RAPID CASTING OF LIGHT METALS: AN EXPERIMENTAL INVESTIGATION USING TAGUCHI METHODS

S. Singamneni, O. Diegel, D. Singh and N. McKenna
School of Engineering, AUT University (Auckland University of Technology), Auckland, New Zealand

Abstract

The phrase 'rapid casting' is being increasingly used to represent specific casting processes designed to reduce the total manufacturing lead time, by expediting selected critical steps. Rapid Prototyping (RP) is the means through which this is achieved, either directly or indirectly. There have been sporadic reports on this topic in the recent literature, but since the approach has the potential for considerable savings in production time, it offers opportunities for more design freedom in terms of patternless moulding, a scientific understanding of the process needs to be developed. This paper is an attempt in this direction, considering the rapid casting achieved by direct printing of sand moulds from Computer Aided Design (CAD) models, using 3D printing. The mould performance when used to cast light metals such as aluminium and magnesium under varying conditions is studied in terms of mechanical characteristics and surface quality of the castings. Taguchi L9 experimental design is used to consider the total number of factors and the size of the resulting experimental designs. The results indicate the suitability of patternless moulds for casting aluminium and magnesium alloys without any loss of essential characteristics, but the process variables have a complex influence on the overall outcome in each case and the best results can only be obtained by the optimum combination of factors in each alloy system.

Keywords: *rapid prototyping, casting, manufacturing, 3D printing*

Introduction

Rapid casting is one possible route to rapid manufacturing, the potential revolution in manufacturing processes in the near future, due to the brisk developments occurring in additive manufacturing processes. Additive manufacturing or layer manufacturing techniques have the unique capability to produce very complex shapes with low melting materials such as polymers and wax or powdered metals, such as titanium or steel. Common additive manufacturing techniques were able to produce complex shapes with relatively easy melting materials which led to the production of sacrificial patterns for investment casting and the replacement of time consuming manual patternmaking with Laminated Object Manufacturing (LOM). Direct production of sacrificial moulds followed next with processes such as Selective Laser Sintering (SLS) and 3D printing for the patternless production of complex sand moulds directly from CAD files. This paper focuses on the latter process and attempts to establish the effectiveness of casting light metals (i.e., aluminium and magnesium) through experimental evaluation of casting characteristics using a multi-factorial approach.

The initial application of Stereolithography (SLA) for the production of a sacrificial pattern with a non-engineering plastic[1] and the subsequent extension of the same approach using other RP techniques[2] have produced promising results in terms of dimensional accuracy and surface finish, apart from significant time savings gained. Shell cracking resulting from the thermal expansion of patterns during burnout[3] and the chemical attack of the ceramic shell by ABS (acrylonitrile butadiene styrene) RP patterns from corrosive degradation[4] were some of the other intriguing questions being investigated subsequently. While the residual ash content (2.218%) was typical of the Fused Deposition Modelling (FDM) pattern, compared to traditional foundry wax (0.04%), higher burnout temperatures were expected to lower the residual ash content.[4] Overall, elimination of hard tooling, leading to significant time and cost savings, without any appreciable loss in the dimensional quality was reported for small run production.

Though direct production of sand moulds or shells was attempted by using SLS and 3D printing, early research attention was focused on the SLS process, targeting renewed design freedom, reduced lead times, and costs.[1] While the initial trials assured sufficient dimensional accuracy and repeatability, the surface quality was adversely affected due to the stair-step effect resulting from the mould walls. Intake manifold moulds for a KTM 525-cc single cylinder engine were produced using an EOSINT S700 SLS machine using silica Croning sand resulting in an adequate casting and moulds with good gas permeability.[5] Production of V6 cylinder blocks using aluminium, grey iron and compacted graphite iron through rapid prototyped moulds using the EOS S700 SLS machine proved that the cylinder heads were similar in all aspects to traditional prototypes, but reduced manufacturing lead times from 4-6 months to 2-4 weeks.[6] Investigations led to an understanding of the bonding mechanism of sintered moulds[7] and are indicative of the relatively easy melting of surfaces of the sand particles due to the presence of inclusions such as Al_2O_3, forming a salt-like eutectic with the SiO_2. Taguchi experimental evaluation[8] of the influence of process parameters on significant properties such as strength and permeability of LASER-CORN resin-coated quartz sand particles processed on an EOSINT S700RO SLS machine revealed that the compressive strengths were equal to or better than those of traditional moulds, and that the permeability was considerably higher than referenced industry standards for synthetic sands.

The other RP process that allows direct production of patternless moulds from CAD models is 3D printing by Z Corporation and notably, the potential application of 3D printing for the direct production of ceramic shells as patternless moulds for metalcasting was identified very early by Sachs et al.,[9] while investigating the Direct Shell Production Method. Curodeau et al.,[10] used 3D printing to produce ceramic shells within hours, without the use of any pattern and used the alumina ceramic shells to cast orthopaedic prostheses with CoCr. A comparison between 3D printing and SLS reveals that the SLS technology is expensive, requires long processing times and high power usage. Since Z Corporation offers a ceramic mould material suitable for casting nonferrous metals and alloys, 3D printing finds renewed interest as a means of rapidly producing patternless moulds. Kochan[11] took an early look at the 3D printing process and elaborated on the effectiveness of the process particularly in terms of the build size and the processing time. The ability to cast nonferrous metals into moulds produced directly from CAD files meant considerable time savings, rapid casting of prototypes (using realistic materials), and economical and rapid production of small production runs (10-20 parts). Bak[12] notes that 3D printing is far superior in terms of production capability, compared to SLS and the capability to produce local tooling to facilitate short production runs. Considering the production of 50 dispensing manifolds, it was observed that 3D printing was an effective and economical solution, with tolerances around ±0.38 mm and surface roughness of 200-300 µm.

Lyons[13] compared the green strength and the response of moulds produced by 3D printing to conventional coatings (i.e., paste wax and polyvinyl alcohol) and found that printed moulds can be made to reasonable tolerances. Thermal distortion testing by Rebros et al.,[14] of printed sand moulds using silica sand and a furan binder printed on a ProMetal S15 rapid casting machine in comparison with chemically bonded sand using Phenolic-Urethane Cold Box (PUCB) showed thermal cracking in both samples at elevated pressures and temperatures leading to distortions in specimen shapes. While testing after 90 seconds did not show significant differences between the two sand systems, thermo-mechanical effects and distortions in overall dimensions were higher in the sand produced by the PUCB process.

Once the effectiveness of 3D printing in producing quick castings of nonferrous metals and alloys was established, further research was undertaken to establish the mould and casting characteristics obtained using the rapid casting methods. Bassoli et al.[15] while comparing the relative merits of producing an automotive part, by direct casting into printed moulds and indirectly through the use of a printed starch pattern for investment casting, reported an average surface roughness of 10 µm for the castings made from printed moulds. A benchmark model was used to assess accuracy indicators such as: surface profile, circularity, concentricity, and angular tolerance of parts produced from materials like starch (ZP14) and plaster (ZP100) on a Z400 3D printer, Dimitrov et al.[16] showed that material type, build direction, and magnitude of measurement contribute to deviations in measured accuracies. Plaster-based powders were found to yield higher accuracy, possibly due to finer grain size, while both materials yielded parts that were slightly larger than the original CAD models, though an intelligent selection of the scaling factor could easily resolve this issue. Comparative assessment of the surface quality of castings produced from moulds made by traditional means and printed using ZCAST 501 showed that the surface roughness is slightly higher in the case of RP moulds resulting in a Ra (Ra = arithmetical mean roughness of a surface) value of 14.9 mm compared to 13.6 mm obtained in traditional moulds, possibly due to the stair-step effect of the layered manufacturing technique.[17]

It is apparent that most research in rapid casting methods thus far, is limited to either establishing the effectiveness of a particular technique in the rapid production of functional castings or the evaluation of the surface roughness or dimensional stability of the castings in a few cases. Clearly, the advantage of rapid casting in small run production systems is obvious; these methods are gaining popularity and most likely will become important production techniques suited to specific manufacturing tasks. While traditional casting methods offer a vast amount of data on the mould and casting characteristics, influences of process parameters on key responses and optimum conditions in various situations researched over the past decades, these new mould materials and the rapid casting process lack sufficient information for the foundry practitioners to appropriately choose process conditions. Research into the mould materials characteristics using ZCAST501 conducted by the current authors[18,19] allowed the evaluation of optimum baking time and temperature for the material ZCAST501, suggested by Z Corporation for moulding purposes. While permeability was a bit low, compressive strengths obtained at approximately 1 MPa were acceptable and the optimum baking time and temperature were found to be 227C (440.6F) for 6.2 hours and 173C (343.4F) for 5.5 hours for the best permeability and compressive strength.

Further work in similar lines by Bassoli and Atzeni[20] analysed the compressive strength of cylindrical samples printed using ZCast 501 and baked at 160-250C (320-482F) for 4-8 hours led to the observation that the compressive strength decreases with increasing baking time and temperature. Compressive strengths of baked samples ranged from 2.6-6.2 MPa, much higher than those observed by the current authors. Thermogravimetric analysis showed temperature as the primary influencing factor during baking with respect to compressive strength. Samples lost 6-7% weight after baking for 4 hours at 150C (302F), but the current authors observed that baking time is also significant.

Kaplas and Singh[21] investigated the effectiveness of shell moulds printed using ZCAST 501 and cured at 110C (230F) for one hour, and reported that a shell thickness of 2mm was sufficient while casting zinc, and radiographic testing of castings showed decreased shrinkage and gas levels at lower shell wall thickness. Effectively, lower wall thickness means lower cost moulds, leading to a time and cost savings of almost 40%. Aluminium was cast into printed shell moulds and moulds produced from sacrificial patterns printed using starch on a Z Corp 310 Plus 3D printer and the tolerance ratings in both cases were found to be within normal limits.[22] Surface roughness values of castings produced using the investment casting technique were a slightly lower, around 4µm, when compared to direct printed moulds, showing an average roughness of around 7µm. The shell thickness, when reduced from 12 mm to 6 mm was found to offer better dimensional stability and mechanical properties, possibly due to an enhanced heat transfer rate. Similar results were also obtained while casting lead.[23]

While 3D printing of moulds appears to be promising for quickly producing functional prototypes and end-use parts in small quantities with specific metals though rapid casting, there is very little information available on the actual process, the mould metal interactions and the significance of process parameters. While most existing research is centred on aluminium, there was no significant attention paid to other light alloy systems, other than a few trials with relatively less significant metals like zinc and lead. The ongoing research into mould materials suitable for both 3D printing and ferrous casting is yet to offer some solutions, it is clear that rapid casting is an immediate possibility with light metals, and it is time a scientific investigation into the effects of various parameters on the effective utilisation of the method was initiated. This paper reports the results of statistical experimental investigations carried out to establish the combined and individual influences of various factors such as mould materials, coatings and pouring temperatures, in combination with a few light alloys, on the effectiveness of the rapid casting procedure employing rapid prototyped moulds.

Mould Materials

Different grades of materials were supplied by Z Corporation for 3D printing, and all are proprietary materials, with limited information on the basic ingredients and overall properties. The ZCast 501 is the material approved specifically for 3D printing of moulds and mainly consists of $CaSO_4$, $0.67H_2O$ and $MgSiO_4$ in equal weight proportions. The normal grade for 3D printing for other purposes is ZP131, which is essentially plaster with a small quantity of crystalline silica and varying quantities of vinyl binder, carbohydrate and surface salt. The binding materials are essentially water-based solutions mixed with small quantities of glycerol, sorbic acid salt, surfactant, pigment as in the case of ZCast 501 or humectants, and a polymer as in the case of ZP 131. The basic chemistry and the bonding mechanisms in these material systems are not widely researched and reported as in the case of traditional foundry materials, but this is not the main objective of this research. For casting purposes, it is important to know the overall characteristics of the moulding material such as permeability and compressive strength, under varying baking conditions.

Earlier research by the current authors using response surface methodology[19] established optimum baking conditions for ZCast 501 as stated earlier. Sieve analysis results indicated a wide range of grain sizes, and the fine particles acting as interstitial material, would have adverse effects on the permeability. During the initial casting trials, it was a surprise to find that the plaster material ZP131 was also effective as a mould material and the aluminium castings produced were of much better surface quality. Based on this, ZP131 was also identified as a potential candidate for the 3D printing of moulds, and subsequent experimental evaluation in similar lines as in the case of ZCast 501, using central composite design, revealed that the best baking time and temperatures were 150C (302F) for 3.2 hours for the maximum permeability and 150C (302F) for 7 hours for the maximum compressive strength.

While the two material systems exhibited similar permeability and strength, ZCast 501 was slightly more porous than the ZP131 with mean permeabilities at 2116.7 mD (millidarcy) for ZCast 501 and 2099 mD in the case of ZP131. A T-Test on the permeability revealed high values of probability, at 0.9914, meaning that the two population variances are not statistically different and that the difference in the values are due to natural variation. The maximum compressive strength was higher for the plaster material, probably due to the finer grain size, consuming more binder due to larger grain boundary area and the T-Test resulted in high values of probability as in the case of permeability. Overall, the statistical testing on the repeated central points of the permeability and compressive strength models revealed that no significant differences exist between the two tested ZCorp materials, and ZP131 seems to be more rigid and much better in terms of the definition of the mould faces and edges. Also, the plaster gives a better surface finish, which was clearly evident from the initial casting trials. Based on all of these considerations, it was understood that both materials equally qualify as mould materials, and the following experimental evaluation of the system includes these two as possible experimental factors. The optimum mould processing conditions being already established, the next stage is to produce cast specimens using rapid prototyped moulds of optimum properties and subsequently conduct mechanical testing and micro structural examination to establish the overall suitability of these moulds to process light alloys and produce adequate castings.

Experimental Design and Methodology

The experimental design considers three significant factors, mould material, pouring temperature and mould coating, while three alloys are considered for casting. The approach is to establish the variation of responses such as tensile strength, surface roughness and microstructural appearance, as these factors are simultaneously varied at different levels, within the selected ranges. However, three of the four factors being qualitative in nature, traditional factorial experimental designs were avoided. The Taguchi L9 orthogonal array was finally chosen and each factor was varied at three different levels. This design allowed consideration of three different levels for each of the factors. While the two Zcast materials discussed in the previous section are combined with a traditional foundry sand to constitute the mould

Table 1. Taguchi L9 Experimental Design

L9 Orthogonal Array					Responses			
Trial no.	**Mould Material**	**Mould Coating**	**Alloy type**	**Temp. (°C)**	**UTS (MPa)**	**Elongation %**	**Surface Roughness, Ra (μm)**	**Brinell Hardness, HB**
1	ZP131	ISOMOL	AZ91HP	690	156.42	2.17	9.49	56.82
2	ZP131	ZIRCOAT	SC1	730	130.02	2.56	7.33	48.17
3	ZP131	MAGCOAT	A356	770	127.13	0.75	5.84	60.54
4	ZCAST	ISOMOL	SC1	770	127.99	2.28	23.66	48.87
5	ZCAST	ZIRCOAT	A356	690	132.05	0.85	11.47	65.70
6	ZCAST	MAGCOAT	AZ91HP	730	150.87	1.52	14.33	60.54
7	SILICA	ISOMOL	A356	730	93.27	0.73	12.63	52.63
8	SILICA	ZIRCOAT	AZ91HP	770	127.11	1.54	13.98	56.82
9	SILICA	MAGCOAT	SC1	690	157.39	3.36	11.79	47.48

Table 2. Compositions of Alloys Considered

Sl, No.	**Alloy Designation**	**Composition**												
1	**AZ91HP-F**	**Al**	**Zn**	**Mn**	**Be**	**Mg**								
		8.70	**0.80**	**0.25**	**0.001**	**90.25**								
2	**SC1-F**	**Nd**	**Ce**	**Zn**	**La**	**Zr**	**Mn**	**Pr**	**Fe**	**Ni**	**Cu**	**Si**	**Mg**	
		1.69	**0.71**	**0.50**	**0.40**	**0.38**	**0.13**	**0.07**	**<0.004**	**<0.001**	**<0.002**	**<0.01**	**96.10**	
3	**A356-F**	**Al**	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Ni**	**Zn**	**Ti**	**Pb**	**Sn**	**Sr**
		91.55	**7.36**	**0.325**	**0.027**	**0.022**	**0.463**	**0.008**	**0.021**	**0.015**	**0.0922**	**0.0275**	**0.0046**	**0.0477**

material options, Isomol, Zircoat and Magcoat are used as coatings. Two magnesium alloys, AZ91D and SC1 and one aluminium alloy A356 are the cast materials. As all these alloys have a similar melting and relatively similar ranges of pouring temperatures, temperature could be considered as yet another factor, with a narrow range of variation from 690 to 770C (1274-1418F). Each experiment was repeated four times and the L9 experimental design and average responses are all shown in Table 1. Compositions of different alloys considered are given in Table 2. Normally, experimental designs such as these aim at establishing optimum process conditions for the best values of end responses, in which case, different alloy systems would not be combined in the same experimental design. But the overall aim of the current experimental investigation is limited to find if any of these alloys exhibit any loss of essential mechanical characteristics when cast in RP moulds. These are initial trials to get an overall impression of the performance of the moulds, and so, cast metals are included as one of the variable factors in the Taguchi L9 experimental design.

The Signal to Noise (S/N) ratio is the measure of the robustness of a process and can measure the amount of variation due to uncontrolled (noise) factors. The S/N ratio is actually the transformation of the Mean Squared Deviation (MSD) which measures both the average and the standard deviation. The transformation takes into account the application; the higher the better (strength) or the lower the better (surface roughness) types of situations. The 'Higher is the better' S/N ratio is used to maximise the response and 'the lower is the better' S/N ratio is used to minimise the response.

$$S/N_{HB} = -10 \log_{10}\left(\frac{1}{r}\sum_{i=1}^{r}\frac{1}{y_i^2}\right)$$

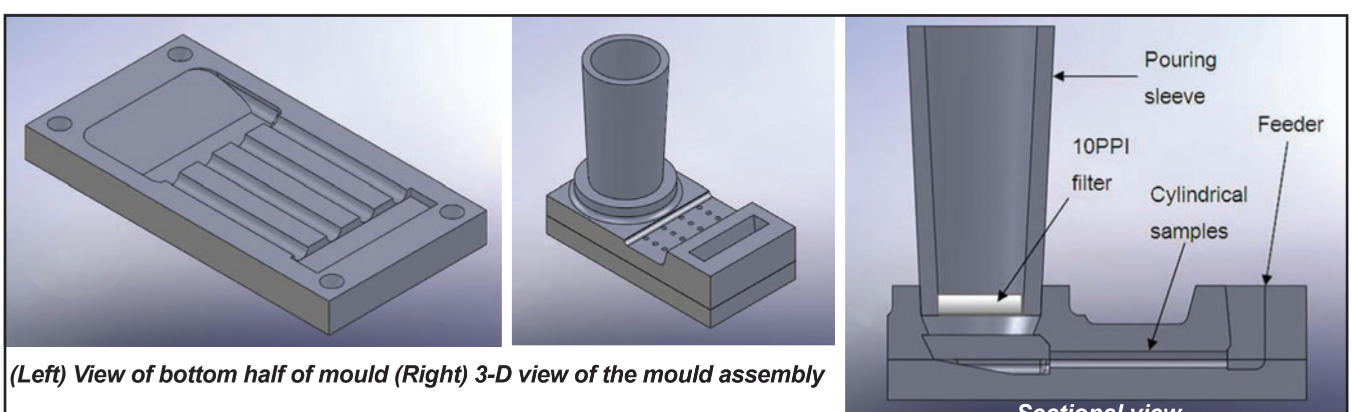
$$S/N_{LB} = -10 \log_{10}\left(\sum_{i=1}^{r} y_i^{2}\right)$$

Where:
S/N_{HB} = Higher is Better (HB) Signal to Noise Ratio
S/N_{LB} = Lower is Better (LB) Signal to Noise Ratio
y_i = Experimental Response
r = Each Response Repetition

The moulds for the current experiment are designed based on certain geometric relationships and experiences from prior testing. The final mould design, as shown in Fig. 1, comprises of a top gated inlet, cylindrical specimens for the final castings, and a feeder situated at the end of the cylindrical cavities to allow for metal shrinkage, during solidification. The mould was parted to form the upper and lower halves, located by means of aligning studs at all corners. Clamps are used at the centre to prevent any movement due to the buoyant forces of the molten metal. Vent holes are also added along the length of the cylindrical specimens to improve permeability and help release gas build-up if any, inside the cavity.

The casting trials were conducted using the induction furnace available at AUT University, with a custom made 1040 carbon steel crucible constructed for the purpose of melting the two magnesium alloys, as a refractory crucible might lead to unwanted reactions. The temperature of the crucible was controlled by the machine controls and a CKY 500 K type thermocouple was used to check the temperature of the liquid metal before pouring. Each 3D printed mould was baked at the optimum values of time and temperature obtained from previous experiments. The foundry sand used was silica sand bonded by an ester hardened alkaline phenol-formaldehyde polymer resin. In the case of magnesium castings, the molten Mg was covered by an inert gas, in this case a mixture of CO_2 and HFC 134a (R134 Refrigerant) as per the recommendations by ASM, American Society for Materials. Foseco MAGREX 36 flux was also used to stop any violent combustion once the metal was brought up to its melting point and as a means of controlling fire incidents if any. The molten metal was filtered with the use of a 10 PPI ceramic foam filter near the bottom of the ceramic pouring cup. The pouring cup was also coated with the mould dressing to avoid any reactions with the molten magnesium.

Once each casting was completed, the risers and sprue were cut off using a hacksaw and each cylindrical specimen was turned on a lathe into a tensile test specimen. Before machining however, the cylindrical cast specimen surface was tested for quality by Taylor Hobson Form Talysurf50. Machining of the tensile specimens was then conducted with low speeds and feed rates and a coolant to avoid excessive



(Left) View of bottom half of mould (Right) 3-D view of the mould assembly

Sectional view

Figure 1. The final mould design for the current experiment is shown above.

heating of the alloys. The tensile testing was carried out on the Hounsfield equipment at AUT University and the loading rate was 1mm/min in all cases.

Results and Discussion

For each experimental response, calculation of S/N ratios and Analysis of Variance (ANOVA) identified the most significant factors and their corresponding levels at given confidence levels. Error terms in an experiment represent the degree of inter-experiment error when the degree of freedom is sufficiently large. When the error degree of freedom is small or zero, which is the case when all the columns (factors) in an orthogonal array are occupied, the small column effects are pooled to form a larger error term, which is known as pooling up.[30] In the current experimental investigation, the factor contributing the least sum of squares to the total sum of squares was pooled as the error. In most cases, this may have been higher than the recommended 10% of the maximum factor outlined by Ross.[31] It may also be noted here that none of the metal specimens received any heat treatment subsequent to being cast in the prototyped moulds.

Tensile Strength

The ANOVA calculations with the tensile strength analysis are presented in Table 3, and Fig. 2 depicts the S/N ratios calculated for the same. The ANOVA indicates that there are no significant factors at any of the tested confidence levels, suggesting that no single factor from the chosen variables was influencing the UTS (Ultimate Tensile Strength) and the variation observed is due to a combination of effects of all constituent factors. Based on the higher the better S/N ratio, results of Fig. 2 depict that

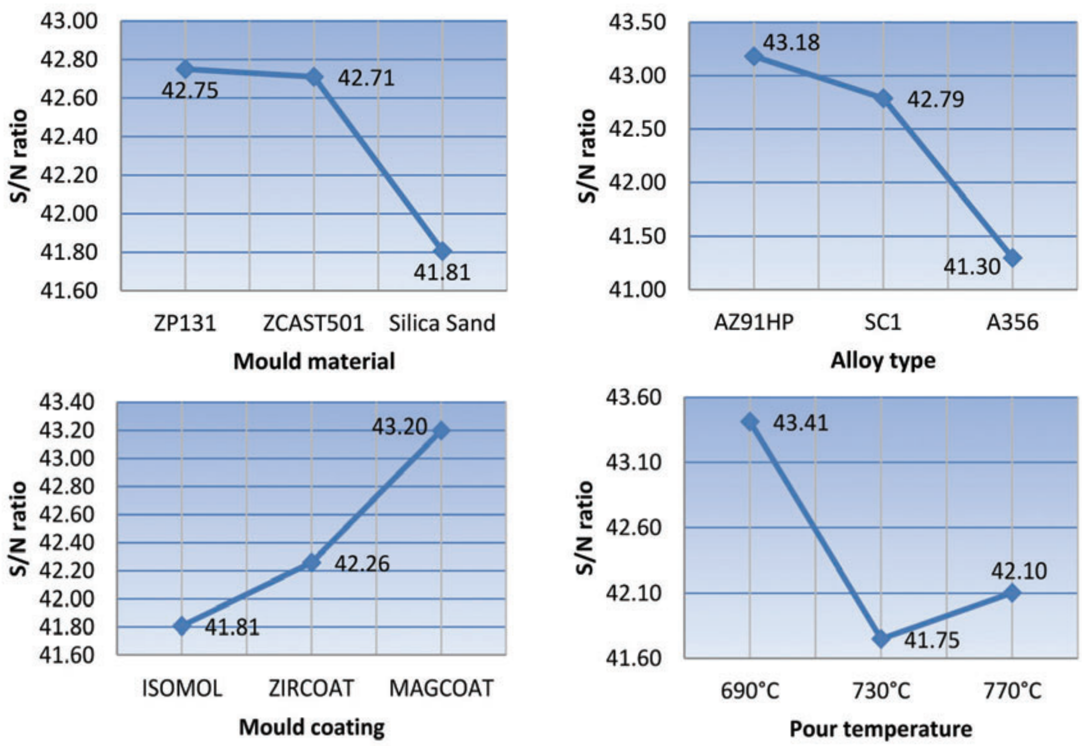


Figure 2. S/N ratios of tensile strength are shown in four graphs.

Table 3. ANOVA of Ultimate Tensile Strength

Rank	Source	DOF	SS	Variance	F_{Ratio}	P value	Percent Contribution
1	Alloy	2.00	5.92	2.96	3.46	0.22	38.77
2	Temp	2.00	4.61	2.30	2.69	0.27	30.21
3	Coating	2.00	3.02	1.51	1.77	0.36	19.80
4	Pooled Mould	2.00	1.71	0.86			11.21
	Total	8.00	15.26	1.91			100.00

AZ91HP, when poured at 690C (1274F), into a ZP131 mould coated using MAGCOAT achieved the maximum tensile strength. Aluminium alloy castings attained relatively lesser UTS values compared to normal expected levels. Metallographic examination of the aluminium samples suggests a modified eutectic morphology, as shown in Fig. 3. The initial suspicion was that aluminium was reacting with the mould materials, and perhaps, was not suitable for casting in these moulds.

The morphology of the plate-like constituent of Si particles appears to be a result of no strontium modification, perhaps due to strontium burn-off, which is a known phenomenon. The resulting large brittle, plate-like silicon structure is detrimental to the mechanical properties.[24] The silicon needles are believed to promote stress concentrations, leading to a reduction in material toughness and typical brittle fractures.[25] Fractography analyses indicate the presence of silicon particles on the fractured surfaces of current tensile test specimens, acting as centres of crack initiation and growth. Apart from the size and shape of the eutectic silicon particles, Fe intermetallics, manifested as large plate-like iron particles also affect the tensile and fracture properties of A356 alloys.[26] The size of the Fe intermetallics in A356 aluminium alloys depends on the cooling rate and the amount of iron present in the alloy. While higher cooling rates decrease the plate size, increasing iron content increases the same and an inverse logarithmic relationship exists between the Fe intermetallic particle length and the percent elongation and UTS of unmodified A356 permanent mould cast samples. From the photomicrograph in Fig. 4, obtained from one of the samples of the current work, an Fe intermetallic particle of around 200μm can be seen, which could lead to reduced ductility and strength.[27] Further, macro examination of the specimens revealed rounded and evenly distributed pores as shown in Fig. 5, indicative of hydrogen porosity, which could have led to the poor tensile strength, as there

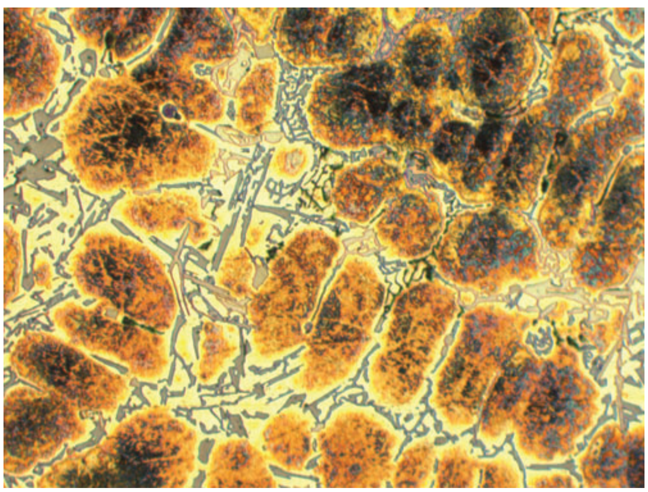


Figure 3. A356 casting produced in ZCast moulds poured at 770°C (1418°F) using Isomol 200 mould coating shown at 200X (σ_{UTS} = 134.30MPa δ = 0.74% HB = 66.70 Grain size: 2.45).

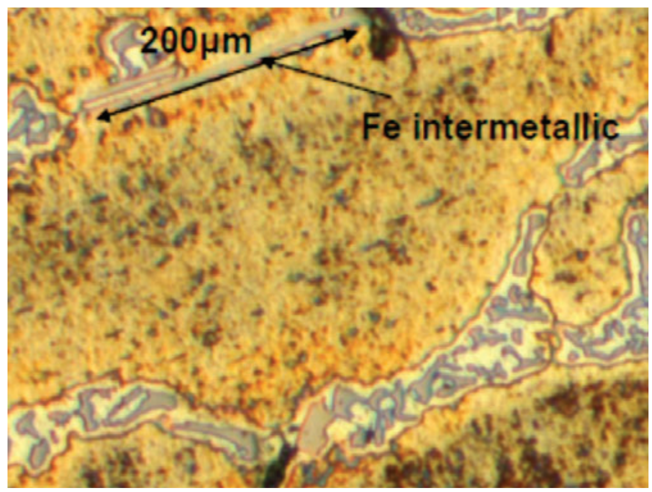
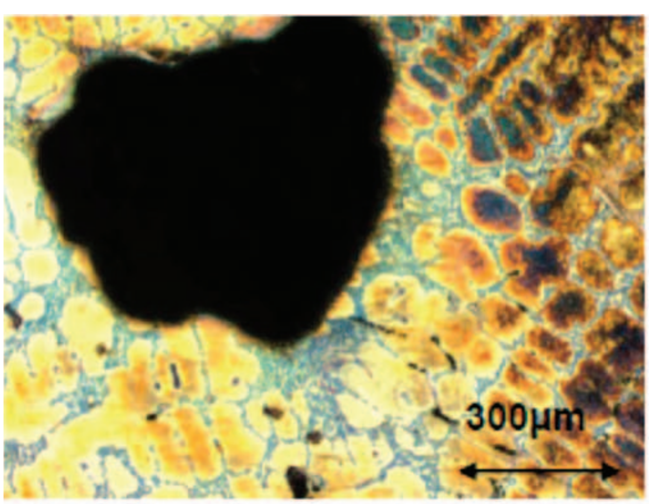
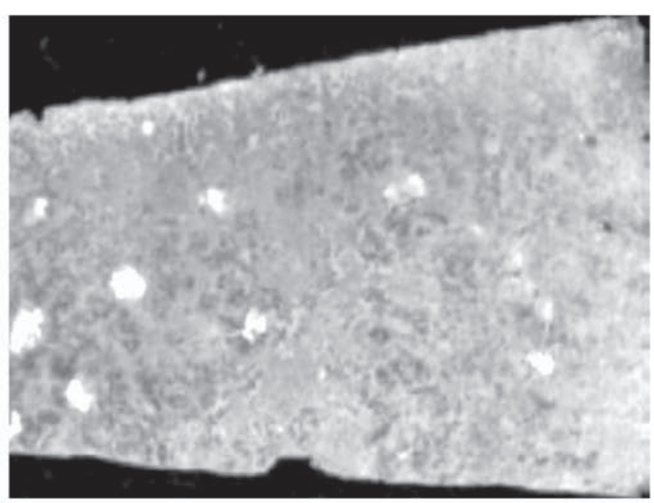


Figure 4. A photomicrograph showing plate-like Fe intermetallics in A356 casting produced in 3D printed moulds.



(Left) Microporosity



(Right) Macroporosity

Figure 5. These improperly degassed A356 specimens show signs of hydrogen porosity in micro and macro structures.

is again, an inverse logarithmic relationship between the pore size and the UTS.[26] Overall, the combination of the unmodified eutectic silicon, porosity and Fe inclusion led to the brittle fracture and poor strength of the aluminium specimens, indicating a poor melt quality rather than the ability of the RP process.

In fact, careful scrutiny revealed that the steel crucible made for magnesium was also used for melting aluminium, due to some constraints in handling metal pouring equipment, and there could have been some contamination of the alloy. Also, the lance degassing was found to be inadequate in effectively handling the gas porosity. Tensile testing conducted on A356 castings produced later with a correct treatment of the molten metal, involving rotary degassing, and the use of cleaning fluxes resulted in strength values at around 142 Mpa.

Surface Roughness

Table 4 presents the ANOVA for surface roughness and the variations of the corresponding S/N ratios are shown in Fig. 6. The pouring temperature has the least significant effect, and hence is pooled as the error term. It appears that the narrow temperature range and the relatively lower upper limit for the temperature did not result in any adverse metal mould reactions. On the other hand, the mould material came out to be the most significant factor at 95% confidence level in influencing the surface roughness, and as can be seen in Fig. 6, the ZP131 material is the most favourable in terms of the best surface quality. While this is an obvious result considering the grain size between the two 3D printing materials, the noteworthy point is that this material is not actually intended for casting as per the manufac-

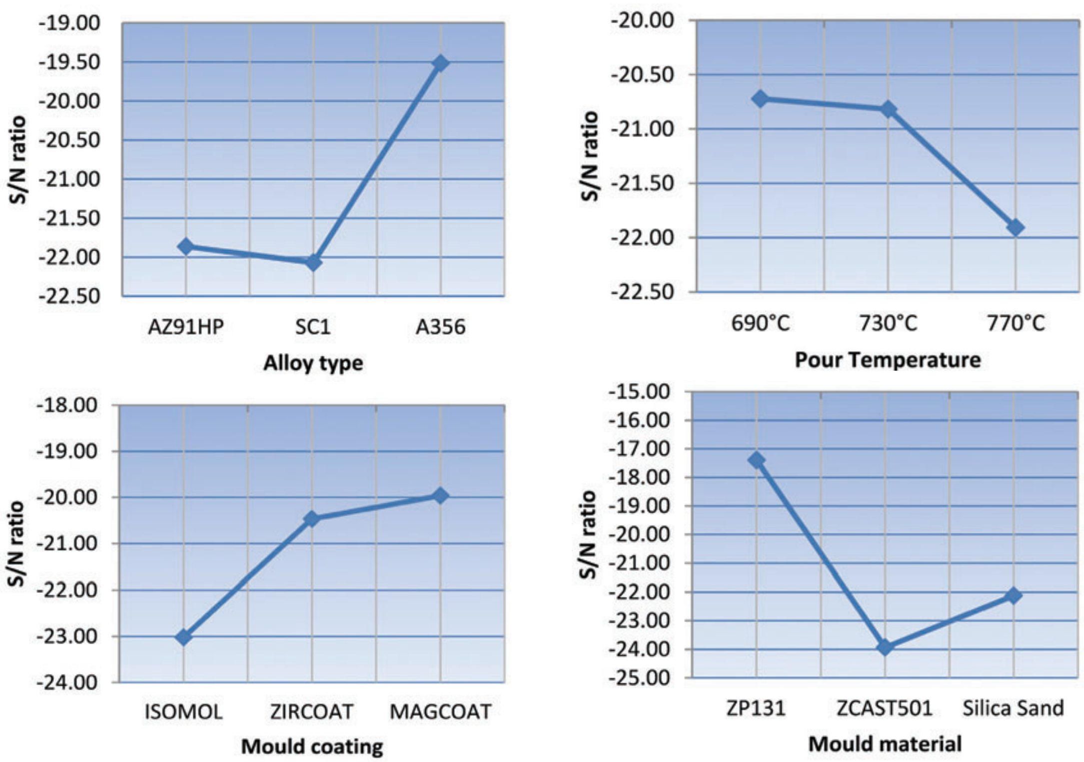


Figure 6. S/N ratios of surface roughness are shown above.

Table 4. ANOVA of Surface Roughness

	Surface Roughness							
Rank	**Source**	**DOF**	**SS**	**Variance**	**F-ratio**	**SS'**	**Significant**	**% Contribution**
3	Mould coating	2	16.12	8.06	6.20	13.53		13.63
2	Alloy	2	12.07	6.03	4.64	9.47		9.54
1	Mould Material	2	68.43	34.21	26.33	65.83	Yes 95%	66.35
4	Error Temp (pooled)	2	2.60	1.30				10.48
	Total	8	99.22					100.00

turer's specification and the outcome of this result is that ZP131 is not only suitable as a mould material for casting light materials, it gives better surface quality without any loss of other properties. Further, from the plots of Fig. 6, it is clear that the best combination of factors for the most favourable surface roughness is A356, ZP131, MAGCOAT and a pouring temperature of 690C (1274F).

The lower surface roughness obtained from ZP131 moulds can be attributed to the lower and more uniform grain size of gypsum particles. ZCAST 501, on the other hand has disproportionately larger sand grains and also suffers from easy mould wall erosion due to relatively lower bonding strengths. The degree of the spherical curvature of the added olivine sand, which is basically a crushed rock, is detrimental to the as-cast surface roughness. Scanning Electron Microscope (SEM) photomicrographs showed highly angular sand grains as shown in Fig. 7, surrounded by the finer gypsum powder.

The confidence level of the mould coating parameter shown in Table 3 is slightly higher than the common acceptable levels, but considering the S/N ratios, it is evident that magnesium oxide-based Magcoat product was the best suited in terms of achieving the best surface roughness (Fig. 7). A356 scored the best when it comes to the surface roughness and both magnesium grade alloys seemed to have undergone some mould-metal reaction. The propensity of Mg alloys to oxidise is governed by the Gibb's free energy change, and the application of a mould coating such as MAGCOAT can reduce this reaction by increasing this free energy.

Percent Elongation

ANOVA results on the percent elongation are presented in Table 5 and it is evident that the alloy factor came out to be the most significant, at 99 % confidence level. It may be reiterated that the analysis across different alloys is only meant to find if all the alloys considered are exhibiting the expected levels of ductility when cast in digitally printed moulds. While SC1 gave the maximum percent elongation, A356 fell short again, from the normal expected ductility levels probably due to the same reasons as explained previously, such as improper degassing and possible contamination from the crucible. In comparison, both mould coating and mould material contributed minimally to the overall variance and are pooled as experimental errors. For completeness however, the S/N ratios of these factors are also shown in Fig. 8. The best combination of other factors in favour of percent elongation is ZP131, MAGCOAT and a pouring temperature of 690C (1274F).

In terms of percent elongation, interestingly, SC1 outperformed AZ91. Alloy SC1 is a special alloy developed by the Australian Research Institute CAST, to increase the creep properties of magnesium in high temperature applications. Additions of special alloying elements such as zinc, lanthanum, cerium, and zirconium create a completely different secondary phase which is intended to act as a more rigid interlocking medium to resist grain movement.[28] The increased ductility in this case perhaps is due to this interlocking secondary phase, as against the brittle secondary phase Mg17Al12, common with the alloys of the AZ series.

Hardness

ANOVA and evaluation of S/N ratios considered in the same lines as above showed that the alloy factor is the most significant at 95% confidence level and within the alloys investigated, A356 castings attained the highest hardness values, followed by AZ91. Mould material was the second ranked factor, with ZCast 501 moulds resulting in the highest hardness, followed by ZP131 and silica foundry sand moulds. Mould coating and pouring temperature had the least significance on the hardness and hence were pooled as experimental error. In terms of actual values, A356 samples gave an average hardness value of 59.62 HB, closely followed by AZ91 at around 58.06, while SC1 was the softest, at 48.17 HB. These measured values of hardness are also close to the values reported in the literature at 60 HB for A356 and 50-65 HB in the case of AZ91HP.[29]

Overall Results

The overall trend of the experimental results is presented in Table 6, with factors ranked according to their relative statistical significances in influencing different responses. While this is a useful comparison of the performance of different alloy systems when rapidly cast using the 3D printed moulds, the overall observation is that 3D printed moulds can be effectively used for casting light metals and alloys and the casting characteristics are not much different from other processing routes. Within the combination of factors however, there are differences from one alloy system to the other. Keeping in view, certain limitations with the aluminium castings and within the experimental ranges and, AZ91HP and SC1 exhibited expected UTS and ductility levels respectively, while ZP131 is the most favourable mould

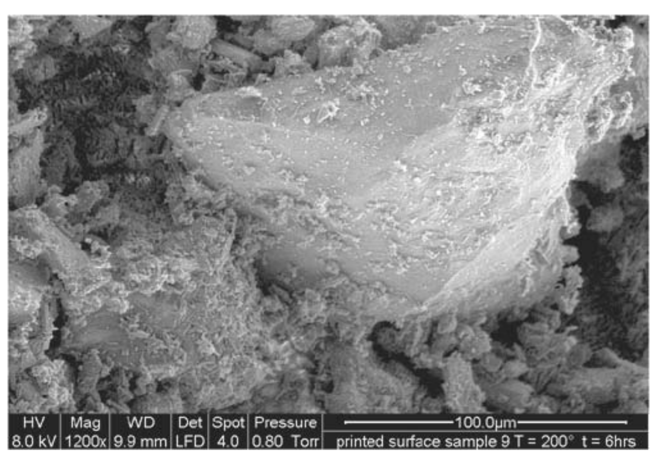


Figure 7. An SEM photomicrograph of ZCast 501: Large and angular olivine sand grains are surrounded by finer gypsum plaster.

material for the best surface quality. However, in most practical cases, parts are made of different alloys for different reasons and for each of the alloys considered, a preliminary assessment suggests that combining ZP131 as the mould material and MAGCOAT as the mould coating would give better surface roughness and ductility when poured at 690C (1274F). A complete optimisation of process variables for different alloy systems would require further research.

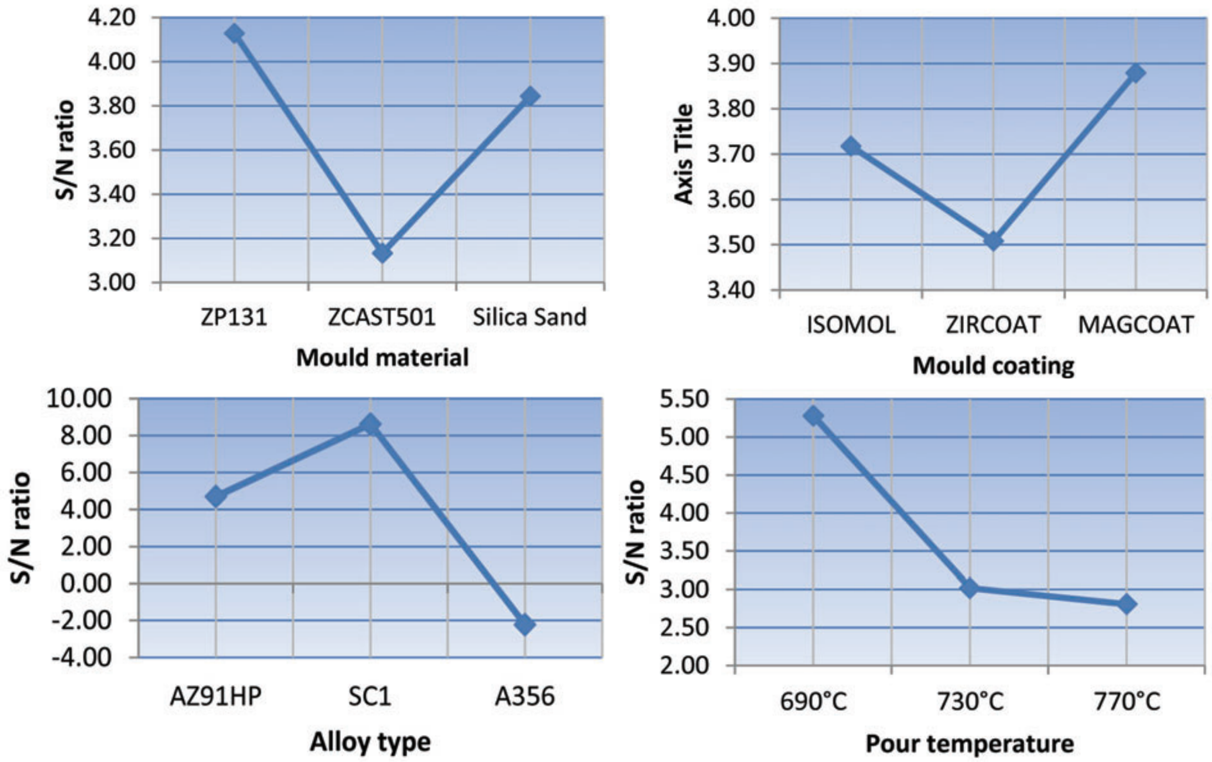


Figure 8. S/N ratios of percent elongation are shown graphically.

Table 5. ANOVA of Percent Elongation

	% Elongation							
Rank	**Source**	**DOF**	**SS**	**Variance**	**F-ratio**	**SS'**	**Significant**	**% Contribution**
1	**Alloy**	2	180.84	90.42	101.39	179.95	99.99%	92.81
2	**Temp**	2	11.27	5.63	6.32	10.37	90%	5.35
4	**Mould coating (pooled)**	2	0.21	0.10				
3	**Mould Material (pooled)**	2	1.58	0.79				
	Error	4	1.78	0.891				1.84
	Total	8	193.89					100

Table 6. Overall Ranking of Factors with Each Response

	Factors			
Response	**Mould material**	**Mould coating**	**Alloy type**	**Pouring temp.**
UTS	(ZP131) :4^{th}	(Magcoat):3^{rd}	(AZ91HP):1^{st}	(690°):2^{nd}
Strain	(ZP131):3^{rd}	(Magcoat) :4^{th}	SC1: 99.99%:1^{st}	690°C:90%: 2^{nd}
Ra	ZP131:95%: 1^{st}	(Magcoat) :2^{nd}	(A356):3^{rd}	(690°C):4^{th}
HB	(ZCast501):2^{nd}	(Zircoat):3^{rd}	A356: 90%:1^{st}	(690°):4^{th}

Conclusion

The application of 3D printing to produce patternless moulds is researched and proved to be a viable means of rapid casting of light metals. Effects of significant factors such as mould materials, coatings, and pouring temperature on principal casting characteristics are experimentally evaluated and statistically analysed together with a few light alloys. The best combinations of factors and their corresponding levels are identified for different conditions. The mechanical properties of aluminium and magnesium castings produced are comparable to those reported in the traditional casting literature. The following are some of the important observations:

- ZP131 moulds are best suited for processing Al and Mg in combination with a magnesium oxide based mould coating and a pouring temperature of 690C (1274F).
- The best surface roughness obtained is 5.84µm, using ZP131 with SC1, which is better than the normal 6-13µm.
- The optimum percent elongation is 2.56%, obtained in ZP131 moulds, again with SC1, which is also above the normal value of 2%.
- The best UTS is 170 Mpa, obtained while casting AZ91 in ZP131 moulds, which is also above the expected 160 Mpa.
- Overall, light metals can be cast in rapid prototyped moulds, without any significant loss of essential mechanical characteristics

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Technical Review & Discussion

Rapid Casting of Light Metals: An Experimental Investigation Using Taguchi Methods

S. Singamneni, O. Diegel, D. Singh and N. McKenna, School of Engineering, AUT University, Auckland, New Zealand

Reviewer: The choice of material is not a true variable for metalcasting and is likely predetermined by the application.

Authors: *Most of reviewer's comments on the choice of different casting alloy grades in the current experimental investigations are valid and represent true concerns. It is agreed that considering the cast alloy as a variable is not a valid experimental factor, provided the overall aim of the experiment is to find optimum combinations of all experimental factors, for the best values of specific responses. However, the main objective of the current experimental plan is to establish the validity of a relatively new casting technique for light metals processing under varying conditions. While mould materials, coatings and pouring temperature are the true variable factors, different alloys are included to simultaneously experience the process performance over a range of light metals. This approach, together with the use of Taguchi L9 design allowed rather economically, some preliminary experiences with using rapid prototyped moulds for different light metals casting. The experiment is not to find the optimum factor combinations for the best strength or other properties, but to establish, if essential characteristics with any of the alloys tested are lost due to any inherent weaknesses of the process, as yet unknown.*

Reviewer: The statistical analyses presented for UTS and elongation are a serious concern. It is not really appropriate to conduct an analysis of this type with different alloys. It also appears that metallurgical factors important for casting quality were over looked. The authors concluded that; "Overall, the combination of unmodified eutectic silicon, porosity and Fe inclusion led to the brittle fracture and poor strength of the aluminum specimens, indicating a poor melt quality rather than the ability of the RP process." What then, was the purpose of the preceding statistical analysis?

Authors: *The overall objective is to experimentally investigate the effectiveness of RP moulds for casting selected light metals. A separate set of experiments could have been conducted for each alloy system, considering variation of selected process parameters. As the total number of experiments in that case is high, and considering that these are initial trials to get an overall impression of the performance of the moulds, cast metals are included in the parameter set of a Taguchi L9 experimental design, from time and cost considerations. The statistical analysis on mechanical properties is conducted mainly to find if castings of any alloys considered produced inferior properties compared to their traditionally cast counter parts. While both alloy grades of magnesium showed no loss of properties, the aluminium alloy castings exhibited relatively poor mechanical properties. The metallurgical factors are considered as much as possible, and the aluminium melt was lance degassed, before introducing into the moulds, however, there were some practical difficulties due to insufficient facilities. This was reflected in the results of the post-mortem analysis on the aluminium castings, which revealed issues such as iron contamination and hydrogen porosity and hence the conclusion that it was due to these practical problems, aluminium castings did not fare well, but not due to any inherent inabilities of RP moulds. Further experiments with aluminium casting using ZP 131 moulds under controlled conditions revealed much better casting characteristics.*