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EFFECT OF THIXOFORMING ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF AL-6%SI-3%CU ALLOY

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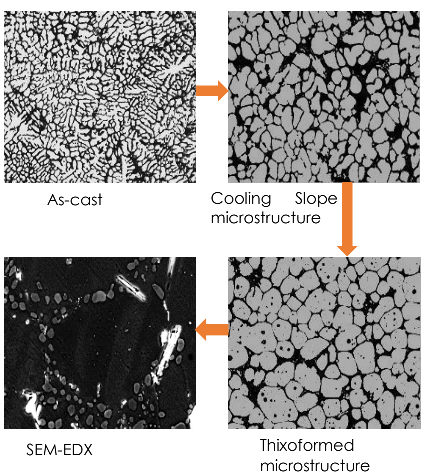
Graphical abstract



Abstract

Thixoforming is a type of semisolid metal (SSM) processing for forming alloys in the semisolid state to near net-shaped products. In the present study, the effect of a thixoforming process on the microstructure and mechanical properties of Al-6Si-3Cu aluminium alloy was investigated. Melt was poured on a cooling slope at 630°C and the samples were obtained through permanent mold casting. They were thixoformed using a hydraulic press after holding at 571°C for 5min to yield a microstructure predominantly composed of α-Al globules and inter-globular Si particles. As-cast and thixoformed samples were characterized using optical microscopy, scanning electron microscopy (SEM), energy dispersive X-ray (EDX) and X-ray diffraction (XRD) as well as hardness measurements and tensile tests. The results indicate that the mechanical properties of thixoformed alloy have improved as compared to permanent mold cast alloy. The ultimate tensile strength of as-cast sample was 210 ± 3.5 MPa and increased to 241 ±3.1 MPa in the thixoformed sample while the yield strength of as-cast alloy was 140 ±4.5 MPa and increased to 176±3.3 MPa in the thixoformed sample. The thixoformed alloy also showed an improvement in elongation to fracture as it increased from 2% in as-cast sample to 3.2% in thixoformed alloy. The fracture of as-cast sample showed a cleavage fracture, whereas in the thixoformed alloy, a combination of dimple and cleavage was observed.

Keywords: Aluminium alloy, cooling slope casting, thixoforming, mechanical properties, fracture behavior

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1.0 INTRODUCTION

In the new global economy, semi-solid metal (SSM) processing has become an important net shape process that combines the advantages of forging and conventional casting and has already become the standard manufacturing route for a number of automotive parts [1, 2]. A primary concern for an alloy to be shaped in the semi-solid state is that it must have non-dendritic structure [3]. It will then behave as 'thixotropic' slurry, in which viscosity decreases with increasing shear rate, while at constant shear rate, the viscosity decreases with increasing time. Such alloy slurries flow in laminar manner, which allows for uniform die filling as opposed to turbulent flow, which is associated with fully liquid state (casting) processes. Several studies have documented that semi-solid metal process has high capability for near net shaping because of less solidification shrinkage and prolonged die life due to the reduced thermal shock and the ability to reduce macro segregation, porosity and forming forces during the shaping process [4, 5].

In recent years, there has been an increasing interest in many techniques to produce non-dendritic feedstock for semi solid metal (SSM) processing. Recent development in the field of semi-solid metal has led to a renewed interest in using the magneto hydro dynamic (MHD) processing route to fabricate automotive commercial products for some automotive manufacturers, due to the fine and uniform globular size of the primary phase in the produced alloy. Although MHD can yield an ideal feedstock for thixoforming, the processing costs for feedstock production are high. According to Atkinson [6], cooling slope casting is a process which requires a small number of equipment. In this method, various parameters, such as the superheating temperature, cooling slope length, cooling slope angle, inclined plate material and mould material can affect the final microstructure of molten superheated alloys [7, 8].

In the recent advancements in semi-solid metal, it is becoming extremely difficult to ignore the existence of Al-6Si-3Cu aluminium alloys, which is commonly used in the automotive industry, due to their good fluidity and mechanical strength [9, 10]. This alloy offers high strength, excellent cast ability, light weight and good machinability in permanent mould and sand casting [11]. There are very limited information on this alloy that processed by thixoformed processing. Therefore, in this study, thixoforming were performed to investigate the microstructural evolution of the alloy. The mechanical properties and fracture behaviour of Al-6Si-3Cu alloy were also investigated.

2.0 METHODOLOGY

The experimental processes in this work began with the Al-6Si-3Cu ingot preparation. Then XRF was carried out to determine the chemical composition. The chemical composition of the alloy was determined using the X-ray fluorescence (XRF) technique, consisting of Si (6.26wt %), Cu (2.81wt %), Mg (0.30wt %), Mn (0.19wt %), Zn (0.71wt %), Ni (0.06wt %), Fe (0.53wt %), Cr (0.03wt %), Ti (0.03wt %), and Al (remainder).

The Al-6Si-3Cu alloy was cut into small pieces (approximately 30mg) in order to be tested with the Netzsch-STA (TG-DSC) thermo-gravimeter. The cooling slope (CS) casting experiments were performed using a resistance furnace. To compare the properties of the Al-6Si-3Cu, three different pouring temperatures (620°C, 630°C, and 640°C) and CS lengths (300mm, 400mm, and 500mm) were used after superheating the alloy up to 700°C, and then cooled down to the selected temperature before being poured on the cooling slope plate. The obtained ingots were sectioned into 40mm long slugs and were ground with a silicon carbide paper, polished and etched in Keller's agent for 20s.

Optical micrographs were captured using an Olympus optical microscope. Image-J software was used to calculate the shape factor (SF) and globule size (GS) of the α-Al phase. The shape factor was defined as $4\pi A/P^2$, where P is the perimeter, A is the area of the particle (the shape factor of a circle is equal to one) [12]. The average globule size of the primary particles was defined as $[\sum 2(A_i/\pi)^{1/2}]/N$, where A_i, is the area of each particle and N is the total number of particles in each image [13]. The best shape factor and smallest globule size of α-Al were selected to undergo thixoforming process. The thixoforming process was performed using a hydraulic cylinder press, which provided a forging load of 20kN and a maximum speed of 85mm/s for the ram. Various phases of the thixoformed samples were identified using a Carl Zeiss (EvoMa10) scanning electron microscope (SEM) equipped with energy dispersive X-ray (EDX) spectroscopy capabilities and verified using XRD.

Samples of the as-cast and as-thixoformed were lightly polished with silicon carbide (SiC) paper and polishing cloths with diamond paste for the hardness specimens. Vickers hardness value was obtained using an average of 10 measurements after the sample imposing a load of 10kg for 10s. Cylindrical tensile specimens with typical gauge dimensions of 20mm in length were machined from the as-cast and as-thixoformed samples to the ASTM: E8M standard. The tensile tests (three sets of specimen) were performed at room temperature using a 100kN Zwick Roell Universal Testing Machine (UTM). The yield stress was based on a 0.2% plastic strain offset. After the tensile test, each specimen was sectioned into smaller sections for microscopic observation.

3.0 RESULTS AND DISCUSSION

The as-cast Al-6Si-3Cu ingot revealed a very fine of α-Al dendritic microstructure and inter-dendritic network of the eutectic phase, as observed in Figure 1a. It was observed that after the cooling slope casting were completed, the microstructural features changed, where α-Al transformed completely from dendritic to near globular microstructure as shown in Figure 1b. The results of the preliminary DSC analysis are presented in Figure 2, where the solidus and liquidus temperatures were estimated to be, 519°C and 610°C respectively. In a study conducted by Birol (2009) [14], it was shown that the cooling slope casting process produced superior non-dendritic of homogeneity microstructure feedstock for thixoforming. Based on the observation, the effect of pouring temperature and cooling slope length had little effect on the size and shape of the globules. α-Al crystals were generated once the molten alloy flowed over the cooling slope, where the temperature of the molten alloy decreased below the liquidus temperature [15]. These crystals were trapped in the following melt where they flowed continuously into the mould and solidified before becoming dendritic. A pouring temperature of 630°C with a cooling length of 400mm were optimal for feedstock preparation of Al-6Si-3Cu aluminium alloys to transform the fully dendritic structure into near spheroidal shape with a shape factor of 0.75±0.09 and a globule size of 34±4.6μm.

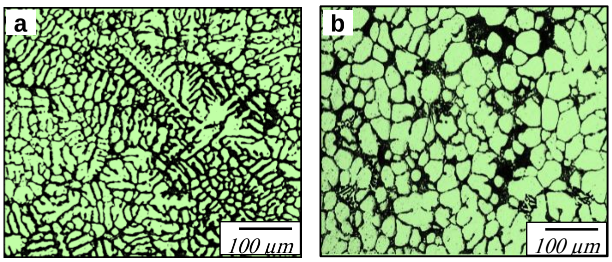

Figure 1 Microstructure of the (a) as-cast and (b) as-thixoformed Al-6Si-3Cu alloy

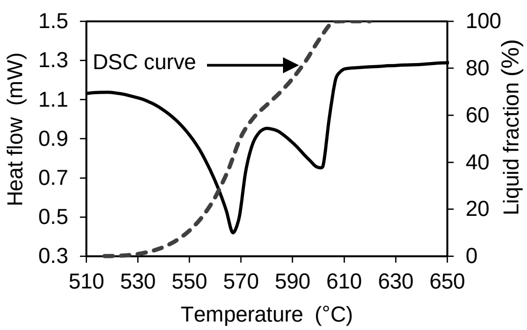

Figure 2 DSC heating flow and liquid fraction curves for Al-6Si-3Cu alloy

3.1 Partial Remelting ad Isothermal Holding

During partial remelting, the recrystallization occurred first. The rapid growths of new grains were replaced by strain-free ones. Meanwhile, liquid film started to surround the recrystallized grains and thickened continuously with longer holding time, which separated the adjacent grains and made it difficult for them to gather again. Consequently, the grains gradually spheroidized. Previously, it was reported that 30–50% fraction liquid was needed in the feedstock for thixoforming [15]. Samples that were sectioned from the cooling slope cast were then heated in an induction coil up to 571°C and were isothermally held at this temperature for 3 min before being quenched in water. Finer solid particles began to appear with longer isothermal holding time (5 min), and the net-like crystal boundary areas were taken over by liquid film completely due to the thickening of liquid films [16]. The average globule size of the slug before and after reheating was 34±4.6μm and 52±5.1μm respectively, implying substantial coarsening during isothermal holding at 571°C.

3.2 Thixoforming and Microstructure Analysis

Figure 3 presents the optical micrographs of the thixoformed sample showing homogenous distribution of solid globules in the liquid matrix. EDX analysis revealed that the composition of the globules consisted of Al and a very small amount of Cu. Surprisingly, the results of the SEM-EDX analyses of the thixoformed Al-6Si-3Cu showed that all elements were well distributed in the sample (Figure 4).

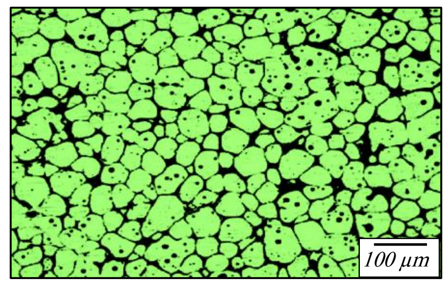

Figure 3 Microstructure along the length of the thixoformed Al-6Si-3Cu alloy

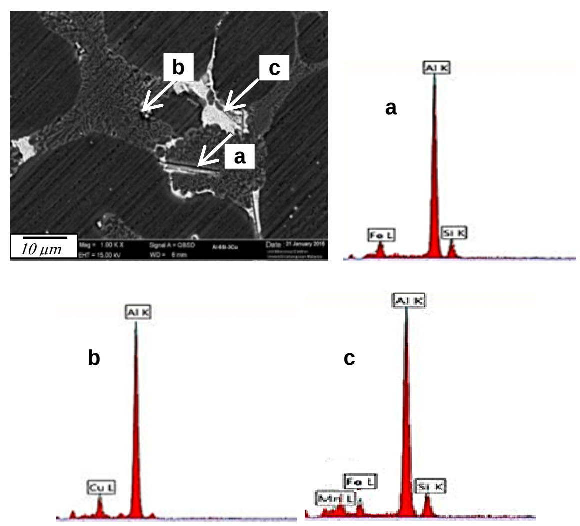

Figure 4 SEM micrograph of thixoformed Al-6Si-3Cu and corresponding EDX signals for (a) β -Al_5FeSi, (b) Al_2Cu and (c) $Al_{15}(Mn,Fe)_3Si$

Cu had homogenous distribution in the structure. EDX also shows that α-Al grain structure had globular form, and Al–Si eutectic structure was quite fine. β-Al_5FeSi in Al-6Si-3Cu alloys appeared as needle-shaped phase in its microstructure and was responsible for deteriorating the mechanical properties of the alloy[17,18]. As seen from Figure 5, the XRD analysis revealed the presence of β-Al_5Fesi

and Al_2Cu phases in addition to Al and Si in the alloys.

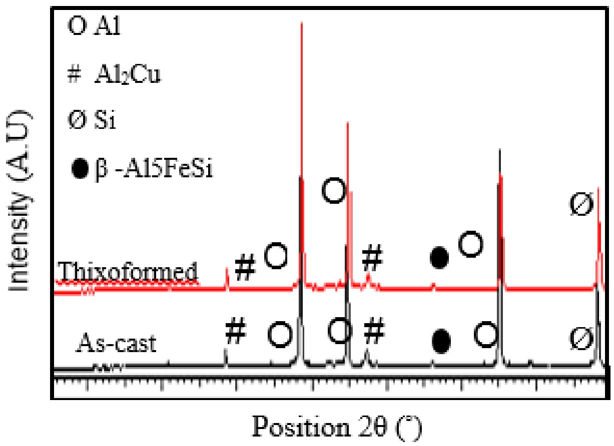

Figure 5 XRD patterns of the as-cast and as-thixoformed

3.3 Mechanical Properties

A positive correlation was found between the results of the tensile and hardness tests, and also supported by the microstructure images, where the spheroidize microstructure ensured that the bonding between the grains was stronger than the dendrite microstructure. Figure 6 showed that the hardness of as-cast Al-6Si-3Cu alloy was 89.7±4.4HV and increased to 104.1±2.7HV in the thixoformed sample. The increased hardness of the thixoformed samples was due to the low porosity and fine size of the a-Al globules in the sample. However, the needle-like morphology of β-Al_5FeSi in as-cast intermetallic led to the decrease in ultimate tensile strength and elongation of the aluminium alloys [19, 20].

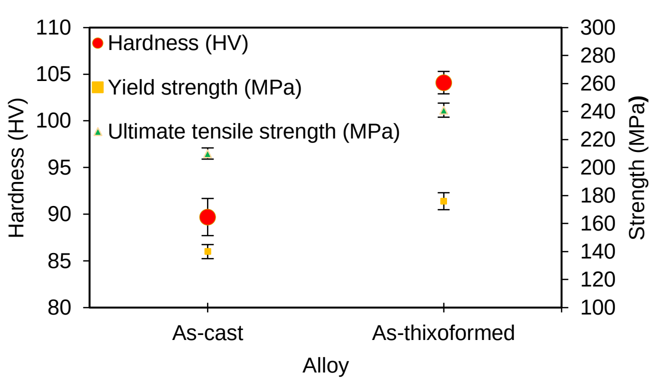

Figure 6 Hardness, yields strength, and ultimate tensile strength of as-cast and thixoformed

Figure 6 also presents the ultimate tensile strength and yield strength results of as-cast and as-thixoformed samples. The yield strength of as-cast alloy was 140±4.5 MPa and increased to 176±3.3 MPa in thixoformed sample while the ultimate tensile strength of as-cast alloy was 210±3.5 MPa and increased to 241±3.1 MPa in thixoformed alloy. Figure 7 shows an increase in elongation to fracture from 2% in as-cast alloy to 3.2% in thixoformed alloy. The improvement in mechanical properties was due to the effect of thixoforming, which helped to spheroidize the microstructure and improved the bonding between α-Al globules.

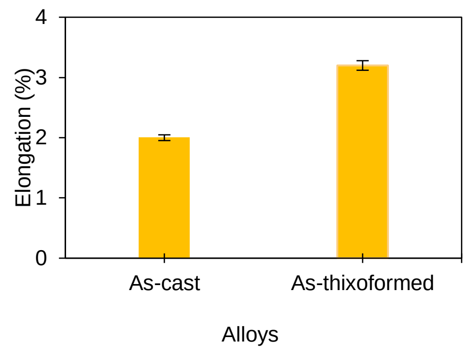

Figure 7 Elongation of as-cast and as-thixoformed alloy

3.4 Fracture Surface Analysis

Figure 8 presents the SEM images of the fracture surfaces obtained from the tensile-fractured samples of as-cast and as-thixoformed samples. As observed in the fractographs, the fracture of as-cast sample was brittle fracture, while the as-thixoformed exhibited ductile fracture. As-cast sample exhibited fracture on long Si particles (see arrow in Figure 8a), while thixoformed samples exhibited fine and well-distributed dimple fracture (see arrow at Figure 8b).

The experimental results confirmed that Fe-rich intermetallics significantly affected the mechanical properties of Al–Si-Cu alloys as shown in Figure 4. Heating the alloys to semi-solid range accelerated the globulation of dendritic α-Al phase and also the formation of uniformly distributed Fe-containing intermetallic compounds. These iron-rich intermetallic compounds led to early fractures by creating notch effects during the tensile test [21-23]. Higher iron concentration in the alloy leads to significant decrease in elongation [5].

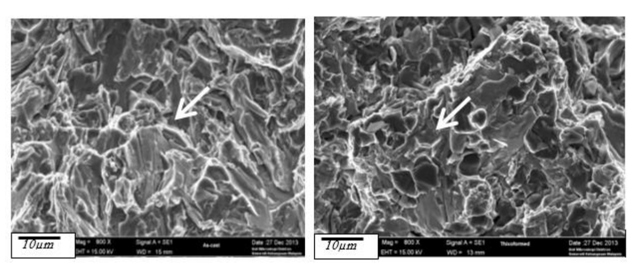

Figure 8 SEM fractographs acquired from the Al-6Si-3Cu alloy (a) as-cast and (b) as-thixoformed

4.0 CONCLUSION

In this work, the effect of thixofmring on the microstructure and mechanical properties of Al-6%Si-3% Cu alloy was investigated and DSC was employed to estimate the pouring temperature and the liquid profile within the semisolid transition range. The experimental results revealed that the cooling slope casting able to change the dendrite microstructure to near-spherical microstructure before thixoforming. The alloy that was thixoformed attained a hardness level as high as 104.1±2.7 HV while the ultimate tensile strength and yield strength were 241 ± 3.1 MPa and 176± 3.3 MPa respectively. The elongation to fracture of the thixoformed sample was also increased from 2.0±0.9% in as-cast to 3.2±0.5% in thixoformed sample. The fracture surface observed by SEM showed a cleavage fracture in as-cast sample whereas mix mode fracture (combination of dimple and cleavage) was observed in thixoformed sample.

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