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Effect of praseodymium addition on wear properties of Al-15%Mg_2Si composites

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A B S T R A C T

Nowadays, aluminium metal matrix composites are widely used in various industrial applications, especially in automotive and aerospace industries. In engineering, rare earth elements (RE), such as yttrium, neodymium and cerium are widely used as alloying elements to improve the strength and wear resistance of composite materials. Therefore, this research project was done to investigate the effect of praseodymium (Pr) addition on wear behaviour of aluminium MMC of Al-15%Mg_2Si composite. Microstructure analysis was carried out by using optical and SEM analyses. In addition, Vicker hardness and dry sliding wear tests were conducted to measure the effectiveness of Pr addition on mechanical and tribological properties of the fabricated composites. The result showed that Pr addition affected the microstructure and wear properties of aluminium composites. Pr addition with 1.0 wt% concentration gave the highest Mg_2Si phase density of area and lowest value of wear rate with average wear rate of 2.3 mm^3/km for 20 N applied load compared to 2.4 mm^3/km for the base composite which indicated the positive effect of Pr addition on the wear resistance of composites.

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1. Introduction

In industry, the material selection for a certain machine or structure is important to ensure that the structure meets the original function. Every material has its own characteristics and properties that can be measured by different procedures and steps. Aluminium metal matrix composite is one of the materials that are commonly used in automotive and aviation because of their advantages and properties. Aluminium MMC is a strong composite that has high strength to density ratio. Recently, Al-Mg_2Si in-situ composites, a new class of ultralight materials, were identified as a potential candidate to replace Al-Si alloys which are used in automotive applications, such as brake disks [1,2]. Nevertheless, under low solidification rates of Al-Mg_2Si composites (e.g. in gravity casting), coarse dendritic primary Mg_2Si phase with sharp corners and brittle flake-like eutectic structures are formed, which could compromise the mechanical and wear properties of the alloys; hence, restrict their improvement and industrial applications [3]. Therefore, it is essential to control the microstructure of composite to obtain the desired morphologies and respective properties. Some research even showed that rare earth (RE) elements have valuable refinement/modification effects on the structure of Mg_2Si phase [4–6]. Praseodymium (Pr) is one of the rare earth elements that is used as alloying element in Mg alloys to improve the strength and wear properties. However, according to the author's knowledge limitations exist on the effect of Pr on wear properties of Al-Mg_2Si composites.

It is expected that the addition of rare earth Pr to Al-Mg_2Si composite will result in microstructure modification and enhancement of mechanical and wear properties. Therefore, in the present research the effect of Pr addition on the microstructure and wear resistance of Al-Mg_2Si was investigated.

2. Methodology

2.1. Sample preparation

For sample casting, pure Al (99.98% purity), silicon (99.0%) and Mg (99.85%) of industrial grade, were used to prepare the Al-15Mg_2Si composite ingot. Pure Al and Si were melted at 800 °C in a graphite crucible in an electric resistance furnace. When the

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temperature dropped to 750 °C, pure Mg was added to the melt and casted in a metal mould to produce the Al-Mg_2Si ingot.

The ingot was then cut into smaller pieces and re-melted in the induction furnace at 750 °C with a single heat weighing 200 g Then, 0.5 wt% of pure Pr was added to the melt, held for 3 min at 750 °C, degassed with dry tablets containing C_2Cl_6, and poured into a cast iron mould which was preheated at 220 °C. The same procedure was followed for 0 wt%, 1.0 wt% and wt. % 2.0 of Pr additions. The amount selection of Pr addition was consistent with the concentration of rare earth elements in previous studies [7,8].

2.2. Hardness test

For Vickers's hardness test, the load was set at 500 g, loading time was for 10 s, loading speed was 50 μm/s. Hardness test was carried out at 8 different locations of the sample surface, and the average values of hardness was calculated. The average value of hardness was compiled and presented in a bar graph.

2.3. Sample preparation for optical microscope

First, the sample was cleaned by using an ultrasonic cleaner. Then, the specimens were ground by using different grits of sic paper from rough until smooth (240, 800, 1200, and 2400). Then, the specimens were polished with a colloidal silica agent. After that, to enhance the microstructure image, the specimens were etched with 2% HF acid for 10 s and 5% HCl with 95% ethanol for 1 min. Then, the specimens were oven dried before it was ready for the optical microscope analysis.

2.4. Wear characterisation

Dry sliding wear tests were conducted to ASTM: G99-06 in a pin-on-disc wear testing apparatus (Ducom TR20-LE) by using 20 N and 40 N normal loads to vary the result. These applied loads were chosen to have a proper effect on wear behavior of the composites during wear tests [9].The fixed parameter on this test was 200 RPM disc speed, 30 mm wear track radius and 2000 m sliding distance. Then, the same wear sample was used on SEM/EDX machine to study the wear severity and pattern.

3. Results and discussion

3.1. Optical microstructure analysis

Fig. 1(a–d) shows the optical images of the cast Al-15%Mg_2Si composites with 0 wt%, 0.5 wt%, 1.0 wt% and 2.0 wt% Pr additions. As shown in Fig. 1(a), the morphology of primary Mg_2Si appeared as dendrites in the unmodified alloy. When the composite was added with 0.5 wt% Pr, the morphology of the primary Mg_2Si changed into a solid polygon as shown in Fig. 1(b) with decreasing in the particle size. With further addition of 1.0 wt% Pr, the morphology of primary Mg_2Si particles changed to a regular polygonal shape (Fig. 1(c)) and their sizes reached to the smallest. However, by increasing the Pr content to 2.0 wt%, the Mg_2Si particles increased in size, which was due to over modification phenomenon [2] as shown in Fig. 1(d). Therefore, it can be observed that 1.0 wt% Pr is the optimum concentration compared to other percentages of Pr, in which the Mg_2Si particles have undergone adequate refinement with better polygonal morphology.

Addition of modifier agent to the Al-Mg_2Si composite resulted in the surface energy of the liquid melt to be changed, which altered the equilibrium solidification and growth process of the respective phases [9,10]. With addition of 1.0 wt% Pr element to the Al-15%Mg_2Si composite, owing to the chemical interaction between the elements, new phases (white contrast) were formed in the matrix of the composite, among the primary Mg_2Si particles as shown in Fig. 2(a). The corresponding EDS analysis conducted on

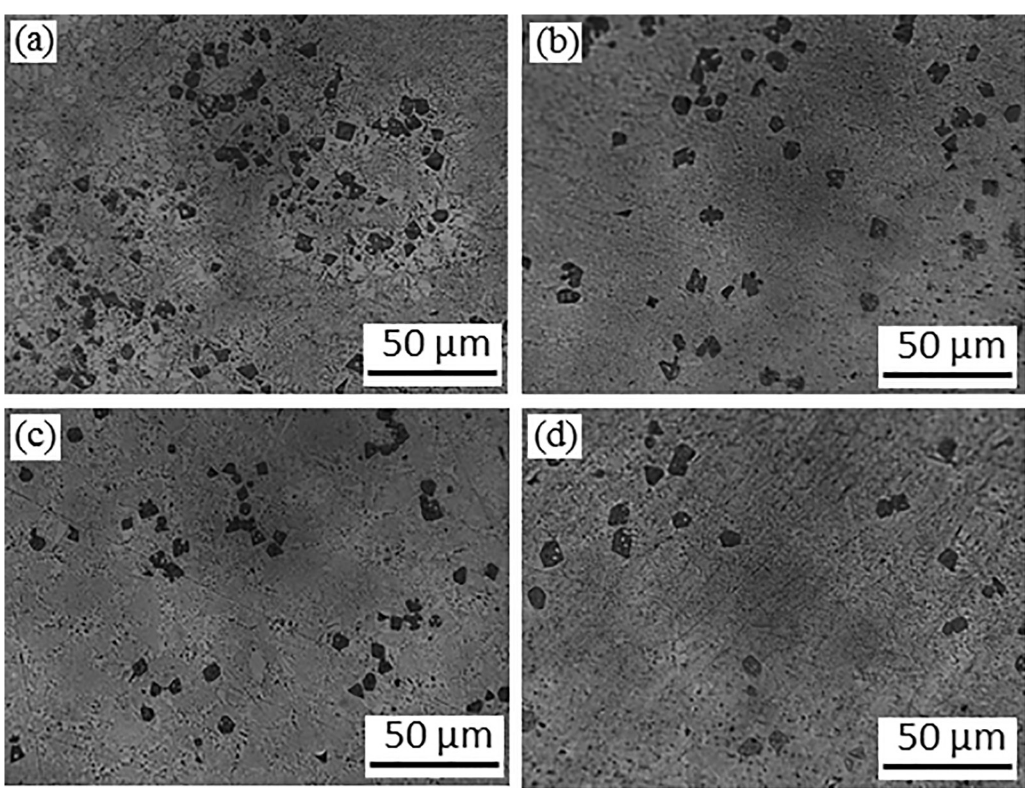

Fig. 1. Microstructure images of Al MMC with Pr addition for (a) base; (b) 0.5%wt; (c) 1.0%wt and (d) 2.0%wt.

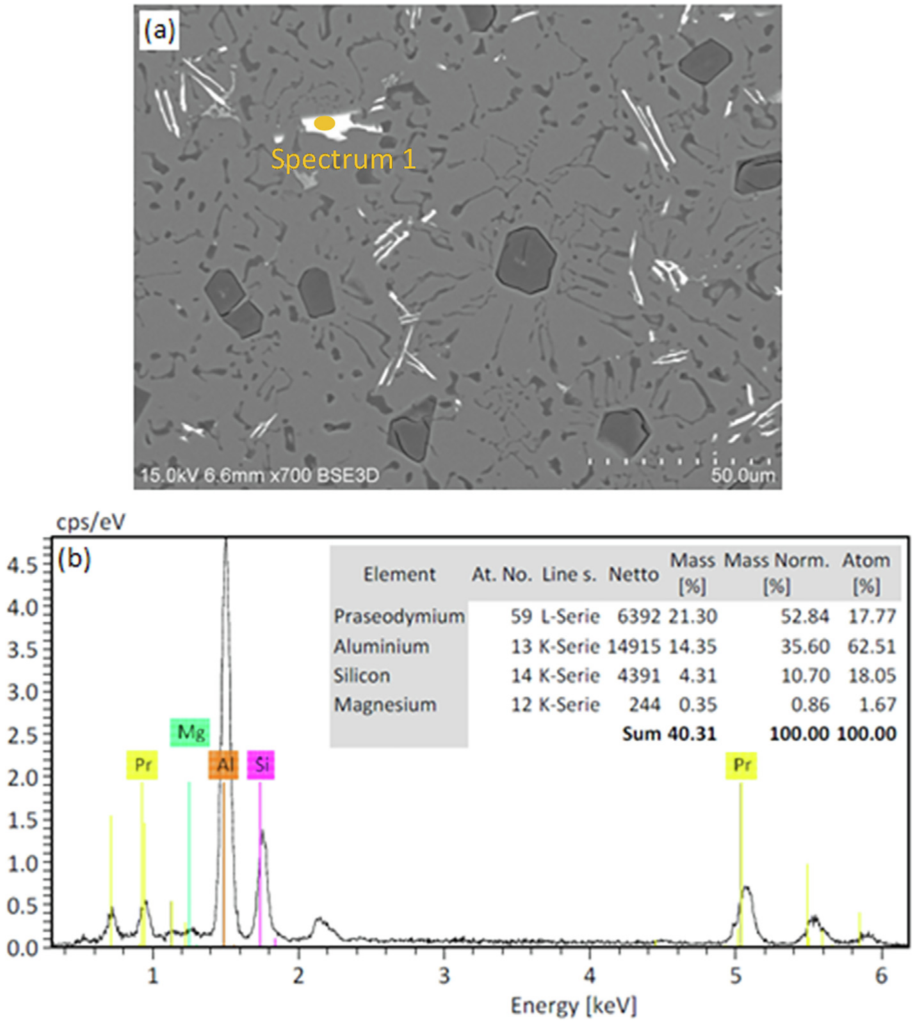

Fig. 2. (a) SEM micrograph of non-uniform Pr white particle, (b) EDX analysis on corresponding non-uniform white Pr particle.

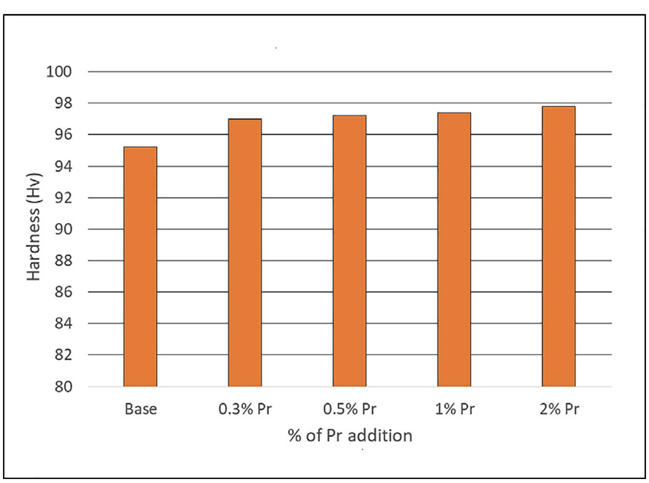

Fig. 3. Hardness test result.

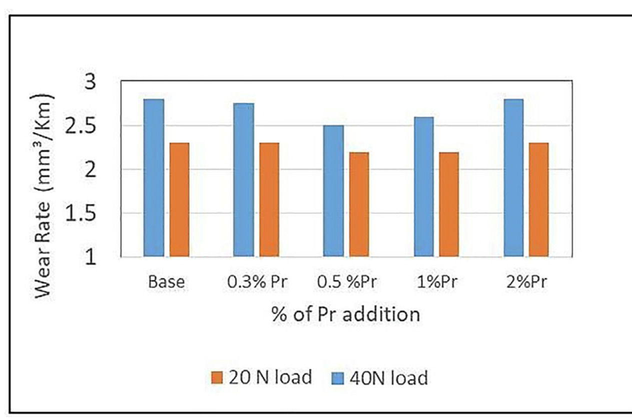

Fig. 4. Wear rate of the composites for 20 N and 40 N applied load.

the Pr phases revealed that the Pr phases are composed of various atomic % of Al, Si and Pr elements, in which the composition of Pr phases are near to the AlSiPr intermetallic compounds (Fig. 2(b)).

3.2. Hardness test

Fig. 3 shows the graph of hardness value in respect of %Pr Addition. The Hardness shown is an average that calculated from 8 different point of hardness test. From the graph, it shows that aluminium MMC will increase of hardness when Pr was added.

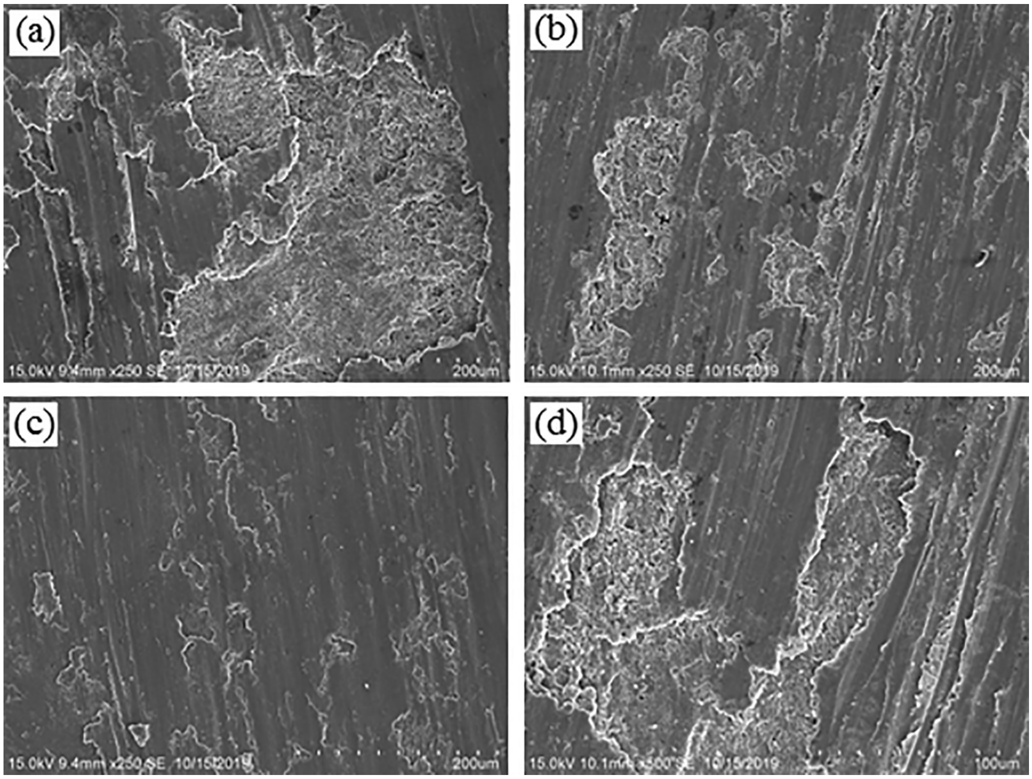

Fig. 5. SEM images on wear for (a) base; (b) 0.5 wt%; (c) 1.0 wt% and (d) 2.0 wt%

However, increase in amount of Pr only gave a small increase in hardness.

3.3. Wear characterization

Fig. 4 shows the wear rate of sample measure and calculated by using Archard's law [4]. It can be seen that the graph shows a trend where the wear rate is decreasing as the Pr is increase until it reach 1.0 wt% of Pr. The reason for decreasing the wear rate is refinement/modification of primary Mg_2Si particles as a result of influence of the Pr addition on the size and morphology of Mg_2Si particles. However, the wear rate will increase as the percentage of Pr increased to 2.0 wt%. The responsible reason for decreasing the wear resistance of the composite by increasing the wear rate after 1.0 wt% is overmodification phenomenon which leads to increasing the Mg_2Si particles size. Furthermore, increasing the density of brittle Pr intermetallic compounds with increasing the Pr addition beyond 1.0 wt% is another factor. Therefore, it can be said that the optimum percentage of Pr addition for this aluminium MMC is 1.0 wt%. In addition, Fig. 4 shows that the wear rate increase when the load applied increases from 20 N to 40 N for all composites. The higher wear rates observed at 40 N are attributed to the fact that at higher loads the stress induced on the wear surface is higher, meaning the number of contact asperities increases and as a result the material surface wears faster [10]. Another feature in Fig. 4 is that the wear rate of Al-15%Mg_2Si composite treated with 1.0 wt% Pr is more than 0.5 wt% Pr under 40 N applied load which doesn't follow the trend. Further study to confirm the exact reason for this increasing will be the focus of our future work. However, based on the microstructural characterization and calculating of the wear rate under 20 N applied load, it can be concluded that the optimum percentage of Pr addition is 1.0 wt%.

3.4. SEM analysis on wear sample

Fig. 5 show the SEM image of wear samples for 15 times magnification. From these images, it can be observed that the worn pattern on the edges of pin quite different between one and another. Base and 2 wt% %Pr show a very severe worn size compare to sample of 1.0% Pr. In fact, with the addition of 1.0 wt% Pr, the worn surface of the composite has a rather smooth appearance with narrow grooves and shallow pits, which is most likely due to the presence of the fine and uniformly distributed hard Mg_2Si particles in the matrix. In addition, the tendency of primary Mg_2Si to fracture decreased leading to more effective wear load distribution [11].These observation satisfy the result that given from wear test which shows that 1.0% of Pr addition gave a best wear resistance. However, in term of adhesive pit in the middle of the surface, the severity from observation can be said quite same. It is fascinating to note that the presence of hard AlSiPr intermetallic compound in the composite treated with 1.0 wt% Pr (Fig. 2) may also contribute to wear resistance compared to the composite without Pr. Similar findings have been reported by Wu et al. [12] for Nd-modified Al–18% Mg_2Si in situ composite.

4. Conclusion

From the microstructure analysis and wear characterization, it can be conclude that the optimum Pr addition on Al-15Mg_2Si is1.0%wt. However, the hardness test show an almost a same hardness value with only a slight increase as the Pr addition increase. In nut shell, it can be said that Pr addition can modify the microstructure and enhance the wear properties of Al-15%Mg_2Si composite.

CRediT authorship contribution statement

Islahuddin Aziz: Methodology, Formal analysis, Investigation, Writing - original draft. **Hamidreza Ghandvar:** Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft. **Tuy Asma Abu Bakar:** Validation, Resources, Supervision, Writing - review & editing. **Chong Chin Yee:** Methodology, Formal analysis, Investigation, Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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