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Optimizing the Cooling Slope Casting Process Parameters for Production of A356 Alloy Thixotropic Feedstocks

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Abstract

This study investigates the optimization of semisolid thixoforming of A356 alloy using the cooling slope (CS) casting technique. By systematically varying process parameters such as pouring temperature, tilt (slop) angle, and cooling length, were explored their influence on the microstructure features of the cast alloy. The Taguchi method was employed to design experiments, and the results were analyzed using analysis of variance (ANOVA). In addition, the ANOVA was used to figure out the effect of CS casting process parameters on the microstructural characteristics. The findings demonstrate that cooling length significantly impacts the shape factor of primary α-Al grains, while pouring temperature primarily affects their size. Optimal conditions, 30° tilt angle, 350 mm cooling length and 620 ºC pouring temperature, were identified to achieve an average grain size of 17.14 µm and a shape factor of 0.9844. These findings contribute to a better understanding of CS casting and provide valuable insights for optimizing the production of thixoformed A356 alloy components.

KEYWORDS: Thixoforming; Cooling Slope Casting; Design of Experiment; ANOVA.

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1. Introduction

Semisolid processing has become a promising production technology for machine tool, automotive, and aircraft components. Semisolid processing makes it possible to produce parts with increased dimensional accuracy, enhanced structural integrity, and superior mechanical and tribological qualities [1,2]. Thixocasting is an economically feasible manufacturing route in the semisolid state with near-net-shaped forming capabilities and high quality [3]. Due to its capacity to use temperatures lower than those used in metal casting and less energy needed in metal forming than standard forging and extrusion processes, this technology offers a solution to the issues with conventional casting and metal forming processes. Thixoforming produces products with reduced shrinkage porosity and flaws, more notable cross-sectional changes, improved weldability, and longer tool life. Recently, the automotive industry has used thixoformed parts regularly [4-6].

A unique feedstock with a non-dendritic microstructure is produced in the first step of the thixoforming process. Then, the metal is heated to the processing temperature, at which the two phases (mushy zone, solid and liquid) exist in equilibrium and are formed through a casting/forming operation. Any successful thixoforming method should create a unique feedstock with fine and spherical solid phase particles encircled by a continuous liquid layer. Several techniques, such as magneto-hydrodynamic (MHD), strain-induced melt activated (SIMA) and stirring, mechanical stirring, chemical grain refining, and cooling slope (CS) casting, have been developed to provide this kind of feedstock [7,8]. The CS casting method requires less equipment and maintenance and is inexpensive and straightforward [9,10].

In the CS casting method, the molted metal with a determined superheat level in the CS casting is poured over an inclined cooling plate. When the prepared CS cast ingot is reheated to the semisolid temperature range, a non-dendritic globular microstructure suitable for thixoforming is obtained. Some theories suppose that the non-dendritic globular microstructures form due to the breaking of the dendritic arms caused by the collision of the dendritic crystal over the cooling slope plate surface. Previous literature showed that the combined effect of the contact over the plate and the gravity effect break the dendritic arms of the poured metal [11]. The molten metal nucleates at the CS plate, moving the molten metal into the mold. Subsequently, the non-dendritic fine microstructures are obtained as the granular solidification of metal continues inside the mold. The globular microstructure is preserved during the processing operations when the prepared feedstock is heated to a semi-solid temperature. Several operating parameters affect the final microstructure obtained. For instance, the pouring temperature, mold temperature, CS plate temperature, mold type, CS plate angle, and CS plate length, as well as the influence of CS plate vibration and rotation of the mold.

A356 is one of the most applied aluminum alloys in the foundry industry. This alloy has several distinguished characteristics: good weldability, hot tearing resistance, wear/corrosion resistance, good castability, and a high strength-to-weight ratio. Applications of A356 alloy include aircraft components, military applications, and automotive parts [3].

Khosravi [12] enhanced the microstructure of A356 aluminum alloy by semi-solid casting by studying the impact of several processing factors utilizing the cooling slope approach. The study utilized a D-optimal design of experiment methodology to perform tests and evaluate the results. This allowed for the identification of the most effective combination of parameters to produce the highest level of globularity in the final microstructure. The optimal parameters for the pouring temperature, cooling length, slope angle, and isothermal holding time were determined to be 660 °C, 360 mm, 48°, and 9 min, respectively. Haga and Suzuki [13] found that the cooling rate of the ingot in the mold is the primary determinant in achieving a globular microstructure for Al−6wt% Si alloy, compared to other factors such as casting temperature, cooling length, and reheating temperature. A rapid cooling rate was noted during the mold-induced spheroidization of primary crystals following the remelting process. Designing experiments using statistical methods is helpful for properly planning the selected number of experiments, choosing an appropriate set of conditions, and reducing the time and effort needed to conduct numerous experiments. Experimental design methods' popularity in the scientific and engineering communities is based on their ability to be applied with little to no statistical understanding. Several design methodologies [10-15], including factorial design, response surface methodology (RSM), and Taguchi methods, have been used for the statistical design of experiments.

The current research aims to investigate the effects of the pouring temperature, cooling slope length, and slope angle during the CS casting process on the microstructural properties of the A356 cast alloy. The CS casting process parameters are determined using Taguchi's experimental design and the analysis of variance (ANOVA) to produce the optimal microstructural features. ANOVA is a helpful statistical method for analyzing the process parameters effects on

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the microstructure. ANOVA also clarifies process parameters maximum and minimum impact on the microstructure [14]. Optimization determines the adjusted set of CS casting parameters for primary α-Al grains that will yield the highest globularity and lowest grain size.

2. EXPERIMENTAL WORKS

The chemical composition of the A356 alloy is listed in Table (1). Generally, the Differential Scanning Calorimetry (DSC) is a thermal analysis technique used to measure the amount of heat absorbed or released by a sample as a function of temperature. It is particularly used for studying phase transitions, such as melting and crystallization of metals. Before remelting it is important to know the melting temperature of the used alloy. thus, in this study, the percentage of liquid and solid phases as a function of temperature is calculated using DSC analysis to ascertain the solidus and liquidus temperatures as well as the fluctuation of melt liquid percentage with temperature The DSC experiments were conducted at the Central Metallurgical Research and Development Institute (CMRDI) in Helwan, Cairo, using the TG DSC16 test equipment. The DSC studies were conducted by heating at a rate of 5 °C/min. The DSC studies were conducted using a 25 mg sample extracted from the ingot and subjected to heating in a helium environment. The resultant fraction solid vs. temperature curve for the A356 alloy is displayed in Fig. (1). The alloy's liquidus and solidus temperatures are 588 °C and 480 °C, respectively. Additionally, the graphic shows the curve that illustrates how the temperature affects the liquid-weight fraction. The area beneath the DSC curve is integrated to generate this curve. Similar results were obtained by Yucel [19], in his work A357 thixoforming feedstock was produced by cooling slope casting. The DSC analysis of A357 determined that the solidus temperature of the parent alloy was 549 °C and the liquidus temperature was 614°C. Temperatures between 620–640 °C were used in the CS casting trials to prevent excessive heating of the melt.

Table (1): Chemical composition of the used A356 cast alloy.

Element	Si	Fe	Ti	Mg	Cu	Mn	Al
Weight Percent (%)	7.29	0.115	0.133	0.257	0.001	0.001	Bal.

The CS casting procedure was performed as follows: about 1 kg of A356 alloy were melted at 680 °C in an electric resistance furnace using a graphite crucible. Argon was used to degas the molten metal, and the produced oxides were scraped. Subsequently, the melted metal was permitted to reach the designated pouring temperature. The molten metal was quickly poured at various slope angles to horizontal and slope lengths onto an inclined low carbon steel plate that had been prepared, and it was then collected into a preheated steel mold. With a draft angle of 2o, the steel mold measured 50 mm in diameter and 160 mm in height, making it simple to remove the solidified billet. A photograph of the CS casting apparatus and the feedstock fabrication process can be found in Fig. (2).

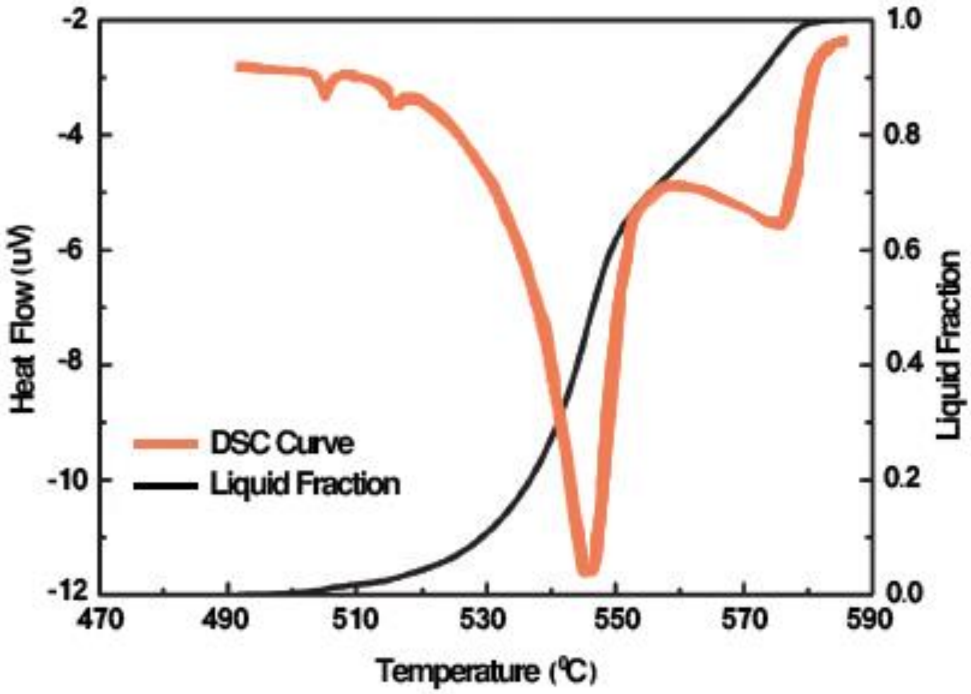
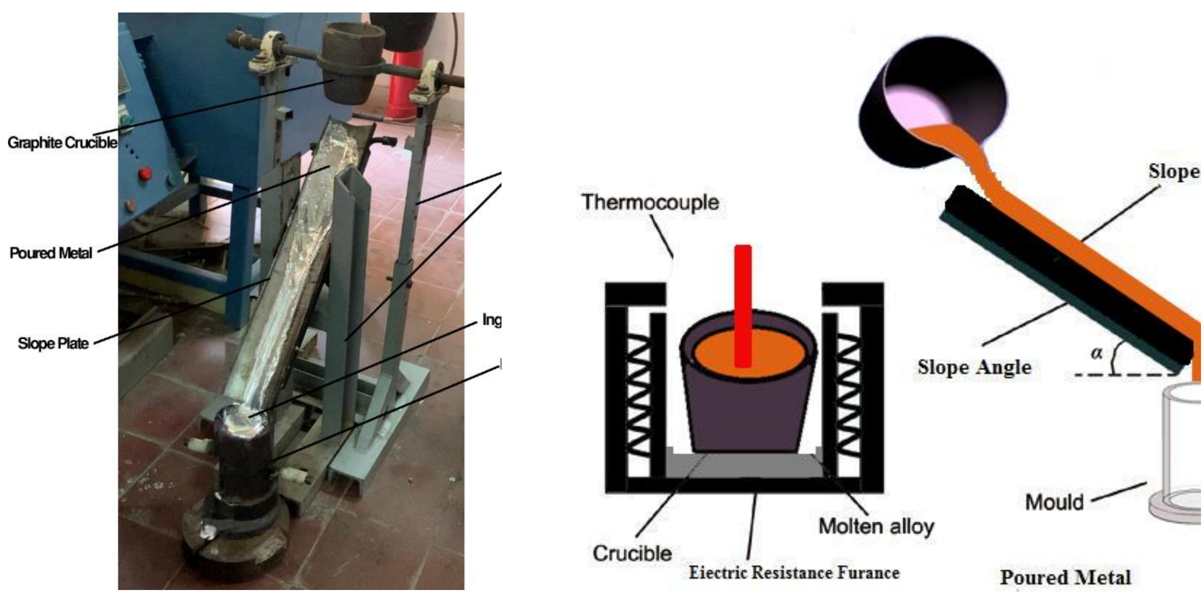


Figure 1: DSC and liquid weight fraction versus temperature curves for A356 alloy.



(a) (b)

Figure 2: The cooling slope casting apparatus (a) a photograph (b) a schematic illustration.

A schematic representation and typical view of the feedstock sample for the CS casting process are shown in Fig. (3). The feedstock upper portion containing the shrinkage cavity was removed once the cast was solidified. As shown in Fig. 3, a specimen with a 50 mm diameter and 5 mm thickness is cut from the middle position of each ingot. Samples are ready for analysis using after metallography. The samples were polished with a 3 μm alumina suspension after being ground with emery sheets of progressively finer grit SiC papers up to 1200 grit. Keller etchant (2 ml. of hydrofluoric acid, 3 ml. of hydrochloric acid, 5 ml. of nitric acid, and 190 ml. of distilled water) was used to etch the specimens. Every specimen was timed for 5 to 10 seconds. As seen in Fig. (3), the metallographic images were obtained from the specimens' edge zone (radius), mid-radius zone, and center zone using an optical microscope. Using image-analyzing techniques, the

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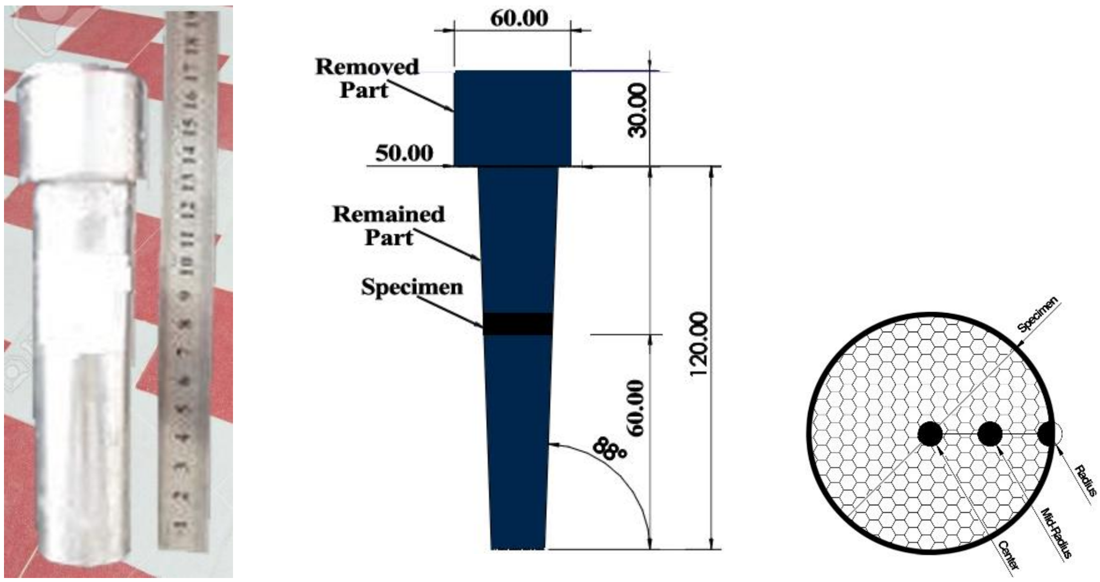
average grains size (GZ) and shape factor (SF) of the main Al grains were measured. The average size of Al grains was determined using the linear intercept method. The following equation was used to calculate the shape factor:

$$S.F. = 4\pi A/P2 \quad \ldots(1)$$

Where P is the perimeter and A is the area of grain. The value of the shape factor ranges from zero (lowest) to one (highest). A perfect circular shape is represented with a value of one. The particle morphology gets less spheroidal as the value goes below one.



(a) (b) (c)

Figure 3: (a) Typical A356 Al alloy feedstock, and (b) a schematic illustration showing the location of the metallographic specimen, and (c) specimen metallographic positioning (Dimensions in mm).

The Taguchi optimization technique was adopted in this research. Based on this technique, the experimental plan was planned considering three CS casting process variables and each has three levels. The process parameters considered for the investigation are pouring temperature (T), cooling length (L), and the tilt angle (A). Within the Taguchi framework, the process parameters setting with the highest signal-to-noise (S/N) ratios always yield the optimal quality with minimum variance [15]. The S/N ratio represents the proportion between the desired signal and the unwanted random noise level. This metric serves as an indicator of the quality attributes within experimental data. The levels of these variables chosen for experimentation are given in Table (2).

Table 2: The Control CS process parameters and their values at 3-levels.

CS casting process parameters	Factors Designation	Levels		
		1	2	3
Pouring temperature (˚C)	T	590	605	620
CS Length (mm)	L	250	300	350
Tilt Angle (degrees)	A	30	45	60

In the present study, the average shape factor is a “larger-the-better” type of quality characteristic since the goal is to maximize it. While average grain size (μm) is a ‘smaller the better’ type of quality characteristic since the goal is to minimize it. The S/N ratio for the lager-the-better using base 10 log is:

$$S/N = -10*\log(\Sigma(1/Y2)/n) \quad \ldots(2)$$

where Y = responses for the given factor level combination and n = number of responses in the factor level combination. In the current case, n=1. The S/N ratio for the smaller-the better using base 10 log is:

$$S/N = -10*\log(\Sigma(Y2)/n) \quad \ldots(3)$$

The S/N ratio values are calculated by taking into consideration the equations using the Minitab statistical software package.

Table 3: Layout of experimental design L9 Standard orthogonal array.

Experiment no.	Process parameters		
	Pouring Temperature, (°C), T	CS Length (mm), L	Tilt Angle, (degrees), A
(L1) 1	590	250	30
(L2) 2	590	300	45
(L3) 3	590	350	60
(L4) 4	605	250	45
(L5) 5	605	300	60
(L6) 6	605	350	30
(L7) 7	620	250	60
(L8) 8	620	300	30
(L9) 9	620	350	45

In the present study, the experiments are designed based on the L9 orthogonal array (OA) technique. The orthogonal array is a fractional factorial design with a pair-wise balancing property. This technique can estimate the effects of multiple process variables on the output characteristic, while it minimizes the number of test runs. Table (3) shows the layout of the experimental design, generated by assigning the chosen process variables and their levels to appropriate columns of L9 OA. The effects of the chosen process variables on the output characteristic, typically, average size (in μm), and the average shape factor of the primary α-Al grains have been estimated by assuming that the other interactions are negligible.

3. RESULTS AND DISCUSSION

3.1. Microstructural Investigations

Figure (4) shows a typical micrograph of the microstructure of A356 Al alloy feedstock produced at constant cooling length and tilt angle of 300 mm and 45o, and at 590 °C, respectively. Microstructural investigations revealed that the morphology of primary α-Al grains (white colored) for the fabricated feedstock are near-globular nondendritic (rosette form). Table (4) lists the results of microstructural measurements for the average size and shape factor of the primary α-Al grains.

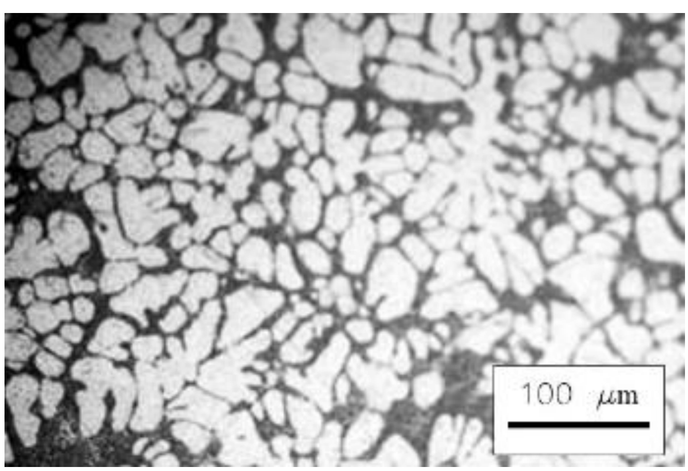


Figure 4: Micrograph of the microstructure of A356 Al alloy feedstock fabricated using cooling length, tilt angle, and pouring temperature of 300 mm, 45o, and 590 oC, respectively.

3.2. Analysis of S/N Ratios

The response for S/N ratios results according to the criteria of smaller-is-better and lager-is-better are given in Tables (5) and (6), respectively. It is evident from the tables that among CS process parameters, the cooling length is the most influential process parameter that affects the shape factor of primary α-Al grains, followed by the pouring temperature. Additionally, the pouring temperature is the most influential process parameter that affects the size of primary α-Al grains, followed by the cooling length. In both cases, the tilt angle is the least influential process parameter that affects the size and shape factor of primary α-Al grains. Figures (5) and (6) graphically represent the main effect plots of S/N ratios for average size and shape factor of primary α-Al grains, respectively.

Table 4: Microstructural Measurements for the average grain size and shape factor.

Experiment no.	Process parameters			Output responses	
	Pouring Temperature, (°C), A	CS Length (mm), B	Tilt Angle, (degrees), C	Average grain size, GZ (μm)	Average Shape Factor, SF
1	590	250	30	22.33	0.9
2	590	300	45	28.55	0.85
3	590	350	60	19.33	0.92
4	605	250	45	24.4	0.88
5	605	300	60	26.7	0.86
6	605	350	30	22.44	0.95
7	620	250	60	22.43	0.94
8	620	300	30	19.34	0.93
9	620	350	45	19.08	0.94

Table 5: Response Table for S/N ratio – Lager is better.

Level	Pouring Temperature	Cooling Length	Tilt Angle
1	1.986	2.149	2.338
2	2.049	1.887	1.984
3	2.432	2.432	2.146
Delta	0.446	0.545	0.355
Rank	2	1	3

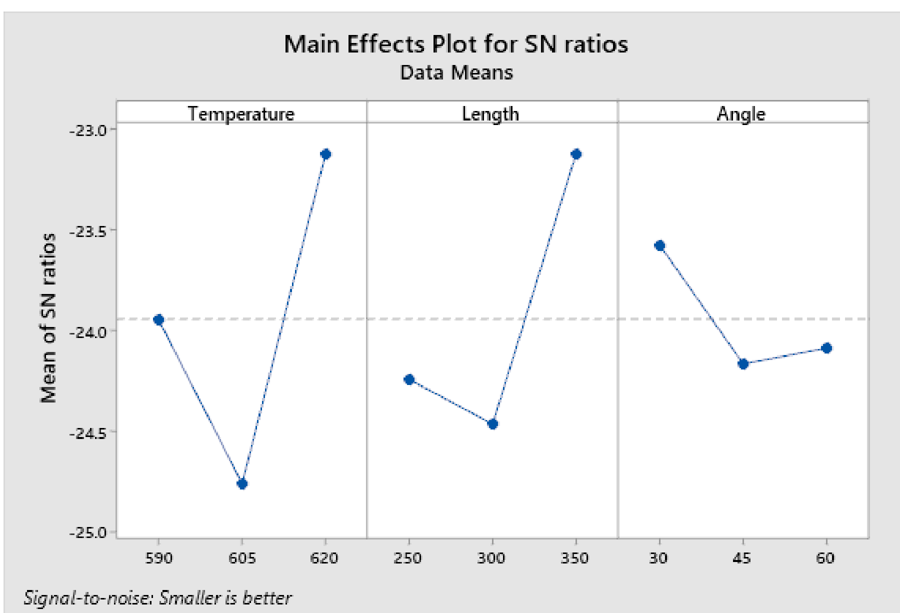


Figure 5: Main effect plot for S/N ratios - average size of primary α-Al grains.

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Table 6: Response Table for S/N ratio – Smaller is better.

Level	Pouring Temperature	Cooling Length	Tilt Angle
1	-23.95	-24.24	-23.57
2	-24.76	-24.47	-24.17
3	-23.12	-23.12	-24.09
Delta	1.64	1.35	0.59
Rank	1	2	3

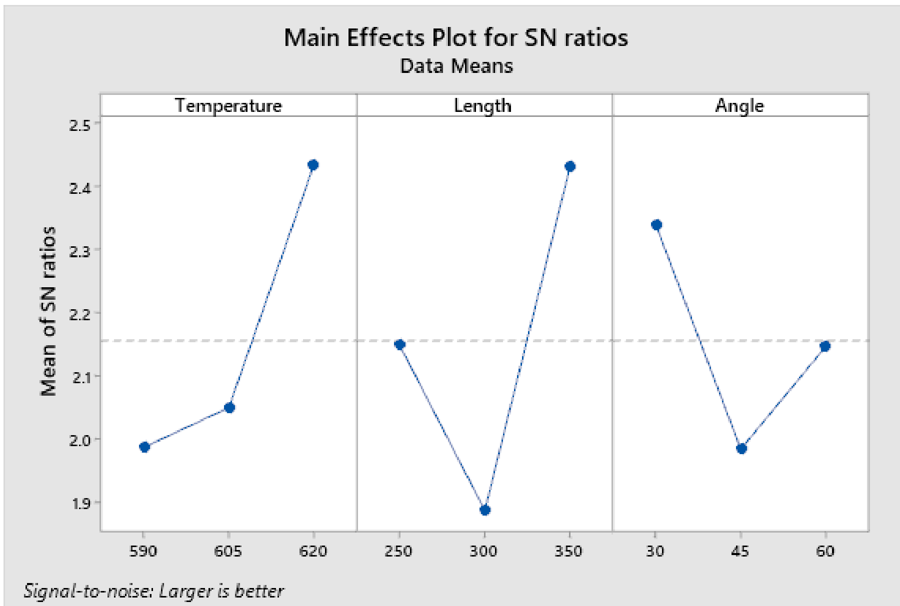

Figure 6: Main effect plot for S/N ratios - shape factor of primary α-Al grains.

3.3. ANOVA Results

Tables (7) and (8) show ANOVA results for the average size and shape factor of the primary α-Al grains, respectively. The ANOVA analysis was performed for a level of
significance of 5% (i.e. the confidence limit is equal to 95%). The last columns in the tables indicate the percentage of contribution (Pc) of each CS process parameter on the total variation indicating the influence of the process parameters on the results.

From the ANOVA results, the most significant influencing parameter on the primary α-Al average grain size is the pouring temperature, which has 43.13% of the total effect, followed by cooling length (33.98%) and finally the tilt angle (7.76%), respectively. The results revealed also that the most significant influencing parameter on average shape factor is the cooling length which has 44.02% of the total effect, followed by pouring temperature (34.88%) and finally the tilt cooling angle (18.46%), respectively.

Table 7: ANOVA results for average grain size of primary α-Al grains.

Source	D F	Adj SS	Adj MS	F- Value	P- Value	Percen t Contribution (%), Pc
Pouring Temperature, oC	2	26.83 9	13.420	2.8 5	0.260	43.13 %

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Cooling Length, mm	2	21.145	10.573	2.25	0.308	33.98 %
Tilt Angle, degree	2	4.828	2.414	0.51	0.661	7.76%
Error	2	9.418	4.709			15.13 %
Total	8	62.231		R-sq	84.87 %	100 %

Table 8: ANOVA results for average shape factor of primary α-Al grains.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Percent contribution (%), Pc
Pouring Temperature, oC	2	0.003822	0.001911	13.23	0.070	34.88 %
Cooling Length, mm	2	0.004822	0.002411	16.69	0.057	44.02 %
Tilt Angle, degree	2	0.002022	0.001011	7.00	0.125	18.46 %
Error	2	0.000289	0.000144			2.64
Total	8	0.010956				100 %

According to the above results, the pouring temperature, cooling length and tilt angle plays an important role in determining the final morphology of the primary α-Al grains produced using cooling slope casting techniques. The combination of the pouring temperature and the cooling length represents more than 76% of the total effect of the process parameters. It is well known that the pouring temperature plays a significant role in determining the size of the grains [15]. At, constant tilt angle, pouring the molten metal on a plate with small cooling length makes the molten metal flow rapidly and this leads to poor formation in solid fraction due to low heat transfer from the molten metal that results in coarse grains with lower shape factor, so when pouring the molten metal on an inclined plate with suitable cooling length this improves the chance of increasing the number of nucleated and detached crystals that produces finer grains with better shape factor. It is also important to mention that, if the tilt angle is small this leads to more time needed for the metal to pass on the slope plate and as a result the cooling rate will be very large which leads to the sticking of the semi-solid metal on the cooling plate and the die will not be filled with the metal [16].

3.4. Response Optimization

Figure (7) shows the optimization plot used to determine the optimal settings for the CS casting process parameters. The optimization plot displays the fitted values for the predictor settings. The results revealed that setting CS process parameters, typically, pouring temperature, tilt angle and cooling length to 620 oC, 30o and 350 mm, respectively, produces the optimal average grain size and shape factor of 17.14 µm and 0.9844, respectively. Table (9) shows the multiple response prediction. The prediction intervals (PI) shown in the table assess the practical significance of the results. If a prediction interval extends outside of acceptable boundaries, the predictions might not be precise enough for the requirements. The predicted results have a good accuracy since it is located within the intervals of the PI.

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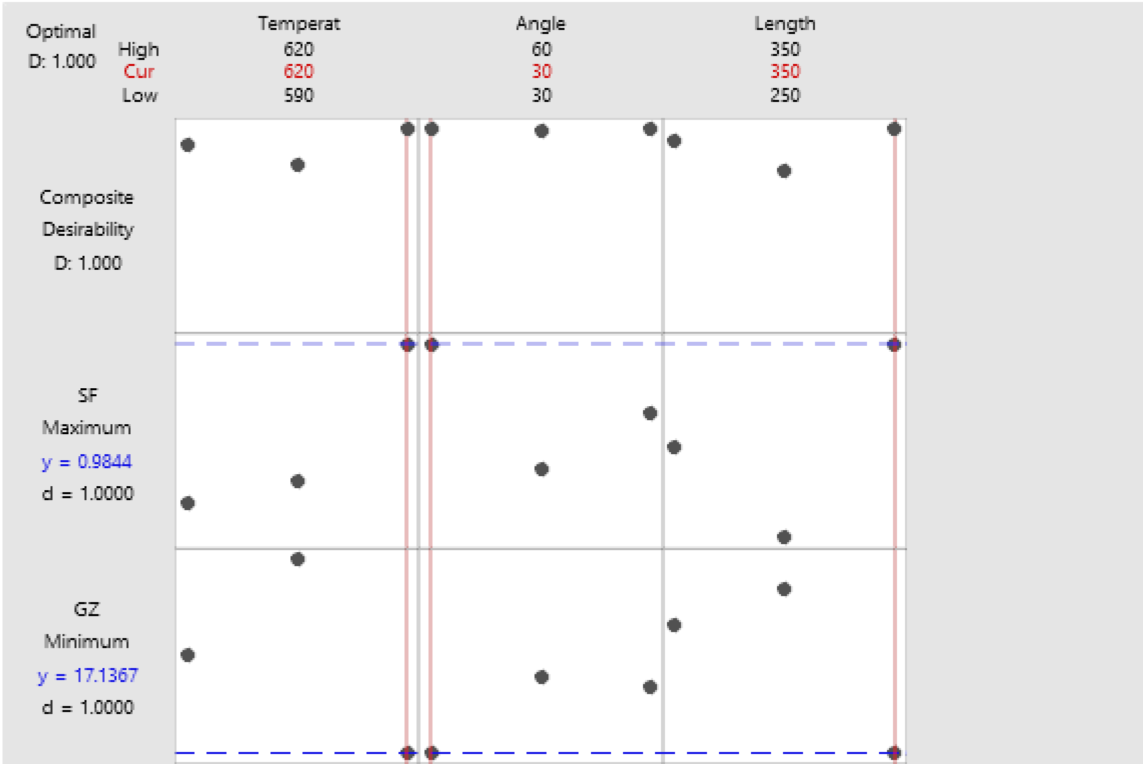

Figure 7: The response optimization plot.

Table 9: Multiple response prediction.

Response	Fit	SE Fit	95% CI	95% PI
Average Shape Factor	0.9844	0.0106	(0.9388, 1.0300)	(0.9155, 1.0534)
Average Grain Size	17.14	1.91	(8.90, 25.37)	(4.69, 29.59)

4. CONCLUSIONS

According to the present investigation, the conclusions of significance are drawn as follows:

1. The cooling length is the most influential process parameter that affects the shape factor of primary α-Al grains, followed by the pouring temperature. The pouring temperature, cooling length, and tilt angle exhibited 34.88%, 44.02%,18.46% of the total effect, respectively.
2. The pouring temperature is the most influential process parameter that affects the size of primary α-Al grains, followed by the cooling length. The pouring temperature, cooling length, and tilt angle exhibited 43.13%, 33.98%,7.76% of the total effect, respectively.
3. The optimization model showed that a pouring temperature, tilt angle and cooling length of 620 oC, 30o and 350 mm, respectively, is the optimal setting of the CS casting process parameters that expected to produce average grain size and shape factor of 17.14 µm and 0.9844, respectively.

Nomenclature

SC	Cooling Slope
ANOVA	Analysis of Variance
MHD	Magneto-Hydrodynamic
SIMA	Strain-Induced Melt Activated
RSM	Response Surface Methodology
DSC	Differential Scanning Calorimetry
CMRDI	Central Metallurgical Research and Development Institute
GZ	Average Grains Size, µm
SF	Shape Factor

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T	Pouring Temperature, °C
L	Cooling Length, Mm
A	Tilt Angle, °
S/N	Signal-To-Noise
OA	Orthogonal Array
DF	Degree of Freedom
Adj SS	Adjusted Sum of Squares
Adj MS	Adjusted Mean Square
Pc	Percent Contribution, %

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