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Optimization of the low superheat casting process parameters for producing of thixotropic a356 alloy feedstock

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ABSTRACT

In the present investigation, low superheat casting (LSC) was employed to produce A356 thixoforming feedstock with athixotropic microstructure. Optimization of the LSC process parameters was carried out to obtain suitable thixotropic feedstock for thixoforming process. The Taguchi's optimization approach has been employed to examine the influence of the LSC process parameters, typically, pouring temperature and mould material on the microstructural characteristics of A356 alloys, typically, the average size and shape factor of the primary α-Al grains. The level of significance of the parameters and optimum parameter combination were determined using analysis of variance (ANOVA) approach. Correlations for microstructural characteristics as functions of LSC process parameters were determined. The results revealed that the mould material is the most influential parameter on both the average grain size and shape factor of the primary α-Al grains. The pouring temperature has lower effect on the aforementioned characteristics than the mould material. There is no interaction between the mould material and pouring temperature. The developed empirical model was successfully used to predict the average grain size and shape factor of the A356 alloy ingots produced using LSC. A356 ingot poured at a pouring temperature of 620 °C in the copper mould exhibited the best microstructural characteristics suitable for thixoforming.

KEYWORDS

Low superheat casting (LSC);
A356 aluminum alloy;
Semi-solid Processing;
Microstructure;
Mechanical properties.

INTRODUCTION

Thixoformingand thixocasting are semi-solid processing (SSP) technologies used to produce near net-shaped components that haveseveral advantages over conventional casting routes. It has been reported that components produced using these techniquesexhibit more homogenous, non-dendrite microstructure, less porosity and improve mechanical properties[1-3]. However, the success of any thixoforming or thixocasting process depends on the producing of a special feedstock,with thixotropic properties, that has a fine globular particles of the solid phase surrounded by a continuous film of liquid[4,5]. Feedstock with thixotropic propertiescan be flow like aliquid when sheared which provide high fluidity and good castability[3-6]. Several commercial aluminum alloys such asA356 and A357 (Al-Si-Mg) cast alloy are used as thixoforming materials[6-8]. The A356 and A357 Al alloy have wide solidification range which makes them suitable for SSP. These alloys are widely used in fabrication of automobile components[2,3,9].

Low superheat casting (LSC) technique is one for reducing energy consumption and environment pollution to produceingotsfor thixocasting and rehocasting with thixotropic (non-dendritic) microstructure and high mechanical properties[10,11]. This technique has several advantages, for example, simple, cheap, low production cycle time, increased die life, and reduced porosity and solidification shrinkage[10]. LSC process utilizing low superheat technique without the need of the application of external shearing action as in magneto-hydrodynamic (MHD) stirring to produce thixotropic feedstock[3]. During this process, molten alloy with aslightly superheated temperature above liquidus temperature is poured and allowed to solidify in a mould. Ingots produced from LSC have thixotropic microstructure required for thixoforming.

The key processing parameters affecting the final microstructure of the feedstock during LSC process are pouring temperature and the mould material. From the industrial point of view, it is essential to find out the best combination of these parameters to attain the best microstructure of the feedstock that is suitable for thixoforming. Accordingly, the aims of the present investigation are to:(1) study the influence of both pouring temperature and the mould material on the microstructural characteristics of A356 Al-Si alloy feedstock; (2) optimize the LSC process parameters to obtain an A356 alloy feedstock with the best microstructural characteristics (i.e minimum size and maximum globularity of the grains) suitable for thixoforming. The Taguchi's and analysis of variance statistical (ANOVA) approaches were employed to find out the optimum settings of each LSC process.

EXPERIMENTAL PROCEDURES

In this study, commercial A356 Al-Si cast alloy with the chemical composition shown in TABLE 1 was used. The differential scanning calorimetric (DSC) analysis was carried out to determine the solidus and liquidus temperatures of the alloy. The DSC experiments were carried during heating with a heating rate of 5 °C/min. Figure 1 shows the resulted DSC curve of the A356 alloy. It has been found that A356 alloy hassolidus and liquidus temperatures of ~572 °C and ~610°C, respectively. Figure 1 shows

TABLE 1 : Chemical composition of A356 aluminum alloys(wt.-%)

Alloy	Si	Mg	Fe	Cu	Mn	Ti	Al
A356	7.38	0.279	0.149	0.002	0.003	0.141	Bal.

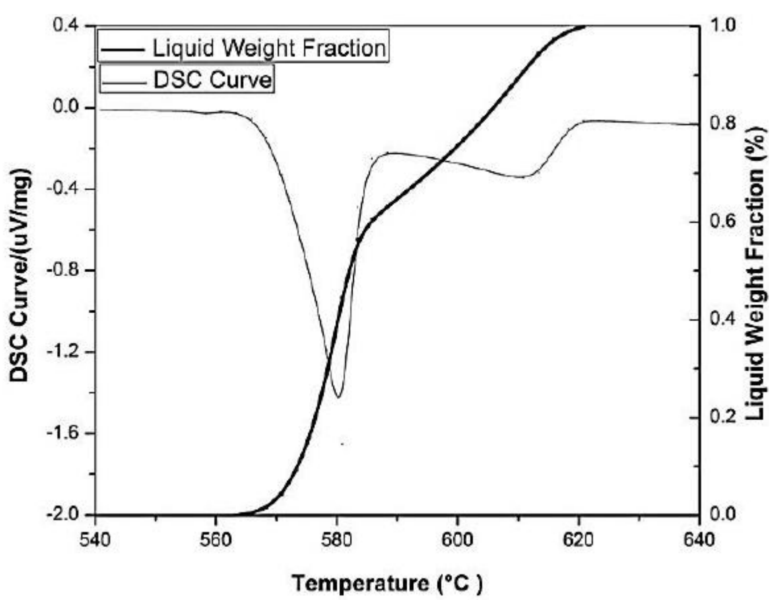

Figure 1 : DSC and liquid weight fraction versus temperature curves for A356 alloy

also the curve representing the variation of liquid weight fraction with the temperature. This curve was obtained after integrating the area under DSC curve.

The low superheat casting (LSC) process was carried as follows: about 900 g of A356 alloy were melted in graphite crucible in an electric resistance furnace at 660 °C. After complete melting, degassing process was carried out by dry Argon inert gas to remove any undesirable dissolved gases in order to prevent the formation of gas bubbles inside the ingot. After that the molten alloy was allowed to cool down to the specific pouring temperature, typically at, 620 °C, 630 °C and 640 °C. This gives superheat values of about 10, 20 and 30 °C. Then the molten alloywas poured directly into the mould. Several mould materialswere used, typically, low carbon steel (St.), pure copper (Cu) and 304 stainless steel(SS) moulds. The moulds have the same dimensions of 50 mm diameter and 160 mm height with adraft angle 2°toremove easilythe solidified ingot. During pouring, the semi-solid metal formed at the start of entering of mold.

Figure 2 shows a photograph of a sample ingot producedfrom the CS casting process. The upper part of the ingot with 35 mm height containing the shrinkage cavity wasremoved from the ingot. The remained part of the ingot was cut longitudinally into two equal

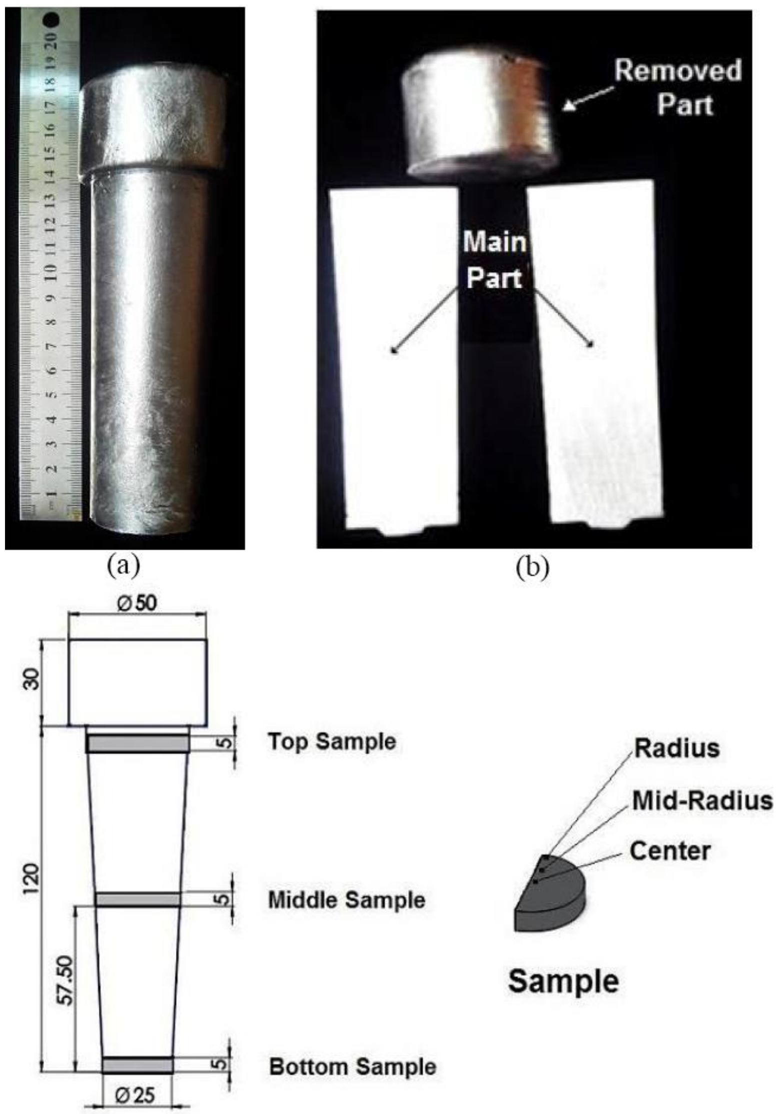

Figure 2 : (a) A photograph of a sample ingot produced from the LSC process, (b) the ingot after removing the upper part and sectioning the remaining part into two half; (c)a schematic illustration of the ingot showing the main dimensions (in millimeters) and the position of metallographic samples

half (see Figure 3b). The first longitudinal half was used for microstructural examinations. From this half, specimen was sectioned horizontally from the top, middle and bottom of the ingot. The metallurgic samples have 25 mm radius and 5 mm thick as shown in Figure 3c. The samples were subjected to standard metallographic procedures and etched using chemical solution of Keller's etchant (2 ml hydrofluoric acid (HF), 3 ml hydrochloric (HCL), 5 ml Nitric acid (HNO_3) and 190 ml distilled water). The etched samples were investigated using an Olympus light microscope. The metallographic images were taken from the wall zone (radius), mid-radius and center zone of the specimens as shown in Figure 3c.

The microstructural analysis of specimens was carried out using images analysis techniques. The size and shape factor of α-Al grains were determined. The shape factor of the grains was determined from the following equation[1]:

$$SF = 4\pi A/P^2 \quad (1)$$

Where: P is the perimeter and A is the area of α-Al grain. For a perfect circle, the shape factor would be one. For each ingot, the average shape factor and average grain size was calculated from the measurements obtained from the top, middle and bottom of ingots as well as the radius, mid-radius and center of the specimens.

In the present investigation, the Taguchi's Orthogonal Array Design of experiment (DOE) was employed in order to study the effect of LSC process parameters (i.e. pouring temperature and mould material) on the different responses (i.e. the size and shape factor of the primary α-Al grains as well as the porosity content). Each of LSC process parameter have three levels as listed in TABLE 2. The standard Taguchi's orthogonal array (OA) L_9 was chosen in this study. This design of experiment gives a total of 9 ingots. The analysis of experimental results was performed using the analysis of variance (ANOVA) statistical approach. From results of ANOVA one can obtain the most and lowest significant parameters. The analysis was carried out for a level of significance of 5 per cent (i.e. the confidence limit is equal to 95 per cent). The design of experiments and ANOVA calculations were performed using *Minitab* commercial statistical software.

The polynomial equation (Eq. (2)) was used to predict the response (Y) as a function of independent factors and their interactions. In this work, the number of independent factors is 2, therefore, the response for the quadratic polynomials becomes:

$$Y = C_1 + C_2 \times X_1 + C_3 \times X_2 + C_4 \times X_1^2 + C5 \times X_2^2 \quad (2)$$

Where: C_1, C_2, C_3, C_4, C_5 are constant, linear, square and interaction regression coefficient terms, respectively; X_1 and X_2 are independent factors. In order to facilitate the comparison between the predicted and the experimental values, an error evaluation was carried out using

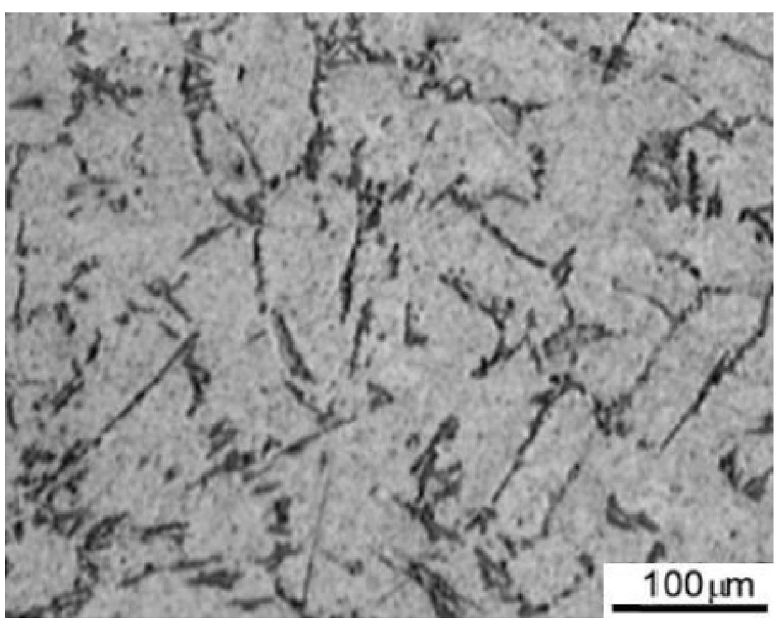

Figure 3 : Microstructure of as-received cast A365 Al alloy

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Mean Relative Error (MRE). The MRE values were calculated using the following equation:

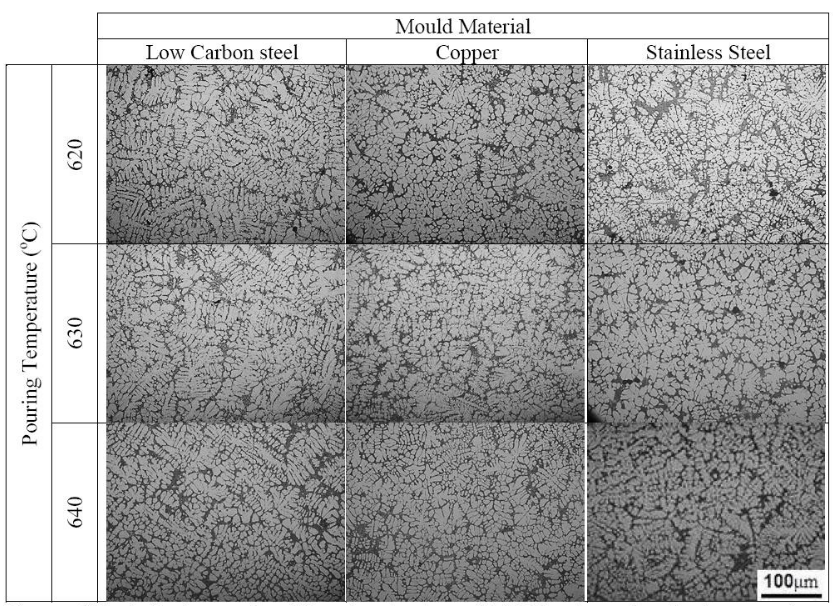
$$MRE = \frac{1}{n}\sum_{i=1}^{n}\frac{100\,|d_i - o_i|}{d_i} \qquad (3)$$

Where d_i is the measured value, o_i the predicted output value and n the number of data.

RESULTS AND DISCUSSION

Figure 3 shows a typical micrograph of the microstructure of the as-received A356 cast aluminum alloy. The as-received alloy exhibits a typical dendritic microstructure. The microstructure of the A356 alloy consists mainly of dendritic primary α-Al grains (white regions) andcoarse Al–Si eutectic structure. Figures 4 shows typical micrographs of the microstructure of the A356 ingots produced using several LSC processing conditions. The micrographs were captured from the central positions of the bottom of ingots. The degeneration of the dendritic structure and refinement in the morphology of the primary α-Al phase is observed. The microstructural investigations results showed also that, the radius zones exhibited the finest primary α-Al grains when compared with both the mid-radius and center zones. This is due to the larger amount of heat dissipated from the molten metal through the wall of the mold allowing the formation of finer grains.

It has been found that the microstructure of the LSC ingots depends significantly on both pouring temperature and mould materials. Figure 5 shows the effect of pouring temperature and mould material on both the average grain size (GS) as well as the average shape factor (SF) of primary α-Al grains of the A356 ingots. It is clear that increasing the pouring temperature increasing the average grain size of the A356 ingots. Such observation was noticed for all LSC ingots poured in the different moulds used in the present investigation. In contrast, increasing the pouring temperature reduces the average shape of the primary α-Al grains. The results revealed also that ingots poured in the copper and low carbon steel moulds exhibited the finest and coarsest average grain size of primary α-Al grains, respectively. The smallest average grain size was about ≈41μm for the ingot poured at 620 °C in the copper mould. Ingots poured in the stainless steel and low carbon steel moulds exhibited the lowest and highest average shape factor of primary α-Al grains, respectively. The highest average shape factor was ≈0.81 for the ingot poured at 620 °C in the stainless steel mould. The ingots poured in copper mould exhibited slightly lower average shape factor when compared with the ingots poured in the stainless steel mould. For example, at constant pouring temperature of 620 °C, the average



Figures 4 : Typical micrographs of the microstructure of A356 ingots produced using several LSC processing conditions. The micrographs are from the central positions of the bottom of ingots

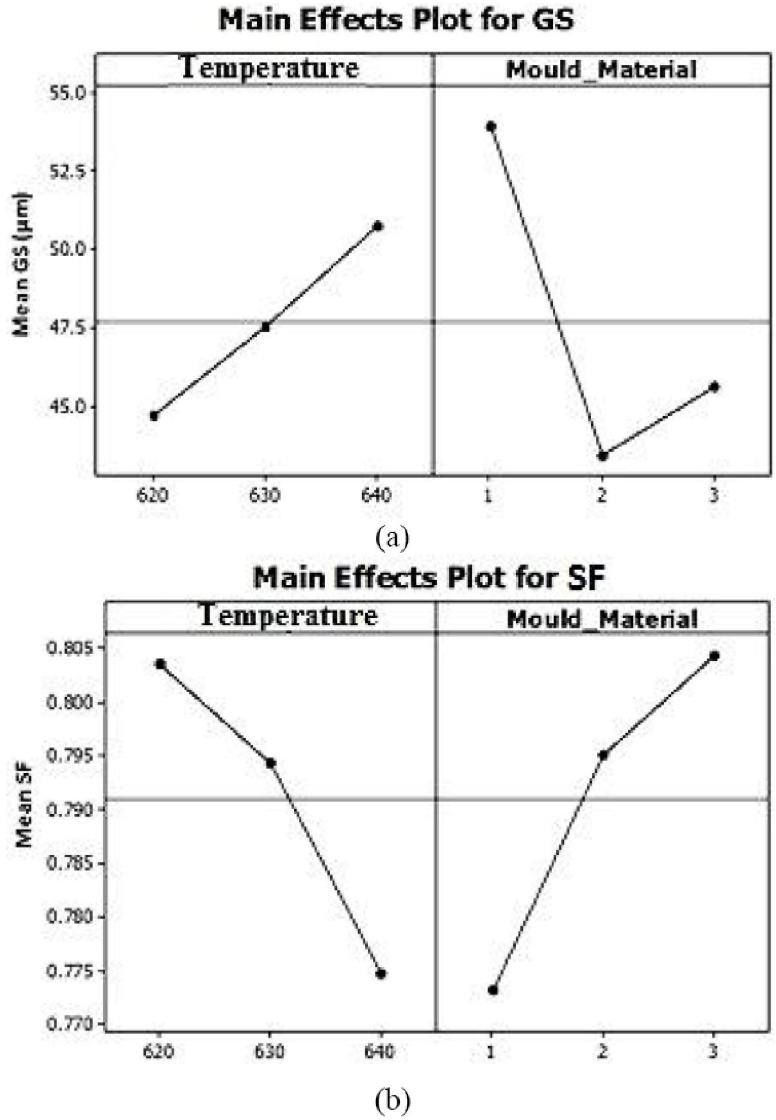


Figure 5 : The main effect plots of the LSC parameters on (a) the average size (GS) and (b) the average shape factor (SF) of primary α-Al grains. 1 = low carbon steel mould, 2 = copper mould, 3 = 304 stainless steel mould

shape factor of ingots poured in stainless steel and copper moulds were, 0.811 and 0.807, respectively.

TABLES 3 and 4 list the ANOVA results for both the size and the shape factor of the primary α-Al grains. The last columns in the tables show the percentage of contribution (P_c) of eachfactor on the total variation indicating the influenceof the factors on the results. The higher the value of the P_c, the more statistical and physical significant the factor is. From the analysis of TABLE 3 and TABLE 4, it can be observed that both mould material and the pouring temperature significantly affect the average grain size and shape factor of the primary α-Al grains, respectively. The mould material exhibited the highest statistical and physical significance on both the grain size and shape factor of the primary α-Al grains. The pouring temperature exhibited lower statistical and physical significance when compared with the mould material. The mould material exhibited P_c values of 77.03 % and 54.26% for the grain size and shape factor of the primary α-Al grains, respectively. While, the pouring temperature exhibited P_c values of 22.97% and 45.74% for the size and shape factor of the primary α-Al grains, respectively. From TABLES 3 and 4, it is clear that the residuals are less than 2%, which indicates that there are no interactions between mould material and pouring temperature. Figure 6 shows the interaction plots of LSC process parameters for the average grain size and

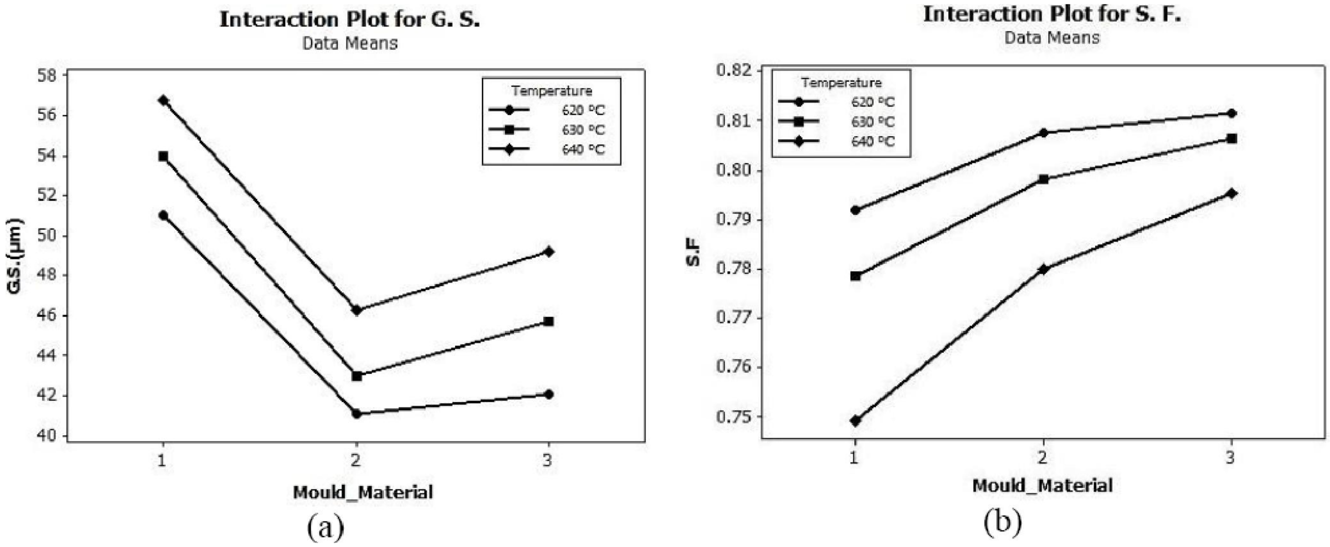


Figure 6 : Interaction plots of LSC process parameters for the average (a) grain size (GS) and (b) average shape factor (SF) of the primary α-Al grains

TABLE 2 : TheANOVA results for the grain size of the α-Al primary grains

LSC Parameter	Levels		
	Level-1	**Level-2**	**Level-3**
Temperature (C°)	620	630	640
Mould material	Low carbon steel	Pure copper	Stainless steel

DF, degrees of freedom; SS, sum of squares; MS, mean square; F, F-test; P, Statistical significance, P_c; percentage of contribution

TABLE 3 : TheANOVA results for the shape factor of the α-Al primary grains

Source of variation	DF	SS	MS	F	P	P_c
Mould Material (M)	2	183.459	91.730	292.91	0.000	77.02568
Temperature (T)	2	54.72	27.360	87.36	0.001	22.97432
Residual	4	1.253	0.313			
Total	8	239.432	119.403			100
			R^2 = 99.48%			

DF, degrees of freedom; SS, sum of squares; MS, mean square; F, F-test; P, statistical significance, P_c;percentage of contribution

shape factor of the primary α-Al grains. It is clear that there are no interactions between mould material and pouring temperature.

Empirical expressions of the grain size (GS) andshape factor (SF) were established as functions of the LSC process parameters; typically, pouring temperature (T) and mould material(M) is given below:

$$\mathbf{GS = 592.0243 - (1.9369\times T) - (29.494\times M) + (1.7767\times 10^{-3}\times T^2) + (6.3369\times M^2)} \quad (4)$$

$$\mathbf{SF = -18.7237 + (6.3237\times 10^{-2}T) - (4.0961\times 10^{-2}M) - (5.1332\times 10^{-5}\times T^2) - (6.3369\times 10^{-3}M^2)} \quad (5)$$

Where: GS- is the grain size of primary α-Al grains in microns, SF- is the shape factor, T- is the pouring temperature in Celsius, M- is the mould material number and it is = 1- for low carbon steel mould, = 2- for pure copper mould, = 3- for 304 stainless steel mould. The regression analysis revealed that the coefficient of determination (R^2) of equations (3) and (4) are 0.995, 0.939, respectively. A comparison of the measured average grain size and average shape factor (experimental data) against the predicted average grain size and shape factor is shown in Figure 7. A perfect prediction would be when all the plotted points were on the 45° line (the dashed line). The accuracy of equations (3) and (4) can be easily compared by the closeness of the data points to this line. It is clear from Figure 7 that the experimental and predicted values are very close to each

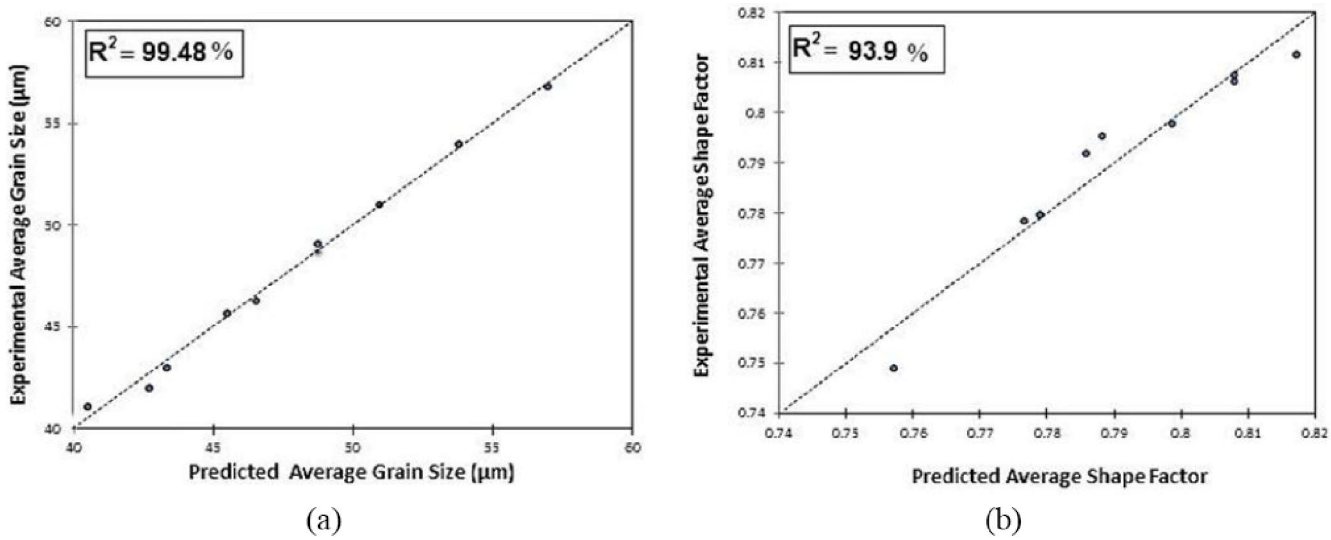


Figure 7 : Plots of the predicted verses measured (experimental) (a) average size and (b) average shape factor of the α-Al primary grains.

other. Equations (4) and (5) exhibited MRE values less than 1%.

CONCLUSIONS

Based on the results presented, the followingconclusions can be drawn:

The microstructure of the LSC ingots depends significantly on both pouring temperature and mould materials. Increasing the pouring temperature increases the average grain size, while reduces the average shape factor, of the A356 aluminum ingots. At constant pouring temperature, ingots poured in the copper mould exhibited the smallest average grain size when compared with those poured in the low carbon and stainless steel moulds. The average shape factor of ingots poured in copper mould was slightly lower than the average factor of ingots poured in stainless steel mould.

The ANOVA results showed that mould material has higher statistical and physical significance when compared with pouring temperature on both the grain size and shape factor of the primary α-Al grains.

Empirical equations were developed to predict the average shape factor and grain size of the primary α-Al grains for A356 ingots as a function of the pouring temperature and mould material. The predicted valuesresulted from the equations were in good agreement with the experimental results.

A356 ingot poured at a pouring temperature of 620 °C in the copper mould exhibited the best microstructural characteristics suitable for thixoforming. The A356 ingot exhibited average grain size and shape factor of the primary α-Al grains of 41.08 μm and 0.807, respectively.

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