Jurnal
Teknologi

Full Paper

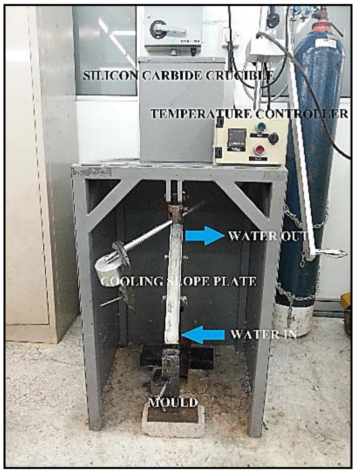
# MICROSTRUCTURAL CHANGES OF ALUMINIUM ALLOY A319 ON COOLING SLOPE PLATE

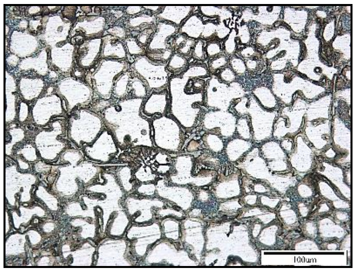
Ahmad Muhammad Aziz[a], Mohd Zaidi Omar[a,c*], Zainuddin Sajuri[a,c], Mohd Shukor Salleh[b]

[a]Department of Mechanical and Materials, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia
[b]Department of Manufacturing Process, Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka, 76100 Durian Tunggal, Melaka, Malaysia
[c]Centre for Automotive Research, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor Darul Ehsan, Malaysia

**Article history**
Received
*18 December 2015*
Received in revised form
*10 March 2016*
Accepted
*25 April 2016*

*Corresponding author
zaidiomar@ukm.edu.my





## Abstract

The cooling slope (CS) casting process is one of the simplest methods for producing a non-dendritic microstructure. To more clearly determine how this microstructure is formed, specifically in A319, requires an examination of how the dendritic microstructure evolves along the entirety of the CS plate. Yet until now, there are still unclear on the verification of microstructures changes on the CS plate. Based on experimental results, this paper offers an explanation for the mechanism involved in producing a nearly globular microstructure in A319. In addition, the mechanism is verified by using the planimetry method. Moreover a quantitative method is used to determine the grain size and shape factor to provide further support for the proposed mechanism. The solid fraction of a-Al at the impact zone is 70 % which is the highest compared to other zones. Grain size and shape factor shown a decreasing and increasing value respectively from the impact zone until the bottom zone.

*Keywords:* Semi-solid processing, evolution, solid fraction

## Abstrak

Proses tuangan cerun penyejukan (CS) adalah salah satu kaedah yang paling mudah untuk menghasilkan mikrostruktur bukan dendrit. Untuk menentukan dengan lebih jelas bagaimana mikrostruktur ini terbentuk, khususnya dalam A319, ia memerlukan kepada pemeriksaan bagaimana mikrostruktur dendrit berkembang disepanjang keseluruhan plat CS. Namun sehingga kini, masih tidak jelas mengenai pengesahan perubahan mikrostruktur di atas plat CS. Berdasarkan keputusan eksperimen, kajian ini menawarkan penjelasan bagi mekanisma yang terlibat dalam penghasilkan mikrostruktur hampir bulat bagi A319. Di samping itu, mekanisma yang terlibat disahkan dengan menggunakan kaedah planimetri. Selain daripada kaedah tersebut, kaedah kuantitatif turut digunakan untuk menentukan saiz butiran dan faktor bentuk untuk menyokong kepada mekanisma yang dicadangkan. Pecahan pepejal a-Al di zon impak adalah 70% adalah merupakan pecahan pepejal yang paling tinggi berbanding dengan zon-zon yang lain. Saiz butiran dan faktor bentuk masing – masing menunjukkan penurunan dan peningkatkan nilai dari zon impak sehingga ke zon bawah.

Kata kunci: Pemprosesan separa pepejal, evolusi, pecahan pepejal

## 1.0 INTRODUCTION

In the automotive industry, a key engineering challenge is reducing the porosity that can occur during the fabrication of equipment, especially in cylinder heads and engine blocks. The existence of porosity can decrease the mechanical properties of a component unless there is strict control over the process [1]. Cast iron is commonly used in cylinder heads. However, aluminum alloy is replacing cast iron in many automotive components due to the need to reduce the weight of vehicles. This and other advantages of aluminum alloy make it is the most prominent and well-known material in the automotive industry [2]. However, the material properties of cast aluminum alloy, such as ultimate tensile test (UTS) and yield strength (YS), still need to be enhanced to improve its performance especially in heavy-duty applications for which cast iron has thus far been particularly suitable. Therefore, a way needs to be found to produce aluminum alloy with better mechanical properties compared to cast iron. Semi-solid metal (SSM) processing is one of the methods that can be used to enhance the mechanical properties of aluminum alloy [3].

Semi-solid metal processing is a hybrid metal processing technique that combines two conventional processes, the casting process and the forging process. SSM processing has advantages over conventional processing such as low shrinkage, reduced porosity defects and the ability to produce a near-net-shape product [4]. However, the feedstock for SSM processing first needs to be prepared to transform it into a non-dendritic microstructure before it can be used. The CS casting method is one of the methods that is often used for feedstock preparation as it is the simplest technique and has a low handling cost [5].

To ensure that the production of a non-dendritic microstructure by the CS casting process is effective, the mechanism of change needs to be clarified. The simplest method of observing microstructural changes is to use an optical microscope. In order to verify the mechanism, volume fraction analysis is also used to determine the α-Al solid fraction. There are two options for determining the volume fraction, the point counting method or the planimetry method. In this study, the planimetry method is used because there is a clear boundary between the α-Al and eutectic phases, therefore it is more practical [6].

The planimetry method requires a computerized process to determine the volume fraction of α-Al. ImageJ software is powerful open-source tool that can be used the estimation of the sectional surface area of α-Al [6]. A valid relationship in the range of statistical scatter can be expressed as in Eq. 1 [7]:

$$V_V = A_A = L_L = P_P. \quad (1)$$

where $V_V$ is the volume fraction, $A_A$ is the area fraction, $L_L$ is the lineal fraction and $P_P$ is the point count.

Changes in the shape of the microstructure and the existence of intermetallic compounds have an impact on the mechanical properties of alloys. As explained in Burapa *et al.* [8], the shape of the grains primary α-Al influences the alloy's mechanical properties such that a higher shape factor gives higher tensile strength and elongation. Obtaining a higher shape factor requires a mechanism to develop a globular microstructure from a dendritic microstructure. In CS casting, the evolution of the microstructure occurs as the molten alloy flows down the CS plate.

Thus it is essential to gain an understanding of how the CS process affects the development of the globular α-Al microstructure as this can guide the manipulation of the parameters of the CS plate to improve the casting process. These parameters include pouring temperature, CS length and CS angle. According to Lashkari and Ghomashchi [9], the viscosity of the molten alloy on the CS plate influences the shape factor and size of the grains of α-Al; for instance, lower viscosity will affect the development of globular microstructure when using a short CS plate.

## 2.0 EXPERIMENTAL

As-received aluminum alloy A319 in the form of an ingot was examined for its chemical composition using X-ray fluorescence, the results of which are shown in Table 1. Differential calorimetric scanning was carried out to determine the liquid fraction profile in order to determine the semi-solid temperature, which is in the range of 20 % to 50 % liquid [10]. The sample was cut into small pieces each weighing approximately 40 mg to be melted in a helium environment in order to prevent oxidation at a heating rate of 10°C/min.

Induction heating using an inductive coil was used to melt down the as-received A319 in a silicon carbide furnace. The temperature was set to 800°C to ensure that the as-received ingot weighing approximately 450 g was homogenously melted. Even though the furnace had a temperature controller for temperature setting, a K-type thermocouple was placed into the furnace to directly monitor the temperature for greater accuracy. Upon melting, the alloy was allowed to cool down until it reached 630°C as this was the pouring temperature set in this experiment based on the optimization determined in Salleh *et al.* [3]

**Table 1** Chemical composition of A319

| Si | Cu | Fe | Mg | Zn | Mn | Cr | Al |
|---|---|---|---|---|---|---|---|
| 6.15 | 2.12 | 0.72 | 0.44 | 0.4 | 0.13 | 0.05 | Balance |

The molten alloy was poured onto a stainless steel CS plate after boron nitride had been sprayed onto the plate. Water at room temperature was circulated underneath the CS plate in the opposite direction to the direction in which the molten alloy was poured down the plate. Rapid cooling occurred immediately when the poured molten alloy made contact with the CS plate, which contributed to alloy solidification on the CS plate. Figure 1(a) shows the apparatus used to obtain a non-dendritic microstructure in the alloy. The angle and length of the CS plate is 60° and 400 mm respectively were set according to the optimization in Salleh *et al.* [3].

The resultant non-dendritic A319 aluminum alloy, which solidified in the form of a horsetail on the CS plate, as shown in Figure 1(b), was removed for analysis. The solid 40 cm alloy was cut into four zones that corresponded to stages along the CS plate, namely the impact zone, top zone, middle zone and bottom zone (Figure 1b) to assess the evolution of the microstructure along the entirety of the CS plate. From these, small pieces of alloy with a thickness of less than 10 mm was done a hot mounting for convenient handling during the grinding and polishing process.

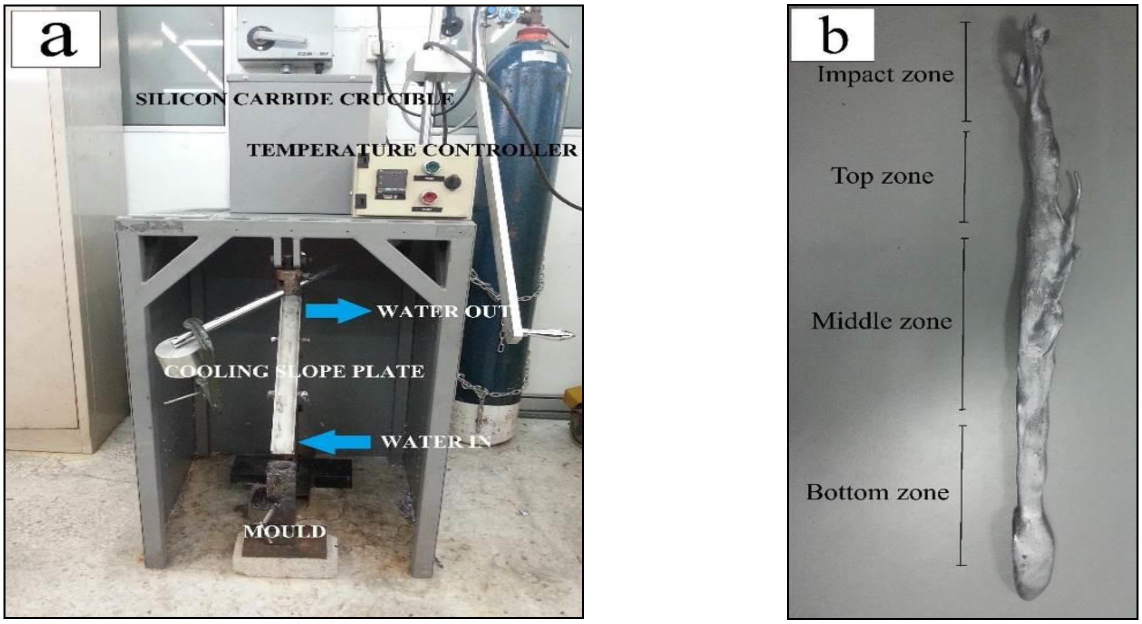
The samples were ground and polished using sandpaper and a polishing cloth, respectively. The grinding process used various grades of sandpaper ascending in fineness from 240 to 1200. The polishing process used a diamond solution of 3 microns and 1 micron. These two processed were followed by an etching process using Keller reagent for 7 seconds. Images of the microstructure were then captured for all four zones using an optical microscope at a magnification of 100 µm.

For the analysis of the images, ImageJ software was used to calculate the solid fraction of a-Al. The scale of the micrograph was set according to the microscope's magnification before proceeding with semi-automated adjustment of the threshold to trace the clear boundaries in the a-Al samples. The result for the a-Al solid fraction was obtained as soon as the threshold had been adjusted. The grain size and shape factor were also calculated using ImageJ software based on Eq. 2 and Eq. 3, respectively:

$$\text{Grain Size} = 2[\sqrt{(A/\pi)}]. \tag{2}$$

$$\text{Shape Factor} = [(4\pi A/P^2)]. \tag{3}$$

where A is the area and P is the perimeter.



(a) CS apparatus (b) Horsetail sample removed from CS plate

**Figure 1** Fixed-end composite sandwich plate model under an impact load

## 3.0 RESULTS AND DISCUSSION

The microstructural evolution of A319 along the CS plate is clearly evident from the images in Figure 2. Figure 2(a) shows the microstructure of the alloy in the impact zone of the CS plate, which is where the molten alloy first contacts the CS plate after it has been melted in the crucible. Rapid quenching occurs in this zone due to the high heat transfer and this leads to the formation of abundant a-Al.

The development of the microstructure from the initial dendritic growth stage in the impact zone continues along the entirety of the CS plate until the microstructure attains a near-globular state. The development consists of four stages, as explained in Kirkwood [11] whose schematic diagram is reflected in the microstructures obtained in this study as shown in Figure 2(a) to Figure 2(d). Schematic diagram from Kirkwood [11] is shown in the Figure 3 was explain the evolution of microstructure on the CS plate. Prosenjit Das *et al.* [12] also explained well on the microstructural evolution on the CS plate but it is focused on the CS angle with verification of degree of sphericity and grain size.

Two key factors seem to contribute to the development of the nearly globular microstructure of A319 on the CS plate: rapid solidification and flow. First, rapid solidification contributes to the formation of nuclei in the mixed shape microstructure. As shown in Figure 2(a), the existence of a number of nearly globular grains is observed among the mainly dendritic microstructure in the impact zone. The emergence of this nearly globular microstructure at this stage on the CS plate is probably due to the high impact of the molten alloy on the CS plate during pouring.

The 0.35 shape factor in the impact zone on the CS plate (Figure 6) is a sign of the early stage of forming a nearly globular microstructure. Rapid solidification in the impact zone of the CS plate is explained in Legoretta *et al.* [13]. The formation of a-Al at the impact zone is the most rapid until it called as “source of nuclei” by Legoretta *et al.* [13]. As examined using ImageJ software, the impact zone has a 70.06 % fraction solid compared to the other three zones that have in the range of a 50 % to 55 % fraction solid.

The solid fraction in the next zone right after impact zone reduces by almost 20 %. This result appears to indicate that the alloy undergoes a re-melting process as there is a decrement in the percentage of a-Al. However, there is no heat being discharged on the CS plate while the molten alloy is flowing down it. In fact, a reduction in the molten alloy temperature occurs during its flow down the CS plate [14]. Thus there should be an increase in the solid fraction of a-Al on the CS plate due to solidification. In this regard, the existence of abundant a-Al in the impact zone of up to 70.09% is undeniable because rapid solidification occurs immediately on contact between the molten alloy and CS plate, as shown in Figure 4.

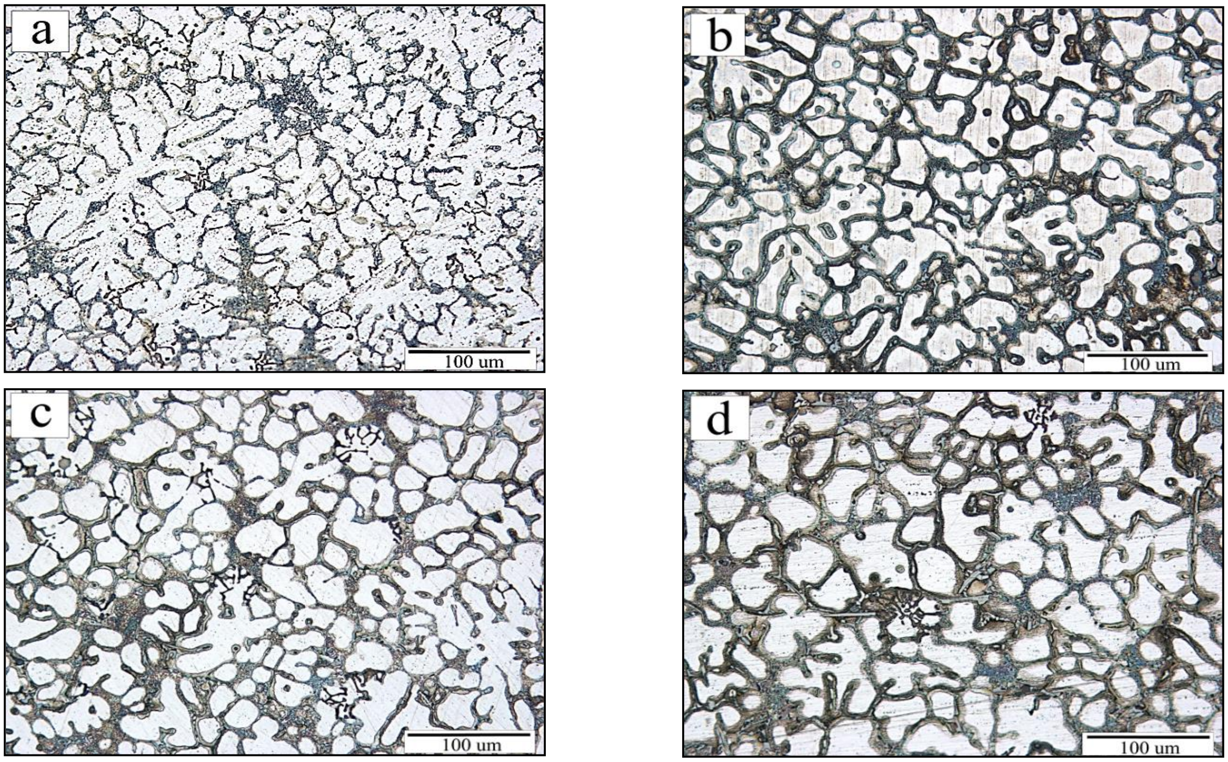


**Figure 2** Development of microstructure on the CS plate from (a) dendritic growth stage to (b) rosette stage, (c) ripened rosette stage and (d) nearly globular stage

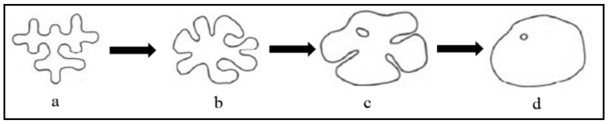


**Figure 3** Schematic diagram of microstructure evolution on the CS plate from (a) dendrite growth stage to (b) rosette stage, (c) ripened rosette stage and (d) nearly globular stage

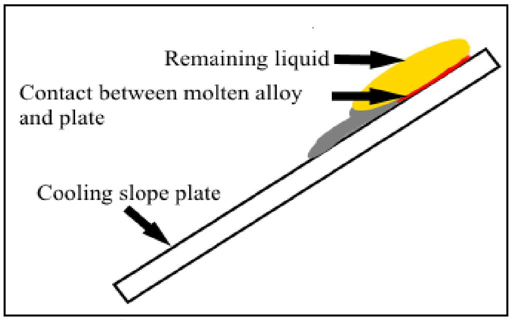


**Figure 4** Layer of contact between molten alloy and CS plate

For nucleation to take place, there needs to be contact between molten alloy and CS plate. However, while the molten alloy is being poured onto the impact zone, it could be possible that segregation of solid and liquid occurs. Thus some remaining liquid probably flows down to the other zones causing the percentage of solid fraction in the next zone to decrease. This phenomenon could be described by the analogy of pouring batter to form pancakes on a heated pan where the bottom side of the pancake starts to solidify browns first compared to the upper side which remains in batter form. If the pan is tilted, the remaining liquid batter will flow over the pan's surface and start to solidify.

As mentioned above, the other main contributory factor to the development of a nearly globular microstructure is that of the flow along the CS plate. The molten alloy flows down the CS plate due to gravitational force and this creates a shearing force between the molten alloy and CS plate. The dendritic growth in the impact zone features include coarse-grained and irregular shaped dendritic arms [15]. The development of the dendritic microstructure illustrated in Figure 2(a) clearly shows that scattered dendritic branches are attached to the main roots. A nearly globular microstructure is achieved through the melting off of these dendritic branches from the main roots. This fragmentation of the dendritic branches is assisted by shearing force where there is a weak connection at the main root due to heat convection.

This fragmentation of dendritic arms on the CS plate results in the development of new nuclei and this process is repeated continuously through the remaining zones of the CS plate. The existence of this development of new nuclei along the CS plate is supported by Taghavi and Ghassemi [16]. As can be observed in Figure 5, a reduction in the grain size also occurs along the CS plate. The existence of new nuclei of fine size contributes to decrease in the average size of the grains in the sample from the bottom zone.

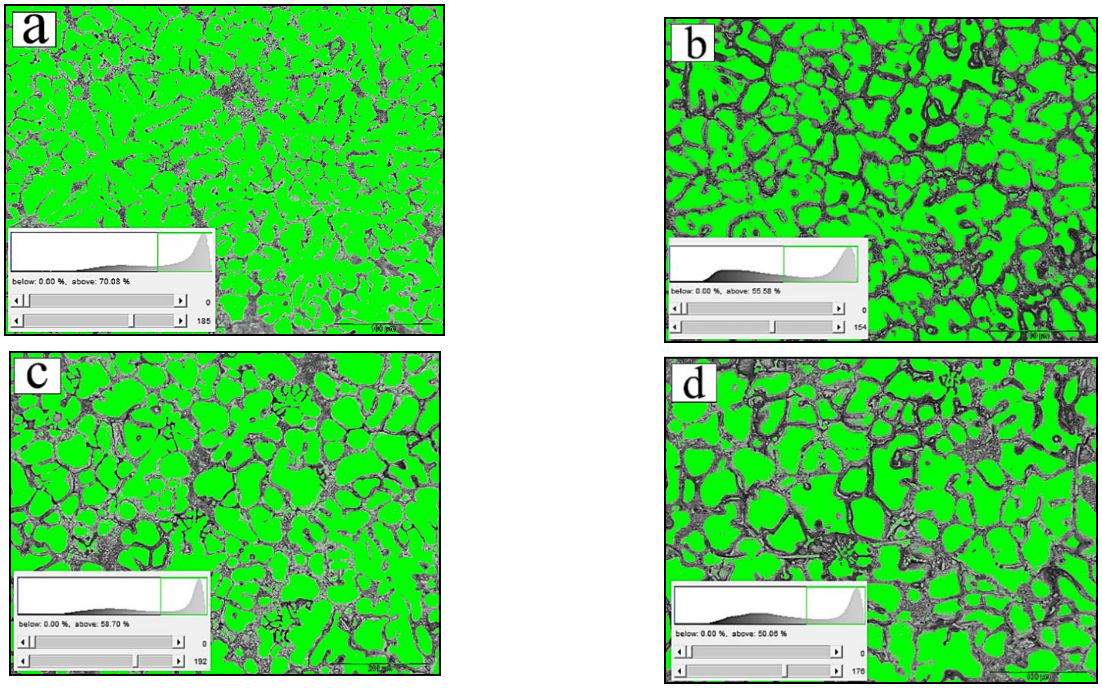


**Figure 5** a-Al solid fraction from (a) impact zone, (b) top zone, (c) middle zone and (d) bottom zone

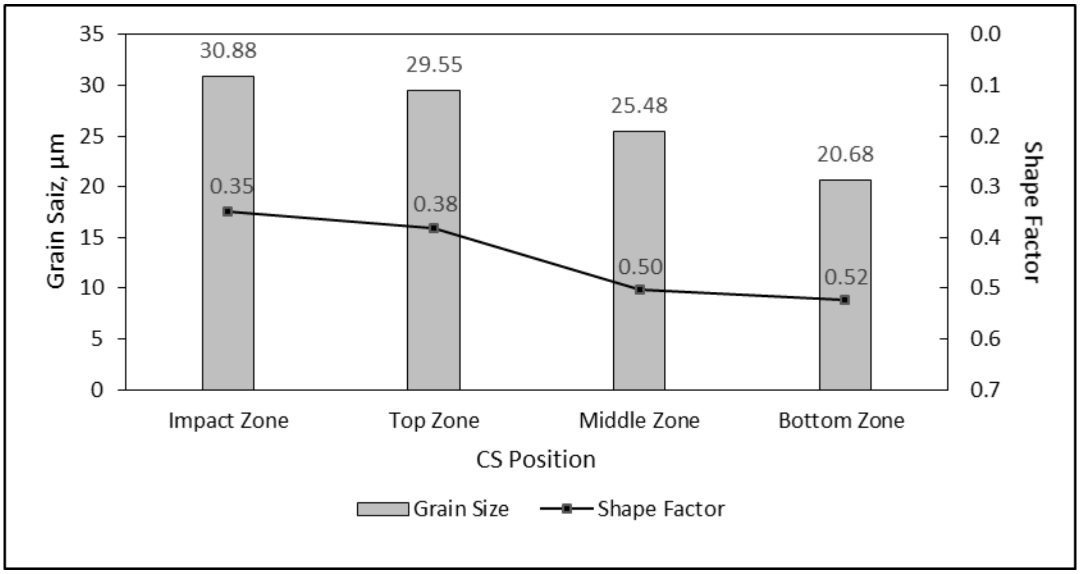


**Figure 6** Grain size and shape factor according to CS position

As can be observed from Figure 5, as the molten alloy flows down the CS plate, the solid fraction decreases until in the bottom zone the percentage of solid fraction is 51 %. This result is commensurate with that in Legoretta *et al.* [13] who found that the percentage of solid fraction at the end of the CS plate is in the range of 48 % to 54 %. There is no stabilization in solid fraction percentage along the CS plate after the first impact zone. The decrement of solid fraction on the CS plate is due to the breaking of the dendritic arms and the tendency of a-Al to agglomerate during its flow down the CS plate. The decrement in the temperature will tend to lead to the agglomeration of a-Al due to the resultant increasing viscosity. The agglomeration of a-Al causes incomplete globular grains [17].

The validity of this explanation is supported by the shape factor obtained in the bottom zone sample, which has a value 0.52 and thus reflects incomplete globularization compared to the shape factor 1.0 which indicates a fully globular structure (see Figure 6). The incomplete globular microstructure of a-Al results not only from grain agglomeration but can also be caused by a high liquid fraction due to a high pouring temperature or a short CS plate.

## 4.0 CONCLUSION

This study showed that two mechanisms are involved in the development of a nearly globular microstructure in A319 aluminum alloy on the CS plate, namely rapid solidification and flow. The effects of this two-fold mechanism were confirmed by analysis using the planimetry method and quantitative calculations. The determination of the solid fractions of a-Al along the CS plate by using the planimetry method showed the influence of the CS plate on flow. A higher solid fraction in the impact zone indicated that rapid solidification occurs at this point. The influence of flow along the CS plate was confirmed based on results obtained for grain size and shape factor through quantitative calculations.

## Acknowledgement

The authors would like to thank Universiti Kebangsaan Malaysia (UKM; The National University of Malaysia) and the Ministry of Higher Education Malaysia for the financial support received under research grants DIP-2014-024 and FRGS/1/2014/TK01/UKM/01/2.

## References

[1] Irfan, M. A., Schwam, D., Karve, A., and Ryder, R. 2012. Porosity Reduction and Mechanical Properties Improvement in Die Cast Engine Blocks. *Materials Science and Engineering: A*. 535: 108–114.

[2] Salleh, M. S., Omar, M. Z., Syarif, J., and Mohammed, M. N. 2013. An Overview of Semisolid Processing of Aluminium Alloys. *ISRN Materials Science*. 2013: 1–9.

[3] Salleh, M. S., Omar, M. Z., Syarif, J., Alhawari, K. S., and Mohammed, M. N. 2014. Microstructure and Mechanical Properties of Thixoformed A319 Aluminium Alloy. *Materials and Design*. 4: 142–152.

[4] Ahmad, A. H., Naher, S., Aqida, S., and Brabazon, D. 2014. Routes to Spheroidal Starting Material for Semisolid Metal Processing. *Comprehensive Materials Processing*. 5: 135–148.

[5] Haga, T., and Kapranos, P. 2002. Simple Rheocasting Processes. *Journal of Materials Processing Technology*. 130–131: 594–598.

[6] Şahin, B., and Elfaki, A. Estimation of the Volume and Volume Fraction of Brain and Brain Structure on Radiological Images. *NeuroQuantology*. 10(1): 87–97.

[7] Geels, K. 2007. *Metallographic and Materialographic Specimen Preparation, Light Microscopy, Image Analysis, and Hardness Testing*. PA, USA: ASTM International.

[8] Burapa, R., Janudom, S., Chucheep, T., Canyook, R., and Wannasin, J. 2010. Effects of Primary Phase Morphology on Mechanical Properties of Al-Si-Mg-Fe Alloy in semi-Solid Slurry Casting Process. *Transactions Nonferrous Metal Society China (English Edition)*. 20(2010): 857–861.

[9] Lashkari, O., and Chomashchi, R. 2007. The Implication of Rheology in Semi-Solid Metal Processes: An Overview. *Journal of Materials Processing Technology*. 182: 229–240.

[10] Liu, D., Atkinson, H. V., and Jones, H. 2005. Thermodynamic Prediction of Thixoformability in Alloys Based on the Al–Si–Cu and Al–Si–Cu–Mg Systems. *Acta Materialia*. 53(14): 3807–3819.

[11] Kirkwood, D. H. 1994. Semisolid Metal Processing. *International Materials Reviews*. 39(5): 173–189.

[12] Das, P., Samanta, S. K., Venkatpathi, B. R. K., Chattopadhyay, H., and Dutta, P. 2012. Microstructural Evolution of A356 Al Alloy During Flow Along a Cooling Slope. *Transactions of the Indian Institute of Metals*. 65(6): 669–672.

[13] Legoretta, E. C., Atkinson, H. V., and Jones, H. 2008. Cooling Slope Casting to Obtain Thixotropic Feedstock II: Observations with A356 Alloy. *Journal of Materials Science*. 43(16): 5456–5469.

[14] Kund, N. K., and Dutta, P. 2010. Numerical Simulation of Solidification of Liquid Aluminum Alloy Flowing on Cooling Slope. *Transactions Nonferrous Metal Society China*. 20: 898–905.

[15] Xia, K., and Tausig, G. 1998. Liquidus Casting of a Wrought Aluminum Alloy 2618 for Thixoforming. *Materials Science and Engineering: A*. 246(1-2): 1–10.

[16] Taghavi, F., and Ghassemi, A. 2009. Study on the Effects of the Length and Angle of Inclined Plate on the Thixotropic Microstructure of A356 Aluminum Alloy, *Materials and Design*. 30(5): 1762–1767.

[17] Tzimas, E., and Zavaliangos, A. 2000. Evolution of Near-Equiaxed Microstructure in the Semisolid State. *Materials Science and Engineering: A*. 289(1-2): 228–240

.