MICROSTRUCTURAL ANALYSIS AND MECHANICAL PROPERTIES OF LM6 ALLOY PROCESSED BY COOLING SLOPE CASTING

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ABSTRACT: In this study, LM6 aluminium alloy was processed by semisolid metal processing via cooling slope casting technique. The primary objective of this study was to investigate the most effective cooling slope parameter that affect the globulization of LM6 alloy. The mechanical properties of the alloy after the process were also discussed. The microstructural characterization was done by optical microscope (OM) while for mechanical test, tensile test and hardness test were performed. Some of the cooling slope samples were subjected to T6 heat treatment and the effect of heat treatment was discussed. The results obtained revealed that cooling slope casting produce a non-dendritic structures compared to conventional casting. The results also revealed that at pouring temperature of 660°C and cooling slope length of 300 mm, the LM6 alloy exhibits a spherical microstructural feature due to all dendritic structures being replaced by α-Al globule and rosette. For mechanical properties, it showed that tensile strength and hardness value increased significantly when processed by cooling slope casting as compared to conventional casting. After T6 heat treatment the tensile strength and Vickers hardness increased by about 23% and 7% respectively for a sample poured at 660°C and 300 mm slope length in cooling slope casting.

KEYWORDS: *Semisolid metal processing, cooling slope casting, aluminium alloy, T6 heat treatment*

1.0 INTRODUCTION

Semi solid metal processing also known as thixoforming, is a technology that involves the formation of metal alloy between solidus and liquidus temperatures [1, 2]. Semisolid processing of metallic alloys and composites has been acknowledged as an innovative manufacturing method based on its thixotropic properties. In thixotropic condition, an alloy decreases in viscosity if it is sheared but it will thicken again if it is allowed to stand. This process requires uniform heating and partial remelting of the alloy slug to obtain a homogeneous consistency throughout. The Cooling Slope (CS) casting is a process to produce a feedstock for semisolid metal processing which engages with simple equipment and employs low operating cost. Cooling slope method is made by a simple process of pouring the lightly superheated melt down a cooling slope and consequent solidification in a mould. Nowadays, semisolid metal processing or thixoforming is popular among manufacturers and is widely used in automotive applications. The products produced by this technique offer high-quality parts at reasonable price and also exhibit better mechanical properties compared to conventional casting [3, 4]. This is due to the globular morphology of α-Al and intermetallic phase which is distributed homogeneously and low porosity produced in the sample. Other than that, this technique could prolong its die lifetime due to low thermal shock and offers more laminar cavity fill which could reduce the gas entrapped [5]. Generally, in this process melted alloys are poured to a cooling slope plate and consequently solidified in a die [6, 7]. The final microstructure of the cooling slope cast samples depends on various parameters such as cooling slope length, cooling slope angle, pouring temperature, incline plate material, and mould material.

Aluminium alloy is very popular and is commonly being used in many industries; mainly in automotive industry and mechanical construction. Today, aluminium alloy is chosen to be used in engine block production for vehicles instead of cast iron as it is light in weight which can reduce fuel consumption [8]. LM6 alloy is an eutectic alloy having lowest melting point that can be seen from the Al–Si phase diagram. The main composition of LM6 is about 85.95wt. % of aluminium, 11wt. % to 13wt. % of silicon, 0.6wt.% of iron and 0.5wt.% of Mn [9]. The phase present in aluminium alloys are dendritic morphology of α-Al, circular shape of blocky silicon phase and sharp edges plate shaped that refers to eutectic silicon [10].

In 2001, Haga et al. [6] investigated the effect of pouring temperature, cooling slope length and material used for mould on the morphology of the primary crystal. In this investigation, pouring temperatures at 640°C, 660°C, 680°C and 720°C, cooling slope lengths of 100 mm and 300 mm and the metal mold (with and without insulator) were used. It was found that the cooling rate of the ingot in the mould plays an important role in making primary crystal globular when the ingot was remelted. In 2014, Salleh et al. [7] investigated the effect of cooling slope parameters (pouring temperature and cooling slope length) on A319 aluminium alloy. They found that pouring temperature at 630 °C and cooling slope length of 400 mm produce an ideal microstructure and suitable for thixoforming.

Although the effect of cooling slope casting on the microstructure of aluminium alloys has been regularly reported, the information about the effect of cooling slope casting parameters on mechanical properties of LM6 is still lacking. Hence in this work, the cooling slope casting parameters such as pouring temperature and slope length that affect the globulization of the primary crystal in LM 6 alloy were investigated. Some of the cooling slopes casting samples were subjected to T6 heat treatment which consists of solute solutioning, quenching and artificial ageing. Microstructural characterization and mechanical properties before and after T6 heat treatment were compared and discussed.

2.0 EXPERIMENTAL PROCEDURE

2.1 Cooling slope casting

The cooling slope inclined plate was made by stainless steel having 90mm width, with 60° tilt angle and slope lengths were marked at 200 mm, 300 mm and 400 mm. In cooling slope casting experiment, LM6 (10%Si, 1%Cu, 0.2%Mg, 1.0%Fe, 0.5%Mn and 0.2%Ti) ingot was superheated at a temperature above 700°C in the furnace. Pouring temperatures of 630°C, 640°C, 650°C and 660°C were selected in this experiment. The superheated LM6 was cooled down to its desired pouring temperature and than was poured onto the slope downward into a vertical stainless steel mould with a diameter of 25 mm and a height of 120 mm. The molten temperature was measured by using type-K thermocouple. The experiment was repeated at different pouring temperatures and slope lengths. The surface of cooling slope was coated with boron nitride to avoid the adhesion of melted alloy to the plate. In the case of conventional casting sample, the molten LM6 was poured directly into the same mould preheated at 120°C. Figure 1 shows the experimental setup for cooling slope casting apparatus.

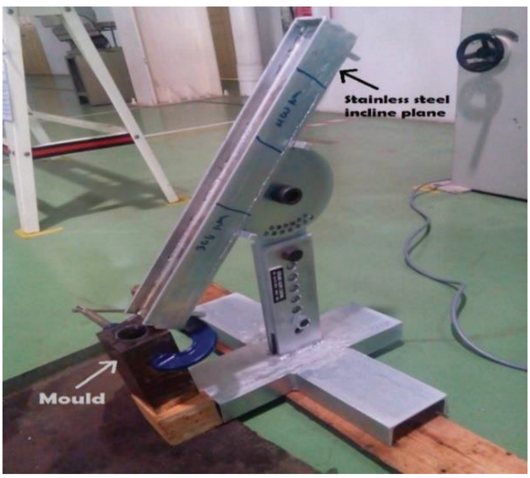

Figure 1: Cooling slope casting apparatus

2.2 T6 heat treatment

The cooling slope casting samples were subjected to the ASTM T6 heat treatment standard that consists of solute solutioning, quenching in water and followed by artifical ageing. This process was performed in a Nabertherm Controller B180 furnace equipped with a programmable temperature controller for both solution and aging heat treatment. The solution heat treatment was performed for 8 hours at a temperature of 530°C. The samples were then quenched in water at room temperature followed by aging process at 155°C for 3 hours.

2.3 Microstructural characterization

The microstructure of each sample was examined by using a Carl Zeiss optical microscope (OM). The samples were grinded using three types of silicon carbide abrasive paper (300, 800 and 1200 grit) and polished with microid diamond compound (3μm). The samples were then etched in Keller's agent for 15 seconds before being examined. Image analysis were done by calculating the shape factor (SF) and globule size (GS) of the α-Al phase in the sample. An Image-J was used to analyse the image. The shape factor and average grain size were determined by using the equations (1) and (2) respectively [11]:

$$Shape\ factor = \frac{4\pi A}{P^2} \tag{1}$$

$$Average\ grain\ size = \frac{[\sum 2(\frac{Ai}{\pi})^{1/2}]}{N} \tag{2}$$

Where p is the perimeter and A is the area of the particle and N is the total number of particles in each image.

2.4 Hardness test

Hardness testing was carried out on a Vickers hardness tester imposing a load of 100 N for 10 seconds. The obtained ingots were sectioned transversely 40 mm from the bottom surface and were ground with silicon carbide paper, polished and etched in Keller's agent for 20 s. The Vickers hardness value was obtained using an average of at least 10 measurements.

2.5 Tensile test

Cylindrical tensile specimens with typical gauge dimensions of 20 mm in length were machined from the as-cast and cooling slope samples according to the ASTM: E8M standard. The tensile tests were performed at room temperature using a 100 kN universal testing machine (UTM). An extensometer was placed on the gauge length and the total elongation values were measured until fracture. The yield stress was based on a 0.2% plastic strain offset.

3.0 RESULT AND DISCUSSION

3.1 Cooling slope casting

Figure 2 shows the optical micrograph of as-cast aluminium alloy using permanent mould casting at temperature 700°C. It was observed that for as-cast sample in Figure 2, dendritic structures were shown and very fine interdendritic of Al eutectic were distributed all over the sample. Figure 3 shows the optical micrograph of the alloy after a cooling slope casting technique was applied at a temperature of 660°C. The α(Al) dendritic microstructure found in conventional casting was almost replaced by the α(Al) globule and rosettes after cooling slope casting. As the molten alloy flowed over the cooling slope plate, its temperature dropped below the liquidus temperature hence generating the α(Al) crystals which were detached from the slope. The crystals were trapped in the following melt where they flowed from the cooling slope plate into the mould and solidified in the mould [12].

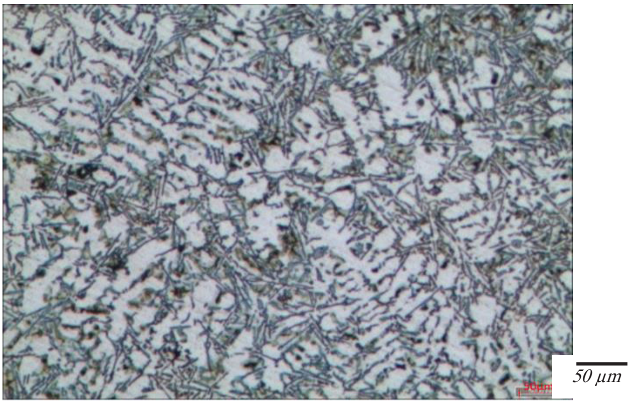

Figure 2: Microstructure of permanent mould cast alloy at 700°C

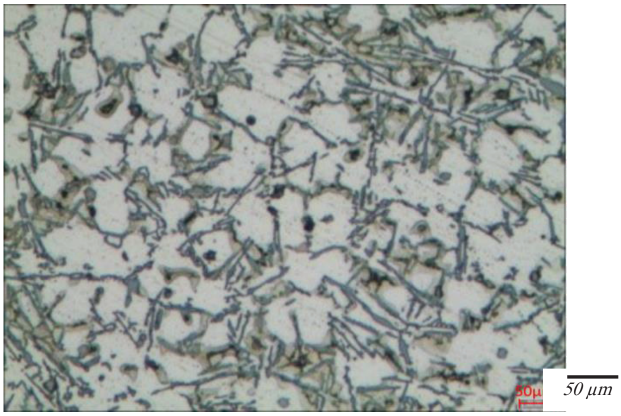

Figure 3: Microstructure of cooling slope cast alloy at 660°C

Figures 4-7 show the microstructures of sample poured at different temperatures (630°C, 640°C, 650°C and 660°C), and different cooling slope lengths (200 mm, 300 mm and 400 mm). From Figures 4-7, it was observed that increasing the pouring temperature resulted in changing of α-Al features from dendritic to globule and rosettes. The images of the microstructure were analysed by calculating the shape factor and globule size. From the experiment, it was found that pouring temperature of 660°C with a cooling slope length of 300mm exhibit higher shape factor (about 0.7) and the smallest globule size (about 38 μm) when compared to other parameters. It can be concluded that pouring temperature of 660°C and cooling slope length of 300 mm is optimal for cooling slope LM6 cast aluminium alloy.

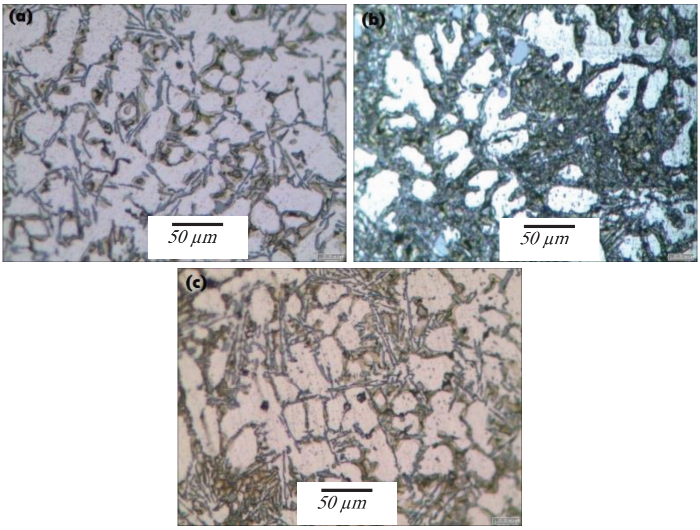

Figure 4: Microstructure of cooling slope cast alloy at 630°C with cooling slope length of (a) 200 mm, (b) 300 mm and (c) 400 mm.

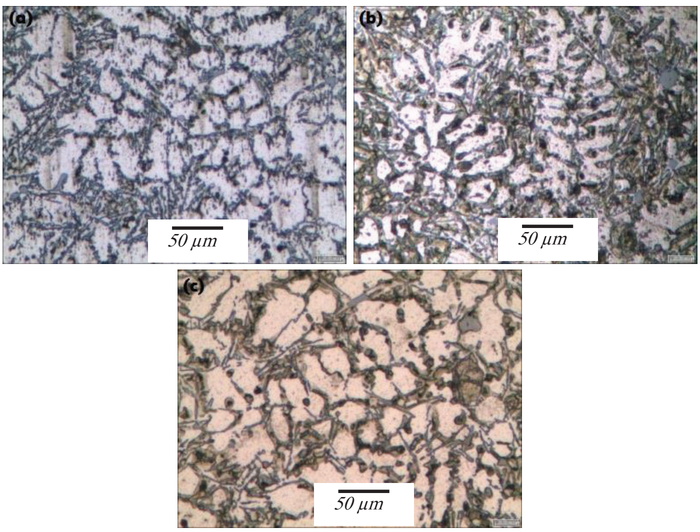

Figure 5: Microstructure of cooling slope cast alloy at 640°C with cooling slope length of (a) 200 mm, (b) 300 mm and (c) 400 mm.

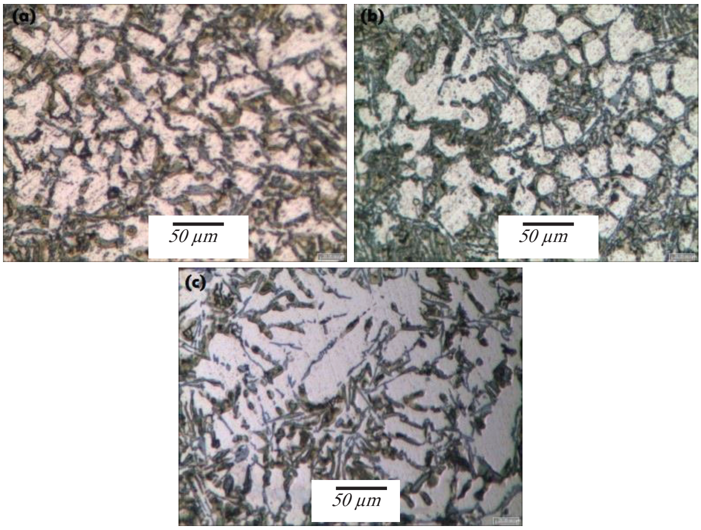

Figure 6: Microstructure of cooling slope cast alloy at 650°C with cooling slope length of (a) 200 mm, (b) 300 mm and (c) 400 mm.

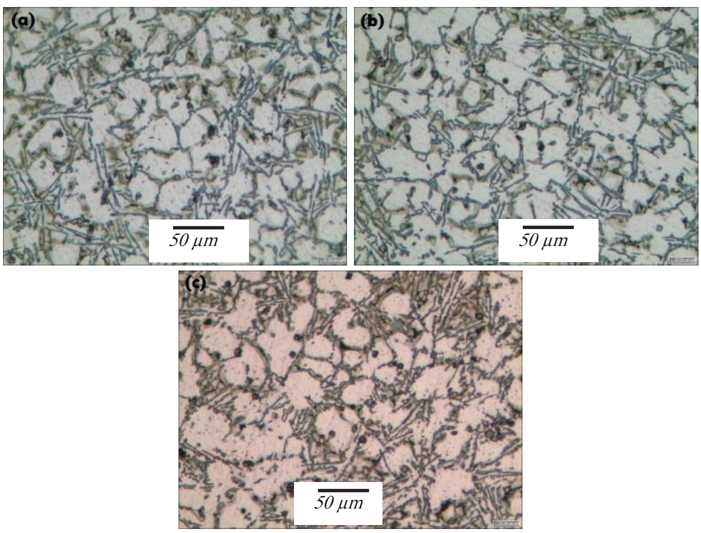

Figure 7: Microstructure of cooling slope cast alloy at 660°C with cooling slope length of (a) 200 mm, (b) 300 mm and (c) 400 mm.

3.2 T6 heat treatment

Figure 8 shows the microstructure of conventional cast alloy poured at 700°C while Figure 9 shows a microstructure of cooling slope cast sample poured at 660°C. Both of the samples were treated with T6 heat treatment. It was observed that T6 heat treatment process helped to spheroidise the Si particles during solution treatment and developed an intra-granular contrast throughout aging process [13-14]. The microstructure of T6 cooling slope casting alloys displayed the dispersion of Si particles and intermetallic phase surrounding the α-Al and particle distribution was homogeneous. In Figure 9, it shows that the α-Al was more spherical and exhibited smaller globular size compared to the microstructure in Figure 8, which displayed an uneven spherical shape throughout the sample. It is evident that the cooling slope casting helps to promote a good distribution of α-Al and intermetallic phases in LM6 aluminium alloy.

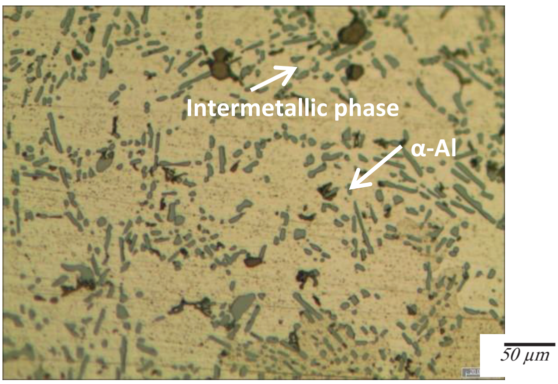

Figure 8: Microstructure of conventional cast alloy at 700°C after T6 heat treatment

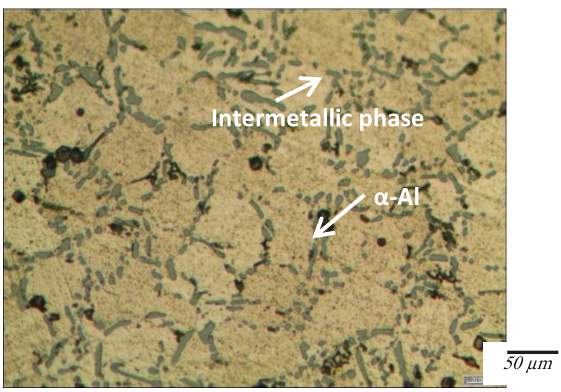

Figure 9: Microstructure of cooling slope cast alloy at 660°C after T6 heat treatment

3.2 Hardness properties

The hardness value of each samples were taken and interpreted in Figure 10. The conventional cast alloy gives the lowest hardness value about 70.83 HV. It was observed that the average hardness value of the alloy poured at 660°C in cooling slope casting with slope length 300 mm increased up to 78.77 HV from 70.83 HV in conventional casting. The increase of hardness value of cooling slope casting sample was caused by the formation of globular microstructure in the alloy and the α-Al particles became smaller and distributed homogenously all over the sample. The globular shape in the cooling slope sample occupied more eutectic phase compared to conventional cast sample.

The cooling slope sample with the highers value of Vickers hardness (refer to Figure 10) was choosen to undergo the T6 heat treatment. In this case, a sample with a pouring temperature of 660°C and cooling length of 300 mm was selected. After the T6 heat treatment, the hardness value obviously increased up to 92.34 HV which comprised about 17.2% increased when compared to the sample without heat treatment. During solution treatment, some alloying elements were dissolved into the α-Al matrix and solid solutioning strengthening generated. Moreover, the formation of an intermetallic phase that precipitated in α-Al globules during aging helps to increased the hardness of the alloy.

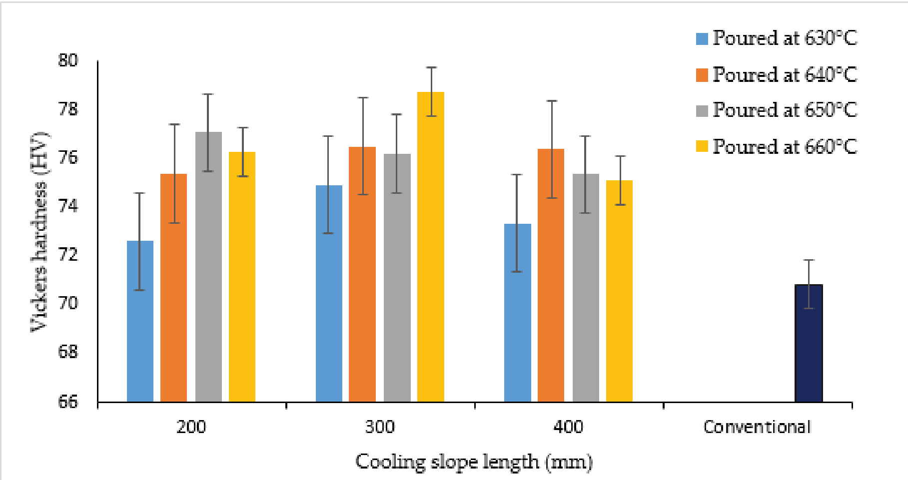

Figure 10: Vickers hardness of conventional cast alloy and cooling slope cast alloy at different pouring temperatures and slope lengths.

3.4 Tensile properties

The results of ultimate tensile strength and yield strength are illustrated in Figures 11 and 12. Based on the results obtained, it showed that the ultimate tensile strength (UTS) increased in a sample that processed by cooling slope casting. The ultimate tensile strength of conventional cast alloy is much lower than cooling slope cast alloy which is about 44 MPa. The ultimate tensile strength and yield strength of alloy poured at temperature 660°C and length of 300 mm in cooling slope casting technique exhibit the highest UTS value which was 166.34 MPa and 141 MPa respectively while the elongation before fracture is recorded as high as 2.8%. The results obtained in this work revealed that the mechanical properties of the alloy can be enhanced by the microstructure uniformity caused by the sphericity of α-Al, smaller grain size of α-Al and homogeneous distribution of intermetallic phases.

After T6 heat treatment, the tensile properties of the alloy increased considerably. The ultimate tensile strength and yield strength for cooling slope cast alloy poured at temperature 660°C with slope length of 300 mm achieved 240 MPa and 180 MPa respectively, while the elongation is 3.5%. The T6 heat treatment promoted an appreciable precipitation of Cu rich-phase (Al_2Cu), accounting for the strength exhibited by the alloy in the cooling slope T6. The Al_2Cu precipitates help to make a dislocation difficult thus increasing the tensile properties of the alloy.

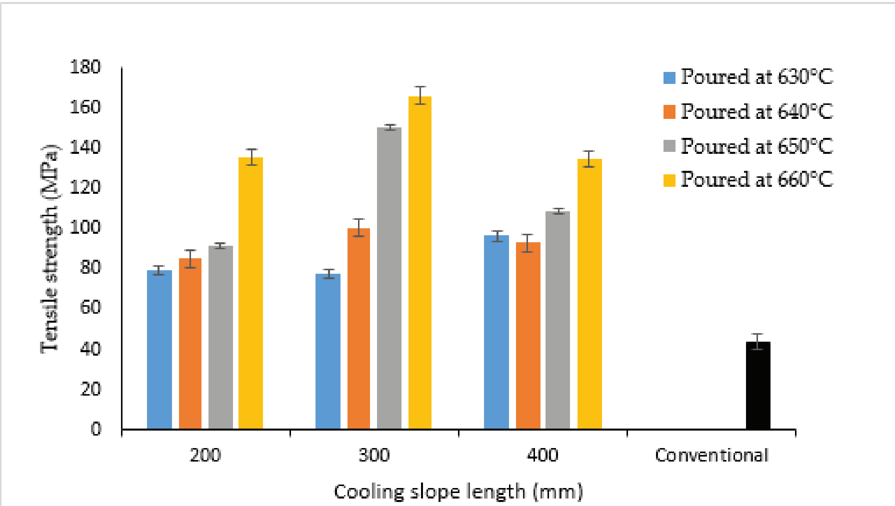

Figure 11: Ultimate tensile strength (UTS) of cooling slope casting and conventional casting

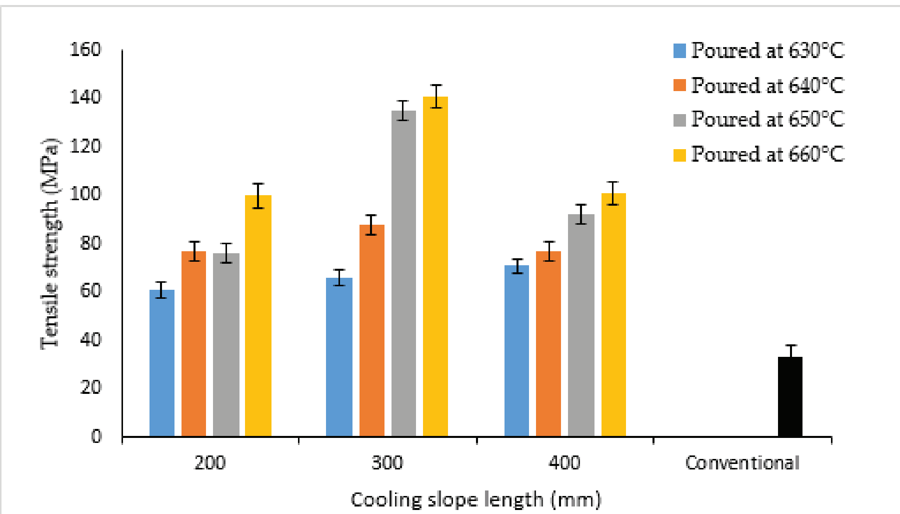

Figure 12: Yield strength of cooling slope casting and conventional casting

4.0 CONCLUSION

In this study, the influential parameters that affect the globulization of the primary crystal in LM6 alloy were investigated. The hardness and tensile properties of the alloy after cooling slope casting process and T6 heat treatment were compared and investigated. Some points were drawn as conclusion of this work.

I. It was found that cooling slope casting process poured at temperature 660°C and slope length of 300 mm was an optimum parameter for LM6 in producing a spherical microstructural feature since all dendritic structures were replaced by globule and rosette structure.
II. Cooling slope parameters such as pouring temperature and cooling slope length have a strong influence in the formation of a globular microstructure of LM6 aluminium alloy.
III. Smaller globular size of α-Al microstructure obtained in cooling slope sample improved its hardness properties as compared to conventional casting. Moreover, ultimate tensile strength (UTS) and yield strength (YS) value of cooling slope cast aluminium alloy were increased compared to the conventional cast due to the homogenous formation of α-Al phase in the samples.
IV. The hardness and mechanical properties of cooling slope alloy that were subjected to the T6 heat treatment increased considerably as compared to the non heat treated alloy.

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