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MICROSTRUCTURAL INVESTIGATION AND MECHANICAL PROPERTIES OF THIXOFORMED AL-6SI-XCU-0.3MG ALLOYS

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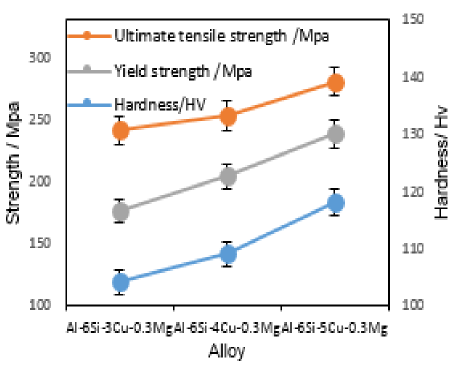
Graphical abstract



Abstract

In this study, the effect of different amounts of copper (CU) on the microstructure and mechanical properties of thixoformed Al-6Si-xCu-0.3Mg (x= 3, 4 and 5, mass fraction, %) were investigated. The alloys were prepared via cooling slope casting technique, before there were thixoformed using compression press. All of the alloys were then characterized using optical microscope (OM), scanning electron microscope (SEM) and energy dispersive X-ray (EDX). The results obtained revealed that cooling slope casting produced a non-dendritic microstructure and the intermetallic phase in the thixoformed samples was refined and evenly distributed. The results also revealed that as the Cu content in the alloy increases, the hardness and tensile strength of the thixoformed alloys also increase. The hardness of thixoformed Al-6Si-3Cu was 104.1 HV while the hardness of Al-6Si-5Cu alloy was increased to 118.2 HV. The ultimate tensile strength, yield strength and elongation to fracture of the thixoformed alloy which contained 3wt.% Cu were 241 MPa, 176 MPa and 3.2% respectively. The ultimate tensile strength, yield strength and elongation to fracture of the alloy that contained 6wt.% of Cu were 280 MPa, 238 MPa and 1.2% respectively. The fracture surface of the tensile sample with lower Cu content exhibited dimple rupture while higher Cu content showed a cleavage fracture.

Keywords: Aluminium alloys, cooling slope casting, thixoforming, mechanical properties, fracture behaviour

1.0 INTRODUCTION

Semi-solid metal processing is also known as thixoforming, a technology that involves the formation of metal alloy between solidus and liquidus temperatures. Thixoforming process offers more benefits compared to conventional casting process, especially in producing a near net shape product. The products produced by this technique offer high-quality parts at reasonable price and also exhibit better mechanical properties compared to conventional casting [1, 2]. This is due to the globular morphology of a-Al and the intermetallic phase distributed homogeneously with very low porosity formed in the sample during the solidification process. For semi-solid metal forming to be effective, a globular microstructure with a suitable liquid content is a must. The viscosity of the material will decrease and the material will behave like liquid as the near globular particles move freely when shear force is applied. On the other hand, in conventional casting, when the shear force is applied on dendritic microstructure, the liquid is blocked between the dendrite arms and it cannot move easily, hence increases its viscosity [2].

Other benefits offered by this technology are extending die life due to low thermal shock and gives more laminar cavity fill which could decrease the gas entrapment [3, 4].

Cooling slope casting is one of the techniques that is widely used to produce a non-dendritic microstructure feedstock for thixoforming [5, 6]. In this process, molten alloy is poured into a cooling slope plate and subsequently solidified in a die [7, 8]. The microstructure of the feedstock depends on various parameters such as cooling slope length, cooling slope angle, pouring temperature, incline plate material, and mould material [6].

Aluminium alloy is widely known and it is used in many industries; particularly in the automotive industry and mechanical construction. These days, aluminium alloy is preferred to be used in engine block production for vehicles instead of cast iron because of its light weight which can reduce the fuel consumption [4]. Cu and Mg are usually added to increase the mechanical properties of cast Al-Si alloy. Although there are a report on the effect of Cu content in Al-Si alloys, but it was mainly for conventional casting process. Therefore, this work investigated the effects of Cu contents (3wt.% -5 wt.%) on the microstructure and mechanical properties of Al-6Si-Cu alloy processed by thixoformed processing. Mechanical test is also performed on each alloy and the results obtained are compared and discussed.

2.0 METHODOLOGY

The type of alloy used in this work is Al-6Si-xCu-0.3Mg alloy, where x is 3, 4, and 5 mass fractions(%). These alloys were prepared using conventional casting process. X-ray fluorescence (XRF) technique was used to determine the chemical composition of the alloys while differential scanning calorimetry (DSC) was used to estimate the liquid temperature and liquid fraction profile within the semi-solid range of as-cast material.

Cooling slope casting was used to produce an aluminium billet for the thixoforming process. The apparatus needed for cooling slope casting technique includes resistance furnace, 90 mm wide incline plate, and stainless steel mould. A pouring temperature of 630°C and 400 mm cooling length was selected in this process [8]. 1 kg of each alloy was melted and superheated using a resistance furnace that was set at 700°C and then was brought down to a pouring temperature of 630°C before it was poured onto the surface of the plate. The tilt angle of the slope plate was 60° and the plate was cooled with water to increase the nucleation rate of the solid particles. A cylindrical stainless steel mould preheated at 160°C was used to collect the melted alloy.

Thixoformed process was performed using a hydraulic cylinder press that provides 20kN load and the maximum ram speed was 85 mm/s. A high-frequency induction coil (80kHz, 35 kW) was placed under the die and the K-type thermocouple was used to monitor the temperature. The slug was placed on the ram inside the induction coil and it was rapidly heated at a rate of 130°C/min to prevent undesirable grain growth. Thixoforming was performed at 50% liquid content for all samples.

The microstructure of each alloy were examined by Olympus optical microscope (OM) and the various phases of the samples were identified using Carl Zeiss (EvoMa10) scanning electron microscope (SEM) equipped with energy dispersive X-ray (EDX) spectroscopy. The samples for OM and SEM were prepared by applying the standard technique of grinding using silicon carbide abrasive paper and then the samples were polished with LECO microid diamond compound. After that, the samples were etched for 20 seconds with Keller's reagent.

The hardness measurement was performed using a Vickers hardness tester after imposing a load of 10 kg for 10 seconds. At least 10 measurements were taken to obtain the Vickers hardness value.

Tensile test was carried out using a 100kN Zwick Roell Universal Testing Machine (UTM) at room temperature. For each group, three samples were tested to obtain reliable tensile test results. The elongation value was measured using an extensometer that was placed on the gauge length. Yield stress was based on 0.2% plastic strain offset. The fracture surface of the tensile samples was investigated using Carl Zeiss SEM.

3.0 RESULT AND DISCUSSION

3.1 Cooling Slope Casting

The curves of heat flow versus temperature for each alloy is shown in Figure 1. It was used to determine the liquid fraction and temperature of the alloys before thixoforming. Figure 2 shows the optical micrographs of the alloys after cooling slope casting technique was applied. The cooling slope casting process produced a non-dendritic feedstock for the thixoformed samples. The α(Al) dendritic microstructure that usually exists in conventional casting was almost replaced by the α(Al) globule and rosettes in the cooling slope casting. A pouring temperature of 630°C and 400mm cooling slope length, slightly affected the size and shape of the globules. During the cooling slope casting process, the temperature of the molten alloys decreased below the liquidus temperature as it flowed over the cooling slope plate, then it generated α(Al) crystals which were detached from the slope [5]. After that, the crystals were trapped in the following melt in which they flowed continuously into the heating mould and solidified before it became dendritic.

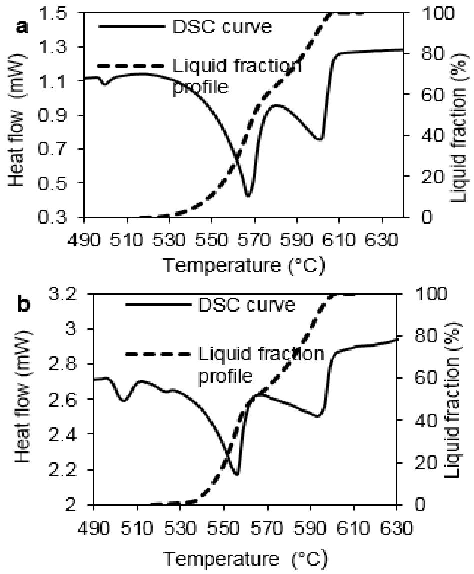


Figure 1 DSC curves and liquid fraction profile for (a) Al-6Si-3Cu-0.3Mg, (b) Al-6Si-5Cu-0.3Mg

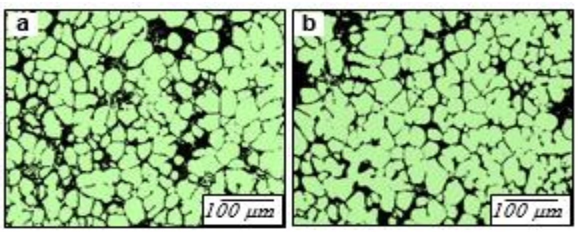


Figure 2 Optical micrographs of the alloys after cooling slope casting (a) Al-6Si-3Cu-0.3Mg and (b) Al-6Si-5Cu-0.3Mg

3.2 Thixoforming And Microstructure Analysis

The samples of cooling slope casting were machined and thixoformed after being heated in situ in a compression press. Previously, researchers have stated that 30-50% of liquid content are needed during thixoforming process [9-11]. In this case, 50% of liquid fraction was selected for thixoforming to prevent uneven eutectic phase melting. Figure 3 displayed the microstructure of alloys after thixoforming process. It was observed that the α(Al) globule distributed uniformly and no porosities were spotted.

By comparing a microstructure of cooling slope casting at Figure 2 with Figure 3, the microstructure of thixoformed samples have smaller α(Al) phase due to the heating rate used in thixoforming in which it helps in reducing the size of α(Al) globules. The globule size of each alloy illustrated in Figure 4 concluded that 3% of Cu did not give a major effect on the refining of α(Al) globules size.

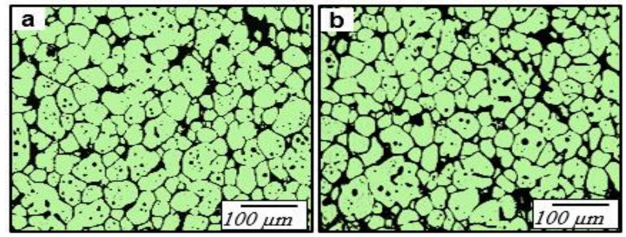


Figure 3 Microstructure of thixoformed of (a) Al-6Si-3Cu-).3 Mg and (b) Al-6Si-5Cu-0.3Mg

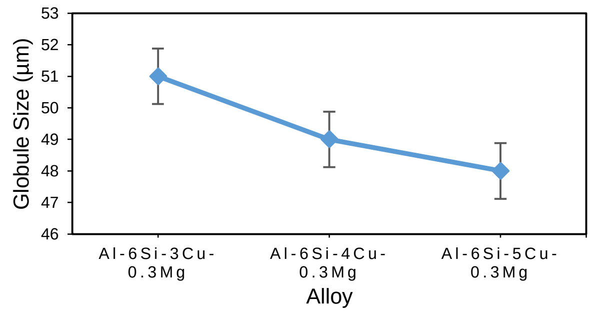


Figure 4 Globule size of thixoformed alloys at difference Cu content

The SEM images of thixoformed Al-6Si-3Cu-0.3Mg and Al-6Si-4Cu-0.3Mg are shown in Figure 5. There were a small amount of Si, Cu, Mg, and Fe elements in the Al matrix. These elements gathered in the eutectic phase at the grain boundaries. It was verified that the bright phase in the SEM images as pointed at point *c* represents Cu phase and a needle-like dark colour particle at point *a* represents Fe intermetallic compound. Cu phase distributed evenly at the grain boundaries between globules and this could improve the mechanical properties. However, the needle-like Fe intermetallic could reduce the tensile properties in which cracks will easily propagate within this region [12, 13].

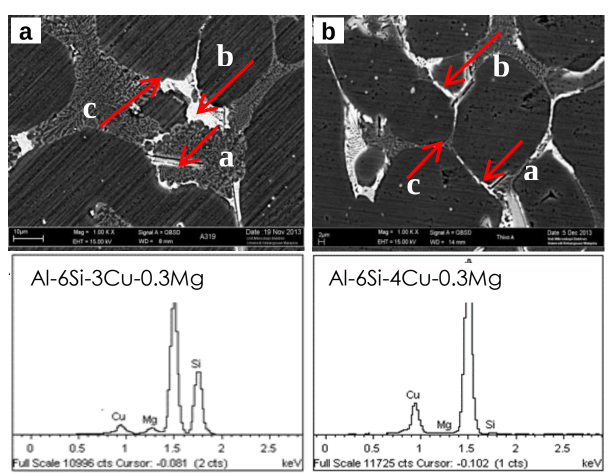


Figure 5 SEM-EDX image of thixoformed (a) Al-6Si-3Cu-0.3Mg and (b) Al-6Si-4Cu-0.3Mg (arrow a: β-Al_5FeSi; b: $Al_5Cu_2Mg_8Si_5$ and c: Al_2Cu)

3.3 Mechanical Properties

The hardness values of each thixoformed alloy (3wt%, 4wt%, and 5wt%) were interpreted in Figure 6. Some of the alloying elements melted into the α(Al) matrix during the thixoforming process and generated solid solution strengthening [14]. The amount of solid strengthening depends on the number of solute atoms in the α(Al) matrix which is influenced by the Cu content in the aluminium alloys [15]. Hence, it can be seen in the graph that increasing the Cu content may increase the hardness of aluminium alloys. The hardness value increased from 104.1 HV for Al-6Si-3Cu-0.3Mg to 118.2 HV for Al-6Si-5Cu-0.3Mg alloys.

3.4 Tensile Properties

Based on the results obtained, the ultimate tensile strength (UTS) and yield strength (YS) increased as the Cu content in the alloys increased. The results for tensile strength with different Cu content in thixoformed alloys were also illustrated in Figure 6. According to Anasyida *et al*. [16], adding some minor alloying element such as Cu, Mg, and Zn could improve the quality of an aluminium alloy, thus improved the mechanical properties of the alloys. For the thixoformed Al-6Si-3Cu-0.3Mg, the UTS and YS were 241 MPa and 176 MPa. The strength increased to 280 MPa and 238 MPa after adding more Cu content in the alloy.

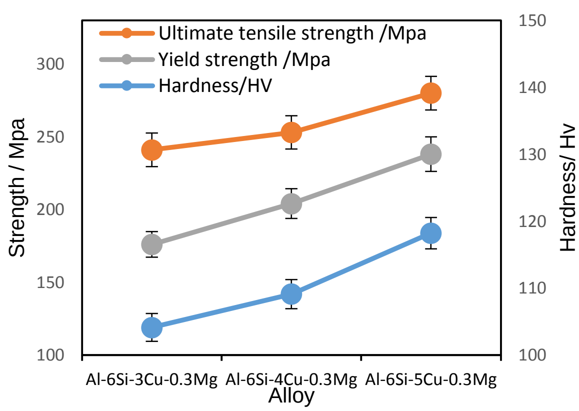


Figure 6 Comparison of hardness (HV), ultimate tensile strength (MPa) and yield strength (MPa) of thixoformed alloys at different Cu content

Figure 7 shows the comparison of the elongation before the fracture occurred in each alloy. It was noted that the elongation of the thixoformed samples was reduced because of the ductility of a material decreased as the tensile strength increased. For the thixoformed samples, the elongation for Al-6Si-3Cu-0.3Mg was 3.2% and it reduced to 2.8% and 1.2% for Al-6Si-4Cu-0.3Mg and Al-6Si-5Cu-0.3Mg respectively. From the observation, the ductility of the alloys was reduced as the Cu content increased. It was discovered that uniformity of microstructure could lead to the improvement of mechanical properties of aluminium alloys [17].

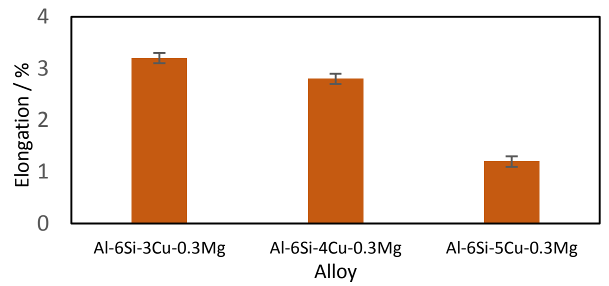


Figure 7 Comparison of the elongation of thixoformed alloys at different Cu content

3.5 Fracture Surface Analysis

The surface of tensile fracture in the samples was then characterized using SEM to determine the type of fracture. Figure 8 shows the SEM fractographs of thixoformed samples for 3, 4, and 5wt. %. It can be seen that the thixoformed Al-6Si-4Cu-0.3Mg and Al-6Si-5Cu-0.3Mg showed a mix mod fracture because there were some dimple and cleavage structures as pointed in Figure 8b and 8c. On the other hand, the thixoformed aluminium alloys that contained 3 wt. % of Cu exhibited ductile fracture since several voids were found in the sample as shown in Figure 8a.

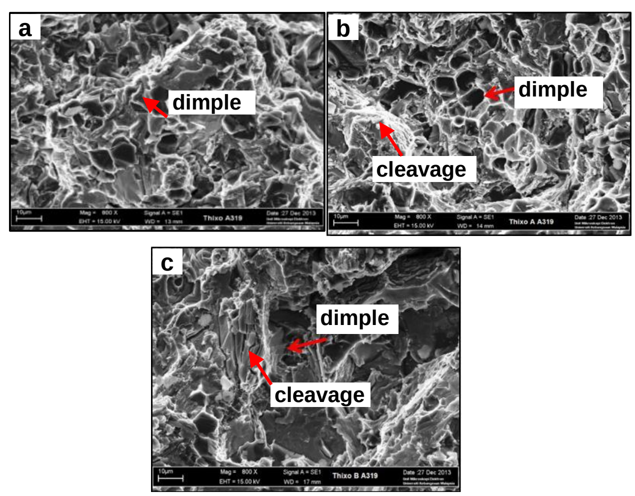


Figure 8 SEM fractograph of thixoformed samples (a) Al-6Si-3Cu-0.3Mg, (b) Al-6Si-4Cu-0.3Mg and (c) Al-6Si-5Cu-0.3Mg

4.0 CONCLUSION

Thixoformig is a vital process in improving the mechanical properties, especially the ultimate tensile strength, yield strength and elongation to fracture. This is due to the changes in the Si particles morphology, such as the particle size an distribution, caused by thixoforming. With increasing Cu content, the hardness, ultimate tensile strength and yield strength increased while the elongation to fracture is reduced. The alloy hardness of the alloy with 3wt.% Cu content was 104 HV and increased to 118.2 HV in the alloy that content 5wt. % of Cu. The highest ultimate tensile strength and yield strength exhibited by the alloy with the highest Cu contained (5wt. %) were 280 MPa and 238 MPa respectively, but the elongation reduced to 1.2 %. The fracture surface of alloy with 3wt.% Cu content showed a dimple rupture while for the sample with highest Cu content (5wt. %) showed a cleavage fracture.

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