ISSN : 0974 - 7486 Volume 14 Issue 6

Materials Science

An Indian Journal

Full Paper

MSAIJ, 14(6), 2016 [208-220]

On the production of al-A356alloy semi-solid feedstock using cooling slope casting technique

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ABSTRACT

In the present paper, the effect of cooling slope casting (CSC) parameters, typically, pouring temperature (T), cooling slope length (L) and tilt angle (θ), on the microstructure of A356 cast aluminum alloyswas studied. The analysis of variance (ANOVA) statistical technique wascarried out to explain the relationship between the aforementioned parameters and the microstructure variablesof the α-Al primary phase such as theshape factor (SF) and the grain size (GS). The uniformity of the microstructure in both the axialand radial positions of the ingots wasalso evaluated. The results revealedthatthe tilt angle has the highest significant effect on both shape factor and grain size. The shape factor exhibited maximum value ofabout 0.812for ingotspouredat θ= 30^o, L = 300 mm, T= 630 ^{o}C. The minimum grain size was about32.85 μm for ingots casted at θ= 60^o, L = 200 mm,T = 630 ^{o}C. Ingots poured at θ= 60^o, L = 300 mm, T = 630 ^{o}C exhibited the highest grain size uniformity. While ingots casted at θ= 30^o, L = 400 mm,T = 620 ^{o}C, investigated the highest shape factor uniformity.

KEYWORDS

Cooling slope casting;
A356 aluminum alloy;
Semi-solid processing;
Microstructure.

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-dendriticfeedstock microstructure can be obtained by a varietyof means during cooling including mechanical stirring andelectromagnetic 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 force[2-4,7,10,11]. The semi-solid slurry is allowed to flow down an inclined surface. Duringthis 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 625ºC 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 sphericitycan 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 sphericitycan be obtained, at a constant pouring temperature and cooling slope length. There 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. *Hagaet 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 thought out the A356 aluminum ingots was also examined. The analysis of the experimentalresults was carried out using analysis of variance(ANOVA). The ANOVA is a useful method in understandingthe effect of CSC parameters and theirinteractions on the microstructural characteristics of the α-Al primary phasesuch as the shape factor (S.F.) and grain size (G.S.).

EXPERIMENTAL PROCEDURES

Material

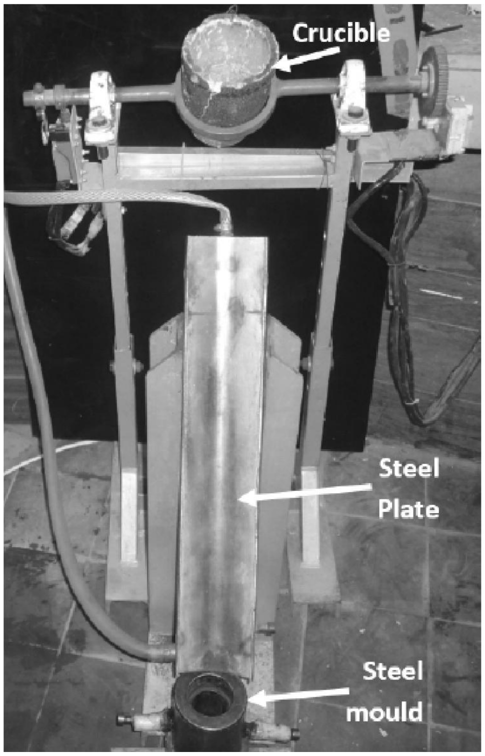
In the present work, the A356 Al-Si cast aluminum alloy is used with the chemical composition shown in TABLE 1. Thedifferential scanning calorimetric (DSC) analysisshowed that the liquidusand solidus temperatures of the alloy are 615and 572 °C, respectively.

Cooling slop casting process

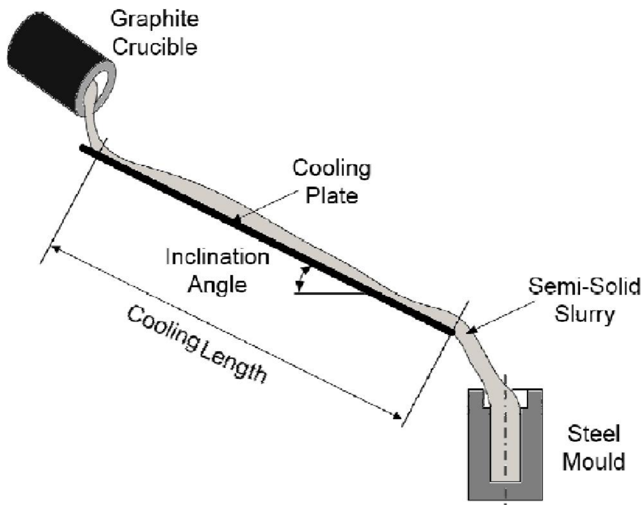
The CSC process was carried as follows:about 850 g of A356 alloy was meltedat 680 °Cin a graphite crucible located at a resistance furnace. After complete melting, degassing process by dry argon inert gas was carried out to remove any undesirable dissolved gases in order to prevent the formation of gas 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 inclined100 mm wide mild steel plateas shown in Figure 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 the desired valueswith 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 2º for easy removal of the solidified ingot.

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.



(a)



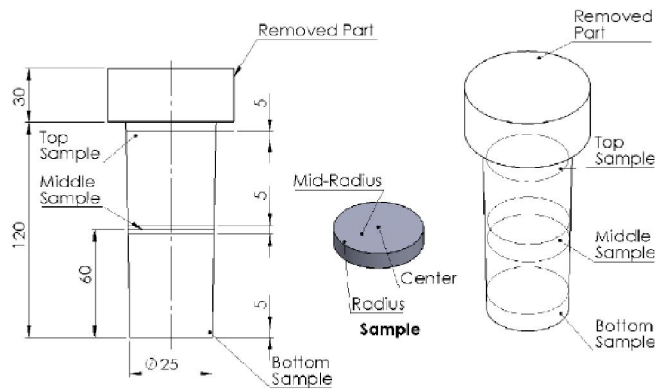
(b)

Figure 1 : The cooling slope casting (CSC) apparatus (a) a photograph (b) a schematic illustration

Microstructural investigations

After complete solidification, the produced ingots were sectioned horizontally into discs, having 25 mm radius and5 mm thick, from the top, middle, and bottom sections as shown in Figure 2. Metallographic specimens were ground and polished using standard metallographic techniques. The samples was etched using keller's etchant (2 ml Hydrofluo-

(a)



(b)

Figure 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)

ric 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 Figure 2. The size and shape factor of ±-Al grains were determined using image analyzing techniques. The shape factor of the grains was determined from the following equation[1]:

$$SF = 4\pi A/P^{-2} \qquad (1)$$

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

Design of experiment (DOE)

TABLE 2 : The independent parameters and their levels

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

In order to investigate the effect of CSC process parameters on the different responses (i.e. grain size and shape factor),thethree levelsfactorial 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, tile 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 *Ghavamodiniet al.*[4]. Also, the levels of the tilt angle were selected relying on the work of *Hagaet al.*[13]. In addition the levels of the cooling slope length were selected as presented in the work of *Hosseiniet 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 highest 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 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 statiscial ANOVA calculations were performed using *MiniTab* commercial statistical software.

RESULTS& DISCUSSION

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

Figures 3and 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 anglefrom 30^{o} to 45^{o}decreases the averagesize of the primary α-Al grains. For example, at constant pouring temperature of 620 ^{o}C and cooling slope length of 200 mm, increasing the tilt angle from 30^{o} to 45^{o} reduced the average size of the primary α-Al grains from 59.82to 54.22 μm. Increasing the tilt angle more than 45^{o} (i.e. to 60^{o}) tends to increases 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

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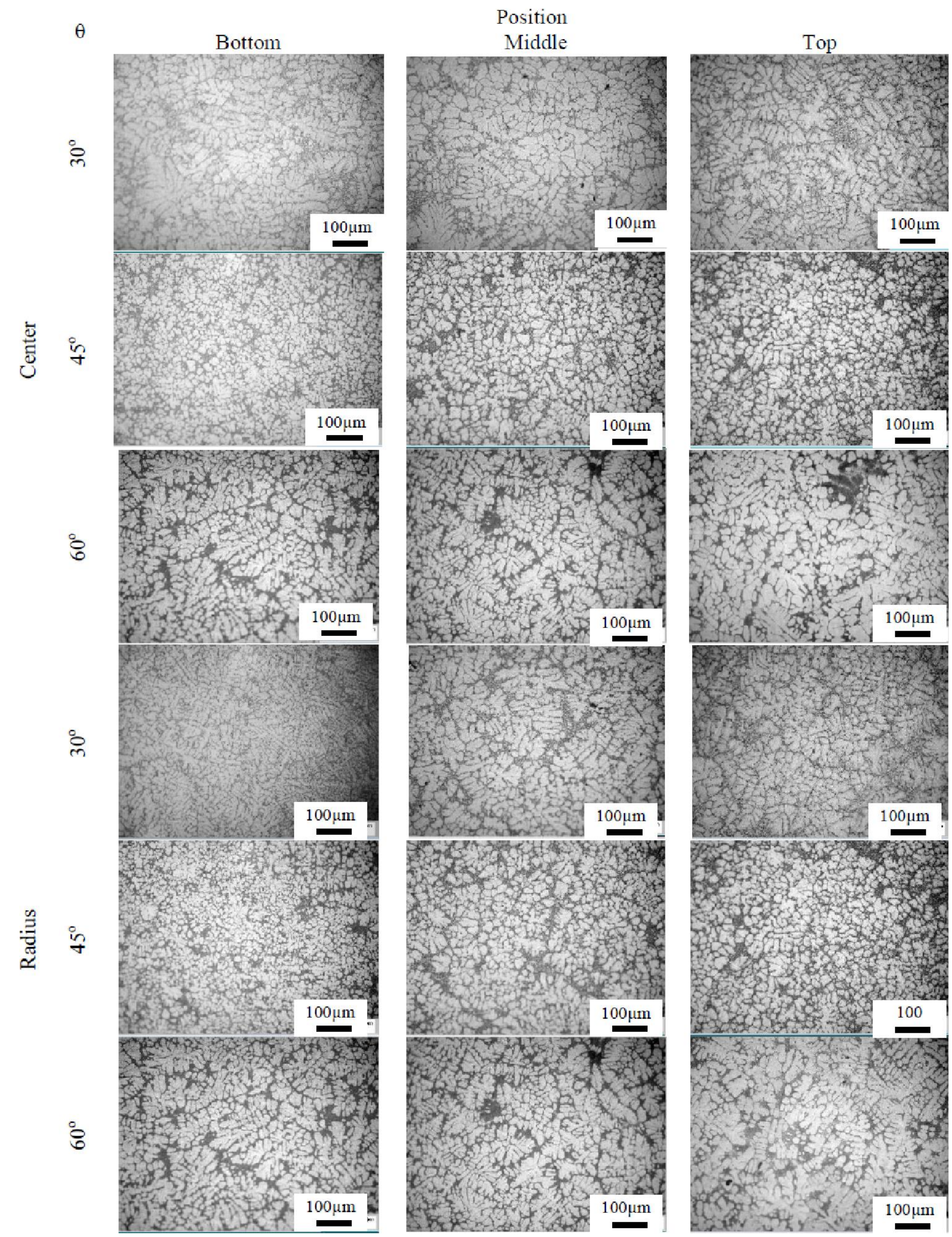

Figure 3 : Optical micrographs of the microstructure of the A356 alloy poured usingseveral tilt angles (θ). The pouring temperature and cooling length were kept constantat 640 °C and 400 mm, respectively

both tilt angle values of 30° and 45°. But When the tilt angle increased than a certain value this make the slurry passing the inclined plate with very high speed, decreasing the amount of heat dissipated from the molten metal that makes it reaches at 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].

Also, 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 Figure 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 and 640 °C), the effect of the cooling slope length could not clearly determined since the ingotsshowed practically the same average α-Al grain size. The results also revealed that increasing the pouring temperature from

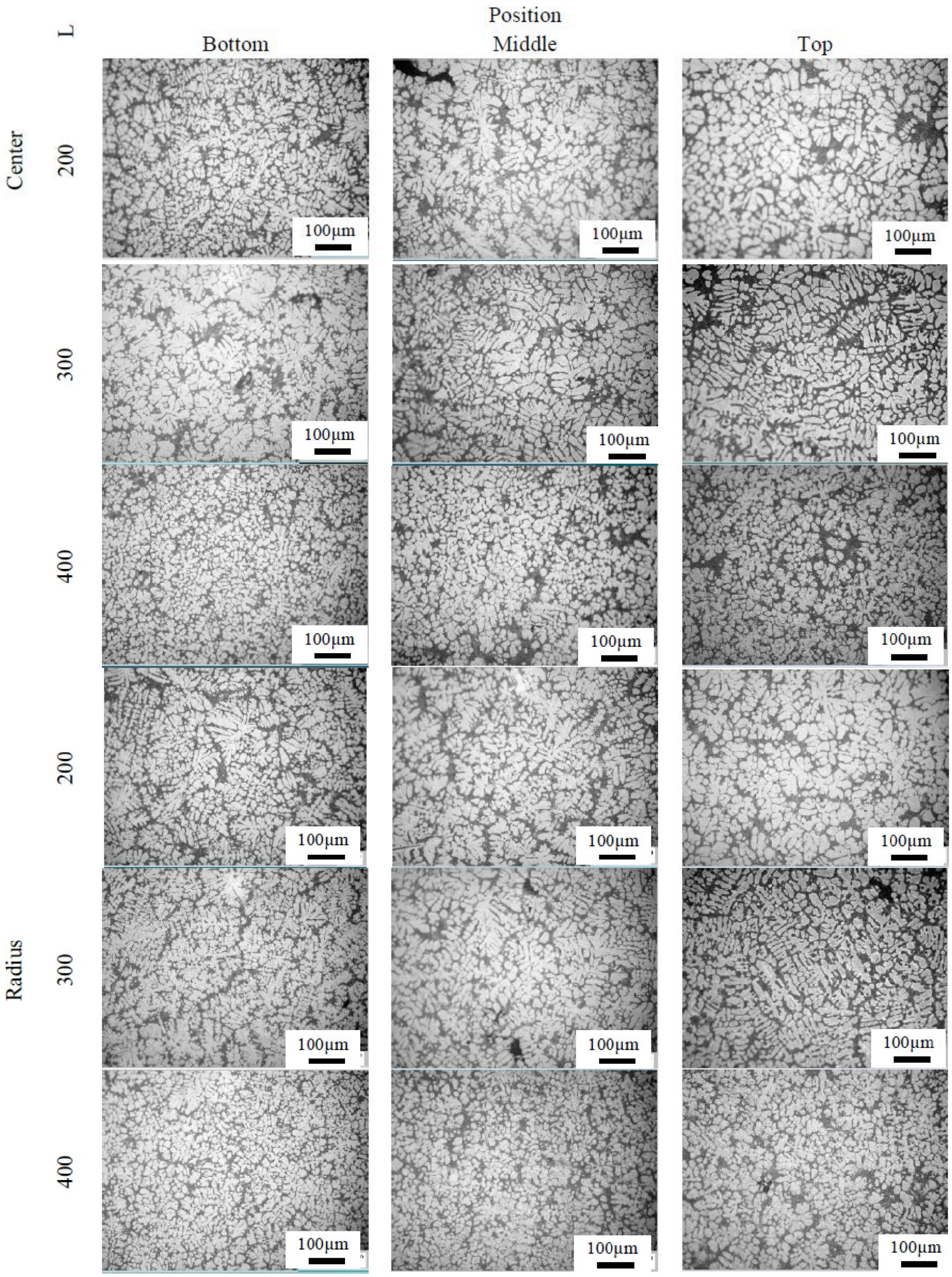

Figure 4 : Optical micrographs of the microstructure of the A356 alloy poured usingseveralcooling slope lengths (L). The pouring temperature and tilt angle were kept constantat 620 °C and 45°, respectively

620 °C to 630 °Cdecreases the average grain of the primary α-Al grains. After that the grain size starts to increase with increasing the pouring temperature more than 630 °C. 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

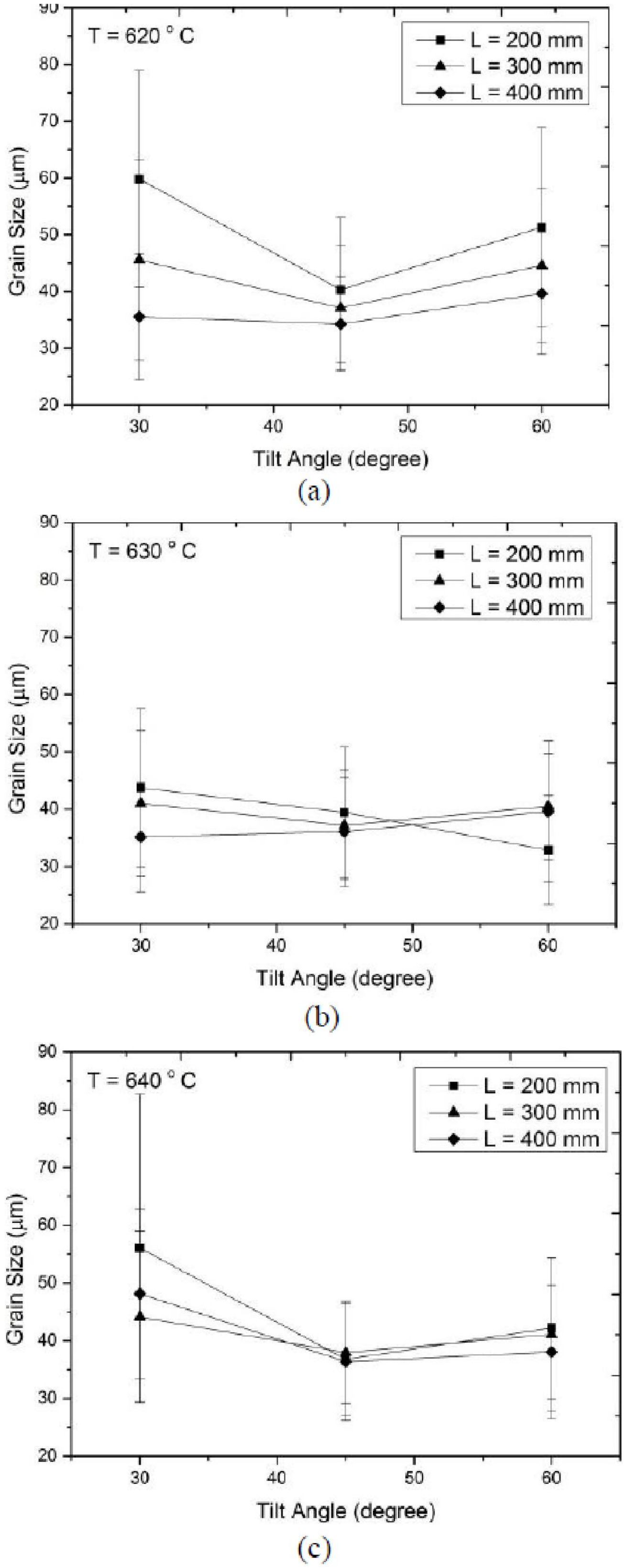

Figure 5 : Variation of the average grain size of the α-Al primary grains with the tilt angle at different cooling lengths and pouring temperatures

reduced the average grain of the primary α-Al grains from 59.82 to 43.73 μm. It has been reported[16] that higher value of pouring temperature than 630 °C leads to decrease in nucleation, re-melting the primary crystals and undesired grain growth will occur.

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 Figure 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 Figure 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.

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 grainsrevealed thatthe minimum value (i.e. maximum uniform grain size distribution)of about 0.14613was obtained foringots poured at θ=60°, L=400 mm, and T=640 °C. The ingots poured at θ = 30°, 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

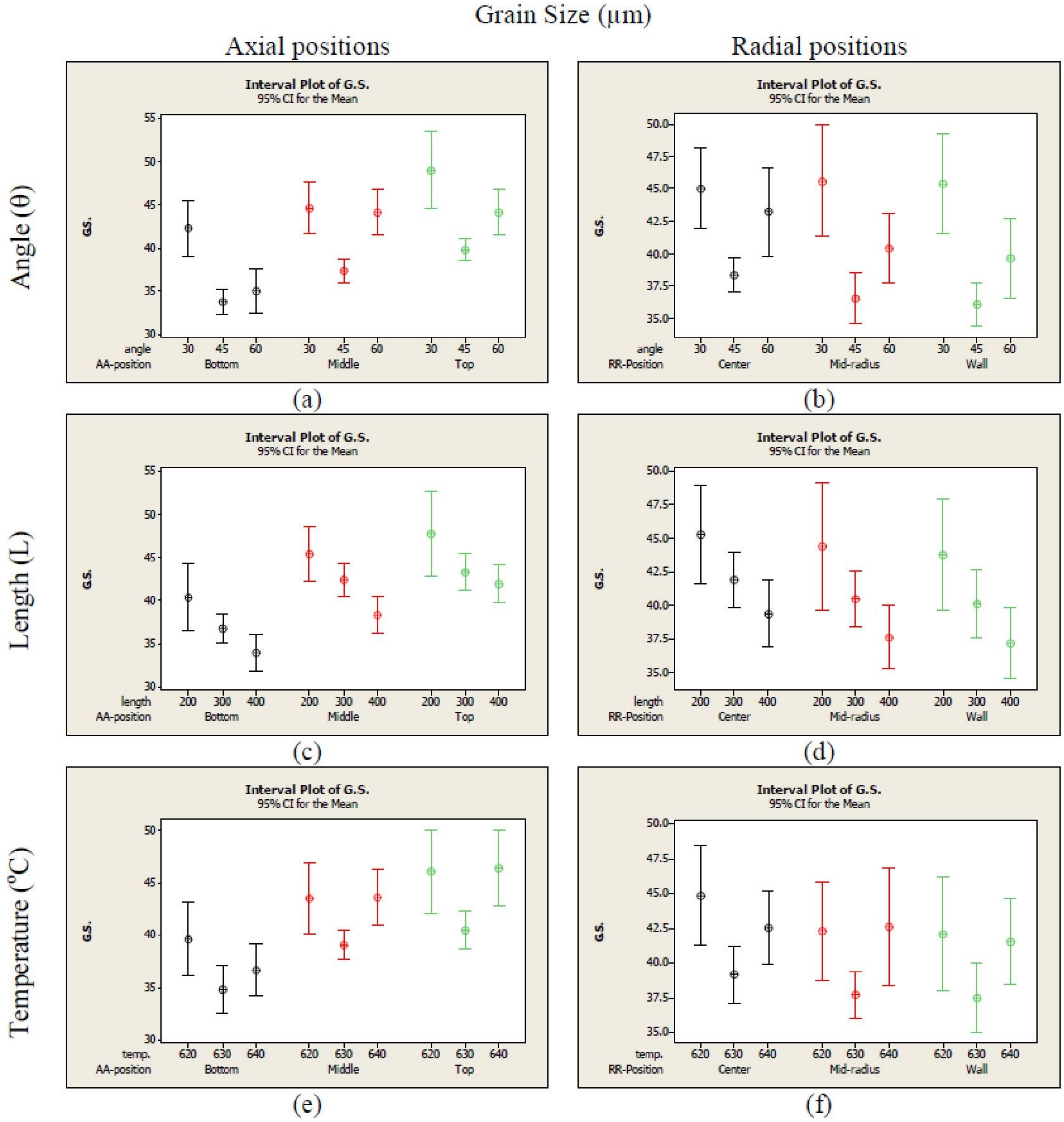

Figure 6 : Variation of grain size of primary α-Al grains with different values of tilt angle (30,45 and 60°), cooling slope length (200,300 and 400mm) and pouring temperature (620, 630 and 640°C) at both (a,c,e) axial and (b,d,f) radial positions

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
θ×L	4	1136.67	284.17	9.43	0.000	11.5426
θ×T	4	958.01	239.50	7.94	0.000	9.7268
L×T	4	1335.53	333.88	11.07	0.000	13.56
θ×L×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-Sq. = 60.20% R-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

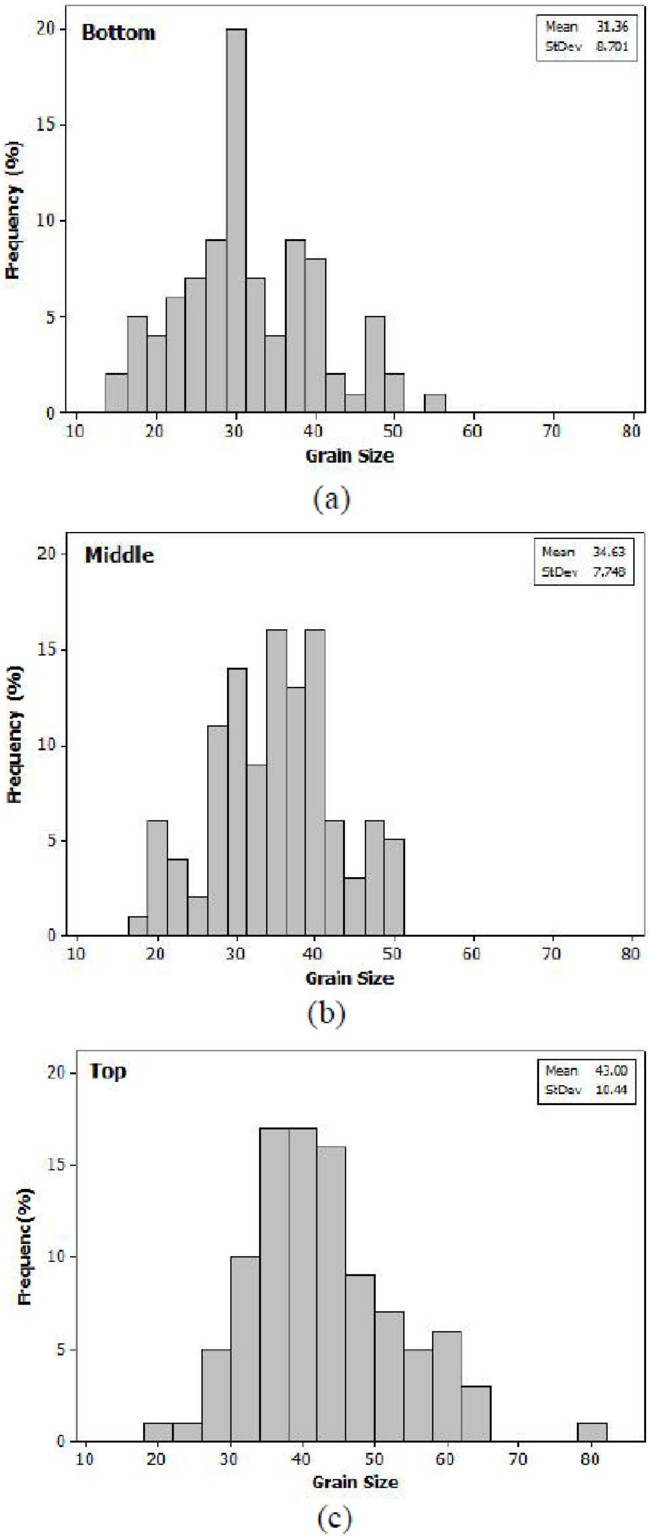

Figure 7 : A sample of the frequency plot (histogram) of the size of the α-Al primary grains at the top, middle and bottom positions of A356 ingot poured at 45°, 400 mm and 640 °C

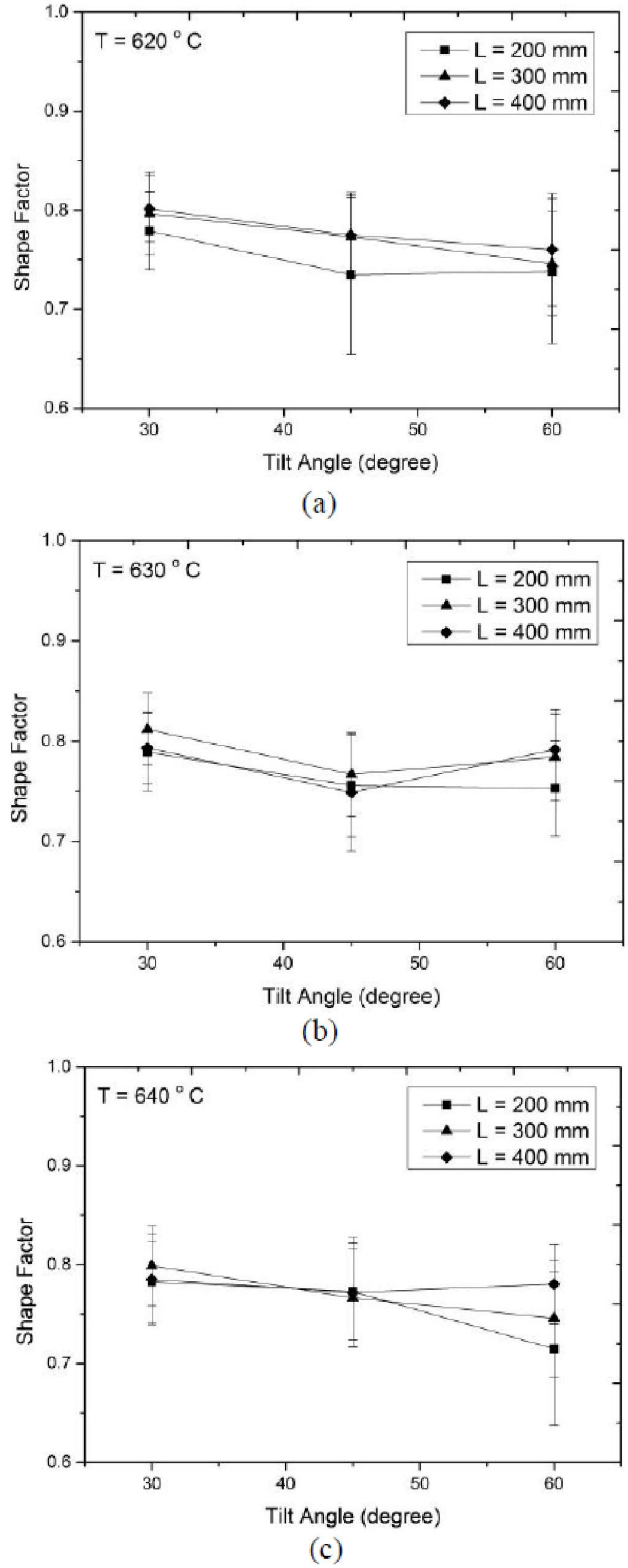

Figure 8 : Variation of the average shape factor of the α-Al primary grains with the tilt angle at different cooling lengths and pouring temperatures

of 5 percent(i.e. the confidence limit isequal to 95 per cent). The last column in TABLE 3 shows the percentage of contribution (P_c) of eachfactor on the total variation indicating the influenceof 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.

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 increasing the average shape factor of the ingots. For

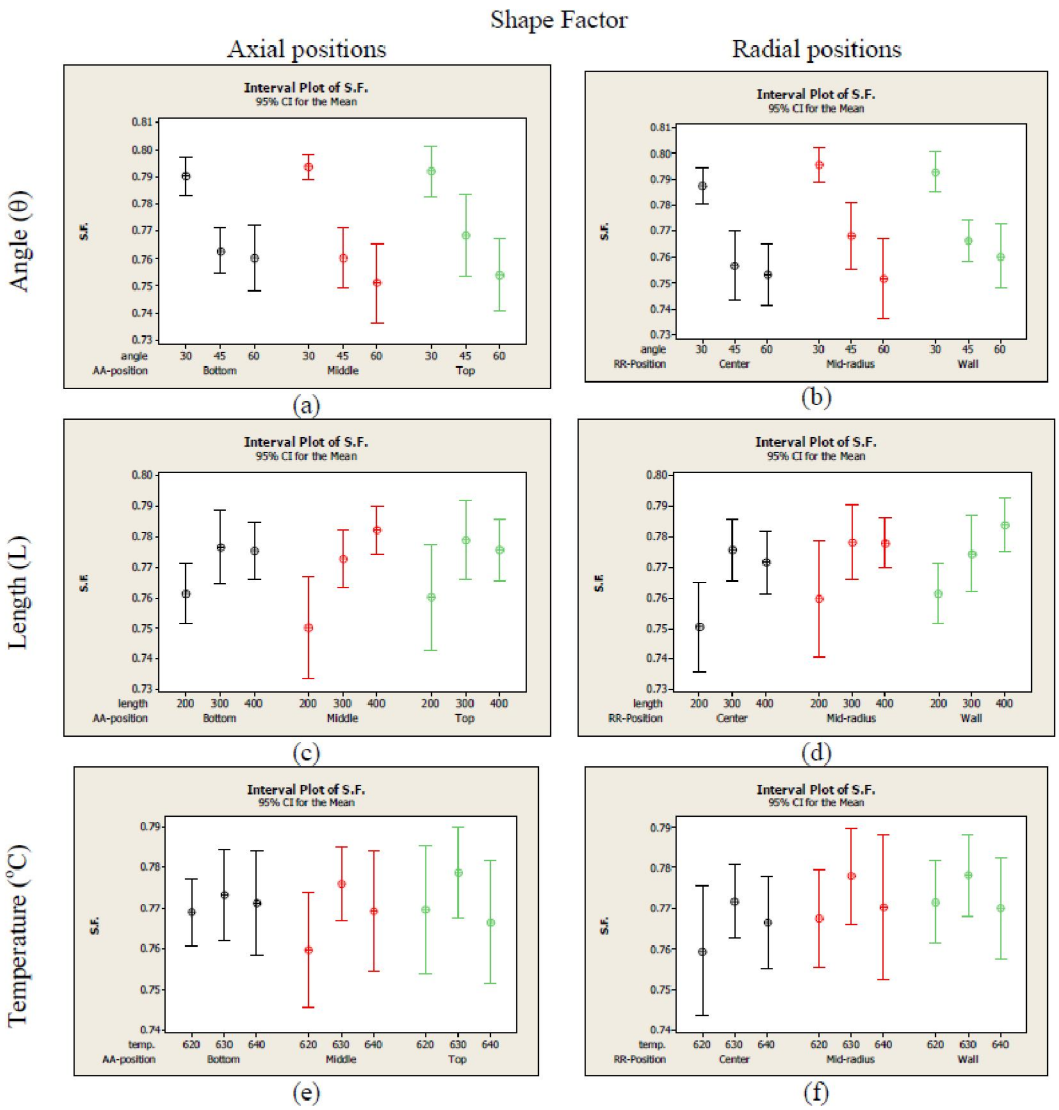

Figure 9 : Variation of shape factor of primary α-Al grains with different values of tilt angle (30,45 and 60°), cooling slope length (200,300 and 400 mm) and pouring temperature (620, 630 and 640 °C) at both (a,c,e) axial and (b,d,f) radial positions

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 Figure 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.

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 θ = 30°, L = 300 mm and T = 640 °C. While the maximum RSD value was about 0.20424 for ingots poured at θ = 45, L = 200 mm and T = 620 °C. TABLE 4 shows the results of the ANOVA for the shape factor of the primary α-Al grains. 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]. For example,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

TABLE 4 : ANOVA table for the shape factor of the primary α-Al 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
θ×L	4	0.0074845	0.0018711	3.65	0.007	5.459
θ×T	4	0.0161958	0.0040489	7.89	0.000	11.813
L×T	4	0.0105761	0.0026440	5.15	0.001	7.714
θ×L×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 R-Sq = 55.30% R-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

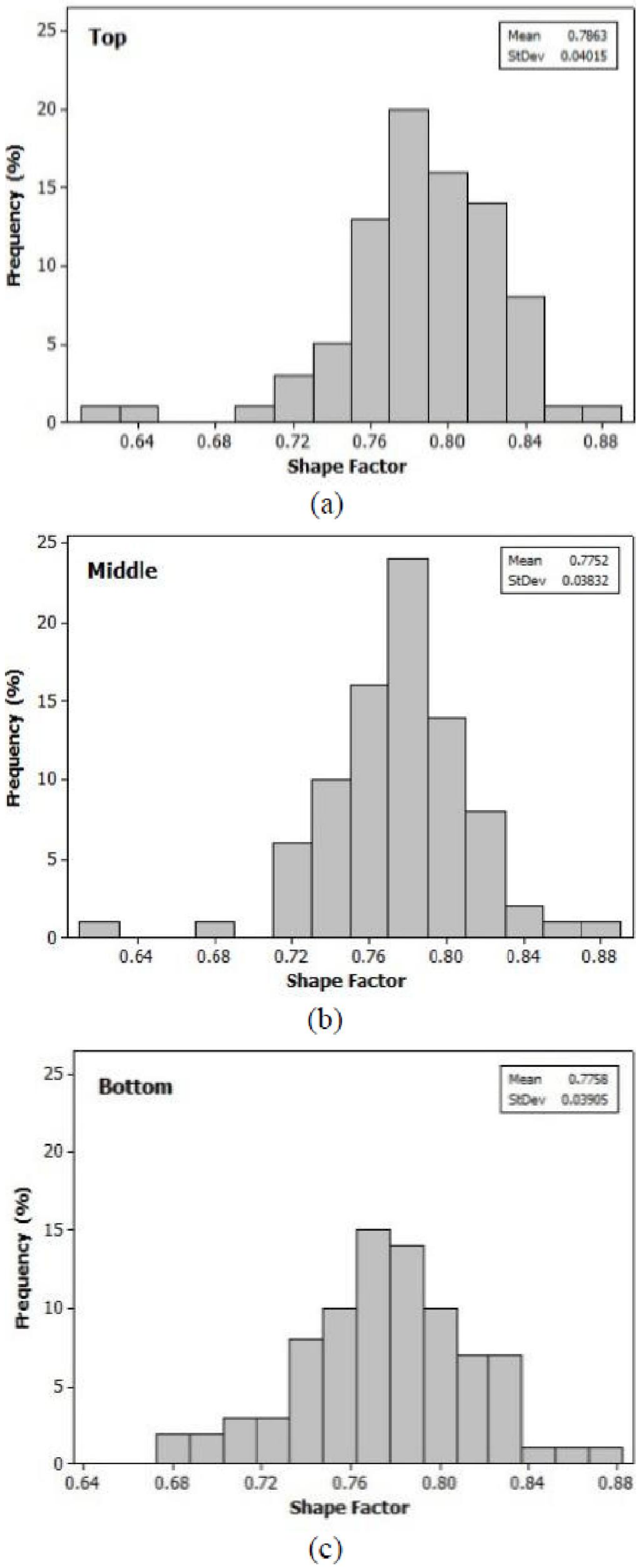

Figure 10 : Typical histograms of the shape factor of the α-Al primary grains at the top, middle and bottom positions of A356 ingot poured at 30^o, 200 mm and 620 ^oC

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^o is the most suitable angle for pouring the A356 alloy. At this angle, in most cases, the grain size is minimum and the shape factor is maximum for the α-Al primary grains.

CONCLUSIONS

The conclusions of significance are drawn as follows:

The tilt angle exhibited the highest statistical and physical significance on the grain size and shape factor of the primary α-Al grains. Increasing the tilt angle from 30^o to 45^o reduced the average size of the primary α-Al grains of the A356 aluminum alloy ingots. But increasing of the tilt angle to 60^o increases the average size of the primary α-Al grains.

The pouring temperature exhibited the lowest statistical and physical significance on the grain size and shape factor of the α-Al primary grains. Increasing the pouring temperature from 620 ^oC to 630 ^oCreduced the average grain size of the primary α-Al grains. While, more increase in the pouring temperature tends to increase the value of the grain size.

A356 aluminum alloy ingots poured at tilt angle, pouring temperature and cooling length of 60^o, 640 ^oC 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^o, 640 ^oC and 200 mm, respectively exhibited the minimum uniform grain size distribution.

The maximum uniformity of the shape factor distribution was exhibited by ingots poured 30^o, 300 mm and 640 ^oC. While the minimum uniformity of the shape factor distribution was exhibited by ingots poured at 45°, 200 mm and 620 °C.

ACKNOWLEDGMENTS

The authors are thankful to Benha University – Shoubra Faculty of Engineering for providing financial support and facilities for carrying out this work. 13

REFERENCES

[1] S.S.Hosseini, S.Nourouzi, S.J.Hosseinipour, A.Kolahdooz; "Effect of slope plate variable and pouring temperature on semi-solid microstructure of A356 aluminum alloy", in the 4th international conference, Krakow, Poland, **(2012)**.

[2] Farshid Taghavi, Ali Ghassemi; Study on the effects of the length and angle of inclined plate on the thixotropic microstructure of A356 aluminum alloy, Materials and Design, **30**, 1762–1767 **(2009)**.

[3] H.Budiman, M.Z.Omar, A.Jalar; Effect of water cooling on the production of Al-Si thixotropic feedstock by cooling slope casting, European Journal of Scientific Research, **32**, 158-166 **(2009)**.

[4] S.M.Ghavamodini, S.Nourouzi, H.Baseri, A.Kolahdooz; "Effect of casting temperature and cooling system on the microstructure of Al-A356 feedstock produced by cooling slope method", In the 4th international conference on metal forming, Krakow,Poland, **(2012)**.

[5] Cardoso E.Legoretta, H.V.Atkinson, H.Jones; Cooling slope casting to obtain thixotropic feedstock II: Observations with A356 alloy, Journal of Material Science, **43**, 5456–5469 **(2008)**.

[6] S.A.Sadough, M.R.Rahmani, V.Pouyafar; Rheological behavior, Microstructure and hardness of A356 aluminum alloy in semisolid state using backward extrusion process, Transactions of Nonferrous Metals Society of China, **20**, 906-910 **(2010)**.

[7] Prosenjit Das, Sudip K.Samanta, B.R.K.Venkatpathi, Himadri Chattopadhyay, Pradip Dutta; Microstructural evolution of A356 al alloy during flow along a cooling slope, Trans Indian Inst Met., **65(6)**, 669–672 **(2012)**.

[8] K.Sukumaran, B.C.Pai, M.Chakraborty; The effect of isothermal mechanical stirring on an Al"Si alloy in the semisolid condition, Journal of Materials Science and Engineering A, **369**, 275-283 **(2004)**.

[9] M.Kaykham, A.Kamarei, M.Safari, V.Arbabi; Semi-solid structure and parameters for A360 aluminum alloy prepared by mechanical stirring, journal World Academy of Science Engineering and Technology, **73**, 872-874 **(2011)**.

[10] Xiao-Rong Yang, Wei-Min Mao, Bin-Yu Sun; Preparation of semisolid A356 alloy slurry with larger capacity cast by serpentine channel, Transactions of Nonferrous Metals Society of China, **21**, 455-460 **(2011)**.

[11] S.Deepak Kumara, R.Pandu, Vundavillia, SisirMantryb, A.Mandalc, M.Chakrabortyc; A Taguchi optimization of cooling slope casting process parameters for production of semi-solid A356 alloy and A356-5TiB2 in-situ composite feedstock, Procedia Materials Science, **5**, 232–241 **(2014)**.

[12] T.Haga, R.Nakamura, R.Tago, H.Watari; Effects of casting factors of cooling slope on semisolid condition, Transactions of Nonferrous Metals Society of China, **20**, 968-972 **(2010)**.

[13] Hamed Khosravi, Reza Eslami-Farsani, Mohsen Askari-Paykani; Modeling and optimization of cooling slope process parameters for semi-solid casting of A356 Al alloy, Transactions of Nonferrous Metals Society of China, **24**, 961-968 **(2014)**.

[14] Pradip Dutta, Sricharan k.Babu, h.Pratik, K.N.Rahul, P.Maadhav, P.L.Srinivasa Murthy; Design and fabrication of cooling slope for semi-solid forming of aluminium A356 alloy, Journal of Mechanical Engineering Research and Technology, **2**, 347-354 **(2014)**.

[15] N.K.Kund; Influence of melt pouring temperature and plate inclination on solidification and microstructure of A356 aluminum alloy produced using oblique plate, Transactions of Nonferrous Metals Society of China, **24**, 3465-3476 **(2014)**.