



EFFECT OF COOLING SLOPE CASTING PARAMETERS ON THE THIXOTROPIC MICROSTRUCTURE OF A356 ALUMINUM ALLOY

D. M. Adss¹ E-A. Attia¹ T.S.Mahmoud¹ I.S. El-Mahallawi² T.A. Khalifa¹

¹Mechanical Engineering Department – Shoubra Faculty of Engineering – Benha University, Cairo, Egypt.

²Mining, Petroleum and Metallurgical Department, Faculty of Engineering, Cairo University, Giza, Egypt.

ABSTRACT

In the present paper, the effect of cooling slope casting (CSC) parameters process, typically, pouring temperature (T), cooling slope length (L) and tilt angle (θ), on the microstructure of A356 cast aluminum alloys was studied. The analysis of variance (ANOVA) statistical technique was carried out to clarify the relationship between the aforementioned parameters and the microstructure variables, typically, the shape factor (S.F.) and the grain size (G.S.) of the α -Al primary phase. The uniformity of the microstructure in both the axial and radial positions of the ingots was also evaluated statistically. The results revealed that the tilt angle has the highest significant effect on both shape factor and grain size. The shape factor exhibited maximum value of about 0.812 for ingots poured at $\theta = 30^\circ$, L = 300 mm, T = 630 °C. The minimum grain size was about 32.85 μm for ingots casted at $\theta = 60^\circ$, L = 200 mm, T = 630 °C. Ingots poured at $\theta = 60^\circ$, L = 300 mm, T = 630 °C exhibited the highest grain size uniformity. While ingots casted at $\theta = 30^\circ$, L = 400 mm, T = 620 °C, exhibited the highest shape factor uniformity.

KEYWORDS: Cooling Slope Casting, A356 aluminum alloy, Semi-solid Processing, Microstructure.

1. INTRODUCTION

Thixoforming is a semi-solid processing (SSP) technique that has the advantage of both die casting and forging processes [1-5]. It uses semi-solid slurries that has a thixotropic property, i.e. it can be flow like a liquid when sheared and when it at rest it solidifies again [3,5]. Such technique is used to produce parts needed for the automotive industry [2,3,6,7]. In thixoforming a specialized non-dendritic (thixotropic) feedstock is required. The non-dendritic feedstock microstructure can be obtained by a variety of means during cooling including mechanical stirring and electromagnetic stirring [8-10]. Such techniques involve application of some sort of external shearing action. Recently, a simple and versatile technique known as cooling slope casting (CSC) was developed to produce thixotropic feedstock without the need of the application of external shearing action [2-4,7,10,11]. The semi-solid slurry is allowed to flow down an inclined surface. During this process, the shearing action takes place within the mush which slides down an inclined cooling slope due to natural gravity

The influence of the CSC parameters on the microstructural characteristics of A356 aluminum ingots was studied by many investigators [1,2,4,7,11-13]. For example, *Taghavi* and *Ghassemi* [2] studied the effects of the cooling length and angle of inclined plate on the thixotropic microstructure of A356 aluminum alloy. The molten alloy with 680 °C superheat was poured on the surface of the inclined plate at different values of angles and lengths. It was found that the slope angle and cooling length of inclined plate affect the size and morphology of α -Al grain. *Hosseini et al.*[1] investigated the effect of pouring temperature, cooling length and tilt angle of copper made plate on the microstructure of the A356 aluminum alloy. The molten alloy with the temperature of 680, 650 and 625°C was poured on the surface of the plate where cooled with water circulation in various tilt angles (30°, 40°, 50°, 60°) and lengths (300, 400, 500, 600, 700 mm). It was found that there is an optimum length in which minimum grain size and maximum sphericity can be obtained, at a constant tilt angle and pouring temperature. Also, it was found that there was a suitable tilt angle in which minimum grain size and maximum sphericity can be obtained, at a constant pouring temperature and length. These results indicate that condition of 60° and 600 mm is suitable cooling plate tilt angle and pouring length presenting the minimum grain size of 81 μm and maximum shape factor of 0.72 with highest uniformity. *Haga et al.* [12] studied the effects of the casting factors such as tilt angle and cooling length on the process to make semisolid slurry. The results show that these factors affect the behavior of the semisolid slurry on the cooling slope. The tilt of the slope is the factor that has major influence on the behavior of the semisolid slurry.

In the present study, the influences of the CSC parameters such as pouring temperature, cooling slope length and tilt angle of the inclined plate on the microstructure of A356 cast Al-Si aluminum alloy were investigated. The effect of the aforementioned parameters on the uniformity of the microstructure through the A356 aluminum ingots was also examined. The analysis of the experimental results was carried out using analysis of variance (ANOVA). The ANOVA is useful in understanding the effect of CSC parameters and their interactions on the microstructural characteristics of the α -Al primary phase such as the shape factor (S.F.) and grain size (G.S.).

2. EXPERIMENTAL PROCEDURES

2.1. Material

In the present work, the A356 Al-Si cast aluminum alloy is used with the chemical composition shown in Table 1. The differential scanning calorimetric (DSC) analysis showed that the liquidus and solidus temperatures of the alloy are 615 and 572 °C, respectively.

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.

2.2. Cooling Slope Casting Process

The CSC process was carried as follows: about 850 g of A356 alloy was melted at 680 °C in a graphite crucible located at a resistance furnace. After complete melting, degassing process by dry argon inert gas was carried out to remove any undesirable dissolved gases in order to prevent the formation of gas bubbles inside the ingots, then the molten alloy was allowed to cool down to the required pouring temperature, then poured on the surface of an inclined 100 mm wide mild steel plate as shown in Fig. 1. The plate is coated with a thin layer of hard Chromium to prevent adhesion between the molten metal and the plate. The cooling plate tilt angle was adjusted to desired angles of with respect to the horizontal plane. Also, the

flow length of the molten metal over the plate can be adjusted to the required pouring length. The semisolid metal formed at the end of the inclined plate collected in a steel mold located under the inclined plate then leaved to cool down. The steel mold had a diameter of 50 mm and height of 160 mm with a draft angle of 2° for easy removal of the solidified ingot.

2.2. Microstructural Investigations

After solidification, the produced ingots were sectioned horizontally into discs, having 25 mm radius and 5 mm thick, from the top, middle, and bottom sections as shown in Fig. 2. Metallographic specimens were ground and polished using standard metallographic techniques. The samples was etched using keller's etchant (2 ml Hydrofluoric acid, 3 ml Hydrochloric acid, 5 ml Nitric acid, and 190 ml distilled water), then examined using *Olympus* optical microscope. The metallographic images were taken from the wall zone (radius), mid-radius and center zone of the specimens as shown in Fig. 2. The size and shape factor of α -Al grains were determined using image analyzing techniques. The shape factor of the grains was determined from the following equation [1]:

$$S.F. = 4\pi AP^2 \quad \dots(1)$$

Where: P is the perimeter and A is the area of α -Al grain. For a perfect circle, the shape factor would be one.

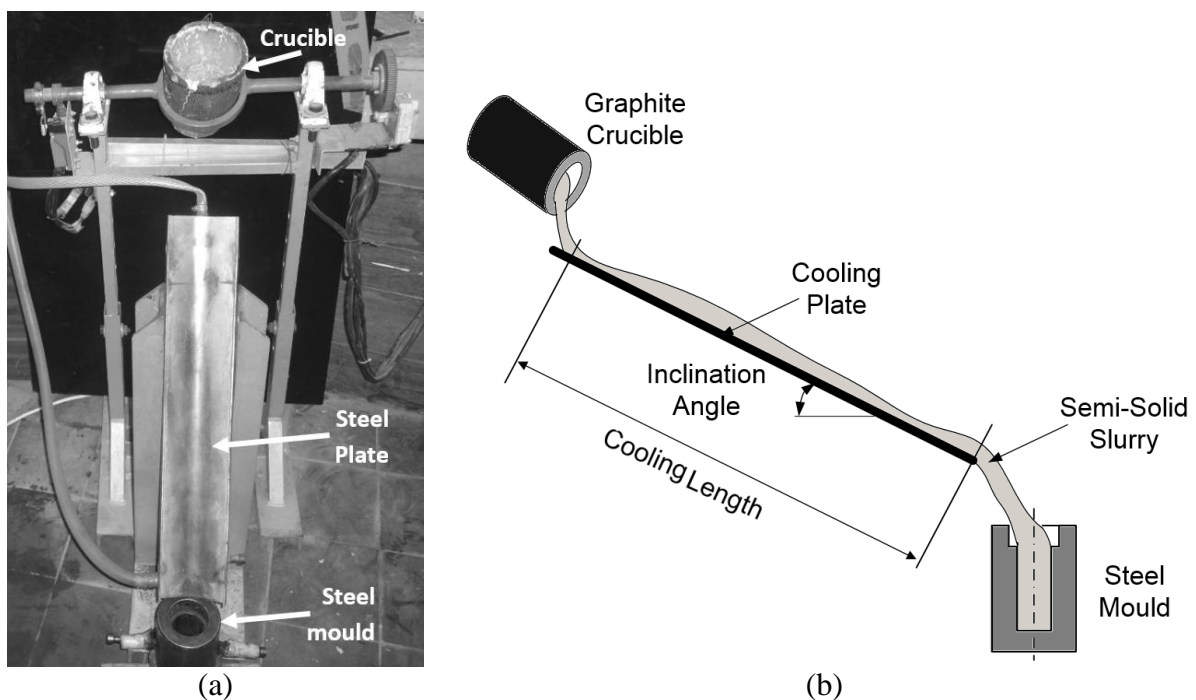


Fig. 1. The cooling slope casting (CSC) apparatus (a) a photograph (b) a schematic illustration

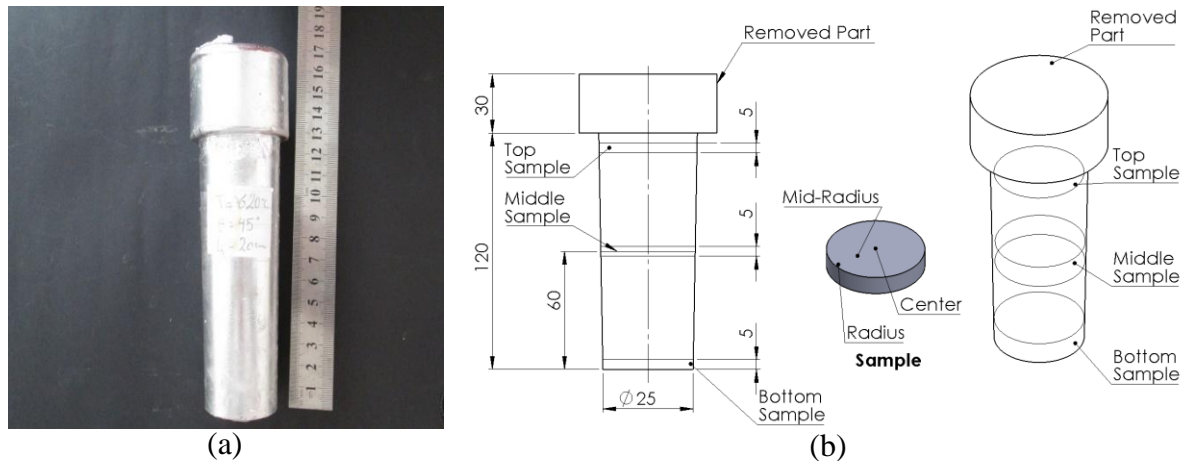


Fig. 2. (a) A photograph shows a typical A356 ingot and (b) a schematic illustration of the ingot showing the locations of the metallographic samples (Dimensions in mm)

2.3. Design of Experiment (DOE)

In order to investigate the effect of CSC process parameters on the different responses (i.e. grain size and shape factor), the three levels factorial design of experiment (DOE) technique was performed. The factorial design technique was adopted in order to investigate the different interactions between CSC variables. With factorial design one can have responses at all combinations of the factors levels. Other reason is the number of generated runs with three factors and three levels is acceptable from the economical perspective. The independent parameters are pouring temperature, tilt angle and the cooling slope length. Table 2 summarizes the independent parameters and their levels. The pouring temperature levels were adopted based of the work of *Ghavamodini et al.* [4]. Also, the levels of the tilt angle were selected relying on the work of *Haga et al.* [13]. In addition the levels of the cooling slope length were selected as presented in the work of *Hosseini et al.* [1]. This design of experiment gives a total of 27 ingots.

The analysis of experimental results was carried out using analysis of variance (ANOVA) approach. The ANOVA is a very useful statistical method in understanding the effect of casting parameters and their interactions on the value of shape factor and grain size of α -Al grains. From results of ANOVA one can obtain the most and lowest significant parameters. Furthermore, the relative standard deviation (RSD) has been used to determine the maximum uniformity of shape factor and grain size in both axial and radial directions of the ingot. The RSD gives the variation as a percentage of the mean (average). More uniform data yield a smaller RSD. It is expressed as a relative relation between variation and data mean. It can be obtained according to the relation: $RSD = \sigma/\mu$, where σ : is the standard deviation and μ is the mean value of the data. The statistical and ANOVA calculations were performed using *MiniTab* commercial statistical software.

Table 2. The independent parameters and their levels.

Parameters	Levels		
	Level-1 (minimum)	Level-2 (mean)	Level-3 (maximum)
Pouring Temperature ($^{\circ}$ C)	620	630	640
Cooling Plate Tilt Angle (Degree)	30	45	60
Cooling Length (mm)	200	300	400

3. RESULTS & DISCUSSION

3.1. Effect of CSC Parameters on the Grain Size of the primary α -Al Phase

Figures 3 and 4 shows typical micrographs of the microstructure of the A356 ingots poured at various CSC parameters. The micrographs were taken from different locations of the A356 ingots. It can be observed that the degeneration of the dendritic structure and refinement in the morphology of the primary α -Al phase in the CSC ingots is the consequence of the fractional solidification that occurs on the cooling slope plate. Generally, the radius zones exhibited finer primary α -Al grains than 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.

Figures 5 shows the variation of the average grain size of the primary α -Al grains of the A356 ingots with the tilt angle at different pouring temperatures and cooling slope lengths, respectively. It has been found that, at constant pouring temperature and length, increasing the tilt angle from 30° to 45° decreases the average size of the primary α -Al grains. For example, at constant pouring temperature of 620°C and cooling slope length of 200 mm, increasing the tilt angle from 30° to 45° reduced the average size of the primary α -Al grains from 59.82 to 54.22 μm . Increasing the tilt angle more than 45° (i.e. to 60°) tends to increase the average size of the primary α -Al grains. The increase of the tilt angle results in the increase of the shear stress that helps to break the dendritic microstructure and converts it to nearly more fine grains [1]. This result is obviously seen with the comparison of the microstructure at both tilt angle values of 30° and 45° . When the tilt angle increased than a certain value this makes the slurry passing the inclined plate with very high speed, decreasing the amount of heat dissipated from the molten metal that makes it reach the end of the inclined plate and collected in the die in the form of semi-solid with low solid particle content and high liquid fraction [15].

It has been found that, for ingots poured at 620°C , increasing the cooling slope length reduces the average size of the primary α -Al grains (see Fig. 5a). For example, at constant tilt angle of 30° , increasing the cooling slope length from 200 to 400 mm reduces the average grain of the primary α -Al grains from 59.82 to 36.79 μm . At pouring temperatures higher than 620°C (i.e. at 630°C and 640°C), the effect of the cooling slope length could not clearly be determined since the ingots showed practically the same average α -Al grain size. The results revealed also that increasing the pouring temperature increases the average grain of the primary α -Al grains. For example, at constant tilt angle of 30° and cooling slope length of 200 mm, increasing the pouring temperature from 620°C to 630°C reduced the average grain of the primary α -Al grains from 59.82 to 43.73 μm . It has been reported [16] that high pouring temperature leads to decrease in nucleation, remelting the primary crystals and undesired grain growth.

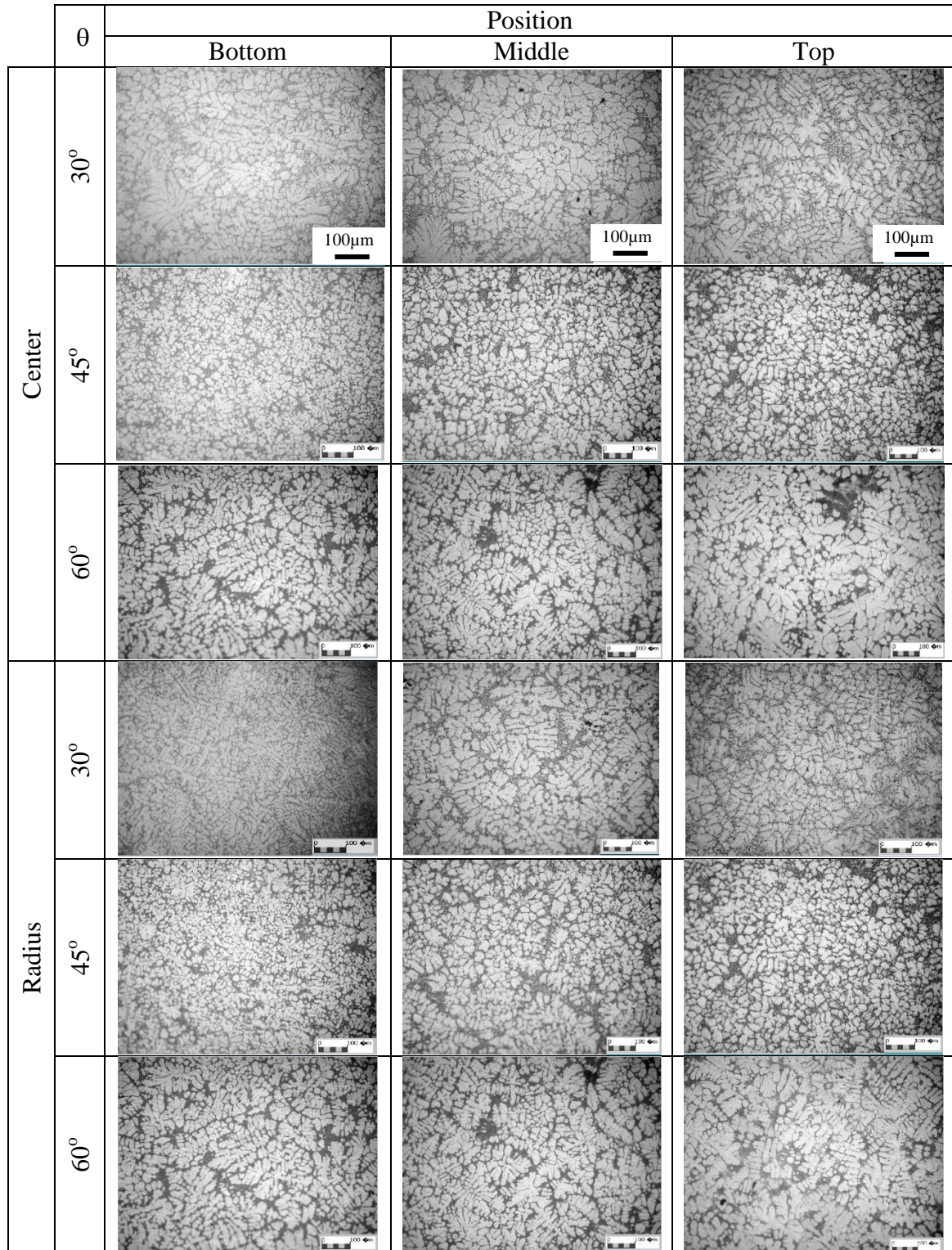


Fig. 3. Optical micrographs of the microstructure of the A356 alloy poured using several tilt angles (θ). The pouring temperature and cooling length were kept constant at 640 °C and 400 mm, respectively.

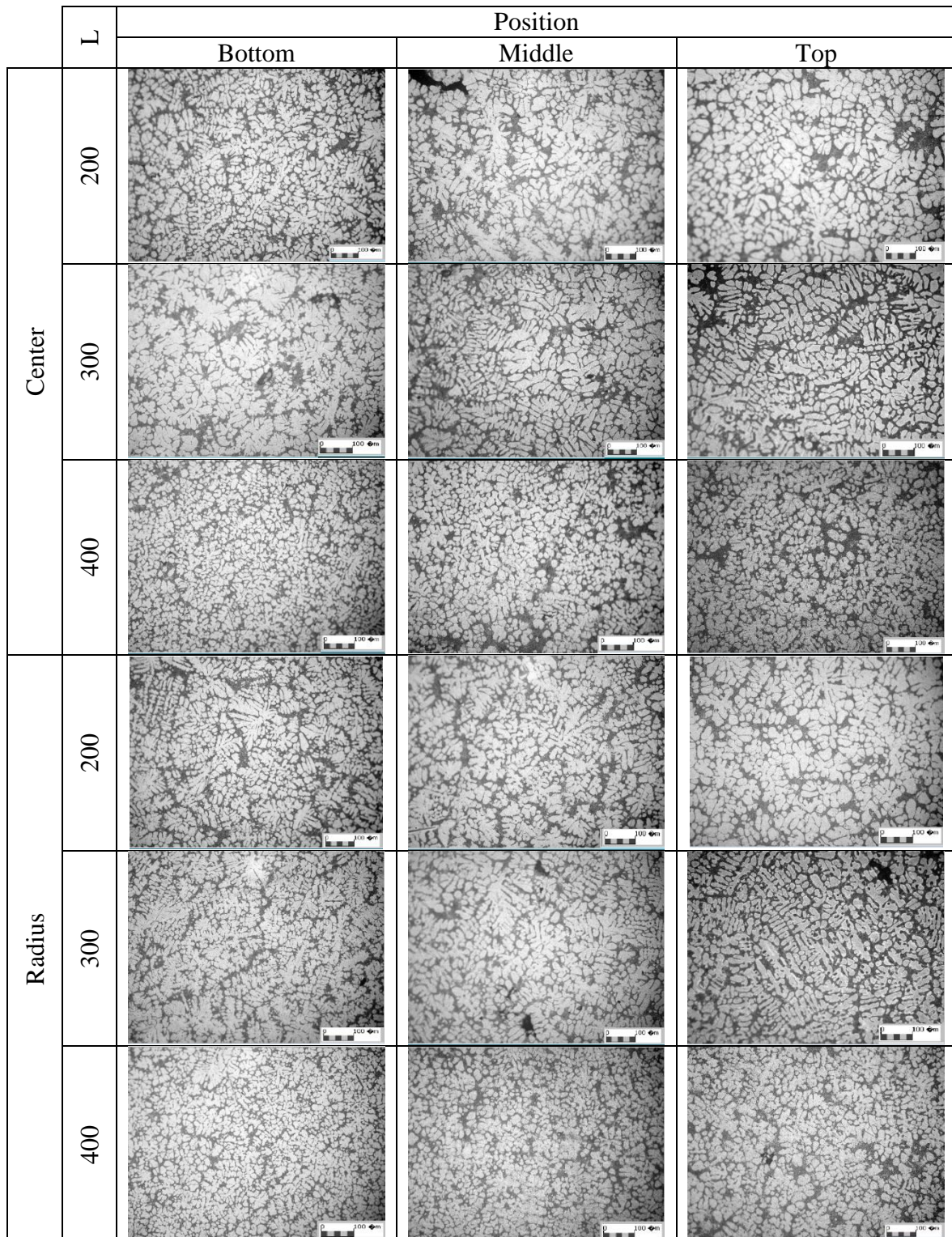


Fig. 4. Optical micrographs of the microstructure of the A356 alloy poured using several cooling slope lengths (L). The pouring temperature and tilt angle were kept constant at 620 °C and 45°, respectively.

Figure 6 shows the variation of the primary α -Al grains at both axial and radial directions with the cooling slope casting parameters studied in the present investigation. The bottom of the ingots exhibited the smallest grain size when compared with the top and middle positions. Also, the grains at the radius positions showed the smallest size when compared with the center and mid-radius positions. Increasing the cooling slope length reduces the size of the primary α -Al grains at both the axial and radial positions of the ingots (see Fig. 6c and

6d). At both axial and radial positions, increasing the tilt angle from 30 to 45° reduces the size of the primary α -Al grains. However, increasing the tilt angle from 45 to 60° tends to increase the size of the primary α -Al grains at both axial and radial positions (see Fig. 6a and 6b). The results showed also that, at both the positions increasing the pouring temperature from 620 to 630 °C reduces the size of α -Al grains at the bottom, middle and top of the A356 alloy ingots. Increasing the pouring temperature above 630 °C (i.e. to 640 °C) increases the grain size of the primary α -Al grains. Such observation was noticed at the radial positions. In the radial position, the radius position (near wall position) exhibited largest grain size when compared with the mid-radius and center positions of the ingot.

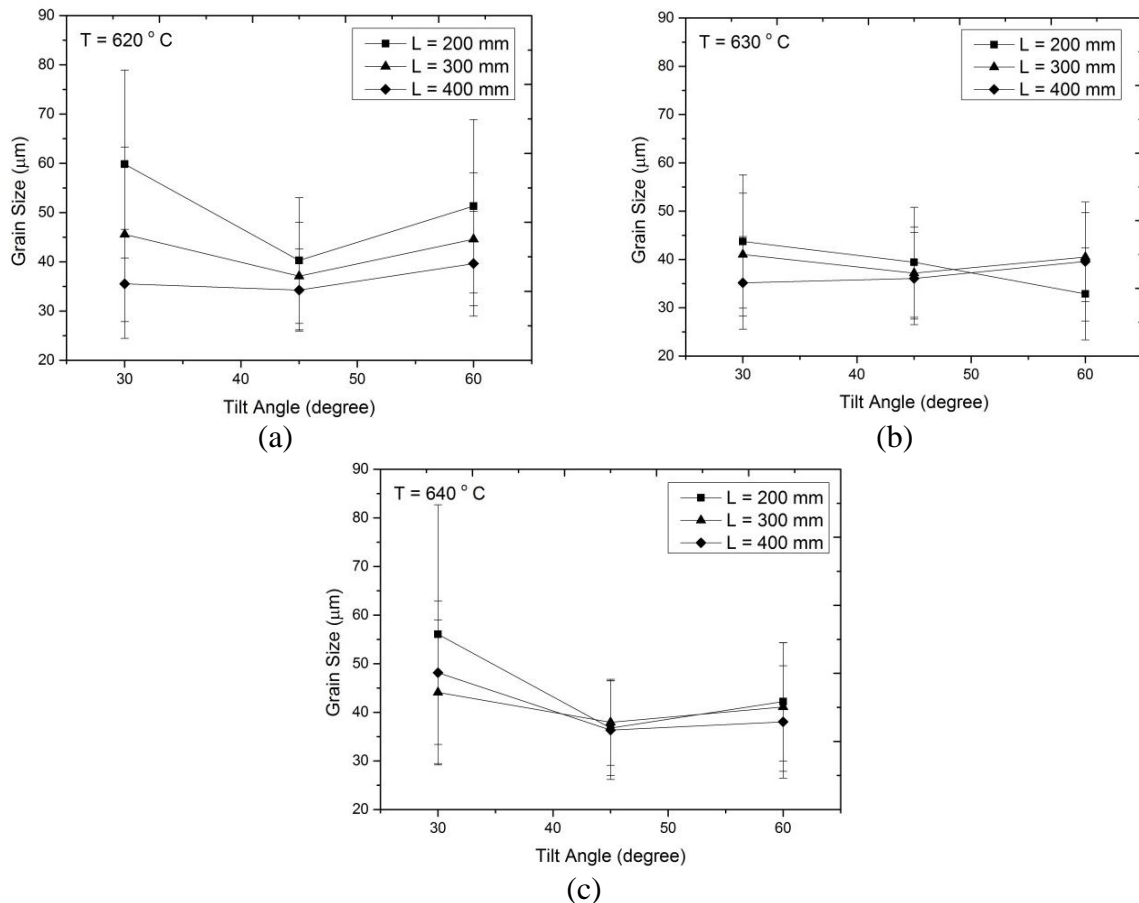


Fig. 5. Variation of the average grain size of the α -Al primary grains with the tilt angle at different cooling lengths and pouring temperatures.

Figure 7 shows typical histograms of the size of the α -Al primary grains at the top, middle and bottom positions of A356 ingot poured at at 45°, 400 mm and 640 °C. The values resulted from the RSD calculations of the size of the primary α -Al grains revealed that the minimum value (i.e. maximum uniform grain size distribution) of about 0.14613 was obtained for ingots poured at $\theta = 60^\circ$, $L = 400$ mm, and $T = 640$ °C. The ingots poured at $\theta = 30^\circ$, $L = 200$ mm, and $T = 640$ °C exhibited the maximum RSD value of about 0.557152 (i.e. the minimum uniform grain size distribution). Table 3 lists the ANOVA results for the size of the α -Al primary grains. The analysis was carried out for a level of significance of 5 percent (i.e. the confidence limit is equal to 95 per cent). The last column in Table 3 shows the percentage of contribution (P_c) of each factor on the total variation indicating the influence of the factors on the results. It can be observed that tilt angle ($P_c = 28.97\%$), cooling slope length ($P_c = 17.1326\%$), pouring temperature ($P_c = 11.568\%$), the interaction tilt angle/cooling slope length ($P_c = 11.5426\%$), and the interaction cooling slope length/pouring temperature ($P_c = 13.56\%$) have the greatest statistical and physical significance on the grain size of α -Al grains. It was also found that the interaction tilt angle/pouring temperature ($P_c = 9.7268\%$) and the

interaction tilt angle/cooling slope length/ pouring temperature ($P_c = 7.5\%$) have lower significant effect on the grain size of the α -Al primary grains. The results indicated that the tilt angle parameter has the highest statistical physical significance on the grain size of the α -Al primary grains.

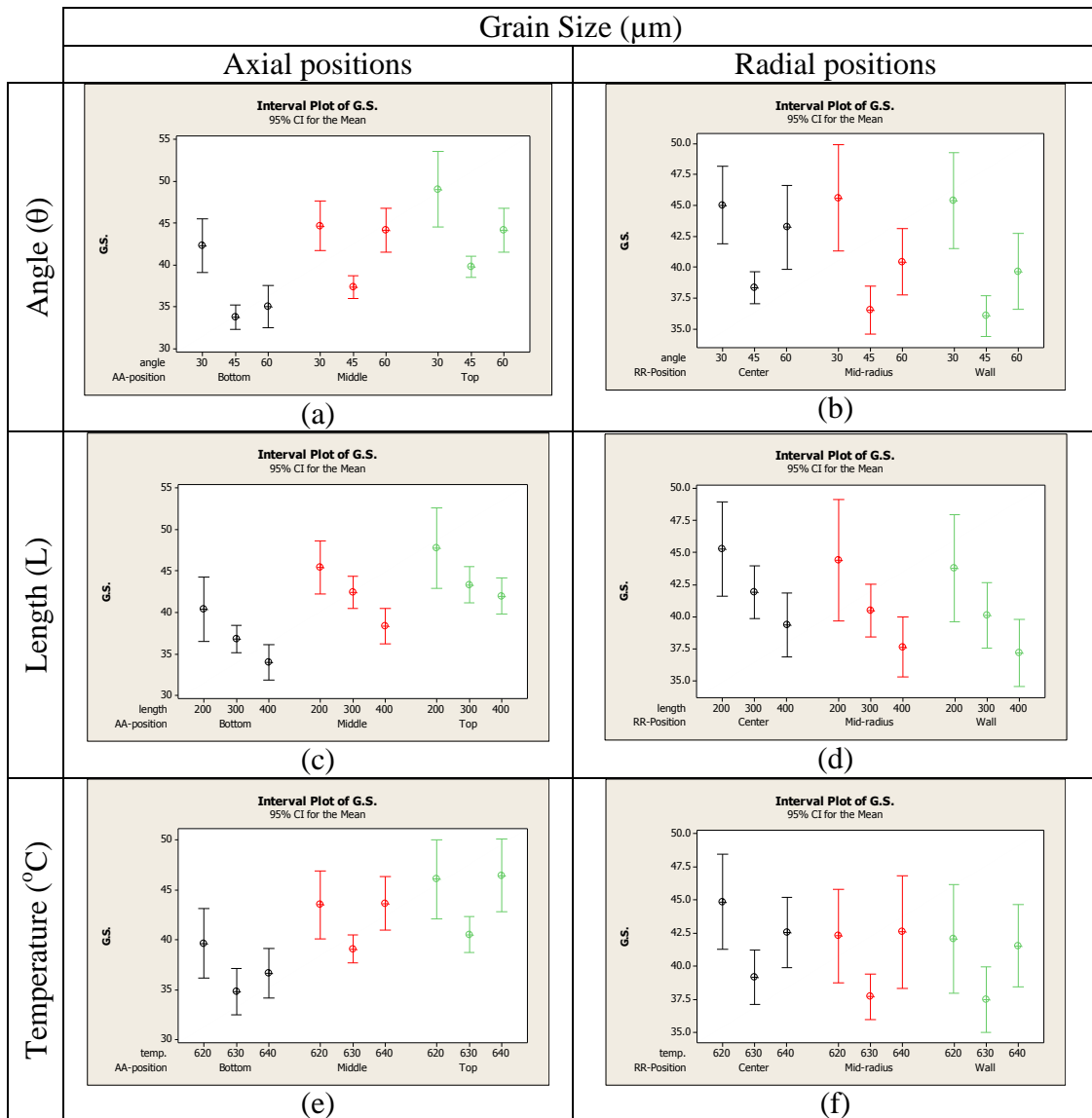


Fig. 6. Variation of grain size of primary α -Al grains with different values of tilt angle (30,45 and 60°), cooling slope length (200,300 and 400 mm) and pouring temperature (620, 630 and 640°C) at both (a,c,e) axial and (b,d,f) radial positions.

Table 3. ANOVA table for the size of the α -Al primary grains.

Source of variation	DF	SS	MS	F	P	P_c
θ	2	2853.30	1426.65	47.32	0.000	28.97
L	2	1687.42	843.71	27.99	0.000	17.1326
T	2	1139.38	569.69	18.90	0.000	11.568
$\theta \times L$	4	1136.67	284.17	9.43	0.000	11.5426
$\theta \times T$	4	958.01	239.50	7.94	0.000	9.7268
$L \times T$	4	1335.53	333.88	11.07	0.000	13.56
$\theta \times L \times T$	8	738.86	92.36	3.06	0.003	7.5
Residual	216	6511.92	30.15			
Total	242	9849.18				100

$S = 5.49070$ $R\text{-Sq.} = 60.20\%$ $R\text{-Sq.}(adj) = 55.41\%$.

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

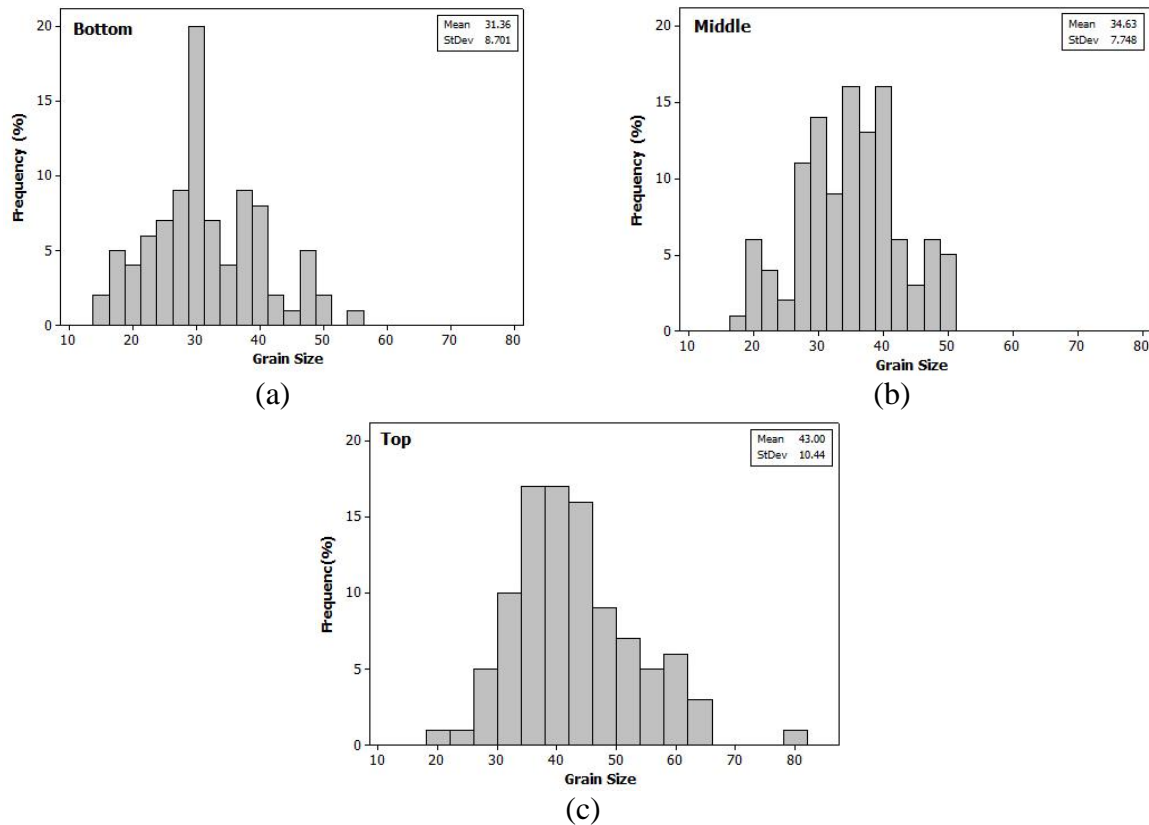


Fig. 7. A sample of the frequency plot (histogram) of the size of the α -Al primary grains at the top, center and bottom positions of A356 ingot poured at 45° , 400 mm and 640°C .

3.2. Effect of CSC Parameters on the Shape Factor of the primary α -Al Phase

Figure 8 shows the variation of the average shape factor of the A356 alloy ingots with the tilt angle at different pouring temperatures and cooling slope lengths. At constant pouring temperature and cooling slope length, increasing the tilt angle reduces the average shape factor of the A356 alloy ingot. For example, at constant pouring temperature of 620°C and pouring length of 200 mm, increasing the tilt angle from 30° to 60° reduces the average shape factor of the primary α -Al grains from 0.7791 to 0.7384. In contrast, increasing the cooling slope length increases the average shape factor of the ingots. For example, at constant tilt angle of 30° and pouring temperature of 630°C , increasing the cooling slope length from 200 to 400 mm increases the average shape factor of the primary α -Al grains from 0.7891 to 0.7933 μm . Moreover, at constant tilt angle and cooling slope length, increasing the pouring temperature increases slightly the average shape factor of the primary α -Al grains. For example, at constant tilt angle of 30° and cooling slope length of 200 mm, increasing the pouring temperature from 620°C to 630°C increases the average shape factor from 0.7791 to 0.7891.

Figure 9 shows the variations of the average shape factor with the different cooling slope casting parameters at both axial and radius positions of the A356 alloy ingots. Generally, increasing the tilt angle reduces the shape factor at both axial (top, middle and bottom) and radial (radius, mid-radius and center) positions of the poured ingots. In contrast, increasing the pouring temperature increases the shape factor at both the axial and radial positions of the A356 ingots (see Fig. 9c and 9d). The top positions of the ingots exhibited higher shape factor than the bottom and middle of the ingots. Moreover, the radius (near wall) positions exhibited higher shape factor than the center and mid-radius positions of the ingots. Increasing the pouring temperature from 620 to 630°C increases slightly the shape factor of the α -Al primary grains. Such observation was noticed at both axial and radial positions of the

ingots. Further increase in the pouring temperature (i.e. to 640 °C) tends to reduce the shape factor of the α -Al primary grains at both axial and radial positions of the ingots.

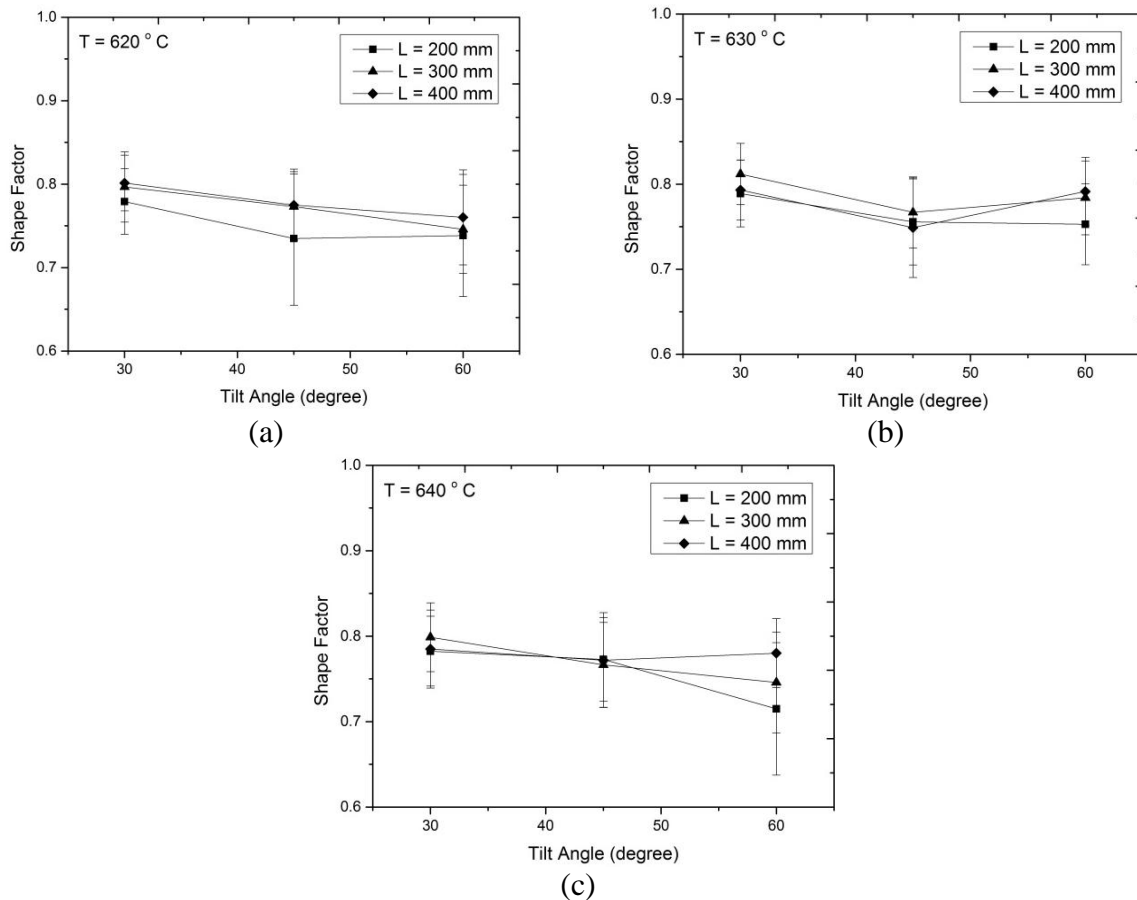


Fig. 8. Variation of the average shape factor of the α -Al primary grains with the tilt angle at different cooling lengths and pouring temperatures.

Figure 10 shows typical histograms the shape factor distribution of the α -Al primary grains at the top, middle and bottom positions of ingot poured at 30°, 200 mm and 620 °C. The minimum RSD value of the shape factor was about 0.026955 for ingots poured at $\theta = 30^\circ$, $L = 300$ mm and $T = 640$ °C. While the maximum RSD value was about 0.20424 for ingots poured at $\theta = 45^\circ$, $L = 200$ mm and $T = 620$ °C. Table 4 shows the results of the ANOVA for the porosity content. The analysis was carried out for a level of significance of 5 per cent. From the analysis of Table 4, it can be observed that tilt angle ($P_c = 43.885\%$) and cooling length ($P_c = 15.537\%$) have the highest statistical and physical significance on the shape factor of the α -Al primary grains. The pouring temperature ($P_c = 3.044\%$) have lowest statistical and physical significance on the shape factor.

From the aforementioned results, it can be concluded that the tilt angle has the most significant effect on both the grain size and shape factor of the α -Al primary grains. While the pouring temperature has the lowest significant effect on both the grain size and shape factor of the α -Al primary grains. Such results were reported by many workers [1,13,15,16]. Pouring the molten metal on a slope plate with large angle make the 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 bad shape factor, so when pouring the molten metal on a cooling slope plate with small tilt angle this give the chance of increasing the number of nucleated and detached crystals that produces fine grains with better shape factor, but if the tilt angle become very 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 completely filled with the metal. In the

present investigation, it has been found that a tilt angle of 45° is the most suitable angle for pouring the A356 alloy.

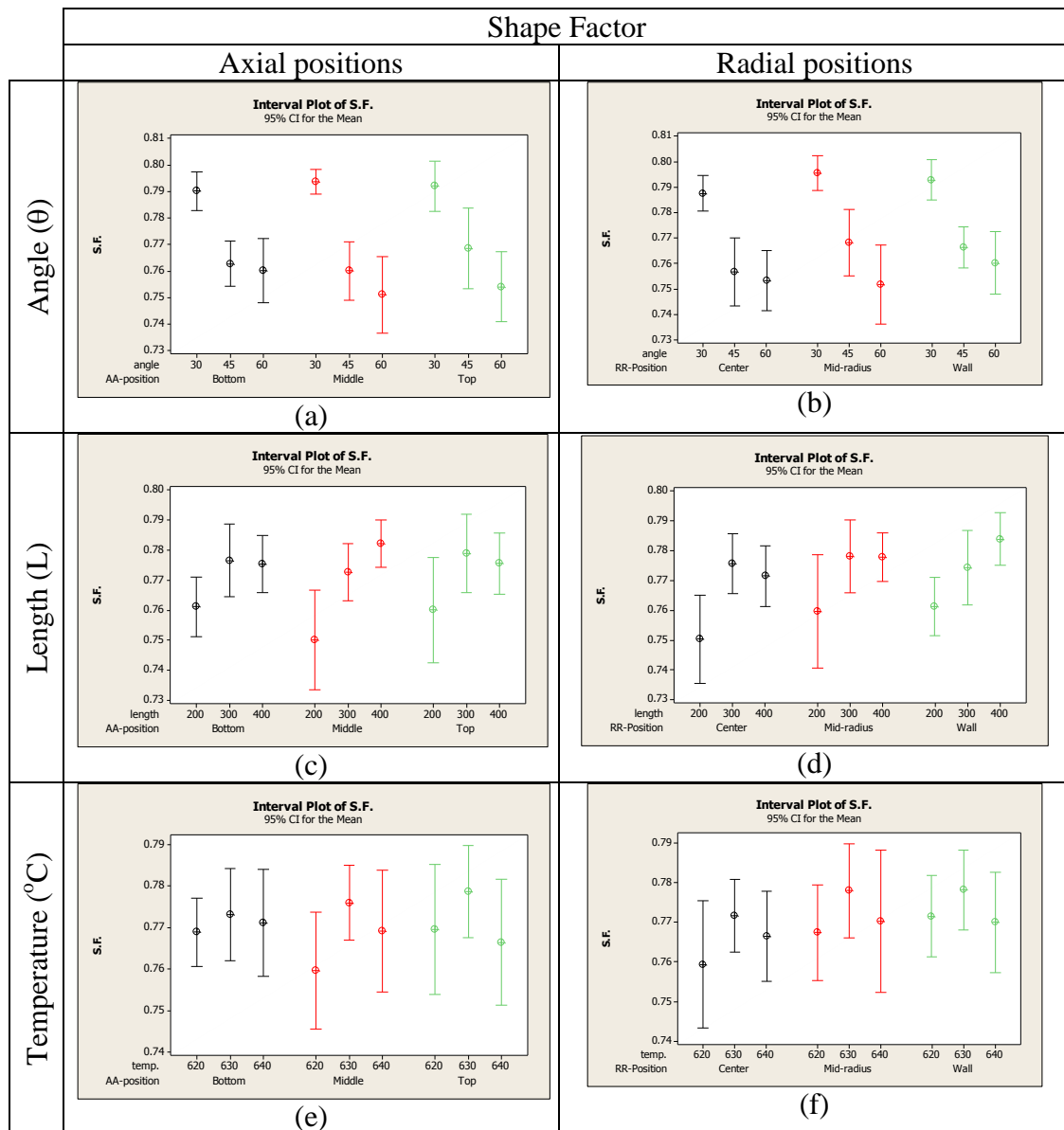


Fig. 9. Variation of shape factor of primary α -Al grains with different values of tilt angle ($30, 45$ and 60°), cooling slope length ($200, 300$ and 400 mm) and pouring temperature ($620, 630$ and 640 °C) at both (a,c,e) axial and (b,d,f) radial positions.

Table 4. ANOVA table for the shape factor of the α -Al primary grains.

Source of variation	DF	SS	MS	F	P	P _c
θ	2	0.0601661	0.0300830	58.64	0.000	43.885
L	2	0.0213010	0.0106505	20.76	0.000	15.537
T	2	0.0041730	0.0020865	4.07	0.018	3.044
$\theta \times L$	4	0.0074845	0.0018711	3.65	0.007	5.459
$\theta \times T$	4	0.0161958	0.0040489	7.89	0.000	11.813
$L \times T$	4	0.0105761	0.0026440	5.15	0.001	7.714
$\theta \times L \times T$	8	0.0172036	0.0021504	4.19	0.000	12.548
Residual	216	0.1108052	0.0005130			
Total	242	0.1371001				100

$$S = 0.0226492 \quad R\text{-Sq} = 55.30\% \quad R\text{-Sq(adj)} = 49.92\%$$

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

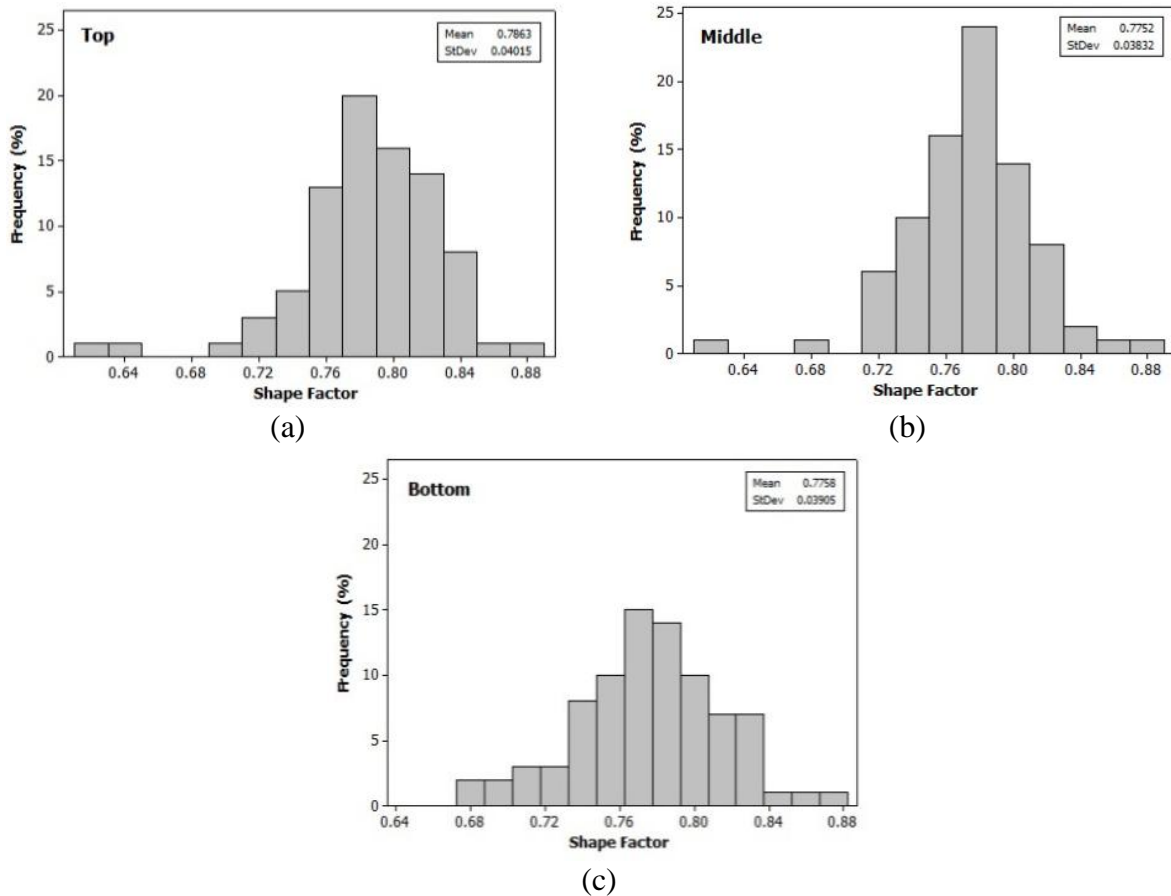


Fig. 10. Typical histograms of the shape factor of the α -Al primary grains at the top, center and bottom positions of A356 ingot poured at 30°, 200 mm and 620 °C.

4. CONCLUSIONS

The conclusions of significance are drawn as follows:

1. The tilt angle exhibited the most statistical and physical significance effect on the grain size and shape factor of the α -Al primary grains. Increasing the tilt angle from 30° to 45° reduced the average size of the primary α -Al grains of the A356 aluminum alloy ingots. Increasing of the tilt angle to 60° increases the average size of the primary α -Al grains.
2. The pouring temperature exhibited the least statistical and physical significance effect on the grain size and shape factor of the α -Al primary grains. Increasing the pouring temperature from reduced the average grain size of the primary α -Al grains
3. A356 aluminum alloy ingots poured at tilt angle, pouring temperature and cooling length of 60°, 640 °C and 400 mm, respectively, exhibited the maximum uniformity of grain size distribution at both the axial and radial directions. However, ingots poured at tilt angle, pouring temperature and cooling length of 30°, 640 °C and 200 mm, respectively exhibited the minimum uniform grain size distribution.
4. The maximum uniformity of the shape factor distribution was exhibited by ingots poured 30°, 300 mm and 640 °C. While the minimum uniformity of the shape factor distribution was exhibited by ingots poured at 45°, 200 mm and 620 °C.

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