DEVELOPMENT OF TECHNIQUE FOR 3D PRINTED MOULD INTRICATE RAPID CASTING

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Abstract

The development of rapid prototyping (RP) technologies has proven highly significant in the efforts to reduce production times for a number of casting processes. Although rapid prototyping technologies have most commonly be used to produce patterns for investment and sand casting this study demonstrated the use of direct shell production casting using three dimensional printing technology. Statistical methods as well as thermal, visual and dimensional analysis were also applied in order to optimise this rapid casting (RC) process for thin wall non-ferrous parts. Mould dimensions within ± 0.22 mm were achieved with the developed technique. Higher melt temperatures and pouring pressures produced castings with better dimensional accuracy. Mould temperature was not found to affect the casting dimensional accuracy significantly. The results allow for better dimensional specification of CAD file geometry for the rapid casting process.

Introduction

In the last thirty years great strides have been made in developing and adapting processes for higher production rates and reduced lead times. Many useful rapid prototyping (RP) technologies are now available for product development [1]. The advent of rapid prototyping technologies such as selective laser sintering and 3D printing has contributed to this significantly, particularly in the area of non-ferrous precision casting. The use of these new technologies in this respect has been titled rapid casting. An example of the use of this technology is in the production of solid metal moulds, termed Rapid Tooling (RT). The process under examination in this study was direct shell production casting using a 3D printing machine, a technology originally developed by MIT. A number of companies now supply variations along the lines of this original 3D printing technology. In a similar manner to investment casting, but without the wax and sintering, the mould can be printed on the 3-D printer machine and then cast into to produce the final part. New sand based material compositions have also been developed for rapid casting with these machines.

These methods should allow the potential to produce thin wall sections while maintaining high dimensional accuracy. Shrinkage of the rapid prototyped component leading to dimensional inaccuracies is a problem with many RP techniques [2] and gas inclusion is a common problem with conventional plaster moulding. Hygroscopic expansion of the investment and the thermal contraction of the cast metal can lead to dimensional changes [3]. Even on heating or cooling of a mould thermo-mechanical effects can cause dimension changes. Previous workers have presented finite element assessments of the affects of thermal dimensional changes on the tolerance of ceramic mould usage for RT [4]. Appropriate selection and control of the printing process, metal pouring temperature and proper design of the gating system can largely overcome these problems [5-10]. Recent work has shown possibility of using 3D printing for successful large scale production of aluminum, lead and brass alloys [11-13]. Despite these previous studies, there is a lack of work presented in the literature on the possibilities of achieving dimensionally accurate thin sectioned castings using 3D printed plaster moulds. The primary objective of this study was to determine optimal parameters for the 3D printing of plaster moulds and the associated casting process to ensure correct mould filling of thin sectioned moulds.

Materials and methods

The alloys used were aluminium alloy A356 and Sn-10%Pb solder. Initial experiments proceeded using the aluminium alloy. The tin-lead solder was then used in a statistical design of experiments which although a far less industrially useful metallic alloy with respect to casting applications proved useful in inferring the results onto other alloy systems. The critical process parameters selected for examination were filling pressure, mould preheat temperature and melt superheat temperature. The design of experiments method was used to arrive at the more optimal values for the process. A two level three-parameter factorial analysis (23) was carried out resulting in eight experiments in total. Response variables chosen for analysis were measured dimensions of the produced castings. A Vernier callipers and micrometer screw (both accurate to +/-0.01mm) were used for all measurements. The casting dimensions were related to the mould dimensions and CAD file dimensions. The effects of each factor on the response variables were analysed.

Mould design and fabrication

A four-stepped cavity mould design which was used in this work is shown in Figure 1. The first step section, nearest the pouring basin, was 8mm thick. Each subsequent section was 2 mm less thick (providing 6, 4, and 2 mm thick steps respectively). Each step was 35 mm long and 100 mm wide. The total cavity length was 140 mm. Wall thickness of the surrounding cavity (including a printed flat plaster base plate) was nominally set at 10 mm. The wall thickness was larger by the amount indicated above for the smaller steps. A 40 mm diameter sprue was used. Three millimeter diameter holes, central to each step, which ended four millimeters away from the cavity, were incorporated in the mould. These were used to take temperature measurements along the length of the mould during pouring. Type K thermocouples were used for these measurements. Two vent holes, one millimeter in diameter, were also incorporated at either side of the last step in the mould cavity. Figure 2 shows a picture of the mould, thermocouples and casting set-up.

The machine used to manufacture the plaster moulds was the Z402 three-dimensional printer. The 3D printer used STL files of the CAD mould design to produce the plaster parts. The mould production time was typically about 3.5 hours. Once the machine cycle was complete the part was left to dry for between 30 minutes to 1 hour before being depowdered. The moulds were left to air-dry for one day to obtain sufficient strength before casting.

Materials

The principal mould ingredient was calcium sulphate (plaster) powder. Calcium sulphate consists of two different hydrate forms and an anhydrous form. The dihydrate form ($CaSO_4$-H_2O) or gypsum when heated above 128 °C (equilibrium temperature) loses 75% of its water to form the hemi hydrate ($CaSO_4$-$0.5H_2O$), plaster of paris. When it is heated above its equilibrium temperature of 163 °C all of the water of crystallisation is removed producing the anhydrous calcium sulphate ($CaSO_4$). The 3D printing machine printed binder to bind the powder in consecutive 2D layers to build up the mould. The alloys used for these tests were solder alloy Sn-10%Pb and aluminium alloy A356 (Al-7%Si-0.4%Mg). The high silicon content in A356 provides for excellent casting properties including fluidity. The melting range (solidus to liquidus temperature) of the Sn-10%Pb alloy was 183 to 235 °C and that of A356 was 572 to 614 °C.

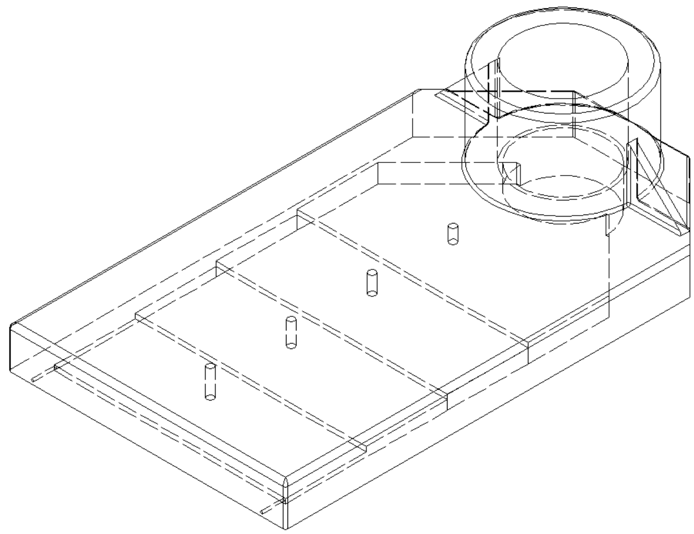

Figure 1 Mould design used in casting experiments.

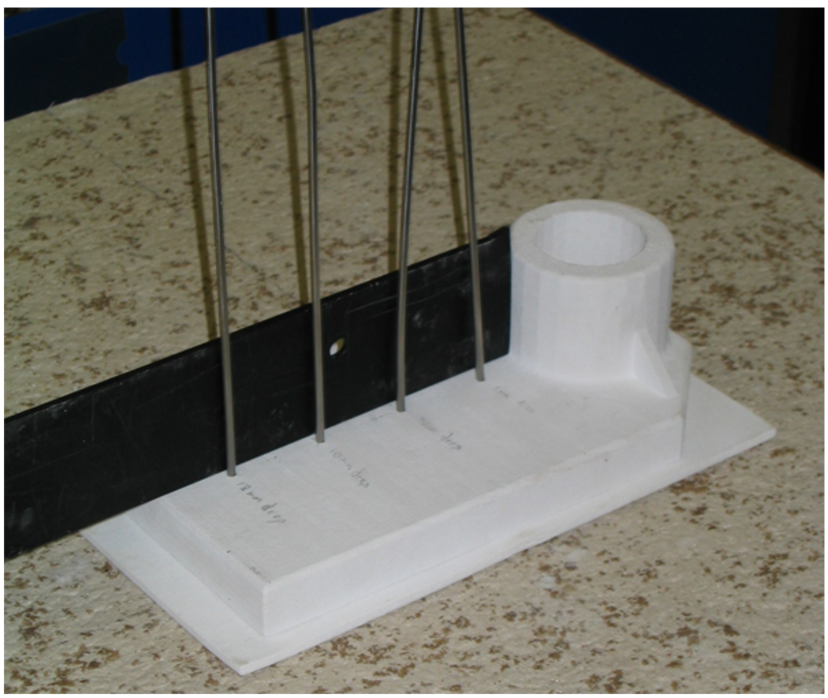

Figure 2 Mould, thermocouples and casting set up.

Casting conditions

Two furnaces were used in the casting process. One was used to dry and preheat the moulds while the other was used to melt the alloy. The moulds were heated for one and a half hours at the preheat temperature to ensure that all moisture had evaporated and that the mould temperature was homogenous. For the casting trials, a 3 kg weight was placed on top of the mould and fire clay was used to seal the mould edges. In the aluminium casting trials, a casting temperature of 725 °C was found to result in successful castings being formed. Initial tests determined that the minimum temperature at which the Sn-Pb melt could be successfully poured without premature freezing was 235 °C. The time for which the alloy was heated was also approximately one and a half hours, half an hour to reach temperature and one hour to ensure temperature homogeneity. Pouring time was approximately 8 - 10 seconds. Surface dross was skimmed off before casting.

Table 1 shows the set of parameters examined and the levels at which each parameter was tested for the Sn-Pb design of experiment castings. The response variables used were the dimensions of the mould and casting such as the length to which the metal filled into the last step. This was quantified by measuring the average length that the melt flow progressed during casting. This average was calculated as the average of five distance measurements taken along the casting (side lengths, middle length and length measurements half way between these). The locations at which other measurements were taken are indicated in Figure 3. Measurements of step heights were also taken and are denoted herein as D1, D2, D3 and D4, for step heights 1 to 4 respectively. The measurement process involved taking three repeated measurements at these positions in ten repeated mould fabrications and corresponding positions in the cast part.

Table 1 Levels of factors used for design of experiments

	Low Level	High Level
A: Mould Temperature (°C)	158	183
B: Melt Temperature (°C)	240	250
C: Pressure (Pa) *	1379	5517

* Low pressure: 20 mm melt head and high pressure: 80 mm melt head

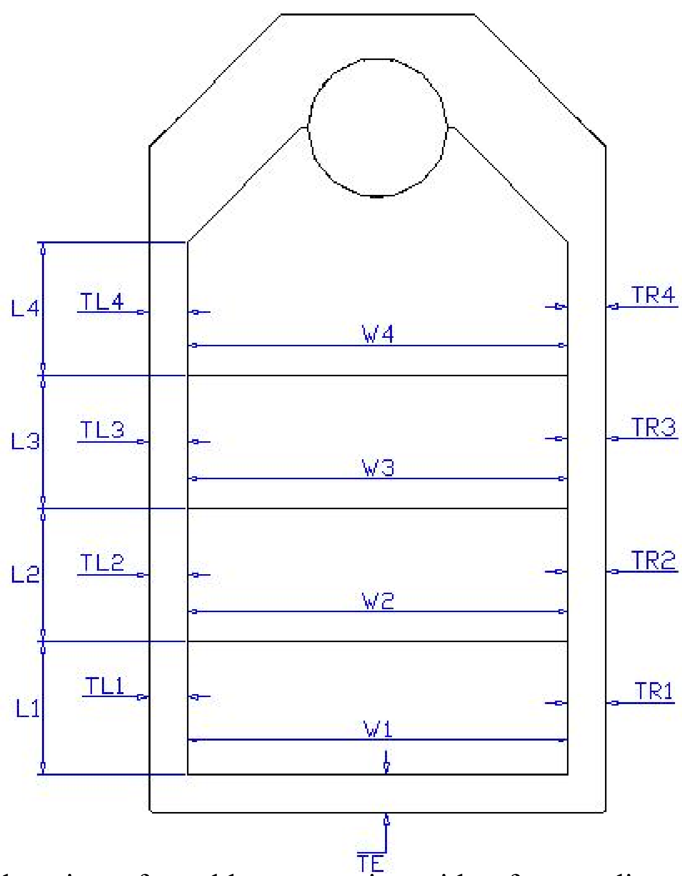

Figure 3 Plan view of mould cross section with reference dimensional tags.

Results and Discussion

During initial aluminium casting trials, some tarnishing of the cast surface resulted due to burning of the mould in contact with the metal. After testing at different temperatures in the furnace it was noted that, if left for sufficiently long periods, burning on the surface of the mould was seen to occur at temperatures above 200 °C. This tarnishing of the casting was overcome by applying very thin (< 0.1 mm thick) surface coatings of graphite in one instance and zircon in another to the mould surface. Although the mould colour faded during casting, it did not excessively burn and the mould coatings protected the casting surface. It was also clear from these aluminium casting tests that the positioning of the vents at the end of the mould was critical to mould filling in order to allow evolved gases to escape. Two one millimeter through vents were placed at the end corners of the mould for all subsequent tests. The lower temperature Sn-10%Pb alloy was also used for the rest of the tests presented below. Mould burning did not occur excessively in this case due to the lower pouring temperatures and so no mould wash (thermal barrier) was used.

Visual Inspection

As occurs with conventional plaster casting, the mould material adhered to the surface of the cast part. After the cast part cooled, water was used to convert the hemi-hydrate plaster material to its soft hydrate form which was easily detached from the cast part. Dross appeared in the gating system and the castings were judged to be largely free of surface dross. A picture of one of the castings is shown in Figure 4. The castings picked up the mould features very well as is typical of plaster casting.

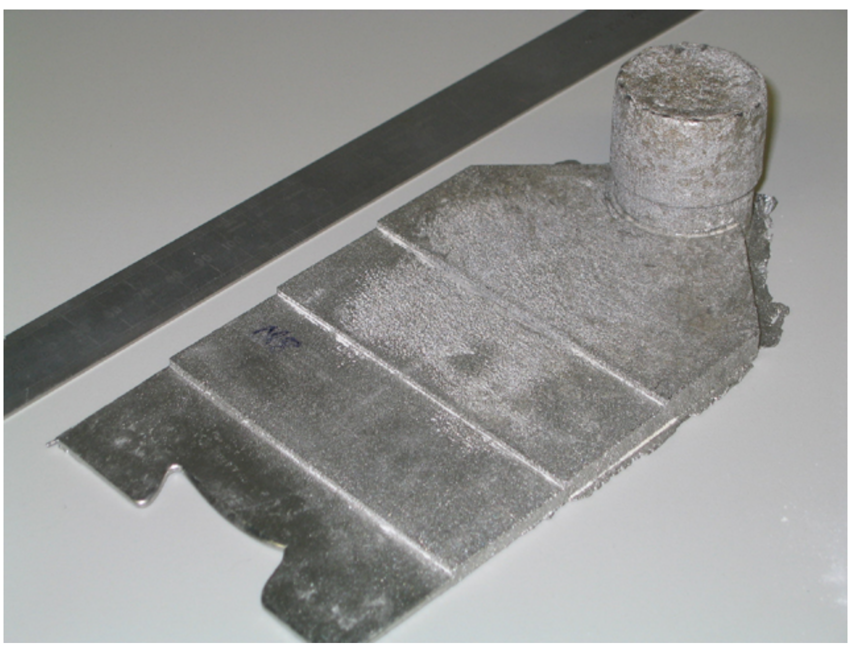

Figure 4 Isometric picture of casting run number three which was processed at the low mold temperature, high pouting temperature, and with low pressure.

Thermal measurements

Temperature profile recordings confirmed the amount of time required for each casting was between within 8 to 10 seconds. A thermocouple which was pierced though the mould also indicated a steady 70 ºC temperature difference between the solidifying metal in the mould cavity and the thermocouple four millimeters away in the plaster mould.

Dimensional Accuracy

The dimensions of produced moulds and castings were compared to the corresponding CAD file dimensions. Table 2 shows the average amount by which the mould and casting dimensions differed from those specified above in the casting conditions section above. The measurements taken from the moulds reveal that the average dimensional accuracy of the printing process was ± 0.22mm. The thin sections of the mould were found to be smaller than corresponding CAD file dimensions. For example, the mould walls were approximately 0.22 mm less than specified in the CAD file. The increase in the mould cavity internal dimensions could also be attributed to this mould contraction and warping. Where the mould filled fully, the casting dimensions were slightly larger than the corresponding CAD file dimensions. The widths and lengths of steps were in general of similar measurement and accuracy to those found in the fabricated moulds. The thickness of each step was however approximately 30% greater in the castings compared to the CAD file dimensions. The length of fill of the last step was dependant on the casting conditions.

The dimensions of the last step are shown in Table 3 for each of the design of experiments casting conditions. The final step (step 1) fill distance (L1) was found to be the best discriminator between different casting conditions. The final step fill distance, width and thickness were lower at the lower pressure and superheat levels. For the two levels examined, the mould temperature was not found to have much effect.

Table 2 Average dimensional accuracies found in the moulds and castings (ref Figure 3).

Dimension	**Mould Dimensional Accuracy (mm)**	**Casting Dimensional Accuracy (mm)**
TE	- 0.22	
TL1	- 0.17	
TL2	- 0.21	
TL3	- 0.23	
TL4	- 0.30	
TR1	- 0.15	
TR2	- 0.18	
TR3	- 0.19	
TR4	- 0.23	
W1	**+ 0.20**	**+ 0.24**
W2	**+ 0.24**	**+ 0.18**
W3	**+ 0.26**	**+ 0.21**
W4	**+ 0.29**	**+ 0.17**
D1	**+ 0.23**	**+ 0.66 (33%)**
D2	**+ 0.20**	**+ 1.19 (29.7%)**
D3	**+ 0.18**	**+ 1.84 (30.7 %)**
D4	**+ 0.30**	**+ 2.40 (30.0 %)**
L1	**+ 0.11**	**- 3.94**
L2	+ 0.14	
L3	+ 0.11	

Table 3 Processing conditions and dimensions of the associated castings.

Run	Mould Temperature (°C)	Metal Superheat (°C)	Pressure (Pa)	Step fill distance (mm)	Step width (mm)	Step thickness (mm)
1	158	240	1379	23.95	100.23	2.49
2	183	240	1379	24..55	100.02	2.40
3	158	250	1379	28.72	100.21	2.51
4	183	250	1379	34.75	100.32	2.55
5	158	240	5517	34.75	100.35	3.27
6	183	240	5517	32.55	100.31	2.57
7	158	250	5517	34.50	99.88	2.75
8	183	250	5517	34.75	100.57	2.73

Statistical Analysis

A model of the following polynomial form was used for the statistical analysis

$$y = \mu + q_1 A + q_2 B + q_3 C + q_{12} AB + q_{23} BC + q_{13} AC + q_{123} ABC \quad (1)$$

where A, B, C represent the mould temperature, melt temperature and pouring pressure; AB, AC, BC, and ABC correspond to the interaction effects of the factors on the response variable; q values are determined model coefficients; and the response variable, Y, is the last step fill distance. The software used to analyse the data was Dataplot, a data analysis program. The coefficients for the above equation are shown in Table 4 and the degree of fit is shown in Table 5. The sum of the square total, equation 2, and that fraction of the variance, equation 3, associated with the each factor demonstrates the level to which the factor effects the response. The F-statistic is the mean square for the factor divided by the mean square for the error.

Table 4 Coefficient effect table where T = q/σ (effect/standard deviation).

Identifier	Mean Effect (q coefficient)	T Value
Mean	31.06500	8.2
C	6.14500	5.7
B	4.23	-4.4
BC	-3.255	-2.9
AC	-2.145	2.6
AB	1.97	2.6
A	1.17	1.6
ABC	-0.745	-1.0

The results from statistical analysis show that the most significant factor in effecting the mould fill level was the pressure followed by the superheat level. This was apparent from the dimensional measurement analysis of each casting as presented in casting dimension results section above. From the residual sum of squares and F statistic values (Table 5) for each factor it is also clear that random error in the experiment had a significant effect in the experiment. The reliability of these results must therefore not be overestimated.

Conclusions

Mould dimensions were found to be accurate to within ± 0.22 mm for all the moulds produced. This value is higher than the best to which the 3D printing process is capable of, now less than 0.1 mm. The accuracy that can be obtained depends however on the mould dimensions. Combinations of thick and thin sections can lead to loss of dimensional accuracy due to shrinkage and warpage. The usefulness of the 3D printing process in developing plaster moulds for rapid casting has been demonstrated. A model has been generated which allowed the relation between processing parameters and casting success to be evaluated. This was measured by the extent to which the process produced casting dimensions close to those of the original CAD file dimensions. Statistical analysis of the results revealed that the dominating factor affecting the extent of mould fill in the casting process was the pouring pressure. The next most significant factor was the melt superheat. The mould temperature was not found to have much effect on casting dimensions. However, the strength of the mould material was seen to vary with temperature which may impact on casting dimensions for higher pressure castings. Further work is also necessary to extend the range of materials to which this process can be applied.

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