$ is the expected number of run up and down.

$$E(\text{run})_{\text{UD}} = 2 \times 6 - \frac{1}{3} = 3.667 \tag{9}$$

$$\sigma_{\text{UD}} = \sqrt{(16N - 29/90)} \tag{10}$$

Where σ_{UD} is the standard deviation for up and down

$$\sigma_{\text{UD}} = \sqrt{(16 \times 6 - 29/90)} \tag{11}$$

$$\sigma_{\text{UD}} = 0.8628 \tag{12}$$

$$Z_{\text{UD}} = \{\text{RUN}_{\text{UD}} - E(\text{RUN})_{\text{UD}}\} / \sigma_{\text{UD}} \tag{13}$$

$$Z_{\text{UD}} = (2 - 3.667) / 0.8628 \tag{14}$$

Table 4. Standard normal deviate and outer diameter in ascending order.

S. No	Pi (Cumulative Probability)	Std. Nor. Deviate Z	Dimensional value in mm
1	0.08333	-1.38299	49.752
2	0.25	-0.67449	49.796
3	0.416667	-0.21043	49.802
4	0.58333	0.21043	49.813
5	0.75	0.67449	49.823
6	0.91667	1.382994	49.84

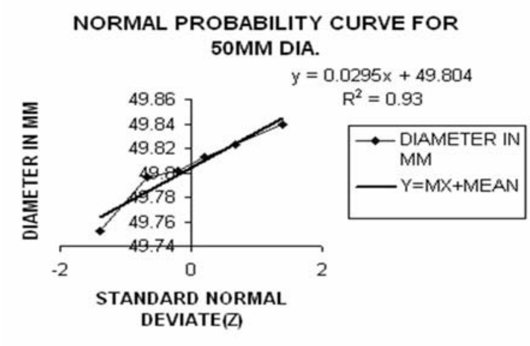

Fig. 13. Normal probability curve (for selected bench mark at 3mm shell thickness).

$$Z_{\text{UD}} = -1.5840 \tag{15}$$

P_{UD} = NORMSDIST (Z) when the value of z is negative (using Microsoft formula)

$P_{UD} = 0.056597$

Normally, decision making is done with a certain margin of error 'α' and taken as equal to 0.005. That is, there can be a 5% chances in arriving at a wrong conclusion.

Decision making:

If $P_{AB} < \alpha$ OR /& $P_{UD} < \alpha$ then a non-random pattern exists.

In the present case $P_{AB} < \alpha$ indicates existence of a non random pattern.

Predicting various statistics or drawing conclusions should not be undertaken unless the normality of distribution has been verified. Even if one has a large amount of data, superimposing the normal curve on the histogram is a more difficult task than imagined. For the histogram, one requires a minimum of 50 observations. However, the more the better as assessing whether the underlying distribution is normal or not becomes more difficult when the number of observations is fewer. For the cumulative probability plot (Pi):

$$\text{Pi} = (\text{S.N} - 0.5)/\text{N} \tag{16}$$

Where S.N is the serial number of data observations arranged in ascending order and N is the total number of observations in the data set. If the standard normal deviate follows normal distribution with mean μ =0 and standard deviation σ =1, then:

$$f(Z) = 1/\sqrt{\left(2\Pi e^{\frac{z^2}{2}}\right)} \quad (17)$$

The equation above follows the normal probability curve and any date close to it also follows the normal probability curve. The values of the standard normal deviate were calculated using cumulative probability and dimensional values were arranged in ascending order as shown in Table 4.

Using Table 4, the normal probability curve was drawn to predict the probability as shown in Fig. 13. As observed in Fig. 13, the aforementioned data follows a non random pattern and is under the normal probability curve. So, there are very strong chances that the process is under statistical control. However X-bar chart and R-bar chart cannot be drawn due to lack of observational data. The co-efficient of determination (R^2) having value 0.93 states that the diameter of observational values lies within the normal probability curve.

4. Conclusions

On the basis of experimental observations made from the zinc alloy castings obtained with different shell wall thicknesses, the following conclusions can be drawn:

It is feasible to reduce the shell wall thickness from the recommended value of 12mm to 1mm for the hybrid RC solution for zinc alloy. The tolerance grades of the castings produced from different thicknesses supported by different types of sand are consistent with the permissible range of tolerance grades (IT grades) as per standard UNI EN 20286-I (1995). Prototypes prepared by the proposed process are for assembly check purposes and not for functional validation of the parts.

Instead of a mould with 12mm shell wall thickness, in the Z Cast process of casting zinc alloys one can select a 3mm shell wall thickness supported by green sand. This is a hybrid rapid casting solution which is observed to produce better dimensional results.

The adopted procedure is better for proof of concept. Strong possibilities are observed for the process under statistical control for the best set shell wall thickness (3mm) supported by green sand in the case of zinc alloy RC.

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Rupinder Singh is Associate Professor in the Department of Production Engineering at Guru Nanak Dev Engineering College, Ludhiana, India. He completed his B.Tech in Production Engineering with Honors' and M.Tech in Production Engineering with Gold Medal from P.T.U. Jalandhar. He obtained a PhD in Mechanical Engineering from T.I.E.T. Patiala. He is a member of ASME, ISTE, ISME, MPAS, ISC and AIE. He has contributed about 115research papers at the national and international level. He has supervised 36 M.Tech theses. His areas of interest include rapid prototyping, non-traditional machining, maintenance engineering and welding.