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Effect of different Mg content on microstructure and mechanical properties of thixoformed Al-Si-Cu-Mg alloys

Mohd Shukor Salleh [1*], Ammar Abd Rahman [1], Raja Izamshah Raja Abdullah [1], Nurhadi Siswanto [2], Sivarao Subramonian [1]

[1] Fakulti Kejuruteraan Pembuatan, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, MALAYSIA.
[2] Department of Industrial and Systems Engineering, Institut Teknologi Sepuluh Nopember, INDONESIA.
*Corresponding author: shukor@utem.edu.my

KEYWORDS

Aluminium alloy
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Fracture behaviour

ABSTRACT

This study investigated the effect of Mg content on microstructure and mechanical properties of thixoformed Al-Si-Cu-Mg alloys. Two sets of alloys containing 1.0 and 1.5 wt.% Mg with non-dendritic structure were fabricated using the cooling slope casting technique. The samples were then analysed under energy dispersive X-ray spectroscopy, optical microscopy, and scanning electron microscopy. The thixoformed samples underwent mechanical testing, such as tensile and hardness tests. The results have shown that various types of intermetallic phases were formed in the alloys, which contributed to the enhancement of the mechanical properties of the thixoformed alloys. An increment of 1.5 wt.% Mg contributed to an increment towards the tensile strength. The T6 heat treatment on the alloys has also recorded noticeably better mechanical properties. The ultimate tensile strength (UTS), yield strength (YS) and elongation to fracture of the heat-treated sample with 1.0 wt.% Mg reached a 270 MPa, 230 MPa and 2.9%, respectively, whereas for the 1.5 wt.% Mg sample, the tensile strength (UTS), yield strength (YS) and elongation to fracture were increased to 320 MPa, 270 MPa and 2.5% respectively. The alloys exhibited a mix-mode fracture behavior, where cleavage and dimple fractures were seen clearly on the samples.

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1.0 INTRODUCTION

Thixoforming is a forming process which utilised a metal rheological behaviour during solidus and liquidus range temperature. This process involves a preparation of a non-dendritic feedstock of the alloys followed by reheating to semisolid temperature and then pressing in the die (Samad et al., 2021). This process uses a lower temperature compared with conventional casting and lower forming forces compared with conventional forging (Hanizam et al., 2020).

The material for thixoforming should possess a spheroidal structure distributed homogenously in a sample. Cooling slope (CS) casting is among the many techniques to produce non-dendritic microstructures tailored for thixoforming. This process involves pouring the slurry over the slope plate and then the nucleation which occurs on the plate will help to produce a fine and near globular of α-Al microstructure (Abdelgnei et al., 2020).

Mg is an important element in aluminium alloys as it can help to refine and increase the strength of the alloys. Basically, various phases, including Al_2Cu, Mg_2Si, $Al_{15}(Mn,Fe)_3Si_2$, β-Al_5FeSi, $Al_5Cu_2Mg_8Si_6$ and $Al_8Mg_3FeSi_6$ are formed under various conditions during shaping of the alloys. Tavitas et al. (2008) examined the effects of Sr and Mg elements on the strength of cast A319 alloy. Yıldırım and Özyürek (2013) investigated the effect of Mg content on the mechanical properties of cast A356 aluminium alloy.

Several literatures have detailed out the effect of Mg addition on conventional casting of aluminium alloys, but the information on the effect of thixoformed alloys with different Mg content was still very limited. Therefore, this study evaluated the influence of different Mg contents within a thixoformed Al–Si–Cu-Mg alloys on the microstructure and mechanical properties. Two alloys were fabricated using the cooling slope casting to get the nondendritic structure and then thixoformed using the hydraulic press. The samples microstructure and mechanical properties were also investigated after a T6 heat-treatment.

2.0 EXPERIMENTAL PROCEDURE

Al–5Si–Cu–xMg (x=1, 1.5 wt.%) were fabricated using a permanent mold casting. The alloys chemical composition shown in Table 1 was determined using an X-Ray fluorescence (XRF). The processing temperatures (i.e liquidus and solidus temperature) at 50% liquid in the alloys (Table 2) were estimated using a Differential scanning calorimetry (DSC). The alloys were heated at 700 °C in the induction furnace. The slurry was cooled to the pouring temperature (approximately at 650 °C) and then manually poured on a cooling plate surface and then, the sample was collected from the mould, which was preheated to 160 °C.

Thixoforming was carried out at 570°C and 575°C for Al-5Si-Cu-1.0Mg and Al-5Si-Cu-1.5Mg respectively and then the sanples were underwent the T6 heat treatment. The solution treatment was carried out for 8 hours at 530 °C followed by quenching in water and aging for 4 hours at 155 °C. After that, the aluminium samples were ground, polished and then etched by immersing the samples in the Keller's reagent for 15 seconds. For the microstructure evaluation, optical microscope and scanning microscope were used while a scanning electron microscope was used to identify the intermetallic phases within the alloy.

Tensile tests were carried out at room temperature using a 100 kN Universal Testing Machine. The samples were prepared following the ASTM-E8M standard for each group (i.e. as-cast, thixoformed and thixoformed with T6 heat treatment). Three samples were used in this testing to obtain a reliable data analysis. The yield stress used in this experiment was according to the 0.2% plastic strain offset.

Table 1: The chemical composition of the alloys (wt.%).

Alloy	**Si**	**Cu**	**Mg**	**Mn**	**Zn**	**Ni**	**Fe**	**Cr**	**Al**
Al-5Si-Cu-1.0Mg	5.14	0.73	1.17	0.12	0.31	0.06	0.23	0.03	Bal
Al-5Si-Cu-1.5Mg	5.21	0.78	1.45	0.10	0.46	0.03	0.18	0.03	Bal

Table 2: Solidus, liquidus and forming temperature of the alloys.

Alloy	**Solidus temperature (°C)**	**Liquidus temperature (°C)**	**Forming temperature (°C)**
Al-5Si-Cu-1.0Mg	535	635	575
Al-5Si-Cu-1.5Mg	540	630	570

3.0 RESULTS AND DISCUSSION

3.1 Cooling Slope (CS) Casting

The optical microstructures of the as-cast alloys Al–5Si–Cu–1.0Mg and Al–5Si–Cu–1.5Mg are shown in Figure 1 (a and b).

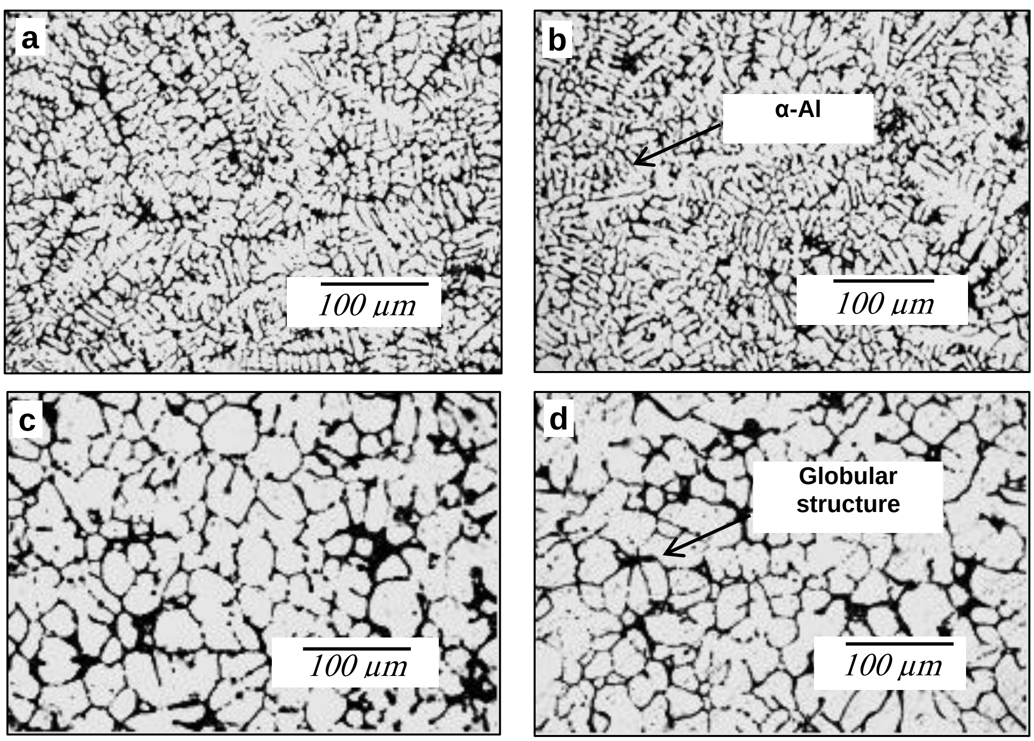


Figure 1: Microstructures of the alloys (a) as-cast Al-5Si-Cu-1.0Mg (b) as-cast Al-5Si-Cu-1.5Mg (c) CS Al-5Si-Cu-1.0Mg and (d) Al-5Si-Cu-1.5Mg.

The microstructural features of the alloys clearly showed that the α-Al dendrites were distributed homogenously in the sample. Figure 1 (c and d) shows the microstructures of the CS casting of Al–5Si–Cu–1.0Mg and Al–5Si–Cu–1.5Mg alloys. As shown in Figure 1 (c and d), α-Al demonstrated noticeable changes after CS casting because all of the α-Al microstructures were replaced by α-Al globules and rosette. This result can be attributed to the shear driven melt flow along the CS plate which influences the changes of the α-Al particles morphology. When the slurry was poured on the inclined plate, the temperature of the molten alloy dropped very fast, thereby generating new α-Al crystals along the plate (Arif et al., 2020) The melt that carries the crystals flowed continuously into a heating mould before leaving afterwards to cool and forming a non-dendritic structure. Non-dendritic structure is a highly important factor because it has a thixotropic behaviour which can be utilised during thixofoming.

3.2 THIXOFORMED SAMPLES MICROSTRUCTURE

Figure 2 shows the micrographs of the thixoformed samples. As observed in Figure 2, the α-Al globules were distributed homogenously throughout the sample. Si particles were observed between these globules. This finding can be described as the uniform distribution of the globules after the segregation of the liquid phase during thixoforming (Hanizam et al., 2020). Moreover, the size of the α-Al was coarser than that of the globules which was observed in CS casting. This observation can be explained by the reheating process, where the Si particles and α-Al structure deposited while melted Si eutectics rearranged during the 5 minutes holding time. Some of the phases, such as Mg_2Si and Al_2Cu, were observed embedded between the α-Al, which contributes to the improvement of the alloy's strength (Hanizam et al., 2020). Figure 2 also shows that some of the liquid (black dot) was entrapped in the α-Al globules. The black dot occurred when shear stress is applied to a dendritic structure during feedstock preparation. The entrapped liquid in the α-Al globules may reduce the thixotropic behaviour of the material when melted to a semisolid state. The thixotropic behavior is very important during thixoforming as it helps to fill up the mould during the forming process (Hashim et al, 2021). Furthermore, Mg addition helps refine the eutectic silicon as evidenced in the Al–5Si–Cu–1.5Mg alloy relative to that in the Al–5Si–Cu–1.0Mg alloy.

Figure 3 shows the heat-treated alloys under T6 condition micrographs. The T6 heat-treated alloys exhibited good dispersion of Si particles throughout the samples. The T6 heat treatment helps modify the eutectic Si particles during solid solution strengthening and develop an intragranular contrast during ageing. Some of the Si particles became coarser, and a small amount of Mg_2Si was precipitated between the α-Al globules during solution treatment at 530 °C. The thixoformed samples is then directly quenched in water and were aged at 155 °C for 4 hours. As shown in Figure 3, the aged samples demonstrated the precipitation of Mg_2Si and Al_2Cu phases in the metastable form, which is necessary in enhancing the mechanical properties. Figure 4 shows the SEM backscattered images of the thixoformed Al–5Si–Cu–1.0Mg alloy. Four intermetallic phases were identified within the alloys: Al_2Cu, Mg_2Si, π-$Al_9FeMg_3Si_5$ and $Al_5Cu_2Mg_8Si_5$. According to Wang et al., 2010, the π-$Al_9FeMg_3Si_5$ phase may reduce the mechanical properties of the alloys. This phenomenon is due to the sharp edge of the iron particles which provide stress in the aluminium structure (Jiang et al., 2017).

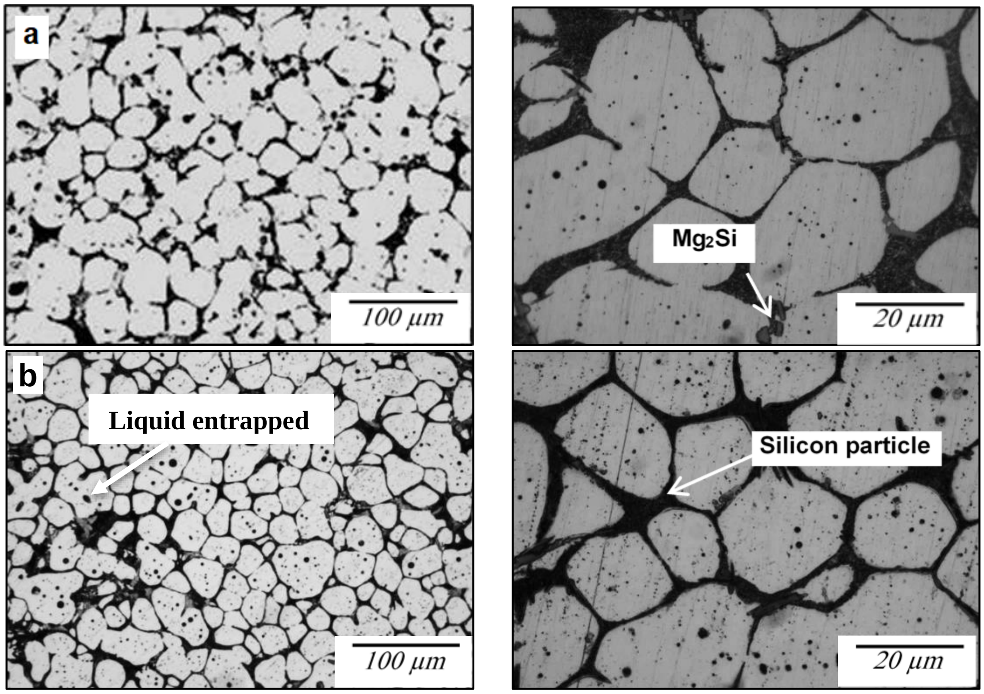
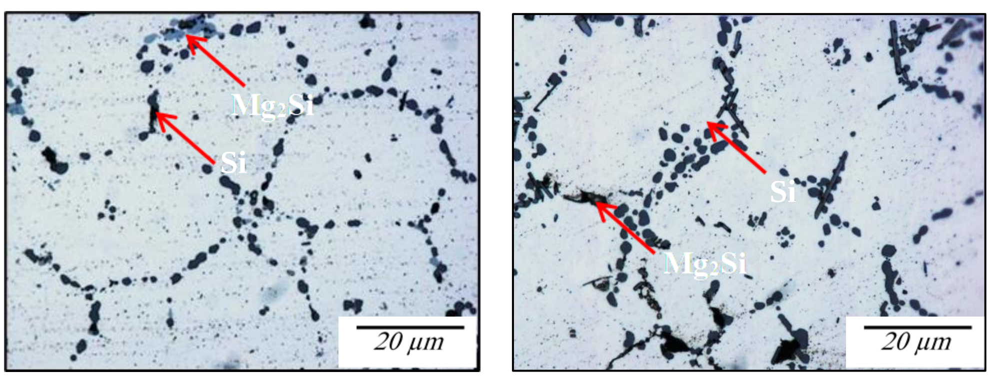


Figure 2: Optical micrographs of thixoformed alloys (a) Al-5Si-Cu-1.0Mg and (b) Al-5Si-Cu-1.5Mg.



(a) (b)

Figure 3: Optical micrograph of thixoformed alloy in T6 heat treatment (a) Al-5Si-Cu-1.0Mg and (b) Al-5Si-Cu-1.5Mg.

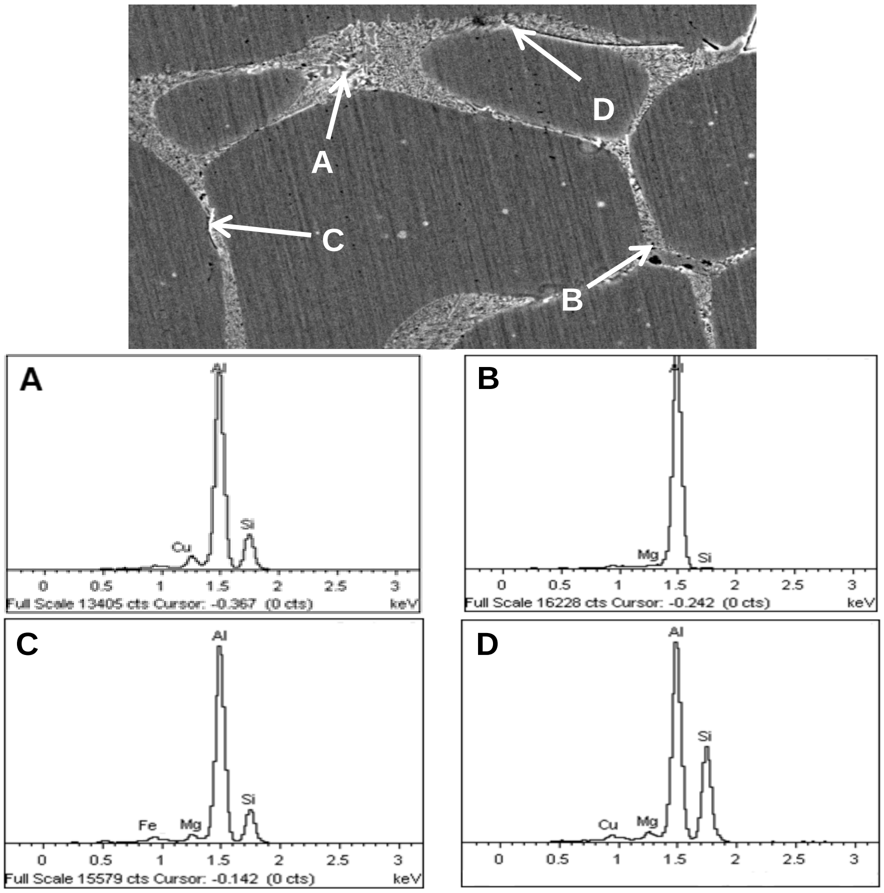


Figure 4: Alloy Al-5Si-Cu-1.0Mg SEM back scatter electron images (arrow A: Al_2Cu B: Mg_2Si, C: π-$Al_9FeMg_3Si_5$ and D: $Al_5Cu_2Mg_8Si_5$).

3.3 MECHANICAL PROPERTIES

The stress-strain graph of the as-cast and thixoformed samples is shown in Figure 5 while Figure 6 depicts the stress-strain graph of a T6 conditioned as-cast and thixoformed samples. Figure 5 indicates that the ultimate tensile strength (UTS) of the thixoformed samples that contained 1.5wt% of Mg is higher than that of the alloy that contained 1.0wt.% Mg, indicating an improvement of the UTS of the thixoformed alloy due to the presence of Mg. The same trend was also observed after the T6 heat-treated samples as shown by Figure 6. The highest value of the UTS was obtained at the alloy that contained 1.5wt% of Mg. It was also noticed that the yield strength (YS) at 0.2% offset varies at different Mg content both in thixoformed and thixoformed T6 alloys. The yield strength can be explained as the stress at which the alloys begin to deform plastically (Alhawari., 2017). The exact value of the UTS, YS and elongation of the studied alloys are presented in Figures 7-9 respectively. The mechanical properties of the thixoformed Al–5Si–Cu–1.0Mg alloy shows an improvement as compared to the cast alloy. In the thixoformed Al–5Si–Cu–1.0Mg alloy, the UTS, YS and elongation were 250 MPa, 200 MPa and 2.1%, respectively. In the case of the thixoformed Al–5Si–Cu–1.5Mg alloy, the UTS values slightly increased to 270 MPa, whereas the YS values significantly increased up to 230 MPa. However, the elongation sharply decreased to 1.8%. This data proved that the alloys contained 1.5wt.% Mg reduced the elongation to fracture, thus increased the brittleness of the alloy as compared to the alloy that contains 1.0wt.% Mg as illustrated in the graph in Figure 5.

The same patterns were noticed on the heat-treated alloys. The UTS, YS and elongation to fracture of the as-cast Al–5Si–Cu–1.0Mg alloy increased to 215 MPa, 192 MPa and 2.3%, respectively, after the T6 heat treatment. Moreover, the UTS for the thixoformed alloys Al–5Si–Cu–1.0Mg and Al–5Si–Cu–1.5Mg were significantly increased to 280 and 320 MPa, while the YS increased to 230 and 270 MPa, respectively. The results also revealed that the thixoformed alloy Al–5Si–Cu–1.5Mg showed the highest UTS and YS. However, the elongation to fracture of alloy that contained 1.5wt.% Mg reduced the elongation to fracture as compared to the alloy that contains 1.0wt.% Mg as illustrated in the graph in Figure 6. Evidently, the thixoforming process has an advantage to improve the mechanical properties of aluminium alloys (Salleh et al., 2017). This improvement is due to the morphological changes of α-Al during thixoforming. In addition, the strength of the thixoformed alloys can be enhanced further by the microstructural uniformity and contiguity of the eutectic phase, reduction of the globule size, and homogenous dispersion of intermetallic phase.

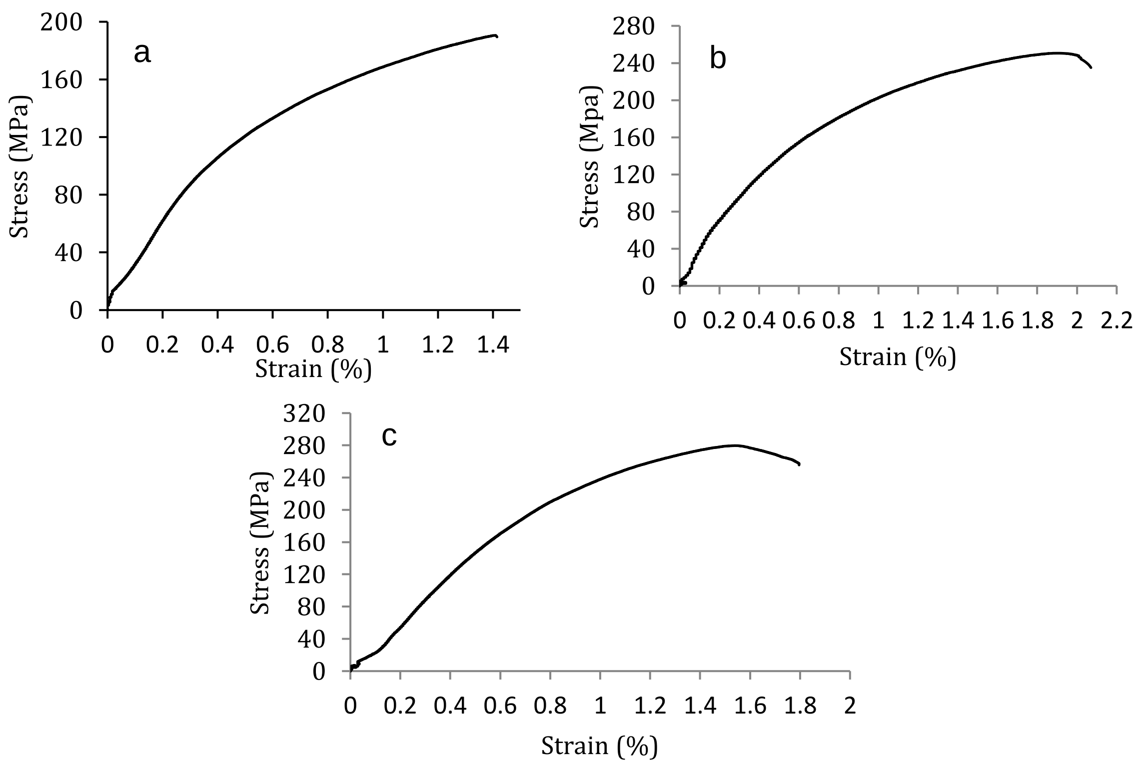
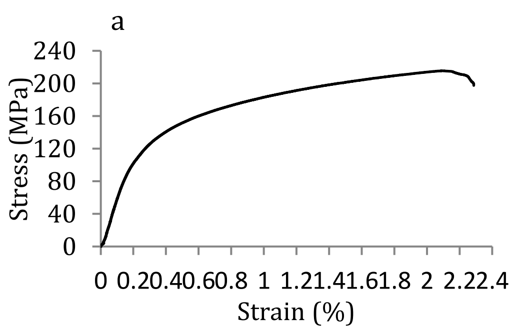
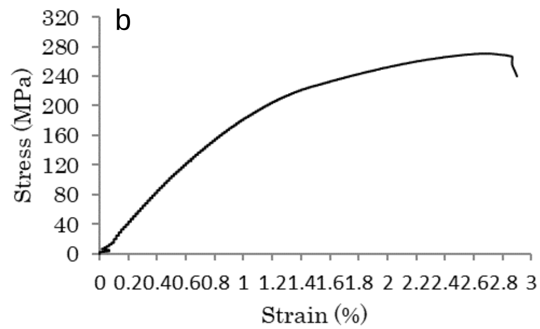


Figure 5: Stress strain graph of (a) cast Al-5Si-Cu 1.0 Mg (b) thixoformed Al-5Si-Cu 1.0 Mg and (c) thixoformed Al-5Si-Cu 1.5 Mg.





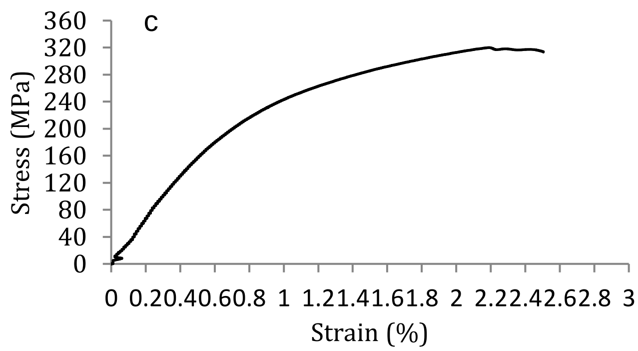


Figure 6: Stress strain graph of (a) cast Al-5Si-Cu 1.0 Mg (b) thixoformed Al-5Si-Cu 1.0 Mg and (c) thixoformed Al-5Si-Cu 1.5 Mg in T6 heat treatment.

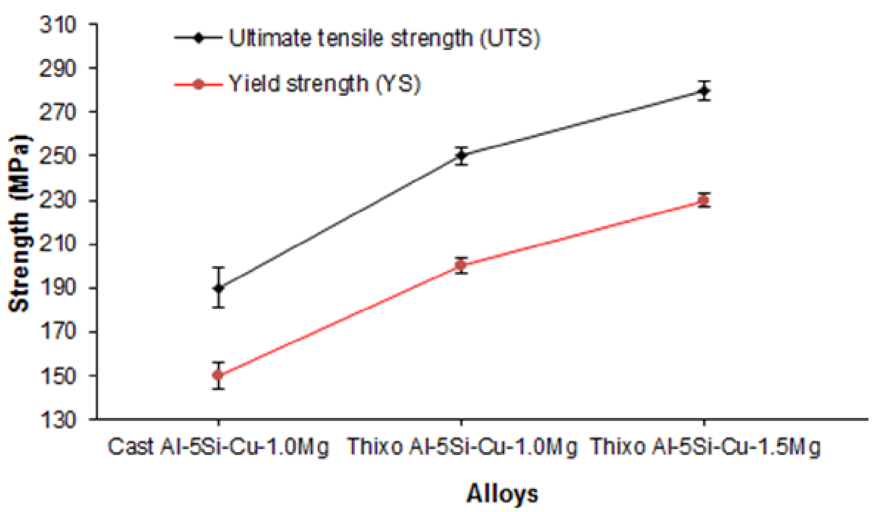


Figure 7: Comparison of the mechanical strength of the thixoformed alloy.

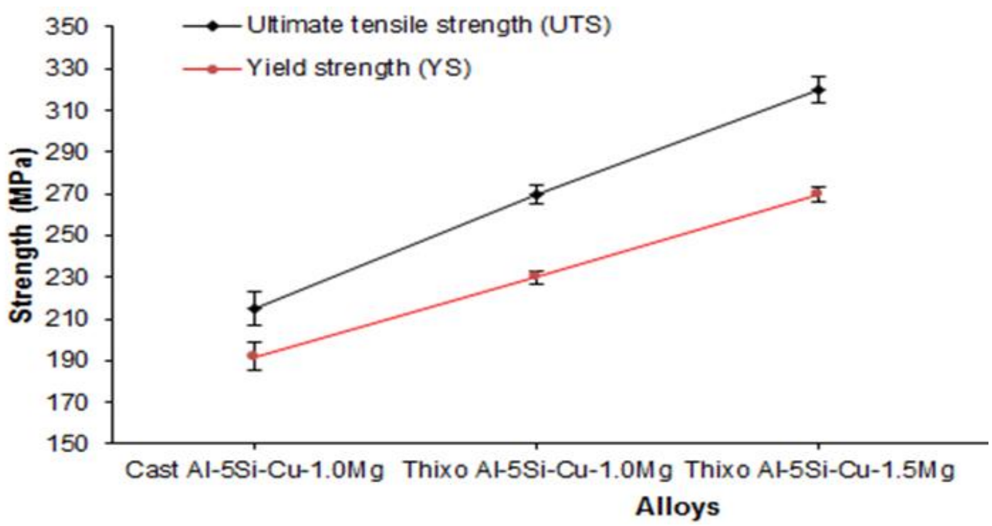


Figure 8: Comparison of the mechanical strength of T6 heat treatment alloys.

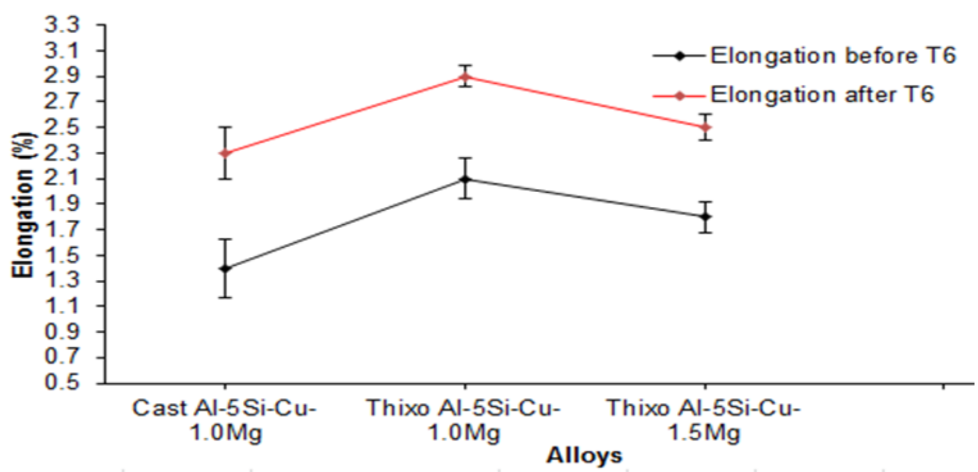


Figure 9: Comparison of percentage of elongation of the studied alloys.

3.4 FRACTOGRAPHY

Fracture analysis was carried out to the aluminium alloys to investigate the fracture mechanisms of the thixoformed samples as shown in Figure 10. The tensile tests were carried out using a 100 kN Universal Testing Machine. Figure 11a-11c show the fracture morphologies of the samples of as-cast Al–5Si–Cu–1.0Mg, thixoformed Al–5Si–Cu–1.0Mg and thixoformed Al–5Si–Cu–1.5Mg alloys respectively. The result in Figure 11a clearly indicates that for the as-cast sample Al–5Si–Cu–1.0Mg, the fracture surface is mainly composed of debonded Al-Si eutectic particle and cracked. A further observation (white arrow) at the crack area in Figure 11a shows that the crack initiates at the brittle phase of Mg_2Si/Al_2Cu between the α-Al. It can also be seen that there was a cleavage fracture on the fracture surface of the as-cast sample, corresponding to the brittleness of the sample (elongation to fracture =1.3%).

In the case of the thixoformed alloy in Figure 11b, it is clearly seen that there were some dimples in the fracture surface of thixoformed alloy that contained 1.0% Mg, which is a good agreement with the tensile results as shown in Figures 7-9 (elongation to fracture =2.1%). The white arrow region in Figure 11b shows the crack propagation at the eutectic phase that contained brittle phase particle between the α-Al globules, indicating that cracking of this phase contributes to the crack initiation, crack propagation and lastly fracture during the tensile test (Gan et al., 2017)

On the other hand, the fractographs of the thixoformed Al–5Si–Cu–1.5Mg alloy in Figure 11c demonstrate a cleavage rupture. It is noticed at the Figure 11c that the crack initiated at the α-Al grain globules (white arrow), which originated at the brittle phase particle and eutectic silicon phase. This was resulted in the debonded of the α-Al grains along the grain boundaries resulted into cellular-morphology type fracture. This fracture normally reduces the ductility of the thixoformed alloys as evidenced by the result of tensile testing (elongation =1.8%) as depicted in Figure 9. Therefore, it can be said that cracking and debonding of the brittle phase particles are the main damage mechanism prior to the fracture of the thixoformed alloys.

Figure 10: Fractured samples of the thixoformed Al-5Si-Cu-1.0Mg.

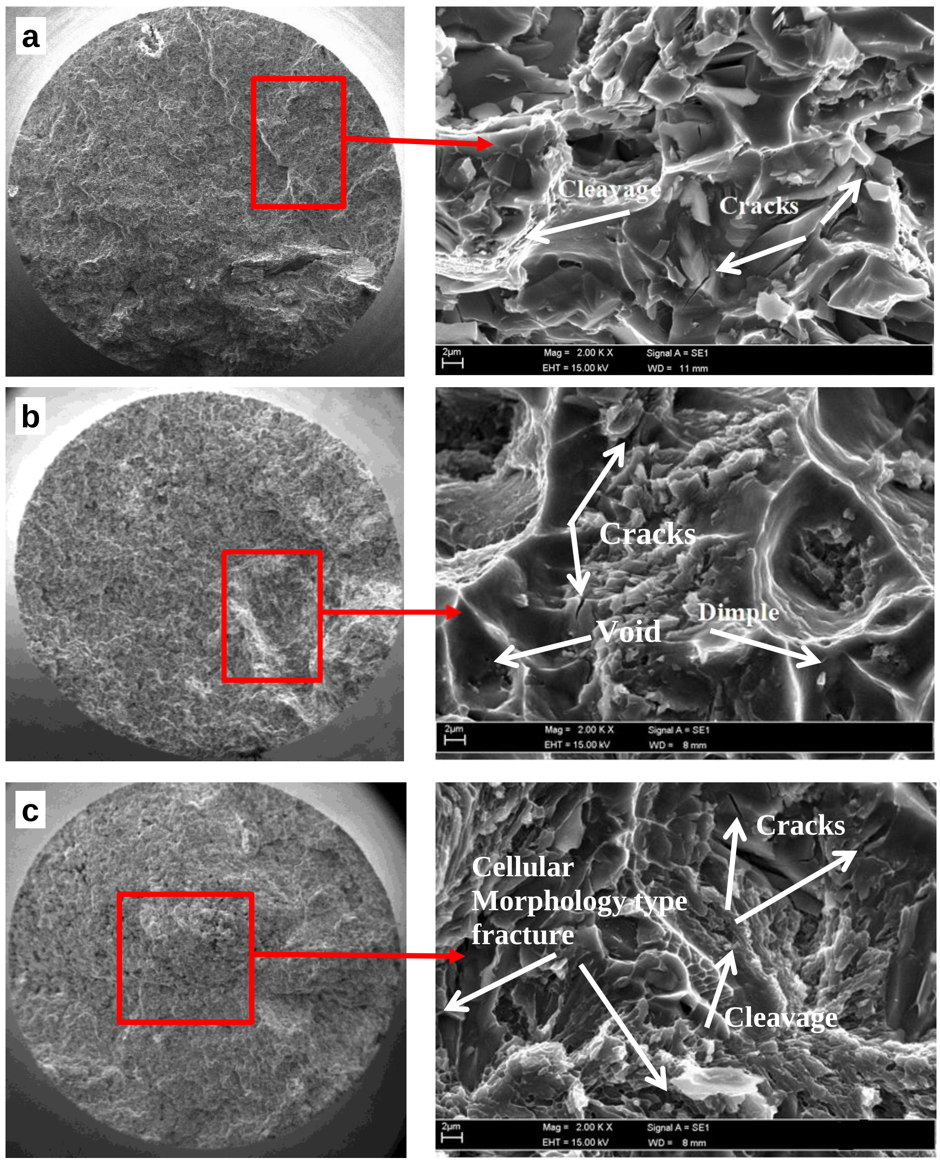


Figure 11: SEM fractographs obtained for (a) as-cast Al-5Si-Cu-1.0Mg, (b) thixoformed Al-5Si-Cu-1.0Mg and (c) thixoformed Al-5Si-Cu-1.5Mg.

CONCLUSION

The investigation of different Mg content of thixoformed aluminium alloys was conducted to improve the mechanical properties of the aluminium alloys. The addition of 1.0 and 1.5 wt.% Mg to aluminium alloy significantly refined the eutectic silicon of the thixoformed samples. The tensile strength of the thixoformed alloy has increased evidently while the elongation percent drops with the increase in Mg content. The T6-treated samples help to improve the mechanical properties, and the UTS and YS values reached a significant increase of 320 MPa and 270 MPa respectively when 1.5 wt.% Mg was added. Conversely, the elongation to fracture decreased to 2.5%. The fracture behaviour of the alloys with 1.0 wt.% Mg content demonstrated a cellular morphology-type fracture, while the 1.5 wt.% Mg content thixoformed alloys exhibited brittle-type fracture with cleavage raptures.

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