

Effect of Heat Treatment on the Microstructure, Hardness and Wear Properties of Al–15Mg₂Si–3Cu with Different Contents of Zn

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Abstract The effects of heat treatment (T6) on the microstructure and dry sliding wear behavior of Al–15Mg₂Si–3Cu particulate metal matrix composite (PMMC) with different contents of Zn have been investigated. The composite was characterized by scanning electron microscopy equipped with energy dispersive spectrometer (EDS). Dry sliding wear experiment was performed in a pin-on-disc wear tester against a DIN 100Cr6 steel disc at a speed of 220 rpm using normal load of 30N. Results show that increasing the Zn content causes a significant improvement in hardness. This is ascribed to the observed increase in matrix strength due to the formation of Al–Zn solid solution in the matrix. Zn was also found to be powerful in increasing wear resistance. The wear results showed that abrasion is the dominant wear mechanism in the composite containing 15 wt.% Zn, whilst a combination of adhesion and delamination appears to be the governing mechanism for as-cast composites.

Keywords Al–Mg₂Si, Heat Treatment, Hardness, Wear Properties, Zinc

1. Introduction

The sliding and rotating components such as brake drums, cylinder liners, pistons, cylinder blocks and connecting rods, intended to work in lubricating conditions may eventually end up working in semi-lubricated or dry conditions. This will result in higher operating temperature with increase in wear and lead to quicker replacement of components. Hence, wear is one of the major problems that need to be tackled in order to improve the life of the component. Composite materials are the promising alternate for alloys, specifically in dry operating conditions. Metal matrix composites (MMCs) reinforced with hard ceramic particles have emerged as a potential material especially for wear resistant

and weight critical applications. These composites exhibit the ability to withstand high tensile and compressive stress by the transfer and distribution of the applied load from the ductile matrix to the reinforcement phase [1-4].

Al-based composites, reinforced with particulates of Mg₂Si have been lately introduced as a new group of particulate metal matrix composite (PMMCs) that shows some new advantages such as good castability and suitable resistance, but quality and properties of the cast products are strongly affected by the microstructural changes during solidification [5]. Hypereutectic Al–Mg₂Si composite consist of primary Mg₂Si and Al–Mg₂Si binary eutectic with different sizes, morphologies and distributions that affect the mechanical properties, specifically the wear [6]. Therefore, it seems desirable to refine the structure of the composite by chemical and mechanical methods [7,8]. It has also been reported that by adding Cu to Al–Mg₂Si composite no significant effect on Mg₂Si particle size and its morphology. However, the presence of some Cu-rich intermetallics, mainly Q and θ phases increased hardness and UTS but reduced the elongation [9]. Also, Jafari Nodooshan et al. [10] applied solutionizing heat treatment to produce the material with dot like shape in eutectic Mg₂Si and round shape in primary Mg₂Si particles. It has been also indicated that solutionizing heat treatment improve wear behavior of Al–Mg₂Si composite.

Zinc–Aluminum (ZA) alloy is a competitive bearing alloy that shows improvement in both mechanical and tribological properties compared with phosphor-bronze, SAE 73, SAE 660 and cast iron. The density of the latter are much higher compared with the former element [11, 12]. Based on Al–Zn binary phase diagram [13], Zn is highly soluble in Al even up to 80 wt.%. Moreover, it has been reported that the addition of Zn to alloys such as Al–Si–Cu does not change the microstructure significantly [14]. It is interesting to investigate the influence of Zn on Al–15 wt.% Mg₂Si microstructure in which prevalence of solid solution hardening is expected; therefore, this study was carried out to

evaluate the effect of Zn addition (0–15 wt.%) on the microstructure and wear properties of the Al–15Mg₂Si–3Cu composite, before and after T6 heat treatment.

2. Experimental Procedure

In order to prepare Al–Mg₂Si ingots, pure commercial Al (99.8%) was first heated up to 760 °C via an electrical resistance furnace (10 Kg capacity) in a SiC crucible (10 Kg capacity). Then, pure Si (99.5% purity), Mg (99.5% purity) and Cu (99.5% purity) were added to the molten Al to make Al–5.5 wt.% Si–9.5 wt.% Mg–3 wt.% Cu alloy ingots. Table 1 shows chemical composition of ingot. Different amounts of Zn (5, 10 and 15 wt. %) were added to the molten MMC in a small furnace. To ensure complete mixing, the molten alloy was hand stirred gently with a graphite rod for about 1 min.

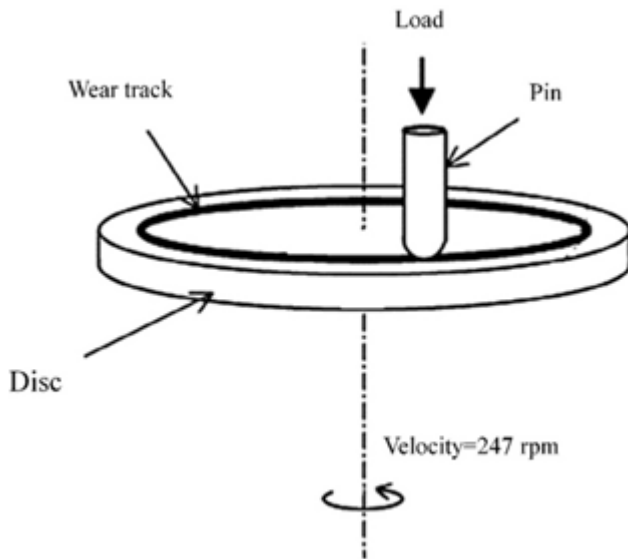


Figure 1. Schematic of pin-on-disk test.

The wear resistance tests were performed under dry sliding condition at room temperature, according to the ASTM G99-05 standard procedures, on a pin-on-disk wear resistance equipment with a counter face of DIN100Cr6 steel which was hardened to 65 HRC at 25°C (Fig. 1). The cylindrical shape pins, (5 mm×10 mm) were in a conformal contact with the steel disk, were prepared by machining. These pins were tested at the rotational speed of 220 rpm

under nominal load 30N for sliding distance of 1000 m. The wear resistance was evaluated by friction coefficient, wear rate and weight loss. The friction coefficient was obtained by dividing the measured friction force by the applied load. The average weight loss of the specimens was measured by a precision balance with an accuracy of 1×10^{-4} g. Moreover, microstructural examinations of the composites were conducted using optical and scanning electron microscopy (SEM) equipped with an energy dispersive X-ray (EDX) analyzer. The XRD measurement was performed using Cu K_α radiation at 40 kV and tube current of 30 mA over the 2θ ranging from 10° to 90°, using a step size of 0.021 with a counting time of 0.5 s at each step.

Heat treatment experiments were performed in a high accurate temperature controlled electrical resistance furnace (± 2 °C). Specimens was tested in T6 heat treatment, it was heated at temperature 500°C for 14 h and quenched in water, then aged at a temperature of 160°C for 10 h followed by quenching in cold water. Metallographic specimens were prepared by using standard polishing technique and etching in a 5% HF reagent. Hardness results were measured using the ESEWAY universal hardness tester. At least five indentations were made on each sample and the average lengths of the diagonals were used to estimate the hardness values.

3. Result and Discussion

3.1. Microstructural Studies

Fig. 2 shows the typical microstructure of Al–15 wt.% Mg₂Si metal matrix composite before and after T6. The microstructure consists of coarse dark particles of primary Mg₂Si and the bright phase α -Al in the matrix. Also, some intermetallic compound were formed in microstructure, which are observed in the form of white-colored phases in Fig. 2. The presence of Cu rich intermetallic phases (Q phase with honeycomb morphology and θ phase with plate like morphology) has been reported in previous investigation [15, 16]. More detailed characterization of the nature of these intermetallic is reported in previous work [9]. The exact composition of the Q phase is unknown but has been stated as Al₅Cu₂Mg₈Si₆ [17], Al₄Cu₂Mg₈Si₇ [18], Al₃Cu₂Mg₉Si₇ [19] and Al₄CuMg₅Si₄ [20].

Table 1. Chemical composition of Al–15Mg₂Si–3Cu composite.

Element	Si	Mg	Cr	Fe	Cu	Zn	Mn	Al
Wt.%	5.61	8.93	0.01	0.36	2.87	0.03	0.02	Rest.

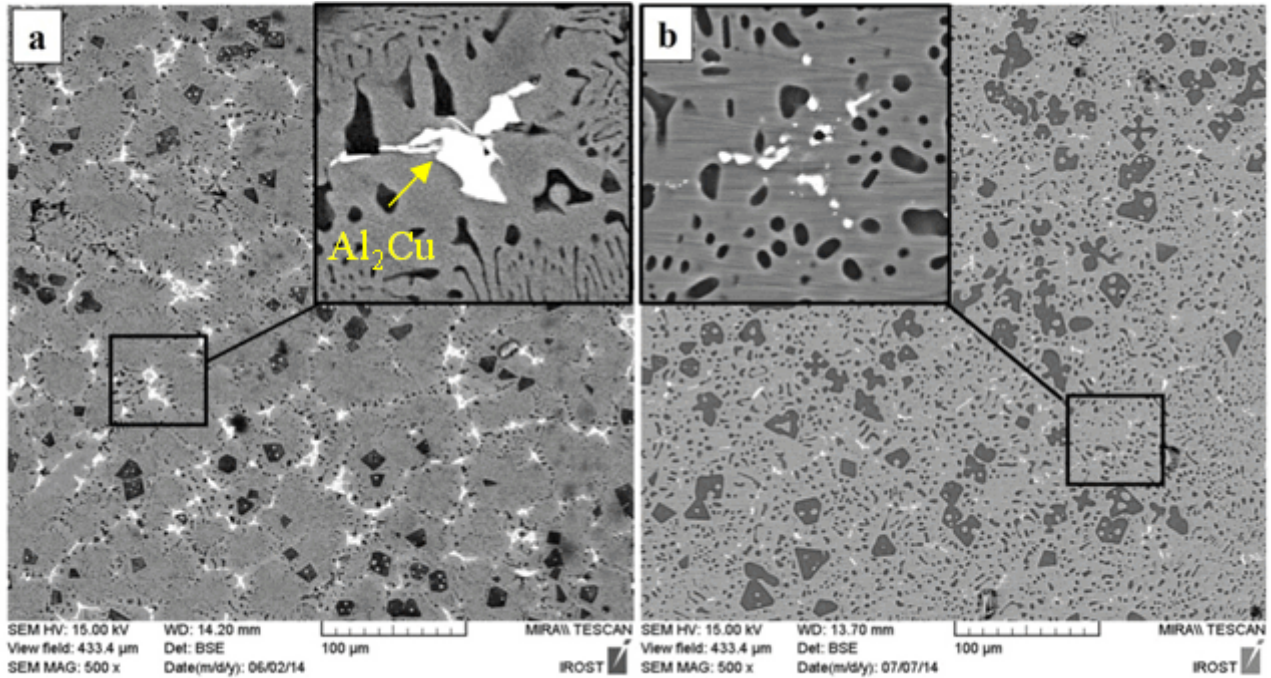


Figure 2. The microstructures of Al-15%Mg₂Si-3Cu composite: (a) as-cast and (b) heat treated.

From Fig. 2b, it can be seen that although slight change is seen in the size and appearance of the primary Mg₂Si phase, heat treatment significantly altered the morphology of these particles from sharp edges to round shape. Also, this figure demonstrates that solution heat treatment influences pseudo-eutectic Mg₂Si structure and alters its shape from continuous eutectic Mg₂Si phase to fine, dot-like and partially round particles. It is interesting to note that T6 heat treatment changes Cu containing phase precipitated in grain cell boundaries to separated fine particles. It is well established that after T6, Cu intermetallic dissolves in α -Al matrix in order to form supersaturated solution [21, 22].

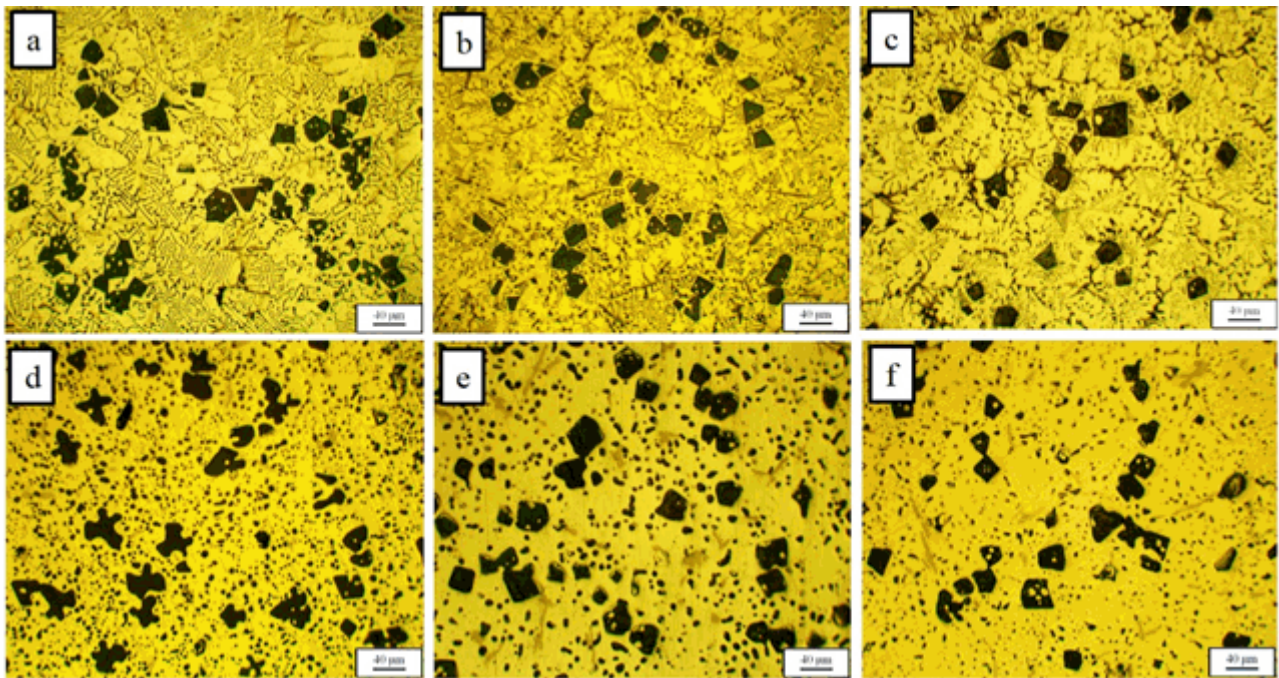


Figure 3. Optical microstructure of Al-15%Mg₂Si-3Cu (a) 5 wt.% Zn before T6, (b) 10 wt.% Zn before T6, (c) 15 wt.% Zn before T6, (d) 5 wt.% Zn after T6, (e) 10 wt.% Zn after T6 and (f) 15 wt.% Zn after T6.

Fig. 3 demonstrates the optical microstructure of Al-15Mg₂Si-3Cu composite containing different Zn contents (5, 10 and 15 wt.%), before and after T6. Regarding the microstructural studies, the morphology of primary Mg₂Si particles showed insignificant changes by Zn addition. However, T6 heat treatment process considerably changes morphology of the eutectic Mg₂Si.

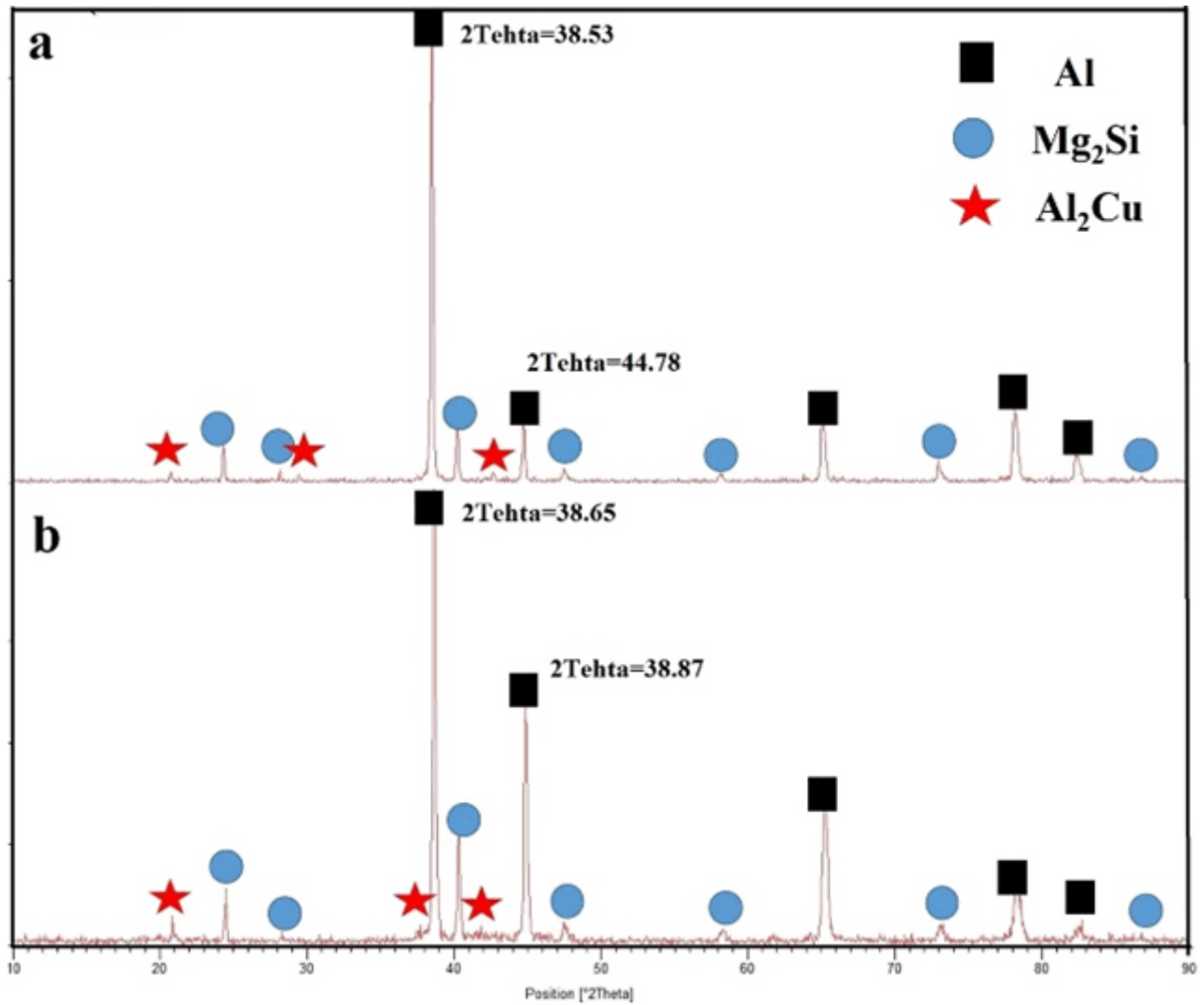


Figure 4. XRD pattern of (a) Al-15%Mg₂Si-3Cu and (b) Al-15%Mg₂Si-3Cu-15Zn.

Interesting results were obtained from XRD analysis, in Fig. 4. The revealed phases of the Cu added MMC consist of α -Al, Mg₂Si and Al₂Cu intermetallic (θ phase). By adding of Zn in the composite, Zn dissolve into Al unit cell and due to decrease the lattice constant of Al, so aluminum peaks in XRD pattern are shifted toward higher angles. Similar result has been shown in previous investigations [23].

3.2. Wear Properties

Fig. 5 shows the Brinell hardness (HBR) values for as-cast and heat treated samples with different content of Zn. It is seen that by adding zinc to the composite, the hardness increased in both as-cast and heat treated samples. The Al-Zn solid solution strengthening mechanism is theorized to be a dominant factor on hardness improvement. Also, by dissolving copper intermetallics after T6, it can be seen that, the hardness values increases in comparison with casting condition.

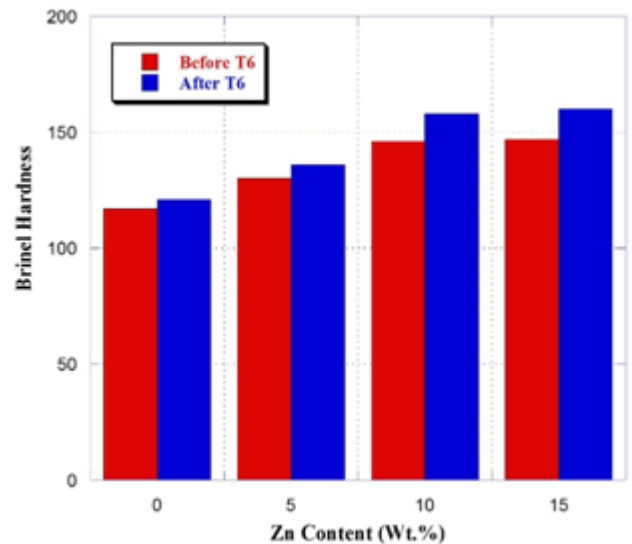


Figure 5. Brinell hardness of Al-15%Mg₂Si-3Cu composite with different contents of Zn, before and after T6 heat treatment.

Figs. 6a and b indicate the variation of weight loss as a function of sliding distance for both as-cast and heat treated composites under 30 N applied loads, respectively. It is observed that the weight loss increased almost linearly with increasing sliding distance in all samples.

It is also seen from the plot that weight loss of heat treated samples are lower than that observed in as-cast and decreases by increasing Zn content.

The main reason for this fact is clearly related to the hardness enhancement of solid solution mechanism and according to Eq. 1, Archad equation, the wear resistance of the composites is directly related to their hardness. The higher resistance enhancement due to solid solution mechanism by Zinc and copper elements for 15 wt.% Zn and heat treated composite.

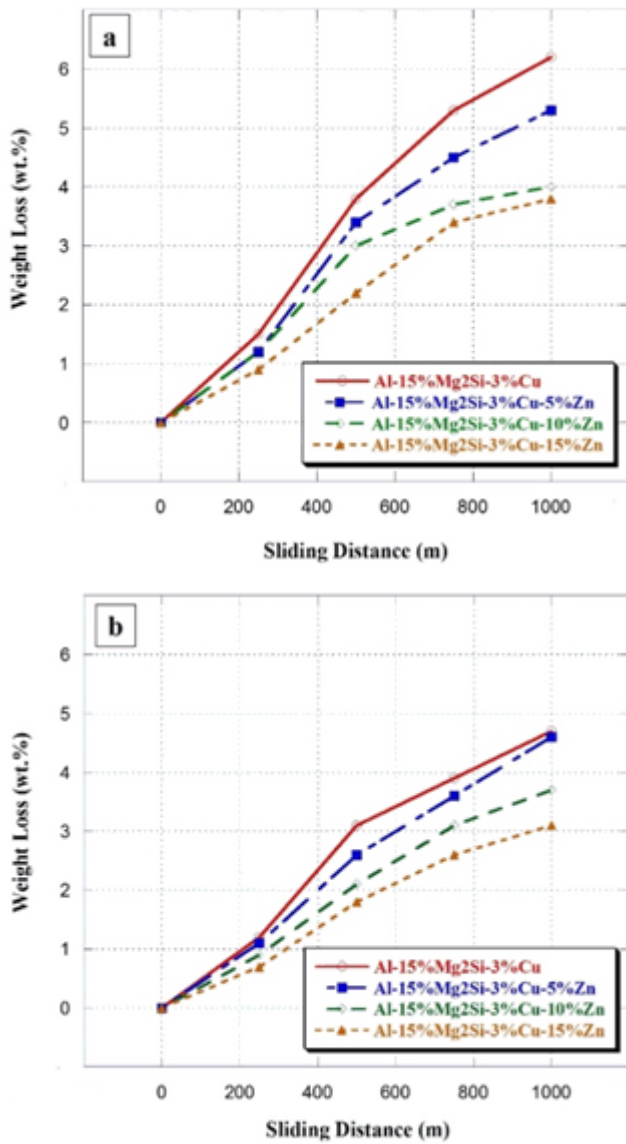


Figure 6. Weight loss against sliding distance for Al-15%Mg₂Si-3Cu with different contents of Zn: (a) before T6 and (b) after T6.

$$R = k (W/H) \tag{1}$$

In this equation, R is wear rate, W the volume of worn

material per distance, k is a constant called wear coefficient and H is the hardness of the specimen [24]. This result is consistent with the rule that in general, material with higher hardness have better wear and abrasive resistance [25, 26].

Fig. 7 shows the variation of coefficients of friction for the as-cast composite and the heat treated samples under 30 N applied load. It is evident from Fig. 7 that the coefficient of friction for the as-cast composite is larger than that for the heat treated composites. Also, by increasing the Zn content the stability of wear is improved in both methods. The increased coefficient of friction can be attributed to fracture of large brittle primary Mg₂Si particles and rod-like Mg₂Si eutectic into smaller particles during sliding. So these particles cannot support the load to lessen the touch area between the pin and counter disc surface. On the other hand, Mg₂Si particles become ineffective to resist the deformation developed in the wear surface so the cracks can propagate in the matrix, causing Mg₂Si particles to pull out from the matrix, expanded on the composites and counterpart and act as hard abrasive particle against the composite. Also, by increasing zinc element into aluminum lattice, due to decrement of propagation of microcracks into matrix.

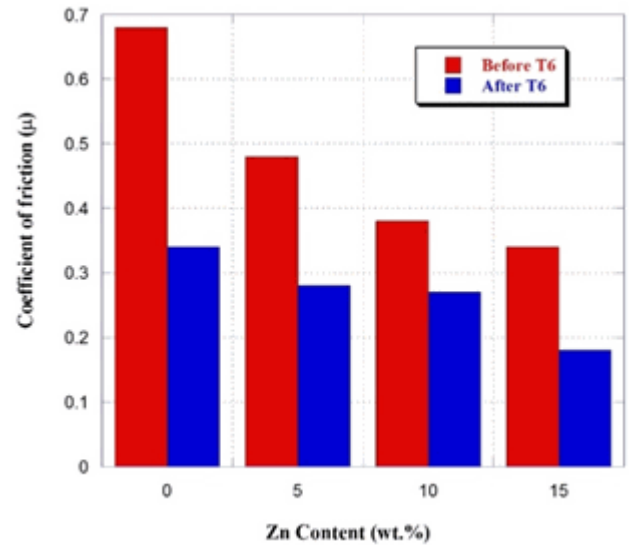


Figure 7. Coefficient friction of Al-15%Mg₂Si-3Cu with different contents of Zn, before and after heat treatment.

SEM analyses were performed after completion of the wear tests. Fig. 8 shows representative photomicrographs of the wear surfaces of samples under 30N applied load at different Zn content, before and after T6 that revealing details of the contributed wear mechanisms.

The topography of the composites surfaces manifests severe adhesion characteristic accompanied by the cracks and abrasion grooves observed on the worn surface of the as-cast sample without Zn (Fig. 8a). It could be signs of material fatigue attributed to the low shear strength and fracture toughness of as-cast composite [26]. As Zn content increase in casting condition, pits and grooves were found more in comparison with sample without Zn (Fig. 8b). From Figs. 8a and b, it can be conclude that zinc addition due to

changes of wear mechanism from adhesion to abrasion mode. Similarly, Fig. 8c indicates that applying T6 heat treatment due to changes of wear mechanism to abrasion mode. It is evident from Fig. 8d that surface sample of modified by Zn and heat treated are smoother than other sample surfaces. By determining width of abrasion grooves, it shows that surficial grooves on sample with 15 wt.% Zn and heat treated are shallower and finer than surficial grooves of samples modified by Zn or heat treated by applying T6. All of the studying on Photomicrograph of the wear surfaces is consistent with result of pin-on-disk test.

4. Conclusions

In the present investigation, Al–15Mg₂Si–3Cu in-situ composites were successfully prepared by the casting route and T6 heat treatment and the effect of different content of Mg₂Si on the microstructure, hardness, and wear behavior

was studied. The results indicate that:

1. The addition of Cu (3 wt.%) to the Al–15 wt.% Mg₂Si composite introduces Cu rich intermetallics, mainly Q and θ phases.
2. The addition of Zn into the microstructure increases the hardness of the composite in both as-cast and heat treated.
3. The wear resistance of 15 wt.% Zn in Al–15Mg₂Si–3Cu composite is significantly high in comparison with lower content of Zn, before and after heat treatment. The lowest weight loss and friction coefficient were observed in the Al–15Mg₂Si–3Cu–15Zn composites.
4. The wear results showed that abrasion is the dominant wear mechanism in the composite containing 15 wt.% Zn, whilst a combination of adhesion and delamination appears to be the governing mechanism for as-cast composites.

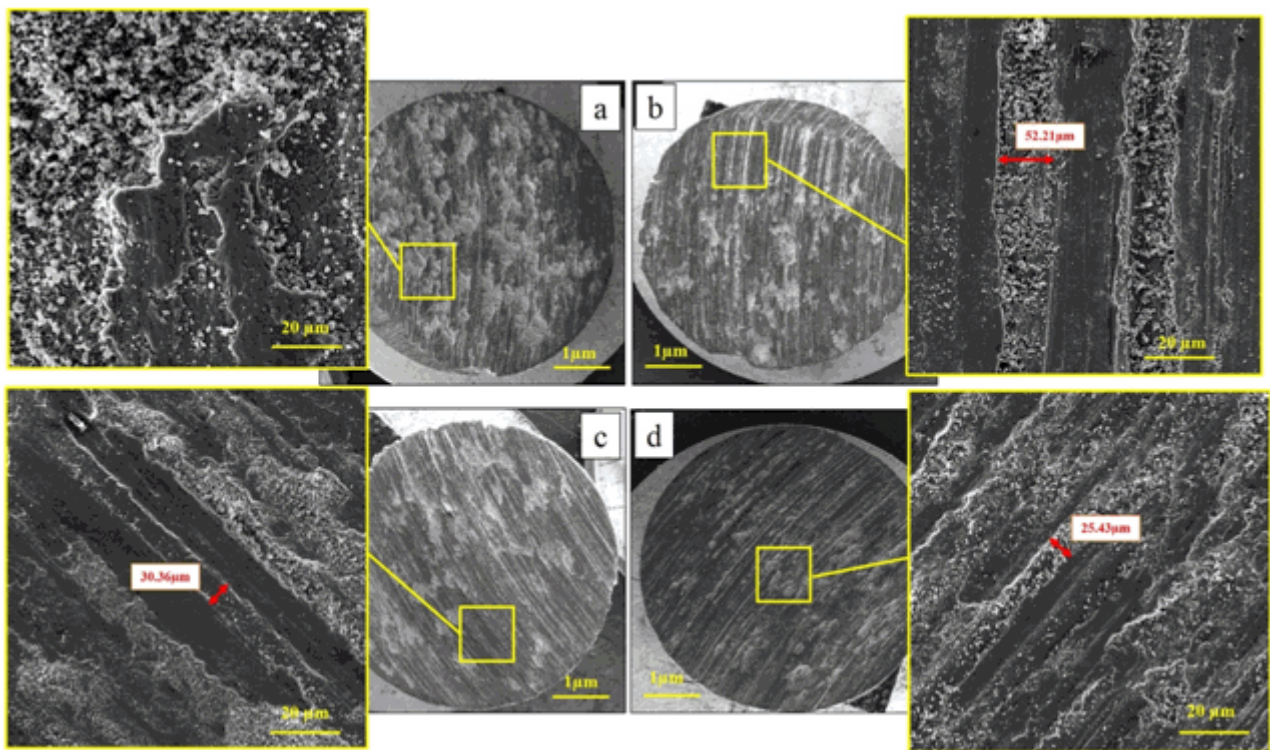


Figure 8. SEM images of worn surfaces of the samples under an applied load of 30 N: (a) Al–15Mg₂Si–3Cu before T6, (b) Al–15Mg₂Si–3Cu–15Zn before T6, (c) Al–15Mg₂Si–3Cu after T6 and (d) Al–15Mg₂Si–3Cu–15Zn after T6.

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