Jurnal Kejuruteraan 31(2) 2019: 317-326
https://doi.org/10.17576/jkukm-2019-31(2)-17

The Effect of the Rheocast Process on the Microstructure and Mechanical Properties of Al-5.7Si-2Cu-0.3Mg Alloy

(Kesan Proses Pembentukan *Tuangan Reo* terhadap Sifat Mikrostruktur dan Mekanikal Aloi Al-5.7Si-2Cu-0.3Mg)

Mnel A H Abdelgnei[a,b,c*], Mohd Zaidi Omar[b], Mariyam Jameelah Ghazali[b] Mohamed A. Gebril[b] & M N Mohammed[d]
[a]Mechanical Engineering Programme,
[b]Centre for Materials Engineering and Smart Manufacturing (MERCU),
Faculty of Engineering & Built Environment, Universiti Kebangsaan Malaysia, Malaysia
[c]Omar Almukhtar University, Albaida, Libya
M N Mohammed[d]
[d]Faculty of Information Sciences and Engineering, Management & Science University, Malaysia.
**Corresponding author: Manal.elkalosh@gmail.com*

Received 14 January 2019, Received in revised form 14 March 2019
Accepted 17 March 2019, Available online 31 October 2019

ABSTRACT

This study shows the results of an experimental investigation of semisolid rheocasting of Al-5.7Si-2Cu-0.3Mg alloy using a cooling slope (CS) casting technique. However, the challenge is to determine process parameters of the CS process to get a desirable microstructure in the semisolid feedstock material. cooling slope technique was employed to create feedstock material for thixoforming under an argon gas atmosphere, where on an inclined plate that was fixed at a 60° slope angle, molten alloy is poured at different temperatures of 640°C, 650°C and 660°C at lengths 300, 400 and 500 mm. Examination the microstructure with optical microscope observed that the microstructure of conventionally cast alloy presented coarse and dendritic primary α-Al phase, whereas rheocast alloy included fine and nondendritic primary α-Al phase with homogeneous distribution of eutectic phase. The best CS processing condition has been identified for optimum pouring temperature of 650°C and the slope length of 400 mm as average globular grain size of around 31.67 ± 3 µm and a shape factor of about 0.66 ± 0.09 were obtained. The mechanical properties of conventional cast alloy were enhanced by the CS casting process. The ultimate tensile strength, the yield strength and elongation of the rheocast alloy were increased by 10%, 12% and 22% respectively compared to the conventional cast alloy. due to a reduction in shrinkage and porosity of the microstructure of the CS alloy.

Keywords: Al-Si alloy; Cooling slope process; Microstructure; Mechanical properties

ABSTRAK

Kajian ini membentangkan keputusan ujikaji tuangan-rio separa pepejal aloi Al-5.7Si-2Cu-0.3Mg dengan menggunakan teknik tuangan cerun penyejuk. Walaubagaimanapun, cabaran utama yang dihadapi dalam kajian ini adalah dalam menentukan parameter proses tuangan cerun penyejuk yang optimum supaya aloi tuangan-rio yang dihasilkan memiliki mikrostruktur bukan dendrit yang halus. Jongkong aloi dileburkan dalam atmostera gas argon sebelum proses penuangan di lakukan ke atas plat logom yang dicondongkan pada sudut kecondongan 60°C. Leburan aloi dituang pada suhu tuangan dan panjang cerun penyejukan yang pelbagai iaitu masing-masing adalah 640, 650 dan 660°C dan 300, 400 dan 500 mm. Pemerhatian ke atas mikrostruktur yang dilakukan dengan menggunakan mikroskop optik mendapati bahawa jongkong aloi yang dihasilkan melalui tuangan konvensional terdiri daripada struktur fasa utama α-Al dengan taburan fasa eutektik yang homogen manakala mikrostruktur bagi aloi tuangan-rio yang dihasilkan melalui proses tuangan cerun pengejuk pula terdiri daripada struktur bukan dendrit yang lebih halus. Mikrostruktur bukan dendrit dengan saiz paling halus (31.67 ± 3 µm) dan faktor bentuk terbaik (0.66 ± 0.09) dapat dihasilkan dengan suhu tuangan 650°C dan panjang cerun penyejukan 400 mm. Keputusan ujian mekanikal mendapati bahawa kekuatan tegangan muktumad, kekuatan alah dan pemanjangan yang dihasilkan aloi tuangan-rio masing-masing bertambah sebanyak 10%, 12% dan 22% disebabkan oleh pengurangan keporosan.

Kata kunci: Aloi Al-Si; Proses cerun penyejukan; Mikrostruktur; Sifat mekanik

INTRODUCTION

Semi-solid metal (SSM) processing was originated from the work of Spencer and colleagues in the early 1970s (Spencer et al. 1972). During the 1990s, this process was commonly used on aluminium alloys (Fan 2002). Today, SSM processing has become a commercially viable method for producing metallic components having high integrity and improved mechanical properties. Semi-solid metal processing is carried out at a temperature between solidus and liquidus (Abedi et al. 2013; Omar et al. 2007). Therefore, it combines the advantages of both the casting and the forging process (Zhou et al. 2014). This method offers some distinct advantages over other conventional casting processes when there is a need to produce near-net-shaped products, particularly for automotive applications, such as longer die life, lower porosity, lower macro-segregation, lower forming temperature, lower energy consumption, reduced porosity, better dimensional tolerance and faster production cycle (Atkinson 2005; Taghavi et al. 2009).

The thixotropic behaviour of a metal is based in part on the SSM processing and is defined as the change in viscosity with shearing time at a constant shear rate (Taghavi et al. 2009). This behaviour arises from the fine and spherical solid particles with an appropriate volume fraction that are distributed uniformly in a liquid matrix. The shape factor (SF) and average grain size (AGS) of the microstructure of the rheocast alloy determines whether the alloy is suitable for the thixoforming process or otherwise.

In recent years, there has been a lot of interest in the development of new alloys and also in the modification of commercially available alloys to tailor them especially for SSM processing (Salleh et al. 2014) because there are only a few cast aluminium alloys (such as A319, A356 and A357) that are available and suitable for the SSM processing of commercial products. Thus far, several methods have been introduced for the production of semi-solid slurries and a few applicable methods for obtaining non-dendritic and globularly structured feedstock have been published in the literature; for example, electromagnetic stirring (Campo et al. 2013), mechanical stirring (Kang & Youn 2004), strain induced melt activation (Li et al. 2008) and recrystallization and partial remelting (Abedi et al. 2013; Jiang et al. 2017). However, one of the most popular SSM processing methods is the cooling slope (CS) casting process because it requires less equipment, is relatively inexpensive and easy to use and has reduced maintenance requirements (Abdelgnei et al. 2018).

The CS casting process was first introduced by Motegi et al. (2000). In this process, the liquid metal is poured over a sloping plate and is then either collected in a steel metal mould or used directly in a shaping process such as rolling (Mohammed et al. 2013; Arif et al. 2018). Due to movement along the slope, the temperature of the molten material drops quickly below the liquidus temperature and the primary α-Al phase starts to nucleate and grow to become a mixed globular and rosette-like microstructure (Alhawari et al. 2015).

Various parameters of the CS casting process, such as pouring temperature, length and angle of inclination of the plate, presence of water cooling, and mould materials have been shown to have a strong effect on the microstructural characteristics (Das et al. 2012; Khosravi et al. 2014; Taghavi & Ghassemi 2009). Among these parameters, pouring temperature and CS length are the most important in terms of their effect on the shape and size of the primary α-Al phase during solidification. Some studies (Legoretta et al. 2008; Salleh et al. 2015; Thuong et al. 2015) have found that an angle of 60° for the slope is ideal because it gives a relatively globular primary aluminium phase and smaller grain size and it can also help to reduce the adhesion force between the slurry alloy and walls of the slope and thus ease the flow of the slurry into the mould (Legoretta et al. 2008).

The effect of cooling slope parameters on the microstructure and mechanical properties of new Al-5.7Si-2Cu-0.3Mg alloys, is not readily available in the literature. Therefore, this study aimed at investigating the effect of pouring temperature and cooling slope length parameters on the microstructure and mechanical properties of Al5.7Si-2Cu-0.3Mg alloy, to determine the optimum CS processing condition to obtain a desirable semisolid feedstock material for thixoforming.

METHODOLOGY

The chemical composition of the test alloy was identified using an X-Ray Fluorescence Spectroscopy (XRF) spectrometer designer Rigaku-R1X3000. The chemical compositions of alloy are shown in Table 1. The liquidus and solidus temperatures of the alloy were determined by using JMatPro software (see Figure 1). A Netzsch-STA (TG-DSC) 449 F3 simultaneous thermogravimeter, was used in the CS casting process was used to obtain non-dendritic feedstock. The alloy was superheated at 700°C inside a crucible of SiC located in a resistance furnace. The alloy ingot was melted in the resistance furnace in an argon atmosphere to prevent oxidation and was then allowed to cool to the required pouring temperature. The pouring temperature should be slightly above the liquidus temperature in order to simplify partial crystallization of α-Al rosettes on the cooling plate and to prevent the alloy from solidifying on the cooling plate. The slope angle was kept constant at 60° while the pouring temperature was varied between 640, 650 and 660°C and the slope length was varied between 300, 400 and 500 mm. The various parameter settings for the rheocast Al-5.7Si-2Cu-0.3Mg are shown in Table 2.

The molten metal was poured along the cooling slope according to the above-specified parameters and collected into a cylindrical mould with dimensions of Ø25 mm × 115 mm, which was first heated at 100°C to reduce the difference between the slurry and mould temperatures in order to obtain a uniform microstructure in the alloy (Das et al. 2014). A schematic of the CS equipment used in the experiment is shown in Figure 3.

TABLE 1. Chemical composition of Al-5.7Si-2Cu-0.3Mg alloy (in Wt. %)

Alloy	Si	Fe	Cu	Mg	Mn	Zn	Ni	S	Cl	Cr	Ca	Al
	5.67	0.32	1.92	0.32	0.12	0.03	0.02	0.16	0.12	0.05	0.04	Bal.

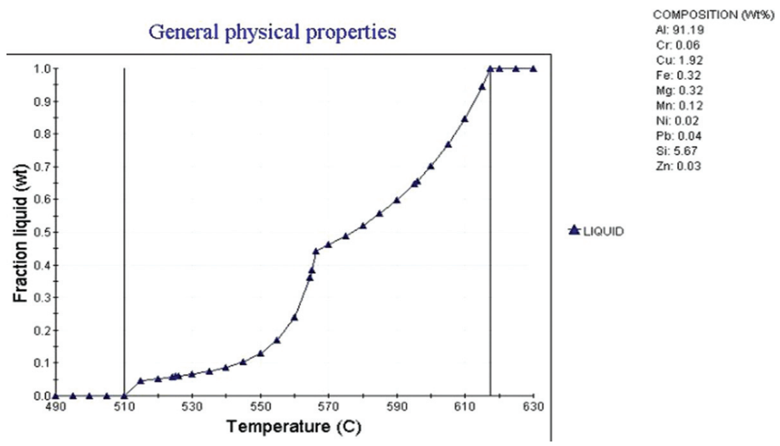

FIGURE 1. Illustrate the calculation of fraction liquid vs. temperature by using JMatPro

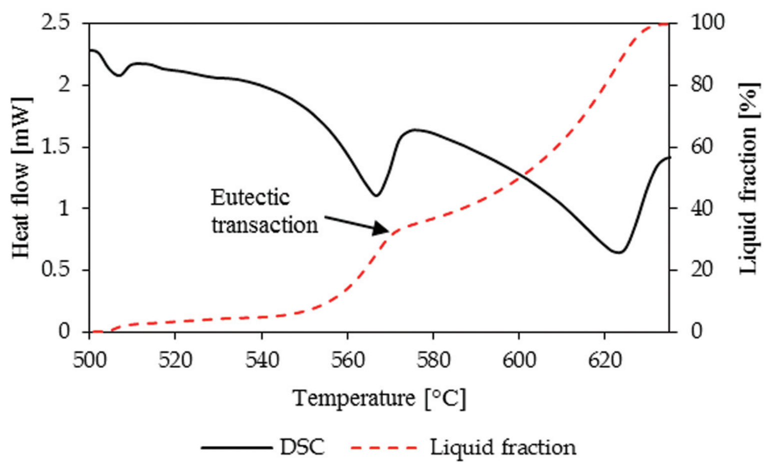

FIGURE 2. DSC and liquid weight fraction versus temperature curves

TABLE 2. Cooling slope casting process parameters of Al-5.7Si-2Cu-0.3Mg alloy

Experimental No.	Slope angle (°)	Cooling length (mm)	Pouring temperature (°C)
1	60	300	640
2	60	300	650
3	60	300	660
4	60	400	640
5	60	400	650
6	60	400	660
7	60	500	640
8	60	500	650
9	60	500	660

Samples were transversely cut from the same position in the middle of the all ingots (collected from the cylindrical mould, Figure 3) for structural investigations. The surfaces of the conventional cast and rheocast samples were prepared to identify their respective microstructures. First, the samples were sanded using a SiC abrasive paper with 400-1200 grit, then polished with 6, 3 and 1 μm diamond paste and finally etched with Keller's reagent (1 ml hydrofluoric acid, 1.5 ml hydrochloric acid, and 2.5 ml nitric acid in 95 ml distilled water). Then optical micrographs of samples were examined by using an optical microscope Olympus optical.

Image-J software was used to determine the optimum grain size and shape factor of alloy by calculating the perimeter and surface area of the α-Al phase in each sample by Eq. (1) and Eq. (2) (Salleh et al. 2014):

$$SF = \frac{4\pi A}{p^2} \quad (1)$$

$$AGS = \frac{\sum 2\left(\frac{A_i}{\pi}\right)^{1/2}}{N} \quad (2)$$

An as-cast sample and an optimum rheocast sample set of specimens were produced for the tensile test. Cylindrically tensile samples with dimensions of Ø6 mm and 30 mm were machined from both sides of the sample according to B 577M-02a (ASTM 2004). The tensile strength of the specimens was measured using a 100 KN universal testing machine at 100 N and a cross-head speed of 1.5 mm/min. Three samples for each condition were tested to calculate an average tensile value. The yield stress (Ys) was based on a 0.002 plastic strain offset. A morphological analysis of the fracture surface of the specimens was performed using a scanning electron microscope (SEM) (model Merlin, Zeiss, Germany).

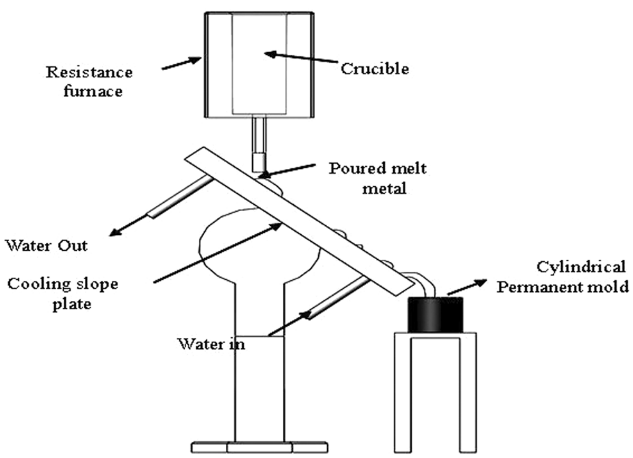

FIGURE 3. Schematic diagram of the cooling slope casting equipment

RESULTS AND DISCUSSION

Figure 4 shows a SEM image and optical micrograph of the microstructure of the as-cast Al-5.7Si-2Cu-0.3Mg alloy. It can be seen that there is coarse fully dendritic solidification, which is due to the low cooling rate and involves primary α-Al dendrites and a eutectic mixture of acicular Si and some intermetallic phases such as Al_2Cu white contrast, Chinese script α-(Al_{15} $(Mn,Fe)_3Si_2$) and β-(Al_5FeSi) plates.

Figure 5 shows the optical micrograph of the rheocast Al-5.7S-2Cu-0.3Mg alloy at different pouring temperatures and different plate lengths. When the rheocast alloy travels along the slope length at a pouring temperature below the liquidus temperature the α-Al phase starts to solidify (Khosravi et al. 2014). The microstructure changes from the dendritic structure seen in the as-cast alloy to one that is non-dendritic (i.e. near-spherical and rosette-like particles) in the rheocast alloy. This change occurs because the molten metal of as-cast alloy is poured quickly onto the slope plate and continues shear along the slope plate due to gravitational attraction, which causes the dendritic arms in the molten metal alloy to break and form into rosette-shaped structures (Kund 2014).

Consequently, the primary α-Al grains start to nucleate, and they then grow further to form a mixed globular and rosette-like microstructure. Then, when the semi-solid slurry pours into the mould, α-Al crystals grow and a spheroidizing effect causes the solid α-Al shaped rosettes to form into spheres (Gautham & Kapur 2005). The growth of spheroidal particles α-Al alloy stops when the temperature reaches the solidus temperature which, as shown in Figure 2, is 510°C.

The microstructure exhibits an α-Al matrix and eutectic mixture phase Al-Si and some intermetallic phases. Figure 6 and Figure 7 show the AGS and the SF of the α-Al phase of Al-5.7Si--2Cu 0.3Mg alloy, respectively. At a 640°C pouring temperature and 300 mm slope length the AGS of the microstructure is smaller than that of the samples with

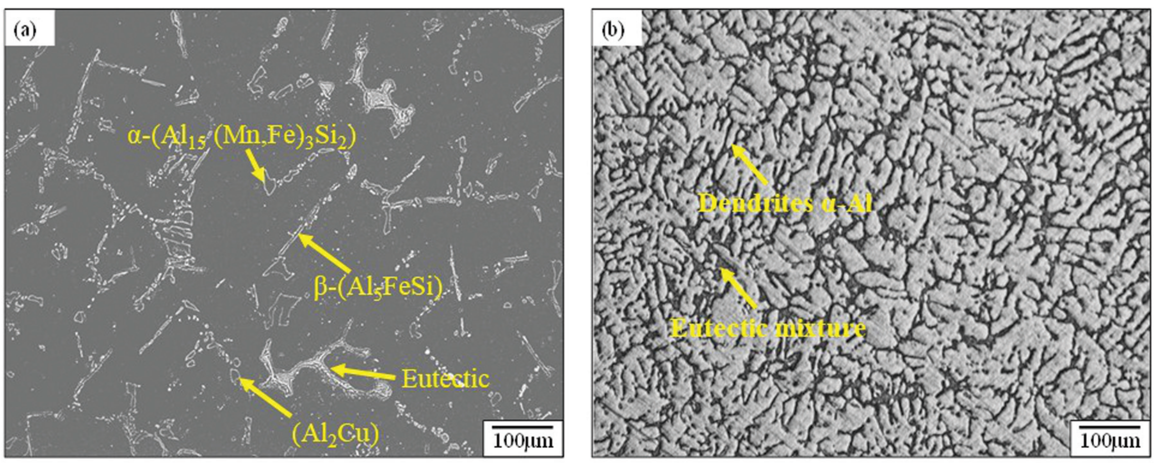

FIGURE 4. Microstructure of Al-5.7Si-2Cu-0.3Mg alloy (a) SEM and (b) optical micrograph

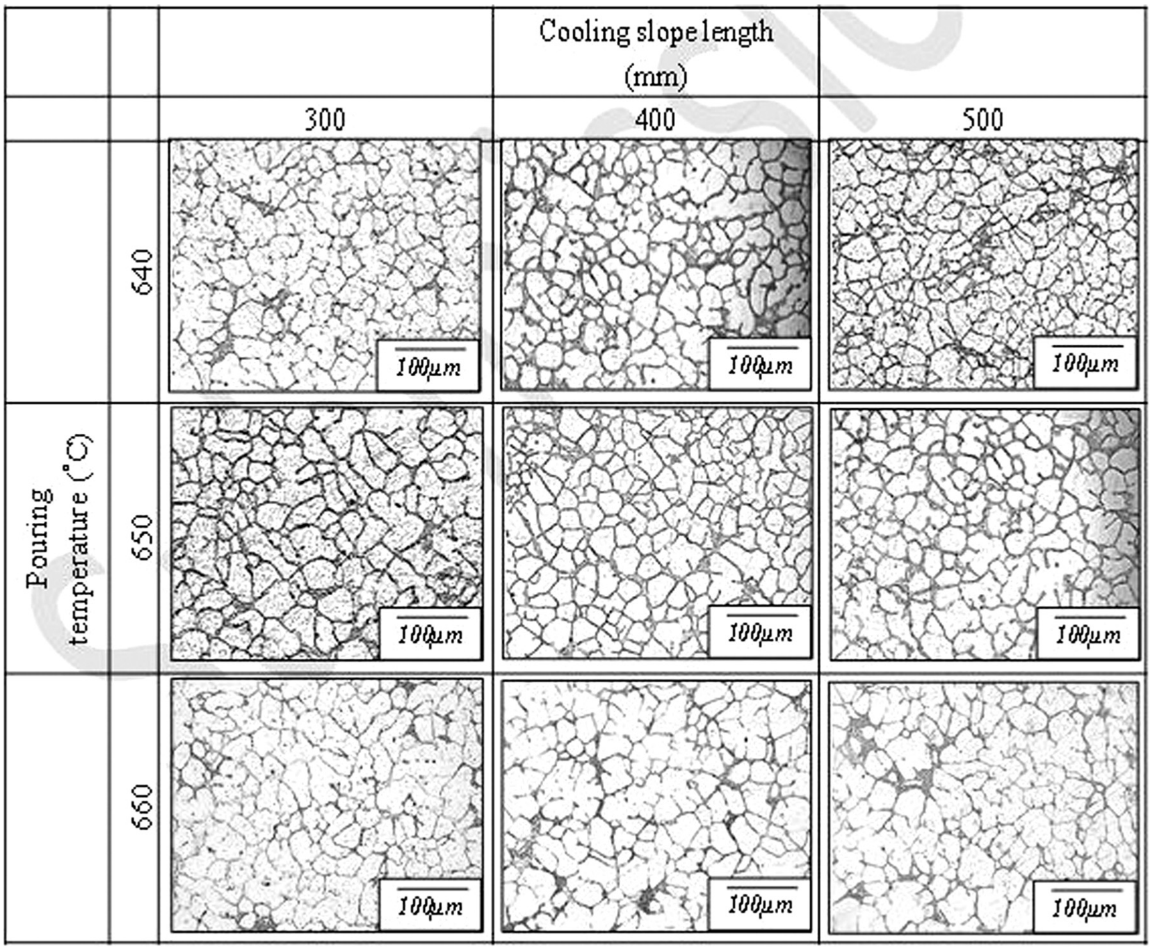

FIGURE 5. Optical micrographs of the rheocast of Al-5.7Si-2Cu-0.3Mg alloy at different pouring temperatures, and different position of ingot

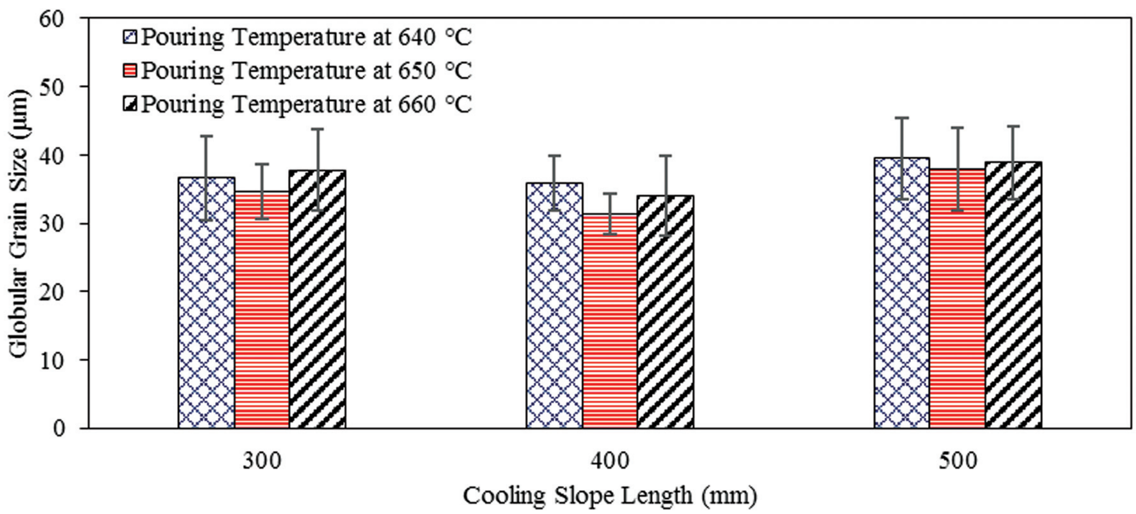

FIGURE 6. Globular grain size of (α-Al) of Al-5.7Si-2Cu-0.3Mg alloy resulting from the different of pouring temperature and slope length

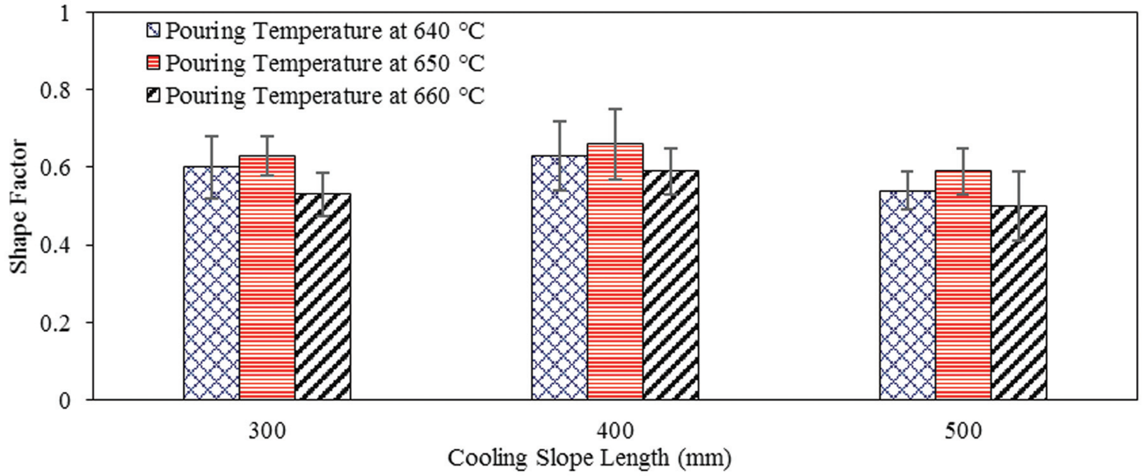

FIGURE 7. The shape factor (α-Al) of Al-5.7Si-2Cu-0.3Mg alloy resulting from the different of pouring temperature and slope length

a CS length of 400 and 500 mm. The microstructure of the alloy at a pouring temperature of 650°C and a CS length 400 mm produces higher shape factor, and smaller AGS of α-Al than that produced at plate lengths of 300 and 500 mm. Furthermore, at a pouring temperature of 660°C and a CS length of 500 mm the AGS of the α-Al phase is smaller than that produced when the length of the slope is 300 and 400 mm.

However, a low pouring temperature requires a shorter slope length to produce a small globular grain size. Conversely, a high pouring temperature requires a long slope length to produce a small grain size of α-Al. It is known that both grain size and shape factor are dependent on the slope length and pouring temperature. In this study the average amount in shape factor and grain size are 31-40 µm and 0.54-0.66 respectively. Additionally, it seems that slope length is found to be affecting on the output characteristics, i.e. the grain size and the shape factor. This result contrasts with the result that shown by Khosravi et al. (2014), who reported that the most important factor in terms of its effect on the microstructure of aluminium alloy, is pouring temperature. This strong effect was because, when the pouring temperature increase, the input heat to the surface increase, which lead to reduce the thickness of primary solidified layer on the cooling slope.

Based on Figure 6 and Figure 7, a pouring temperature of 650°C and a CS length 400 mm are the optimal parameters for producing a globular grain size of 31.67 ± 3 µm and the shape factor was 0. 66 ± 0.09. As result, the pouring temperature had only a slight effect on the grain size and shape factor, when the liquid alloy flowed over the cooling slope, the temperature of the molten alloy declined below the liquidus temperature, producing the α-Al crystals, that were separated along the cooling slope (Salleh et al. 2014), results. Rheocast process used to produce microstructure with fine and less dendritic of α-Al particles. This change in the microstructure is attributed to the low superheat pouring temperature, the cooling effect of the plate which reduces the solidification time and also the shearing effect of the nucleate α-Al grains while the alloy slurry was flowing down to the mould. As the molten material pours over the plate, the temperature drops quickly below the liquidus temperature and the primary aluminium grains start to nucleate and grow to become dendritic, but due to the effect of shearing and rotation on the plate they are fragmented and transformed into a rosette-like microstructure before they finally become nearly spheroidal. Some of the rosette microstructure does not have enough time to become completely globular or to ripen to become dendritic and some grains are agglomerated together to form bigger grains (Alhawari et al. 2015).The effect of the pouring temperature and the CS length on the semi-solid material was observed strongly in the microstructure and the mechanical properties.

The tensile properties of the as-cast and rheocast alloys are shown in Figure 8. The results show that the CS casting process resulted in an improvement in the mechanical properties of the rheocast alloy as compared to those of the as-cast alloy, which was due to the former's non-dendritic microstructure and reduced porosity and segregation as well as the uniform distribution of Si particles. This result because the metal is partially solid as it enters the mould and, hence, less shrinkage porosity occurs. Lee & Oh (2002) state that the mechanical properties of Al-Si alloys are strongly dependent on the shape of the microstructure and liquid segregation. Therefore, the non-dendritic microstructure and the uniform distribution of the rheocast Al-5.7Si-2Cu-0.3Mg significantly improved the tensile property of the alloy as compared to the as-cast alloy.

The ultimate tensile strength of the rheocast alloy was 10% higher than that of the as-cast alloy. The yield strength and elongation characteristics exhibited by the rheocast alloy were also better than those of as-cast alloy. The yield strength in the rheocast samples was 12% higher than that of the as-cast alloy samples, but the largest improvement was seen in the elongation characteristic, which increased by approximately 22% as compared to the as-cast alloy as shown in Figure 9. These improvements were mainly due to there being less shrinkage and associated porosity in the rheocast alloy because the rheocast process utilises a temperature below the liquidus temperature of the alloy.

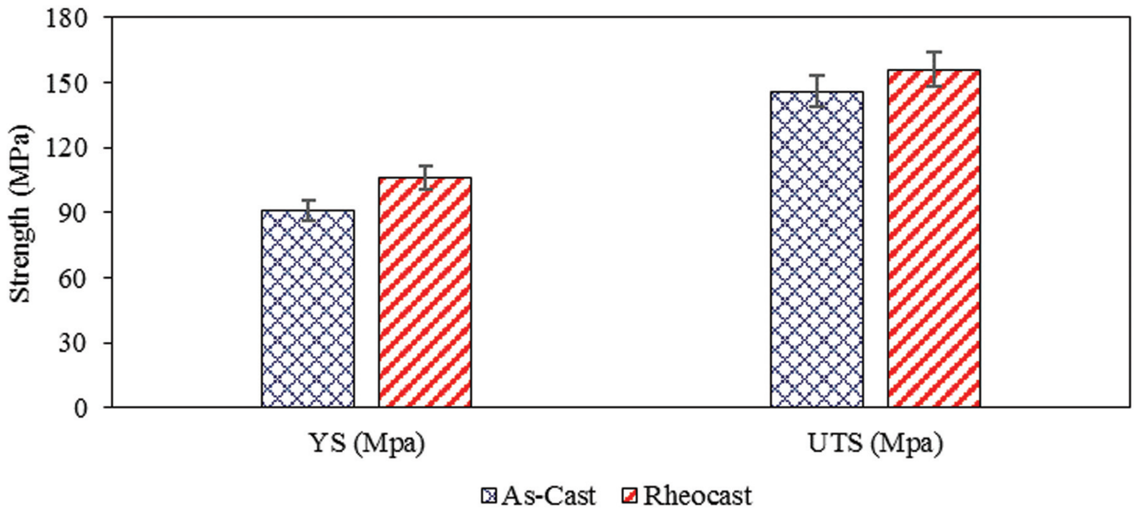

FIGURE 8. Mechanical properties result of the conventional cast and rheocast samples of Al-5.7Si-2Cu-0.3Mg alloys

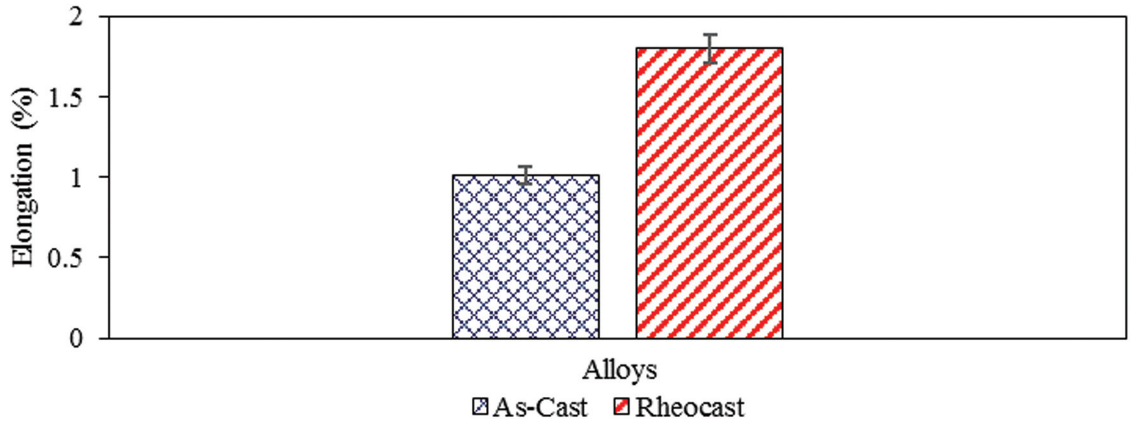

FIGURE 9. Tensile elongation of the conventional cast and rheocast samples of Al-5.7Si-2Cu-0.3Mg alloys

The homogeneous microstructure, the liquid segregation, the non-dendritic shape of the α-Al particles, and the uniform distribution of the compound phase between the metals in the eutectic regions cause the increase in the tensile strength of rheocast alloys.

Scanning electron microscopy images of the fractographic surfaces of both samples are provided in Figure 10(a) and Figure 10(b). In the as-cast and rheocast samples, the tensile fracture paths followed the primary α-Al phase boundaries. A fracture of the long Si particles can clearly be seen in the as-cast sample whereas, the rheocast sample observed a blocking crack, which is due to the amount of aluminium matrix present (Peng et al. 2011). The size and spaces between the eutectic Si in the rheocast alloy are less than that in the conventional alloy. However, the elongation crack was observed on the fracture surface of as-cast alloy.

The fracture surface of the rheocast alloy show a fine, well-distributed dimple fracture, which is due to the fracture surface changing from being brittle as in the as-cast alloy to ductile, due to the microstructure in the fracture surface modifying from long Si particle to a dimple phase, which is illustrated in Figure 10 with the aid of the white arrows. The improvement in the tensile strength of the rheocast sample was due to an increase in the amount of segregation elements present, such as Si, Cu and Mg, which were caused by the segregation of the semi-solid phase. The volume fraction of intermetallic in the final structure attributed to increase that segregation. Figure 11 presents the SEM-EDX micrographs for whole space analysis of the as-cast and rheocast alloys at a pouring temperature 650°C. It is clear that the main reason for the improvement in the fracture surface of the rheocast sample is the increase in amount of Cu and Mg elements present during secondary solidification compared to the amount seen in as-cast alloy. The increase in Cu and Mg elements are because the fragmentation of faceted these elements to small pieces followed by agglomeration and sintering of these pieces to form some large mass.

CONCLUSION

This study investigated the effect of each of pouring temperature and cooling slope length parameters on the microstructure and mechanical properties of Al5.7Si-2Cu-0.3Mg alloy, to determine the optimum CS processing condition to produce a desirable semisolid feedstock

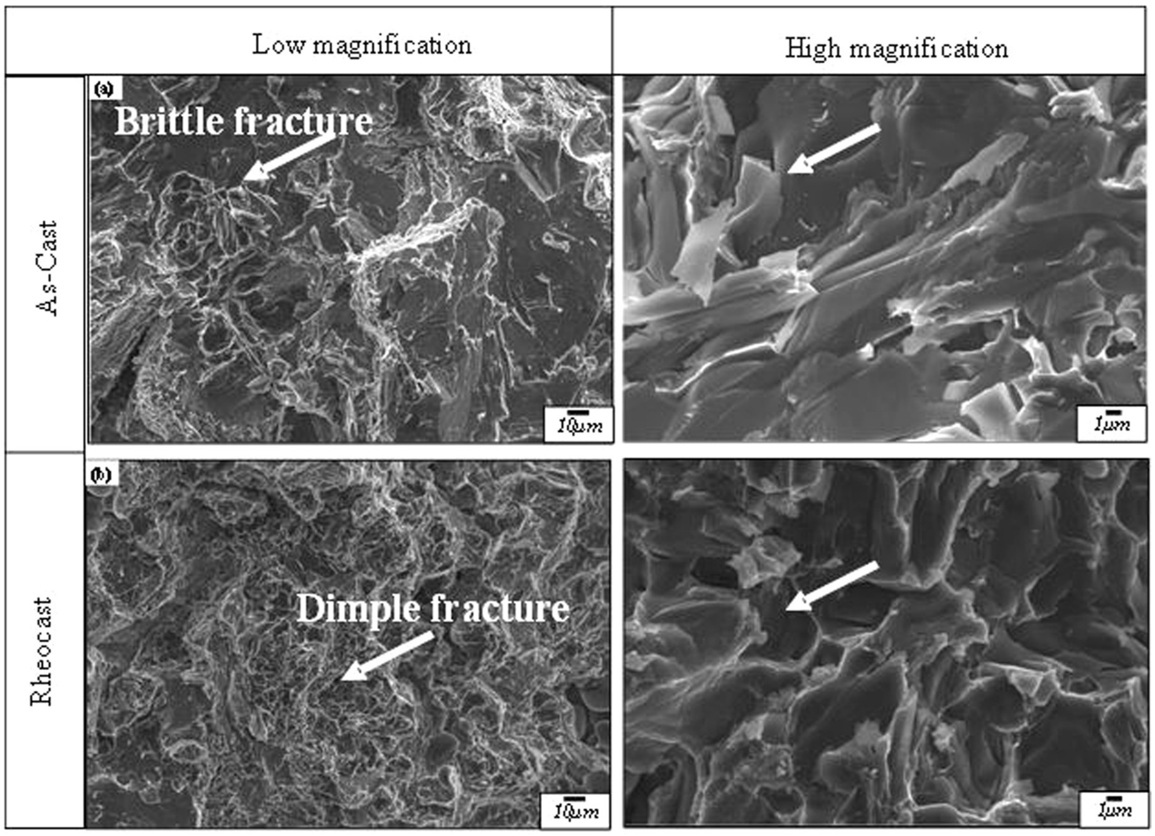

FIGURE 10. SEM micrograph images of tensile test (a) As-cast and (b) rheocast of Al-5.7Si-2Cu-0.3Mg alloys

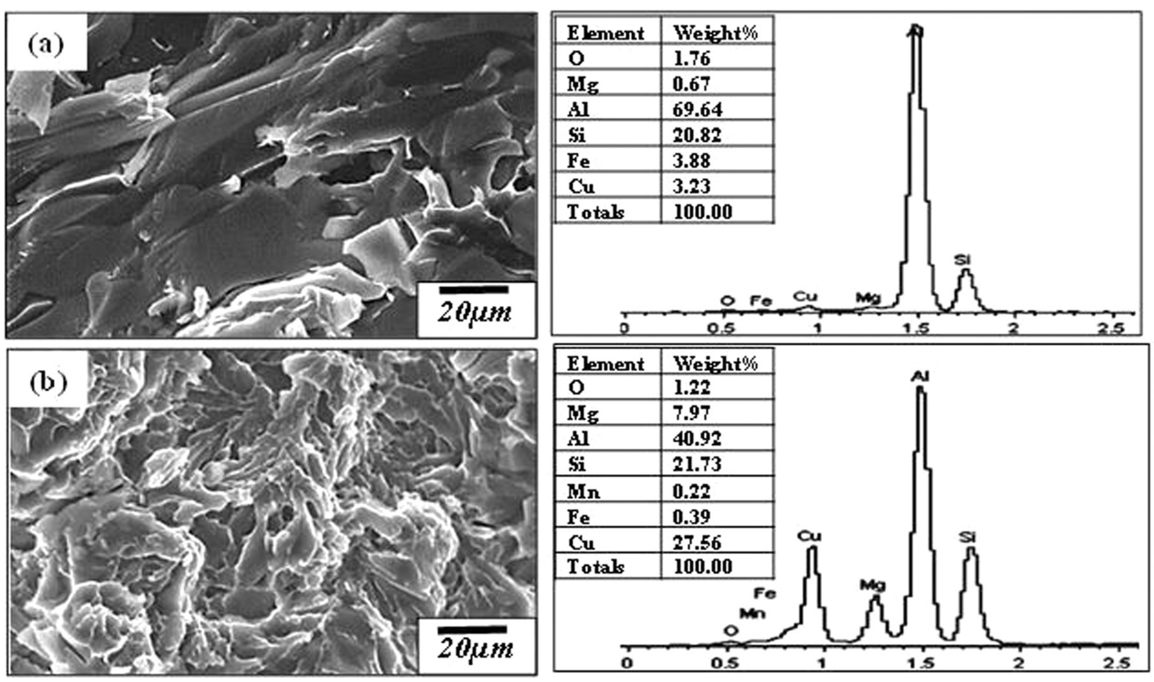

FIGURE 11. SEM-EDX micrograph of (a) As-cast and (b) rheocast samples of Al-5.7Si-2Cu-0.3Mg alloy

material for thixoforming process. Al-5.7Si-2Cu-0.3Mg alloy feedstock produced with CS casting with a pouring temperature of 650°C and a CS length of 400 mm, can be successfully use as feedstock material according to, the smallest grain size obtained was 31.67 ± 3 μm and the highest shape factor was 0.66 ± 0.09. The rheocast alloy showed significant improvement in its tensile properties due to the homogeneous microstructure, the non-dendritic shape of the α-Al particles, and the uniform distribution of the compound phase between the metals in the eutectic regions. There was also a noticeable difference in the fracture surfaces where that of the as-cast alloy was brittle and that of the rheocast alloy was ductile.

ACKNOWLEDGEMENT

Universiti Kebangsaan Malaysia (UKM) and the authors gratefully acknowledge Ministry of Higher Education (MOHE), Malaysia, for the financial support under research grant DIP/2016/007.

REFERENCES

Abedi, A., Shahmiri, M. B. & Amir Esgandari, B. N. 2013. Microstructural evolution during partial remelting of Al-Si alloys containing different amounts of magnesium. *Journal of Materials Science & Technology* 29(10): 971-978.

Abdelgnei, M. A., Omar, M. Z., Ghazali, M. J., Gebril, M. A. & Mohammed, M. N. 2018. Dry sliding wear behaviour of rheocat Al-5.7Si-2Cu-0.3Mg alloy. *International Journal of Engineering & Technology* 7: 38-42.

Alhawari, K.S., Omar, M.Z., Ghazali, M.J., Salleh, M.S. & Mohammed, M. N. 2015. Evaluation of the microstructure and dry sliding wear behaviour of thixoformed A319 aluminium alloy. *Materials and Design* 76: 169-180.

Arif, M.M.A., Omar, M.Z. & Sajuri, Z. 2018. Pembentukan mikrostruktur berbentuk sfera dalam keadaan separa pepejal aloi. *Jurnal Kejuruteraan* 30(2): 275-280.

Atkinson, H. V. 2005. Modelling the semisolid processing of metallic alloys. *Progress in Materials Science* 50(3): 341-412.

Campo, K.N., Proni, C.T.W. & Zoqui, E.J. 2013. Influence of the processing route on the microstructure of aluminum alloy A356 for thixoforming. *Materials Characterization* 85: 26-37.

Das, P., Samanta, S.K., Chattopadhyay, H. & Dutta, P. 2012. Effect of pouring temperature on cooling slope casting of semi-solid Al-Si-Mg alloy. *Acta Metallurgica Sinica-English Letters* 25(5): 329-339.

Das, P., Samanta, S. K., Das, R. & Dutta, P. 2014. Optimization of degree of sphericity of primary phase during cooling slope casting of A356 Al alloy: Taguchi method and regression analysis. *Measurement* 55: 605-615.

Fan, Z. 2002. Semisolid metal processing. *International Materials Reviews* 47(2): 49-85.

Gautham, B. P. & Kapur, P. C. 2005. Rheological model for short duration response of semi-solid metals. *Materials Science and Engineering A* 393(1-2): 223-238.

Jiang, J., Atkinson, H.V. & Wang, Y. 2017. Microstructure and mechanical properties of 7005 aluminum alloy components formed by thixoforming. *Journal of Materials Science and Technology* 33(4): 379-388.

Kang, C. G. & Youn, S. W. 2004. Mechanical properties of particulate reinforced metal matrix composites by electromagnetic and mechanical stirring and reheating process for thixoforming. *Journal of Materials Processing Technology* 147(1): 10-22.

Khosravi, H., Eslami-Farsani, R. & Askari-Paykani, M. 2014. Modeling and optimization of cooling slope process parameters for semi-solid casting of A356 Al alloy. *Transactions of Nonferrous Metals Society of China* 24(4): 961-968.

Kund, N. K. 2014. 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(11): 3465-3476.

Lee, S.-Y. & Oh, S. Il. 2002. Thixoforming characteristics of thermo-mechanically treated AA 6061 alloy for suspension parts of electric vehicles. *Journal of Materials Processing Technology* 130: 587-593.

Legoretta, E. C., Atkinson, H. V. & Jones, H. 2008. Cooling slope casting to obtain thixotropic feedstock II: observations with A356 alloy. *Journal of Materials Science* 43(16): 5456-5469.

Li, J.-Y., Sugiyama, S., Yanagimoto, J., Chen, L.-Y. & Fan, G.-W. 2008. Effect of inverse peritectic reaction on microstructural spheroidization in semi-solid state. *Journal of Materials Processing Technology* 208(1): 165-170.

Mohammed, M. N., Omar, M. Z., Salleh, M. S., Alhawari, K. S. & Kapranos, P. 2013. Semisolid metal processing techniques for nondendritic feedstock production. *The Scientific World Journal* 2013: 1-16.

Motegi, Tetsuichi and Tanabe, F. 2000. Continuous casting of semisolid Al-Si-Mg alloy. *Continuous Casting* 1: 82-86.

Omar, M. Z., H. A. & P. K. 2007. Semi-solid metal processing- a processing method under low flow loads. *Jurnal Kejuruteraan* 30(2): 137-146.

Peng, J., Tang, X., He, J. & Xu, D. 2011. Effect of heat treatment on microstructure and tensile properties of A356 alloys. *Transactions of Nonferrous Metals Society of China* 21(9): 1950-1956.

Salleh, M. S., Omar, M. Z. & Syarif, J. 2015. The effects of Mg addition on the microstructure and mechanical properties of thixoformed Al-5% Si-Cu alloys. *Journal of Alloys and Compounds* 621: 121-130.

Salleh, M. S., Omar, M. Z., Syarif, J., Alhawari, K. S. & Mohammed, M. N. 2014. Microstructure and mechanical properties of thixoformed A319 aluminium alloy. *Materials and Design* 64: 142-152.

Spencer, D. B., Mehrabian, R. & Flemings, M. C. 1972. Rheological behavior of Sn-15 Pct Pb in the crystallization range. *Metallurgical Transactions* 3(7): 1925-1932.

Taghavi, F. & 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.

Taghavi, F., Saghafian, H. & Kharrazi, Y. H. K. 2009. Study on the ability of mechanical vibration for the production of thixotropic microstructure in A356 aluminum alloy. *Materials and Design* 30(1): 115-121.

Thuong, N. Van, Zuhailawati, H., Seman, A. A., Huy, T. D. & Dhindaw, B. K. 2015. Microstructural evolution and wear characteristics of equal channel angular pressing processed semi-solid-Cast hypoeutectic aluminum alloys. *Materials and Design* 67: 448-456.

Zhou, B., Kang, Y. L., Zhu, G. M., Gao, J. Z., Qi, M. F. & Zhang, H. H. 2014. Forced convection rheoforming process for preparation of 7075 aluminum alloy semisolid slurry and its numerical simulation. *Transactions of Nonferrous Metals Society of China (English Edition)* 24(4): 1109-1116.