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EFFECTS OF RHEOCASTING AND THIXOFORMING ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF A356 ALUMINIUM ALLOY

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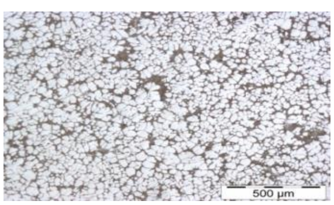

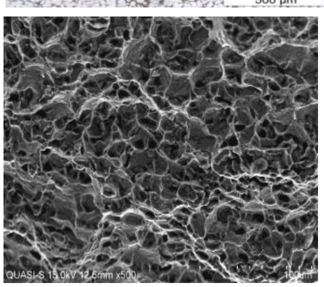

Abstract

This paper presents the changes in mechanical properties and microstructure of aluminium alloy A356 that undergoes cooling slope casting. The alloy was cut into small cubes with an estimated weight of 400g before it was heated in a crucible induction casting machine. The temperature was set to 880 °C with a heating rate of 15 °C per min. Then, the metal was cooled to 620 °C until it turns to a semisolid, before pouring into a stainless steel mould through a 250 mm long and 60° cooling slope before it was cooled to room temperature. For the thixoforming experiments, the liquid fraction was between 30% and 50%, with various semisolid temperatures (583 °C-585 °C). The ram speed and die temperature were 85 mm/s and 200 °C, respectively. The microstructure and mechanical properties of rheocast feedstock in T6 condition were determined and compared with the metal without any heat treatment, rheocast and thixoformed alloy. It was found that thixoformed metal had the highest ultimate tensile and yield strength with reduced ductility. The microstructures are rosette, near globular and spherical, and were obtained in rheocast and thixoformed alloys, respectively. The a-Al grains were larger at higher semisolid temperatures.

Keywords: Semisolid; cooling slope; thixoforming

Abstrak

Kertas ini menjelaskan perubahan terhadap sifat mekanikal dan mikrostruktur aluminium aloi A356 yang telah melalui proses penuangan plat penyejuk. Aloi ini dipotong kecil pada anggaran berat 400g sebelum dipanaskan didalam mesin penuangan elektrik. Suhu disetkan pada 880 °C dengan purata kadar pemanasan 15 °C per minit. Kemudian disejukkan kepada suhu 620 °C sehingga berubah kepada logam separa pepejal sebelum dituang ke dalam acuan keluli tahan karat dengan melalui plat penyejuk pada panjang 250 mm dan bersudut 60° dan dibiarkan sejuk pada suhu bilik. Manakala ujikaji *thixoforming* pula, peratus cecair adalah diantara 30% dan 50%, dengan pelbagai suhu separa pepejal (583 °C-585 °C. Kelajuan ram dan suhu acuan adalah pada 85 mm/s and 200 °C. Mikrostruktur dan sifat-sifat makanikal pada suapan selepas proses penuangan dalam keadaan T6 ditentukan dan dibandingkan secara ujikaji dengan aloi-aloi selepas proses pembentukan separa pepejal, selepas selesai proses penuangan. Didapati bahawa suapan selepas pembentukan separa pepejal memperolehi nilai kekuatan tegangan muktamad dan kekuatan alah yang paling tinggi sebaliknya rendah sifat kemuluran. Mikrostruktur yang *rosette*, hampir membulat dan bulat terhasil dari aloi-aloi selepas proses penuangan dan selepas proses pembentukan separa pepejal. Partikel a-Al pula membesar apabila suhu pemanasan separa pepejal meningkat.

Kata kunci: Separa pepejal; curam penyejuk; thixoforming

1.0 INTRODUCTION

Semisolid metal (SSM) processing has been investigated by many researchers since 1970s. These include electromagnetic system (MHD/EMS), grain refiner (additive), rheocasting, recrystallization and partial melting (RAP), strain melt activated (SIMA), and powder compaction etc. These methods have improved mechanical properties due to modified microstructures, which was obtained by predominant non-dendritic a-Al grains. The processes occur in a semisolid condition, where partial melted feedstock or semisolid molten alloy (slurry) are formed into a near-net-shape component within metal dies. As a result, these methods are able to produce non-dendritic microstructure and near spherical-shaped a-Al particles of feedstock. The average grain size obtained from the SSM processing methods is ≤100 µm, which is a prerequisite for thixoforming. From the literature, very few researches have been carried out on cooling slope casting. The cooling slope casting is actually developed based on the rheocasting method, where the slope is employed before the slurry casting is poured into the mould. Some researchers have paid attention to parameter setups, such as variable length and slope [1-2], condition slope (i.e. vibrate and rotate [3], oscillate [4], water circulate [2], preheated [6]), pouring temperature and mould material [5], and mould circumstance (i.e preheated [3], insulator [1, 5]).

When the cooling slope remains at a 60° angle with the variable length as indicated, the primary crystals achieved are of a smaller size without dendrites [1]. In addition, the a-Al particles were modified to rosette at a range slope of 10° and 30° [6]. However, by adjusting the slope within 40° to 60°, the microstructure became coarser with a low shape factor at the highest pouring temperature of 680 °C, while the optimum condition was obtained at 40° with a 40 cm length [7]. At a low pouring temperature of 630 °C, the optimized primary crystals were obtained at lengths of 150 and 250 mm, but failed at a pouring temperature of 650 °C [5]. The condition of cooling slope can also be considered as another factor that influences the shape of the a-Al particles produced. For examples, (1) water circulation can promote spheroidal and smaller primary crystals even in T6 condition [2], (2) vibration on cooling slope is able to encourage the a-Al particles to a finer size, while rotation gives a coarser structure [3], (3) angular oscillation is capable to form the a-Al particles to become finer and globular at a low frequency with a pouring temperature of 660°C [4], and (4) preheated slope can gain the highest uniformity microstructure and fine and globular a-Al particles [7]. Moreover, mould material and circumstance should be calculated as causes for improved microstructures. High cooling rate material is better for moulds such as copper, while an insulator mould must be kept in a furnace at a semisolid temperature for homogenous and spheroid microstructure, otherwise it will fail [5], as well as preheated mould that is supposed to achieve similar results but without being kept in a furnace [7].

Based on the literature, almost all aspects have been studied on cooling slope for producing homogenous, fine and globular a-Al particle microstructures of A356 aluminum alloys. Considering the challenges to obtain spherical a-Al particles in particular, the literature is almost silent on the details for fixed parameters and their correlation with mechanical properties such as hardness and tensile properties.

The main goal of this study is to determine the effect of rheocasting and thixoforming on the hardness, ultimate tensile strength, yield strength, elongation and microstructure of A356 aluminium alloy. The cooling slope dimensions and pouring temperature are kept constant.

2.0 EXPERIMENTAL PROCEDURES

The composition of the as received aluminium A356 alloy used in this research is presented in Table 1. The composition has been taken from spectrometer readings at different positions. The received alloy was provided by Anglo Asia Aluminium Smelter Sdn. Bhd., Malaysia. The received aluminium A356 alloy was fabricated by conventional gravity casting with a rough weight of ~5 kg per ingot. Figure 1 shows the curve for liquid fraction versus temperature derived from the DSC results. The DSC machine used was manufactured by Mettler Toledo and the heating and cooling rates were set to 10°C/ min. within a pure gas atmosphere. The liquidus and solidus of the received A356 alloy indicate 634 °C and 568 °C, respectively. The temperature range for liquid fractions of 30%-50% is approximately 582 °C-585 °C. Liquid fraction increases rapidly at the temperature of 575°C-585°C, while liquid fraction is constant at the temperature of 585 °C-590 °C and forms a 'knee'. The formed 'knee' is due to wide freezing or heating of a material that normally occurs on A356 alloy. In other words, it is known as 'brake', which becomes an indicator of A356 aluminium alloy for semisolid forming, and within the temperature range, the feedstock can be easily controlled, otherwise the feedstock will collapse at a higher temperature [8-10].

2.1 Rheocasting

The cooling slope casting of the received ingots was carried out using fixed parameters. The parameters are designed with length, slope and pouring temperature at 250 mm, 60° and 620 °C, respectively. The parameters have been determined by the work of Hendry *et al.* [11]. Figure 2 shows the instrument setup for cooling slope casting. The casting by means of cooling slope used is to avoid the formation of dendrites in order to prepare feedstock for thixoforming. The surface of the stainless steel plate was coated with boron nitrite to promote smooth flows of slurry without sticking. The plate was integrated with water circulation, the inlet place on the opposite direction of molten alloy flows for fast cooling. The received A356 ingots were cut into small pieces with the weight of 0.35 kg, then placed in the SiC crucible induction furnace and heated at 880 °C under a hydrogen atmosphere. The heating rate was set at 15 °C per minute. The slurry is casted in a stainless steel mould and cooled at room temperature. The mould has cross-section dimensions of Ø 25 x 110 mm. The cast samples produced is known as rheocast.

2.2 Thixoforming

The thixoforming process, which consists of hot compression tests in the semisolid temperature range, has been performed on the rheocast samples. The hot compression die was preheated at 200 ±3 °C. The tests were implemented using hydraulic ram that provides 20 kN with a maximum speed of 85 mm/s. Prior to any compression tests, the samples were heated at 583, 584 and 585 °C for 10 min approximately and at a frequency of 420 Hz. The thixoformed samples were isothermally deformed to 65-70 mm in height and 30 mm diameter.

Table 1 Chemical composition (wt.%) of the A356 alloy used in this study

Element	Si	Mg	Fe	Ti	Cu	Zn	Sn	Al
Wt.(%)	6.56	0.17	0.13	0.37	0.08	0.01	0.02	Bal.

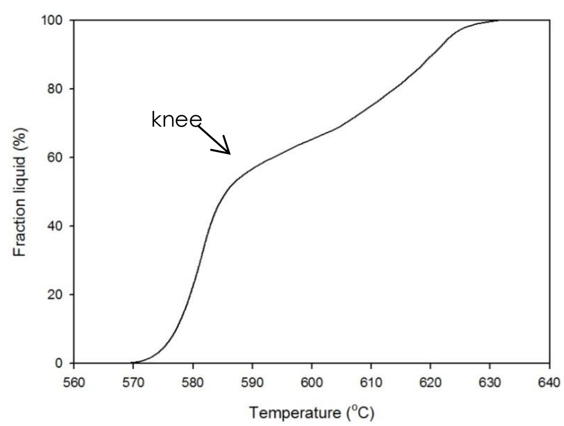

Figure 1 Curve for liquid fraction versus temperature derived from the DSC

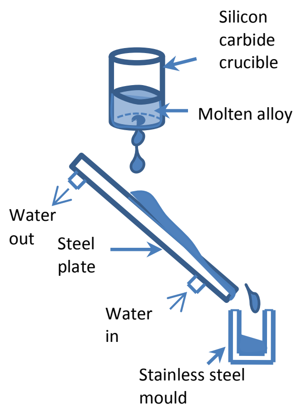

Figure 2 Schematic illustration of rheocasting [11]

2.3 Heat Treatment

The heat treatment T6 for standard alloy A356 has been carried out using rheocast and thixoformed samples. The samples were cut into 5 mm thick specimens. The specimens were heated in an induction furnace at 540 °C for 2, 4 and 8 hours, followed by water quenched at 25 °C, and ageing at 180 °C for 4 hours.

All specimens were ground using 400, 600, 800, 1000 and 1200 grit papers, and polished using 6 µm and 1 µm diamond pastes. The samples were etched in Keller's reagent. Solid grain size ($D = (4A/\pi)^{1/2}$, where A is the area of the solid grain), shape factor, ($S = 4\pi A/P^2$, where P is the solid grain perimeter) was measured from resulting microstructure using an imageJ analysis software. Samples for the tensile tests were machined from the as received, as rheocast, as rheocast + T6 and as thixoformed alloys. The mechanical properties were measured on a dog bone-shaped (ASTM 8M) tensile sample using an Instron testing machine at a frequency of 20 Hz and the Vickers hardness test on the polished samples. Each tensile test value was the average of at least five measurements. Microstructure investigations were conducted using optical microscopy. Tensile fracture surfaces were characterized by a Hitachi SU 1510 scanning electron microscope (SEM).

3.0 RESULTS AND DISCUSSION

Figure 3 shows the microstructure of as received sample, which was directly casted into the mould, and as rheocast sample, which was casted into the mould by flowing on the cooling slope. The microstructure contains a large dendrite of α-Al phases with a size more than 200 µm. Moreover, the average size of α-Al particles in the rheocast sample were 63 µm and the shape factor of α-Al phase obtained was 0.87. A comparison of Figures 3 (a) and (b) reveals that large dendrites of α-Al phases are changed into the rosette structure by the application of the cooling slope. During the cooling slope casting, the melt flowing through the inclined plate exerted shear stress due to gravity leads to the detachment of the newly formed α-Al phase from the breaking of dendrite arms, which are growing on the surface of the inclined surface. The α-Al particles are distributed in the melt during the flowing and descended into the mould [6-7]. It is evident that the fixed parameters used are able to transform the sample into a microstructure without dendrite and are entitled for thixoforming feedstock, which have average α-Al particles of ≤ 100 µm and shape factor of ≥ 0.6 [12].

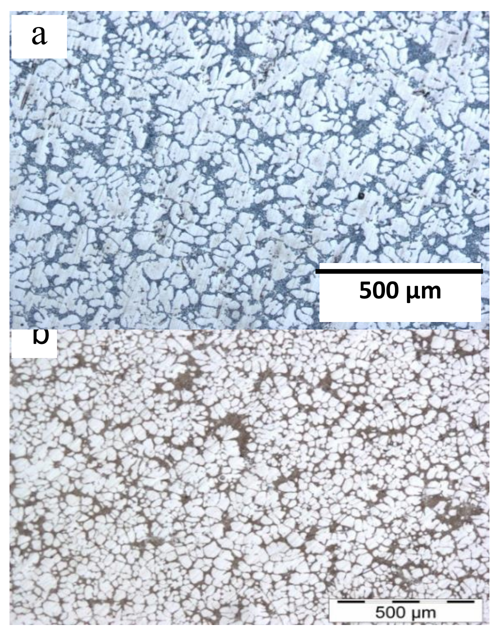

Figure 3 Microstructure of (a) as received and (b) as rheocast samples

Figure 4 shows the obtained microstructures of rheocast samples subjected to T6 heat treatment at 2, 4 and 8 hours solution heat treatment at 540 °C followed by ageing at 180 °C for 4 hours . A comparison of Figures 4(a), (b) and (c) indicates that eutectic Si has emerged all over the grain boundaries.

It is found that increasing duration of solution heat treatment at 4 hours ageing, a large quantity of the silicon has spheroidized. Maybe the ageing time was shot and require optimum time to allow precipitation of dissolved elements.

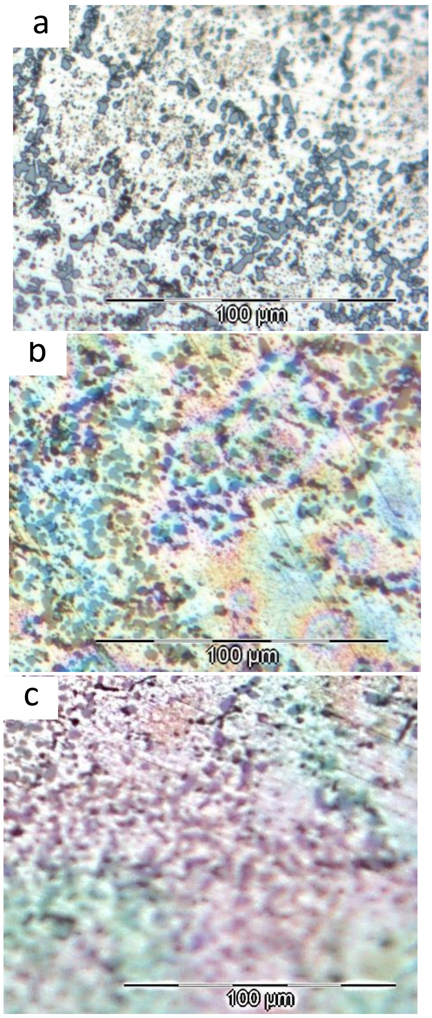

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Figure 4 Microstructures of rheocast samples subjected to T6 heat treatment at different solution heat treatment durations, (a) 2h, (b) 4h and (c) 8h

Figure 5 illustrates the optical microstructures of the thixofomed specimens at different semisolid temperatures of 583, 584, and 585 °C for 10 min. The average grain size was increased to 65.9, 94.16 and 98.85 µm, respectively as temperature increase. According to Figures 5(a)-(c), increasing the reheating temperatures from 583 °C to 585 °C for thixoforming changes the morphology of the a-Al grains to become more globular and makes them disperse more uniformly within the liquid matrix. The microstructure of thixoformed alloy at the reheating temperature of 585 °C is finer than at 583 °C. The existed liquid from the reheating billet probably wetted the grain boundaries due to the eutectic melted encourage to globularization and applied force of compression. It can be seen that a remarkable macroscopic separation phenomenon occurred between the formed solid and liquid phase due to better fluidity that filled the remaining areas completely [13].

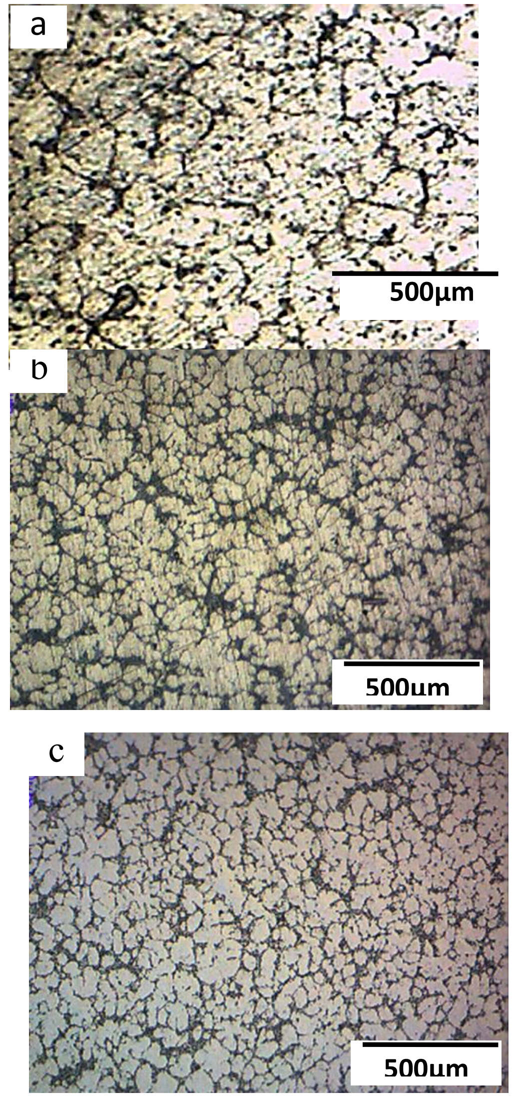

Figure 5 Microstructures of the thixoformed A356 alloy at different semisolid temperatures, (a) 583 °C, (b) 584 °C and (c) 585 °C

The mechanical properties of the as A356 alloy at different conditions, such as received, as rheocast, as rheocast + T6 and as thixoformed alloy, are listed in Table 2. The 0.2% plastic strain (ys) and the ultimate tensile strength (UTS) of the thixoformed at 583 °C alloy are 121.33 MPa and 193.67 MPa, respectively, which are higher than as rheocast and as rheocast + T6 alloy, and achieved good UTS, but poor elongation to fracture. The tensile properties of thixoformed at 583 °C - 584 °C samples are almost similar. Rheocast samples show a 0.2% plastic strain increase (94.07 MPa), while little increment is shown for UTS (149.33

MPa). It can be seen that the tensile strength of the thixoformed sample shows a 37% increase compared to the as received sample, and a 29% increase compared to the rheocast sample. Poor elongation to fracture was obtained for the thixoformed sample, the value shows a decrease by 47-68% and 38% compared with the as received and rheocast sample, respectively. Good elongation to fracture was shown in the as received sample with a 0.2% plastic strain of 65.03 MPa and UTS of 141.33 MPa. Furthermore, the tensile properties of rheocast and thixoformed samples are better than as received sample, while the thixoformed sample has the best properties.

The rheocast specimens were aged at 180 °C 4h, and 2, 4 and 8h precipitation hardening at 540°C. It was found that the hardness of as rheocast sample has increased and then decreased after performing T6. A peak value occurs at the thixoformed sample. The hardness reaches a peak value when the change of α-Al grains was obtained for finer spherical microstructure. The hardness value indicates a reduction in T6 condition that may be due to the standard T6 applied that was not appropriate for the rheocast alloy. An optimized heat treatment needs to be developed for rheocast alloy [14]. Figure 6 shows SEM images of the tensile fracture surface of A356 alloy in different conditions: as received, as rheocast and as rheocast + T6. Figures 6(a) and (b) illustrate almost similar fracture surface, the differences are flat fracture surface, less dimple and shallower for rheocast alloy, which explains the low ductility and brittle mode fracture that were obtained. In comparison, the fracture surface (Fig. 6(c)) of the rheocast + T6 illustrates a lot of dimples and tear ridges, which indicates the occurrence of plastic deformation before failure [15]. The hardness increases in rheocast alloy due to the rosette microstructure obtained. The reduction of hardness is probably due to inhomogeneous α-Al particles in the emerged eutectic Si.

Table 2 The mechanical properties of the as received, as rheocast, as rheocast + T6 and as thixoformed

Condition	0.2% plastic strain (MPa)	Ultimate tensile strength (MPa)	Elongation to failure (%)	Hardness (HV)
As received	65.03	141.33	7.53	52.25 ±1.28
As rheocast	94.07	149.33	2.23	63.38 ±1.85
As rheocast + T6	57.2	112	6.5	44.07 ±1.9
As thixoformed (583 °C)	121.33	193.67	3.07	75.25 ±4.4
As thixoformed (584 °C)	117.5	192	4	75.25 ±1.75
As thixoformed (585 °C)	102.6	160	2.43	75.38 ±2.56

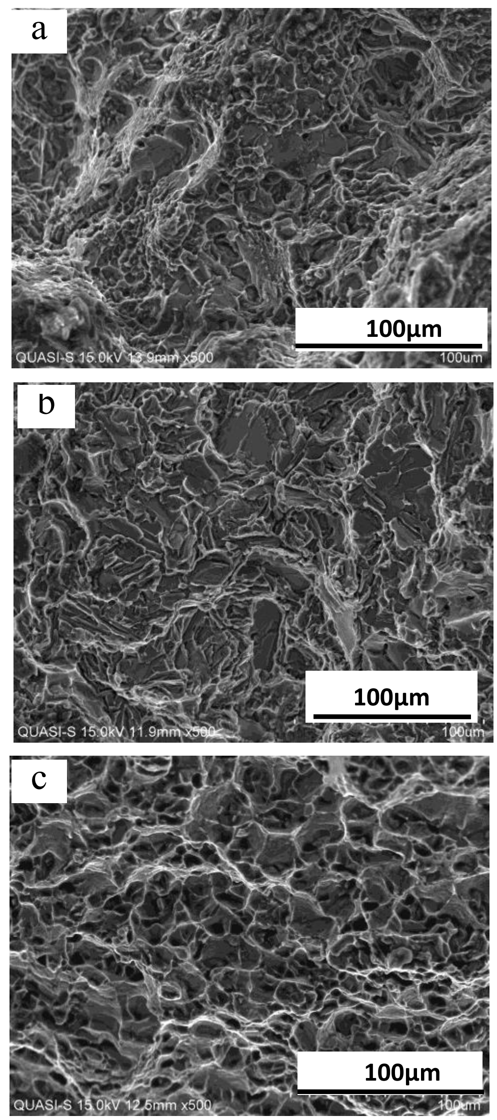

Figure 6 SEM images of the tensile fracture surface of A356 alloy in different conditions, (a) as received, (b) as rheocast, and (c) as rheocast + T6

4.0 CONCLUSION

The following results were obtained from the rheocasting A356 aluminum alloy with fixed parameters for producing feedstock for thixoforming.

1. The pouring temperature of 620 oC, length of cooling slope of 250 mm with 60o slope could produce feedstock in the absence of dendrites and altered the α-Al grains to the rosette microstructure.
2. The average grain size of rheocast alloy obtained was 63μm with a 0.87 shape factor, which exhibits less 100 μm requirements for thixoforming feedstock is passed.
3. The size of α-Al for thixoformed alloys was increased at a higher semisolid temperature. This was due to existing liquid within the billet has wetted the grain boundaries.
4. An excellent result of UTS is obtained for the thixoformed samples compared with the conventional cast samples. T6 heat treatment cannot strengthen the rheocast alloy due to poor results obtained which need to be optimized.

Acknowledgement

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