

## EFFECT OF THE INCLINED COOLING PLATE CHARACTERISTICS ON THE THIXOTROPIC MICROSTRUCTURE OF A356.0 ALUMINUM ALLOY

M. Shahmiri

\* [mshahmiri@iust.ac.ir](mailto:mshahmiri@iust.ac.ir)

Received: June 2016

Accepted: January 2017

School of Metallurgy and Materials Engineering, Iran University of Science and Technology, Iran .

**Abstract:** In the present work microstructural evolution of A356 Aluminum alloy using an inclined cooling plate casting process for thixoforming feedstock production is investigated. The resultant microstructure was evaluated and compared with those of the same alloy produced by the conventional casting process, i.e. directly cast in the same mold without using an inclined cooling plate. It was found that when alloy melt poured over an inclined cooling plate and subsequently cast in semisolid condition into a metallic mould resulted in fine rosettes and nearly globular  $\alpha$ -Al primary phase uniformly distributed in an Al + Si eutectic matrix. The effect of the processing parameters such as the lengths and angles of the inclined cooling plate and their combinations were identified to produce alloy ingot with the most suitable microstructural constituent for thixoforming process.

**Keywords:** Cooling plate, Thixotropic, A.356.0, and Microstructure.

### 1. INTRODUCTION

Thixoforming is an attractive technology which offers the ability to produce components that can meet the stringent requirements for the automotive industry, by combining the near-net-shape capabilities of die casting with the mechanical properties of forging [1-3].

Ingots utilized in the thixoforming processes have the advantages of lower casting temperature, homogeneity of the solidified structures, and good fluidity of semisolid alloys as pointed out by some researchers [4-5].

In general, semisolid alloy slurry is produced by shearing of a solidifying liquid alloy in the two phase regions, by electromagnetic or mechanical stirring. However, the equipment is complicated and the running cost is high. A disadvantage of thixoforming process has always been the expensive production of semi-solid feedstock material and the operation costs documented by several studies [6-8]. Therefore, in spite of its potentials, thixoforming has not enjoyed a wide spread application due to the rather high production costs, limited choice of size and the non-uniform structure of ingots concluded by some research works [1,9].

Since a simple and convenient process is favorable for industrial application, many

scientists have tried to shorten and simplify the process, and some near-net shape technologies have been developed. Processes that meet these are for example the SSR-Process, the SEED-process, the cooling channel process and the inclined cooling plate casting process [9-13]. The inclined cooling plate -ICP process is regarded as a new convenient process for preparing semisolid alloy [13-16].

The ICP-casting process is oncoming semi-solid process which employs simple equipment and involves low running costs [17]. In this process, molten alloy is poured along a sufficiently long inclined plate such that the nucleation together with mixing occurs during the flow of the liquid, thereby producing a starting microstructure that is fine-grained and nearly coarse dendritic-free structure. In the ICP-casting process, there are several process parameters such as mould material, mould temperature, plate length, plate angle, superheat, pouring temperature etc. which directly influence the final microstructure of the solidifying slurry [13, 15, 18].

In the present investigation, the ICP -casting process was employed to produce semisolid cast ingot of A356 alloy for thixoforming operation. The effects of angle and length (slope), and their combinations on the microstructures of the

experimental alloy were investigated in an effort to identify the optimum ICP -casting characteristics.

## 2. EXPERIMENTAL PROCEDURE

The inclined cooling unit (80cm long and 10cm wide) was prepared from a 1cm thick copper plate. To identify the optimum casting characteristics contact lengths of (10cm - 60cm, in 10cm steps) and angles of ( 20°- 70°, in 10° steps) and their combinations were chosen respectively for each casting process. Each experiment on an individual length and angle was repeated at least three times in order to investigate the reproducibility of the casting process. The surface of the plate was coated with a thin layer of boron nitride in order to avoid sticking of the molten alloy.

The material used in this study was A356 with basic composition (Si= 7.25, Mg=0.30, Fe= 0.21, Cu= 0.20, Mn= 0.01, Zn= 0.04 Al = rem, all in Wt %). DSC tests showed that the liquidus and the solidus temperature of the experimental alloy was approximately 615±2°C and 572±2°C respectively.

The alloy ingot was melted in an induction furnace set at 700 °C. The melt was then allowed to cool to the casting temperature set at 620°C. The melt with a low superheat (5 °C above alloy liquidus) was poured on the surface of the ICP and was subsequently cast in the semisolid condition directly into a metallic (stainless steel) mold. The dimensions of the mold were 30cm in length, 20cm in width and 10cm in height. Molten alloy with the same superheat was cast directly into the same mold without using an ICP for microstructural comparison (i.e., conventionally cast alloy).

The specimens for microscopical observations were prepared by the standard metallographic techniques of grinding with SiC abrasive papers and polishing with a diamond suspension solution. Microstructural characterization of the etched samples by standard Keller solution was accomplished using an optical microscope (Carl Zeiss) equipped with CLEMEX-PROFESSIONAL EDITION image analyzer software.

The microstructural characteristics were quantified using an image analyzer in conjunction with the optical microscope, following the usual procedures employed for volume fraction or other measurements of any specific phase(s) [19-22]. The chemical composition was determined with inductive coupled plasma spectroscopy according to ASTM E 1097-97.

## 3. RESULTS

The microstructure of the experimental alloy cast by the ICP process looks significantly different from that obtained by conventional casting. Without the ICP - after casting directly into the mold – the material shows a dendritic structure with grain size exceeding 200µm. This microstructure looks very similar to a conventional as-cast microstructure. Via the ICP process the microstructure changes and typically consists of globular grains sizing less than 100µm. The low superheat casting of the alloy melt removes directional heat conduction from the melt and prevents the formation of dendrites within the slurry [19, 20].

A typical optical micrograph of the conventionally cast A356 alloy is presented in Fig. 1. The characteristic dendritic feature of the primary  $\alpha$ - Al phase and the interdendritic network of the eutectic phase which results from casting into a metal mould with no ICP. Particle

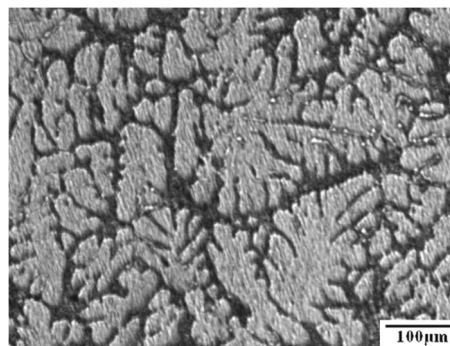
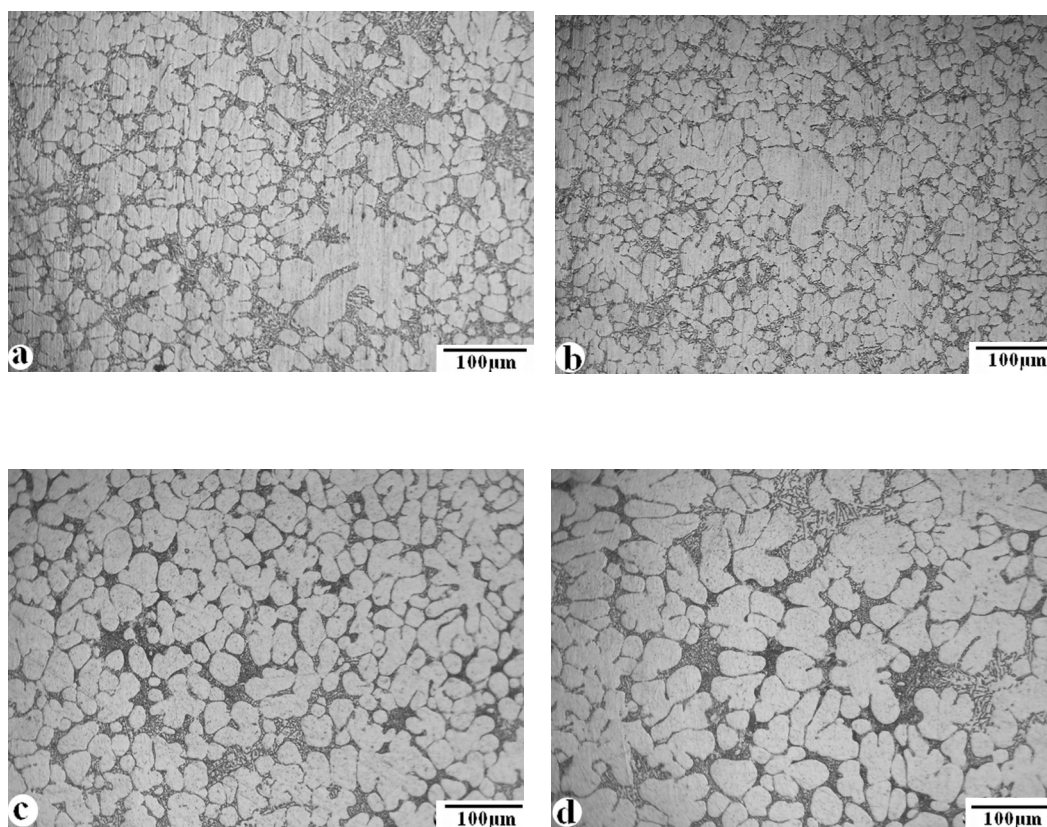


Fig. 1. As cast microstructure of A356.0 alloy.



**Fig. 2.** Microstructure of cast alloy over an inclined plate in the 30° constant angle, (a) 30 cm, (b) 40 cm, (c) 50 cm, and (d) 60 cm lengths.

size measurement of the  $\alpha$ -Al primary phase indicated values ranging from  $220 \pm 4 \mu\text{m}$  to  $320 \pm 4 \mu\text{m}$ . Average dendrite arm spacing of the primary  $\alpha$ -Al dendrites in the as-cast alloy was  $96 \pm 4 \mu\text{m}$ .

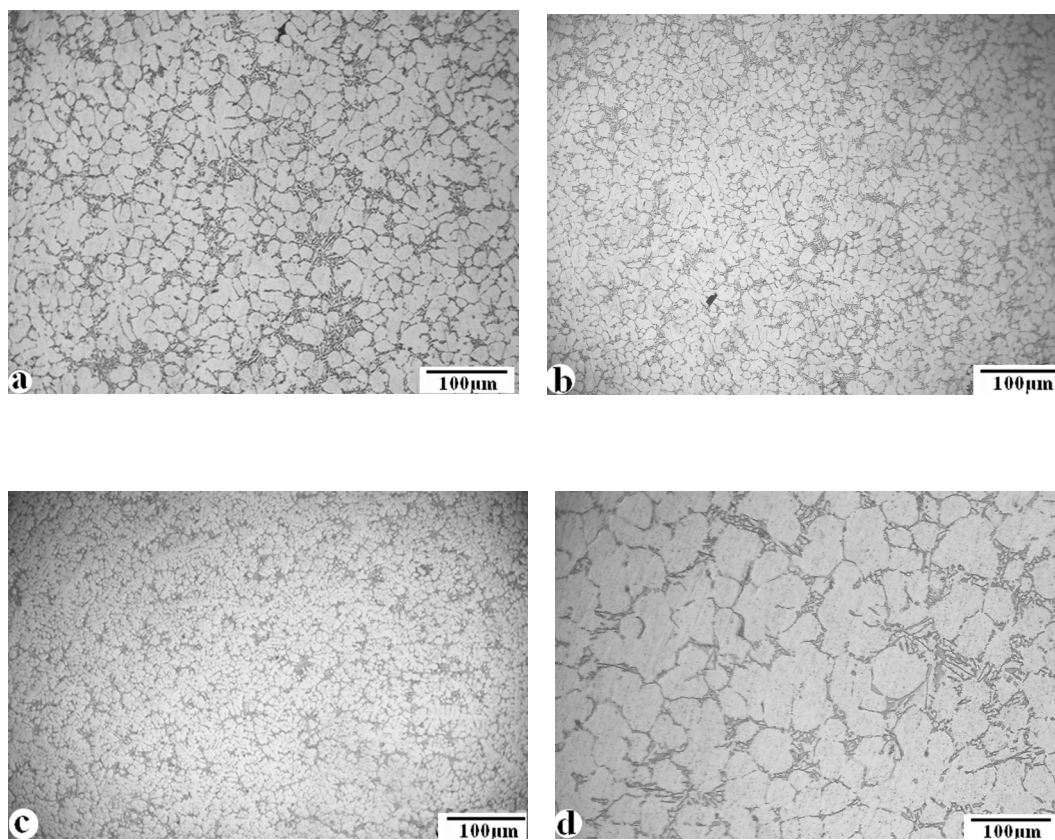
The microstructures of the alloys cast for various angles and lengths are shown in Figures 2-5. When the alloy melt cast over the ICP at a fixed angle of 30° and the lengths of 30, 40, 50, and 60 cm, into a metal mould at room temperature, show a relatively fine equiaxed dendrites (with a few coarse dispersed dendrites) of the primary  $\alpha$ -Al crystals and a few “rosette” crystals. The resulting microstructure showing dendritic character at 30 and 40 cm length and with a small amount of rosette structures at 50 and 60 cm length depicted in Fig. 2.

A comparison between Figs. 2a and 2b reveals that increase in the length up to 40 cm leads to

reduction in the particle size of the  $\alpha$ -primary phase down to  $53 \pm 4 \mu\text{m}$ , for 30° angle. The  $\alpha$ -Al primary shape factor increased to  $2.2 \pm 0.1$  at this condition.

Microstructural comparison of Fig. 2b and 2d shows that the increase in the length from 40 cm to 60 cm leads to increase in the  $\alpha$ -primary phase up to  $61 \pm 4 \mu\text{m}$  and the shape factor of the same phase to  $1.6 \pm 0.1$ .

Microstructural constituents of Fig. 2 when compared with that of Fig. 1 reveals that using angle of 30° cannot eliminate dendritic morphology of the  $\alpha$ -primary phase in the ICP cast structures for all of the plate lengths employed. It can be assumed that the applied shear stress on the slurry was not sufficient to transfer the whole structure to non-dendrites structure and more uniform distribution of the morphological feature.



**Fig. 3.** Microstructure of cast alloy over an inclined plate in the 40° constant angle, (a) 30 cm, (b) 40 cm, (c) 50 cm , and (d) 60 cm lengths.

The microstructures of alloys cast at angles of 40° and 50° for the lengths of 30, 40, 50 and 60 cm are shown in Figs. 3 and 4. A comparison of microstructural features of Figs. 3 and 4 with that of Fig. 2 reveals that using ICP with angles of 40° and 50° leads to the suppression of dendritic growth, and mixtures of rosettes plus globular structures are substituted, for 30-60cm lengths. The proportion of rosette crystals appears to be larger and the spheroids are finer.

At angle of 40°- 50°, increase in the length up to 40 cm leads to produce more structural refinement in the microstructure. The particle size of the primary  $\alpha$ -Al phase reduced to  $26\pm 4\mu\text{m}$  and its shape factor increased to  $1.1\pm 0.1$ , for constant angles of 40°- 50°, respectively. Fig. 5 shows that increase in the angle from 50-60deg lead to increase in the

particle size of the primary  $\alpha$ -Al phase.

From microstructural comparison shown in Fig. 3, 4b and 4c it is quite obvious that at angles of 40°-50° increase in the length from 40 cm to 50 cm cannot further refine the structural constituents and create more globular microstructures. The particle size of the primary  $\alpha$ -Al phase increases and its shape factor decreases again. Fig.6 shows the average particle size and aspect ratio with respect to that of the inclined plate length.

When the effects of the ICP processing parameters such as the lengths and the angles of the cooling plate and their combinations are plotted versus primary particle size (Fig. 7a, b) and the aspect ratio (Fig.7 c, d), the best results (optimum condition) is obtained for the cooling plate employed.

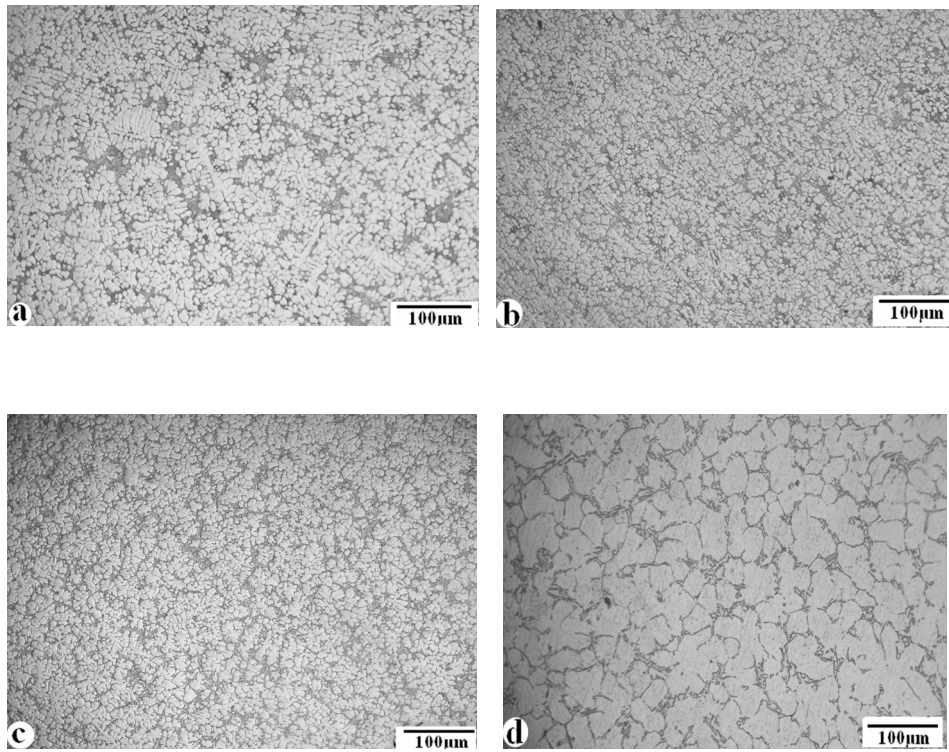


Fig. 4. Microstructure of cast alloy over an inclined plate in the 50° constant angle, (a) 30 cm, (b) 40 cm, (c) 50 cm, and (d) 60 cm lengths.

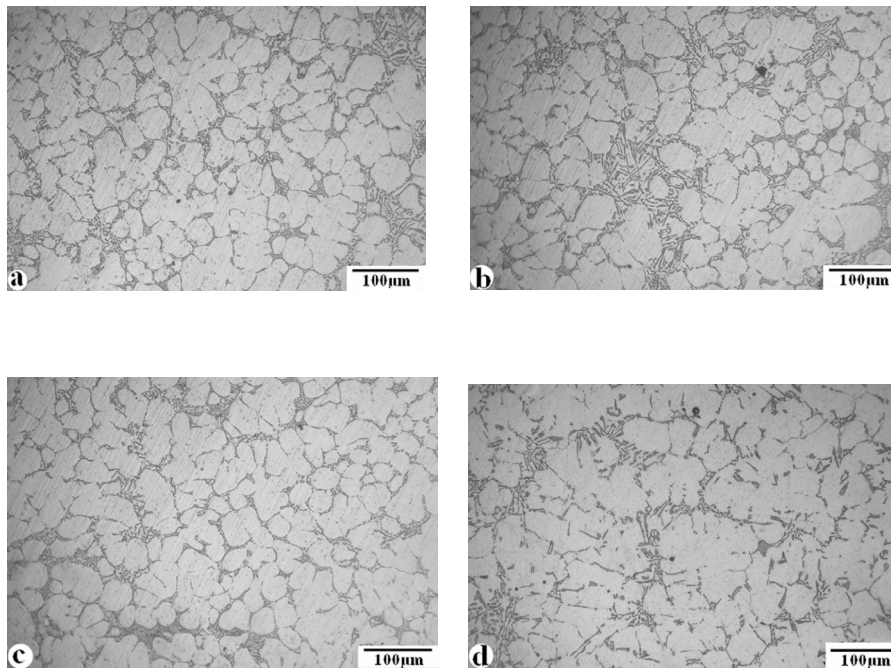


Fig. 5. Microstructure of cast alloy over an inclined plate in the 60° constant angle, (a) 30 cm, (b) 40 cm, (c) 50 cm, and (d) 60 cm lengths.

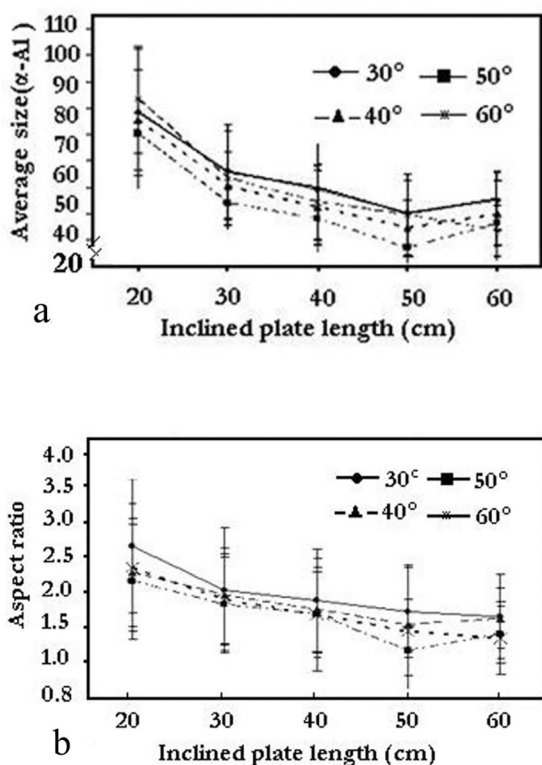


Fig. 6. (a). Average particle size of the  $\alpha$ -Al primary solid phase cast over the ICP, (b). Aspect ratio of the  $\alpha$ -Al primary solid phase cast over the ICP.

Based on the microstructure observations shown in Figs. 2–5 and the results obtained from image analyzer software shown in Figs. 6, 7, it is obvious that there is an optimum length and angle in which the best refined and globular microstructures are obtainable by the use ICP casting process. However, it can be seen that the inclined plate in 50 cm and 50° conditions creates more considerable fine and globular microstructure than in other experimental conditions, in accordance with the previous observations by [22–25].

It can be observed that large dendrites of the  $\alpha$ -primary phase is substituted by fine and equiaxed particles (near rounded crystals) far different from the usual structure produced by conventional solidification in practical cooling conditions. This result shows the efficiency in the suppression of dendritic formation when the ICP process is used.

#### 4. DISCUSSION

The most important effects of melt pouring over the ICP casting process is high heat conduction as a result of contacting the alloy melt with the cooling plate, and the shear stress development in the melt as a result of gravity force [24 and 27].

When the alloy melt is rolling over the surface of the inclined plate, the nucleation of  $\alpha$ -Al primary phase starts due to the high heat conduction. During rolling action of the alloy melt down the ICP, the shear stress due to gravity force leads to the detachment of newly formed primary  $\alpha$ -Al phase from the surface or the breaking of dendrite arms which are growing on the surface of the inclined plate.

These  $\alpha$ -Al particles are dispersed in the alloy melt flowing downwards and pour into the mold located at the end of the inclined plate accompanied to remained melt. The existing  $\alpha$ -Al phases, already present in the melt, act as sources of nucleation during solidification into the mold and finally the microstructures contain fine and globular  $\alpha$ -Al phase produce as shown by comparing Figs. 2–5 and Fig. 1.

As the present results revealed, the angle of inclined plate had remarkable effects on the size and morphology of  $\alpha$ -Al phase.

Some authors such as [28, 29, 22], concluded that the formation of three layers during flowing of the melt over the inclined plate, in which these distinct layers suffered from different rates of heat conduction. The layer immediately adjacent to the surface of the plate (the bottom layer) is a solid layer containing primary  $\alpha$ -Al phase formed due to intense heat conduction between the melt and the inclined plate [31–34].

The intermeddle layer is a semisolid suspended slurry containing the melt and the dendrite arms which produced due to growing primary solid phase toward perpendicular direction of the surface of the inclined plate. The top layer which is in contact with the air contains the molten alloy in which the rate of heat conduction is higher than that in the middle layer. By increasing the angle of the inclined the plate, the intensity of shear stress and the rate of shear strain increase. As a result, more solid particles

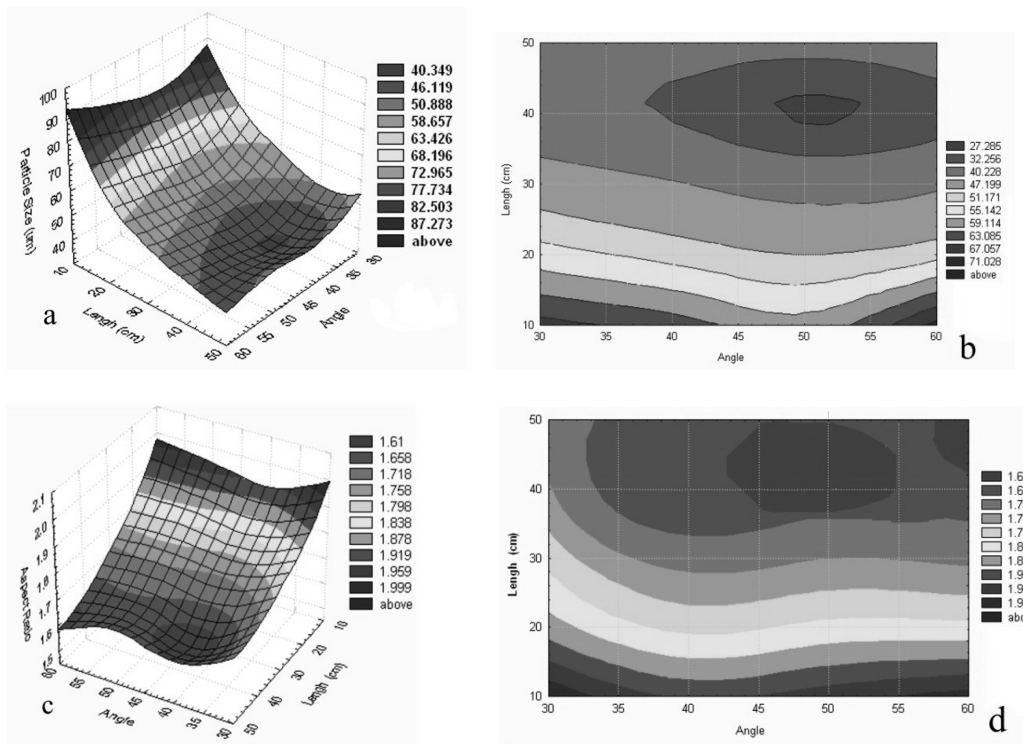


Fig. 7. The combined effect of angle and length on: (a, b) particle size and (c, d) aspect ratio of the primary  $\alpha$ -Al phase poured over a Cu-ICP.

are detached from the bottom layer or are broken in the middle layer.

Furthermore, thickness of solid layer decreases due to an increase in the detachment, and the breaking rate of the formed solid phase decreases due to an increase in the angle of the inclined plate. This layer leads to decrease in the rate of heat conduction occurred between the alloy melt and the surface of the ICP. Therefore, by increasing the angle up to  $40^\circ$ , the rate of heat conduction between the alloy melt and the surface of the ICP increases as a result of decrease in the thickness of the solid layer and higher number of primary  $\alpha$ -Al solid phases is formed into the melt rolling over the surface of the ICP. Finally, the solid particles in the slurry accompanied to remained melt were poured into the mold, and finer and globular microstructure is produced as shown in Figs. 2 and 3.

By further increase in the angle of ICP from  $40^\circ$  to  $60^\circ$ , duration time of the existing shear stress and the heat conduction between the alloy

melt and the surface of ICP decrease.

Therefore, a number of primary  $\alpha$ -Al solid particles and a fraction of solid phase formed in the flowing melt over the surface of the ICP due to decrease in the duration time of heat conduction and exerted shear stress, a majority of the remaining melt is poured into the mold and solidified inside the mold.

Because the rate of heat conduction in the mold is lower than the inclined plate and the exerted shear stress is eliminated, solidification starts under lower nucleation and growth rates conditions. Finally, the microstructures containing coarser solid phase with lower shape factor are created as shown in Figs. 4–5.

The contact length of the ICP is another critical parameter that affects the size and morphology of primary  $\alpha$ -Al phase. By increasing the length of the inclined plate, the duration time of heat conduction and shear stress increases. Therefore, the numbers of detached and broken solid phases increase, and the microstructure containing fine

and globular primary phases is produced. Increasing the length of the ICP leads to the thickening solid layer produced between the melt and the inclined plate. As a result, the rate of heat conduction and the rate of cooling the melt rolling on the surface of the ICP plate decrease which leads to the decline of the nucleation rate of primary solid phase. Then, size of primary solid phase available for the final microstructure solidified into the mold increases as shown in Figs. 3b–5b at 40°–60° for a constant length of 40 cm.

## 5. CONCLUSIONS

1. The primary  $\alpha$ -Al dendritic phase in the microstructure of conventionally cast A356 alloy modified to a fine and non-dendritic structure when a copper ICP casting process was employed.
2. Microstructural constituents of the alloy generated by the ICP were depended on the angle and length of the inclined plate. The present results revealed that there was an optimum length and angle in which minimum grain size and maximum sphericity were generated.
3. Optimum globular microstructure with a uniform distribution of A356 alloy was achieved with slope angle of 50° and plate length of 50cm in the present experimentations.

## REFERENCES

1. Birol, Y., "A357 thixoforming feedstock produced by cooling slope casting," *Journal of Materials Processing Technology*, 2007, Vol. 186, no. 1–3, 94–101.
2. Birol, Y., "Cooling slope casting and thixoforming of hypereutectic A390 alloy," *Journal of Mater Proc Tech*, 2008, Vol. 207, 200–203.
3. Flemings, M. C., "Behavior of metal alloys in the semisolid state, *Metallurgical Transactions A*, (1991), Vol. 22, no. 5, 957-981.
4. Fan, Z., "Semisolid metal processing," *International Materials Reviews*, 2002, Vol. 47, no. 2, 49–85.
5. Kenney, M. P., Courtois, J. A., Evans, R. D. and Farrior, G. M., Kyonka, C. P., Koch, A. A., Young, K. P., 1988. *Metals Handbook*, Vol. 15, 9th ed., 327–338.
6. Zoqui, E. j. and Robert, M. H., "Effect of macrostructure and microstructure on the viscosity of the A356 alloy in the semi-solid state," *Journal of Materials Processing Technology*, 2004, Vol. 153-154, no. 1–3, 300–306.
7. Haga, T. and Nakamura, R., "Effects of casting factors of cooling slope on semisolid condition" *Transactions of Nonferrous Metals Society of China*, 2010, Vol.20: 968–972.
8. Haga, T. and Suzuki, S., "Casting of aluminum alloy ingots for thixoforming using a cooling slopes", *Journal of Materials Processing Technology*, 2001, Vol.118, 169-172.
9. Kapranos, P., Liu, T., Atkinson, H. and Kirkwood, D., "Investigation into the rapid compression of semi-solid alloy slugs", *Journal of Materials Processing Technology*, 2001, Vol.111, 31-36.
10. Nafisi, S. and Ghomashchi, R. "Effects of modification during conventional and semi-solid metal processing of A356 Al-Si alloy, *Materials Science and Engineering A*, 2006, Vol. 415, 273-285.
11. Haga, T., Kapranos, "Billetless simple thixoforming process," *Journal of Materials Processing Technology*, 2002, Vol. 130-131, 581-586.
12. Salleh, M. S., Omar, M. Z., Syarif, J. and Mohammed, M. N., "An Overview of Semisolid Processing of Aluminum Alloys," *ISRN Materials Science*, 2013, Vol. 2013, Article ID 679820, 9-16.
13. Motegi, T., Tanabe, F. and Sugiura, E., "Continuous casting of Semisolid Aluminum alloys," *Materials Science forum*, 2002, Vol. 396-402, 203-208.
14. Robert, M. H., Zoqui, E. J., Tanabe, F. and Motegi, T., "Producing Thixotropic Semi-Solid A356 Alloy-Microstructure Formation x Forming Behavior." *Journal. Achieve. Materials, Manufacturing, Engineering*, 2007, 20(1–2), 19–26
15. Haga, T. and Kapranos, P., "Simple rheocasting processes," *Journal of Materials Processing*

- Technology, 2002, Vol. 130-131, 594-598.
16. Birol, Y. and Akdi, S., "Cooling slope casting to produce EN AW 6082 forging stock for manufacture of suspension components," *Transaction of Nonferrous Met. Society of China*, 2014, 24, 1674-1682.
  17. Wang, T. M., Xu, J., Chen, Z. N., Zhu, N. and Li, T. J., "Study on influence of surface coating during cooling slope rheocasting process," *Materials Science and Technology*, 2001, Vol. 27, no. 11, 1602-1605.
  18. Das, P., Samanta, S. K. and Ray, T., "Mechanical properties and Tensile fracture mechanism of Rheocast A356 Al alloy using Cooling Slope," *Advanced Materials Research*, 2012, Vol. 585, 354-358.
  19. Legoretta, E. C., Atkinson, H. V. and Jones, H., "Cooling Slope Casting to Obtain Thixotropic Feedstock I: Observations with a Transparent Analogue," *Journal of Materials Science* Aug 2008, Vol. 43 Issue 16, 5448-5455.
  20. Legoretta E. C., Atkinson H. V. and Jones H., "Cooling slope casting to obtain thixotropic feedstock II: observations with A356 alloy," *Journal of Materials Science*, 2008, Vol 43, 5456-5469.
  21. Ghalambaz, M., Shahmiri, M., "Neural network modeling of the effect of cooling slope casting parameters on particle size of primary silicon crystals of semisolid cast ingots Al-20Si (wt. %)," *Iranian Journal of materials science and technology*, 2008, Vol 5 no 3, 25-32 (In English).
  22. Ghalambaz, M., Shahmiri, M., "Neural network prediction on the effect of semisolid metal processing parameters on particles and shape factor of primary alpha-Al Aluminum alloy A356.0," *Iranian Journal of materials science & technology*, 2007., Vol 4, no 1&2, 41-47 (In English).
  23. Haga, T., Nakamura, R., Tago, R. and Watari, H., "Effects of casting factors of cooling slope on semisolid condition," *Trans. Nonferrous Met. Soc. China*, 2010, Vol. 20, 968-972,
  24. Robert, M. H., Zoqui, E. J., Tanabe, F., Motegi, T., "Producing thixotropic semi-solid A356 alloy: microstructure formation x forming behavior," *Journal of Achievements in Materials and Manufacturing Engineering* , 2007, Vol. 20, no. 1 & 2, 19-26,.
  25. Yang X., Mao, W., "Preparation of Semisolid A356 Alloy Feedstock Cast via a Pipe Consisting of Partial Inclined and Partial Vertical Sections," *J. Mater. Sci. Techno*", 2009, Vol. 25, no. 2, 273- 276.
  26. Wang, T. M., Xu, J., Chen, Z. N. J., Zhu, J. and Li, T. J., "Study on influence of surface coating during cooling slope rheocasting process," *Materials Science and Technology*, 2011 Vol. 27, no. 11, 1602-1605 .
  27. Birol, Y., "Semi-solid processing of the primary Aluminum die casting alloy A365," *Journal of Alloys and Compounds*", 2009 ,Vol. 473, 133-138.
  28. Mohanty, D. A. K., Nayak, A. K, Barman, N., " *Trans Indian Institute Met*, 2012, Vol. 65(6), 801-807.
  29. Gencalp, S, Saklakoglu, N, "Semisolid Microstructure Evolution during Cooling Slope Casting under Vibration of A380 Aluminum Alloy," *Materials and Manufacturing Processes*, 2010, Vol. 25, pp. 943-947.
  30. Dhindaw .B.K Manish, K, Kumar, A, *Trans Indian. Inst. Met. (December 2012)*, Vol. 65(6), pp. 581-585.
  31. Shahmiri, M., Hosseini, S. and Kanani, N., "Stir-Modification of the Eutectic Silicon Crystals of A356.0 Aluminum Alloy by Mechanical Stirring," 2005, *Metall .59*, Vol.1-2, 557-562.
  32. Shahmiri, M. and Kanani, N., " Stir-modification of Primary Si Crystals in Semisolid Metal Processed Hypereutectic Al-Si (20 wt. %) Alloy by Fatigue-erosion Mechanism", 2008, *Metall. 62*, Vol. 1-2, 548-555.
  33. Guo Guan, R., Zhan," *Boundary Layer and Cooling Rate and Microstructure Formation on the Cooling Sloping Plate*," *Met. Mater. Int*, 2013, Vol. 19, No. 5, 949-957.
  34. Haga, T., Nakamura, R., Tago, R. and Watar, H., "Effects of casting factors of cooling slope on semisolid condition," *Trans. Nonferrous Met. Society of China*, 2010, 20, 968-972.