Sliding Wear Properties of a Composite of Aluminum 2024 Powder Reinforced with Heat Treatment and Silicon Carbide

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Abstract. Wear behavior of aluminum alloy 2024 was investigated. Three patterns of specimens, namely, fabricated (compacted), reinforced with silicon carbide only and reinforced with silicon carbide followed by heat-treatment (quenching and aging processes) were selected. The effect of load on the specimen was studied for each type of pattern. Three values of load (10, 12.5 and 15N) were tested to investigate the wear behavior. The experimental results showed that the weight loss was 0.056 g for the specimen reinforced with silicon carbide and heat treatment, while it was 0.069 and 0.067 g for the as-fabricated specimen and the specimen reinforced with silicon carbide only, respectively. The increase of microhardness caused increased wear resistance and thus the weight loss was reduced. The microhardness increased with the increase of the ratio of silicon carbide, while, conversely, the density decreased with the increase of the ratio of silicon carbide. The maximum value of hardness was observed for the specimen reinforced with 5% of Sic followed with heat treatment at 284 Hv, while for the specimens reinforced with 4% and 3% Sic it was 255 and 227 Hv, respectively. It can be concluded that when heat treatment and reinforcement by Sic particles are performed, the microhardness value of aluminum 2024 will increase.

Keywords: *aluminum 2024; density; microhardness; reinforcement material; silicon carbide; wear test.*

1 Introduction

High-copper content aluminum alloys are generally defined as those with more than approximately 3.8 wt% copper content. Processing an alloy such as 2024 aluminum as a metal matrix composite (MMC) is necessary because it is commonly used in a wide range of industrial parts, such as shafts, gears, aircraft fittings, pistons, hydraulic valve bodies and worm gears. Silicon carbide is often used as reinforcement due to the higher hardness of its particles than that of the matrix. However, if orthodox routes of solidification are used, then negative qualities such as a brittle product or low toughness are obtained [1]. Aluminum matrix composites (AMCs) have good tribological and mechanical properties.

Received February 2nd, 2018, Revised August 23rd, 2018, Accepted for publication November 1st, 2018.
 ISSN: 2337-5779, DOI: 10.5614/j.eng.technol.sci.2018.50.5.3

Hence their use in automobile, space, defense, and aircraft industries. In addition, this characteristic can be convenient to satisfy explicit requirements [2].

There are several factors that influence MMC wear. The influence of speed on wear resistance has been documented. The wear rate is significantly influenced by load and its direction. [3]. Hybrid metal matrix composites have gained increased interest in recent years due to their improved collective properties (tribological, physical and mechanical) [4]. When a ceramic reinforcement is added to the aluminum matrix, such as silicon carbide particles, the properties are further enhanced, thus making it a potential material for abundant lightweight applications [5]. Various common techniques can be used for enhancing the strength of materials, such as strain hardening, grain size refinement, precipitation hardening and solid solution hardening [6]. Studies have proved that aluminum matrix composites reinforced with metal carbide increase wear resistance and thus decrease the wear rate [7].

In the current paper, the constituents were produced with powder metallurgy. The wear resistance was tested in relation to the content of silicon carbide and heat treatment. Various load values were tested.

2. Experimental procedure

2.1 Material

Aluminum 2024 generally has good machinability. It is a light metal that has high ultimate tensile strength compared other aluminum alloys and good surface finishing capability. Therefore it has superseded many other aluminum alloys in industry. The density value for aluminum 2024 is 2.78 g/cm^3. The chemical composition is illustrated in Table 1.

Zinc stearate powder was mixed with aluminum 2024 powder as a binder to facilitate the process. A mixer machine was applied to mix the constituents for 1.5 h, at a speed of 250 RPM to ensure that the mixture was completed. Equal ratios for all specimens were performed. 1% zinc stearate powder and 99% aluminum powder 2024 were used as mixture.

In the current research, cold compaction was conducted on the powder. The process was performed at room temperature. A uniaxial hydraulic press was used as cold press. One side was used to supply the pressure while the other side was fixed. A lubricant-saturated solution was used to clean the wall of the die to ensure the ejection of the specimen from the die after the process was finished [8]. Further bonding between atoms was provided during the sintering process. Hence, atomic diffusion occurred. Heating and cooling rate time affect the sintering process. Similarly, atmosphere and temperature were controlled [9].

Table 1 Chemical composition of Aluminum 2024.

Elem.	Nominal value	Experimental value
Si	0.50	0.48
Fe	0.50	0.49
Cu	3.8-4.9	4.1
Mn	0.3-0.9	0.6
Mg	1.2-1.8	1.4
Cr	0.1	0.9
Zn	0.25	0.23
Ti	0.15	0.12
Al	Rem	Rem

A tube furnace was used during the sintering process; argon gas was used as the inert gas for this process. The sintering temperature was determined according to the relationship between sintering temperature and melting temperature = (0.7 to 0.9 Tm), where Tm is the melting temperature.

2.2 Heat Treatment

Heat treatment was used to improve the mechanical and physical properties. The microstructure changed during exposure of the specimen to an elevated temperature under controlled heating rate after which it was exposed to delay time. Next, it was cooled to room temperature under a controlled cooling rate. Under this process, solid state transformation occurred, whereby the mechanical and physical properties were improved.

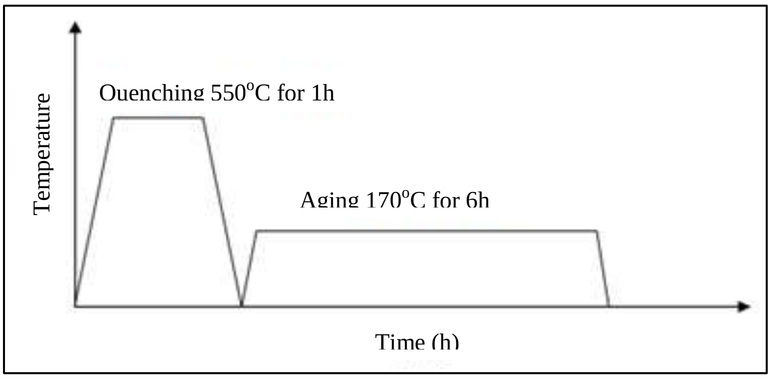

Figure 1 Heat treatment procedure.

The relationship between hardness and wear resistance is proportioned, making the heat treatment beneficial to the process of improvement of the wear rate [10]. Two paths, namely, quenching and artificial aging, were performed in this step. The quenching process was conducted at 550 °C for a duration of 1 h followed by water-cooling to room temperature. The next process (aging) was performed at 170 °C for 6 h followed by air-cooling to room temperature. Figure 1 illustrates the profile of the quenching and aging processes [11].

2.3 Wear Test

A pin-on-disk test was performed. The disk was made of stainless steel, with a hardness of 175 Hv. The thickness and diameter of the disk were 2 and 180 mm, respectively. The distance between the center of the disk and the center of the specimen was 3 cm. The duration of the test was 10 min. A sensitive balance determined the weight with an accuracy of 0.0001 g. The disk was carefully cleaned after each test. Adhesive wear was applied in this research.

Three groups were selected to determine the wear rate. The first group consisted of the as-fabricated specimen under compaction parameters. The second group consisted of specimens reinforced with silicon carbide. The third group consisted of specimens reinforced with silicon carbide followed by heat treatment. The percentages of metal reinforcement were 3%, 4%, and 5% for each group. Three loads were applied to each specimen, i.e. 10, 12.5 and 15 N. Table 2 presents the classification of the specimens.

Table 2 Classification of specimens.

Symbol	Sub-symbol	Detail	
I As-fabricated	I	Load variation at 10, 12.5, and 15 N	
II	II1	3% silicon carbide,	loads of 10, 12.5, and 15 N
Reinforced with silicon	II2	4% silicon carbide,	loads of 10, 12.5, and 15 N
carbide	II3	5% silicon carbide,	loads of 10, 12.5, and 15 N
III	III1	3% silicon carbide,	loads of 10, 12.5, and 15 N
Reinforced with silicon	III2	4% silicon carbide,	loads of 10, 12.5, and 15 N
carbide and heat treatment	III3	5% silicon carbide,	loads of 10, 12.5, and 15 N

3 Results and Discussion

Some components in the action mechanism broke because of problems occurring in the microstructure of the material. The quality and performance of the components were enhanced by improvement of the microstructure. Complicated problems occur with metal wear because of the microstructures and constituents of the materials, thus affecting the wear resistance and mechanism. Weight loss was used to evaluate wear resistance.

Wear, microhardness and density tests were also conducted in the current research. These tests gave a sufficiently good idea for the objectives of the current research.

3.1 Reinforcement by Silicon Carbide

Silicon carbide powder is one of the most common powder varieties. It is used for an extensive range of applications, for example in industrial processing, brake discs, LEDs and casting. Silicon carbide has a hardness of 2800 Hv and a density of 3.16 g/cm^3.

Three reinforcement percentages were selected, i.e. 3%, 4%, and 5%. Figure 2 displays the relationship between load and wear rate of the as-fabricated aluminum specimen and the specimens of aluminum with a certain percentage of silicon carbide powder (heat-treated and non-heat-treated). Figure 2 also shows that the wear rate increased for all samples when the load was increased because the friction force was increased. Conversely, the wear rate decreased for each sample (heat-treated and non-heat-treated) when the silicon carbide percentage increased. Thus, the decreasing rate can be attributed to the higher hardness of silicon carbide than that of aluminum.

The wear rate was affected by using different volume fractions of silicon carbide. The wear rate decreased with the increase of the volume fraction of silicon carbide. This decrease may be attributed to the higher hardness of the sample. At any rate, the heat treatment process improved the wear rate and the results of the heat-treated specimens showed a slightly decreased wear rate, whereas the wear rate increased more in the specimens without heat treatment. Thus, using silicon carbide particles as a reinforcement material with heat treatment was concluded to give better results. The maximum wear rate was observed for the as-fabricated specimen. The wear rate was 790 × 10-9 for 10 N load, while the wear rates were 910 × 10-9 and 1030 × 10-9 for loads of 12.5 and 15 N.

For the second group (reinforced by Sic only), when the applied load was increased, the wear rate increased. The wear rate was 770 × 10-9 for 10 N load, 840 × 10-9 for 12.5N load and 960 × 10-9 for 15 N load. When the particle reinforcement percentage was increased, the wear rate decreased. The wear rate value for the specimen reinforced with 4% Sic, with applied load at 10, 12.5 and 15 N was 750 × 10-9, 800 × 10-9, and 920 × 10-9, respectively. Likewise, the wear rate value for the specimen reinforced by 5% Sic with applied load at 10, 12.5 and 15 N was 710 × 10-9, 760 × 10-9, and 880 × 10-9, respectively.

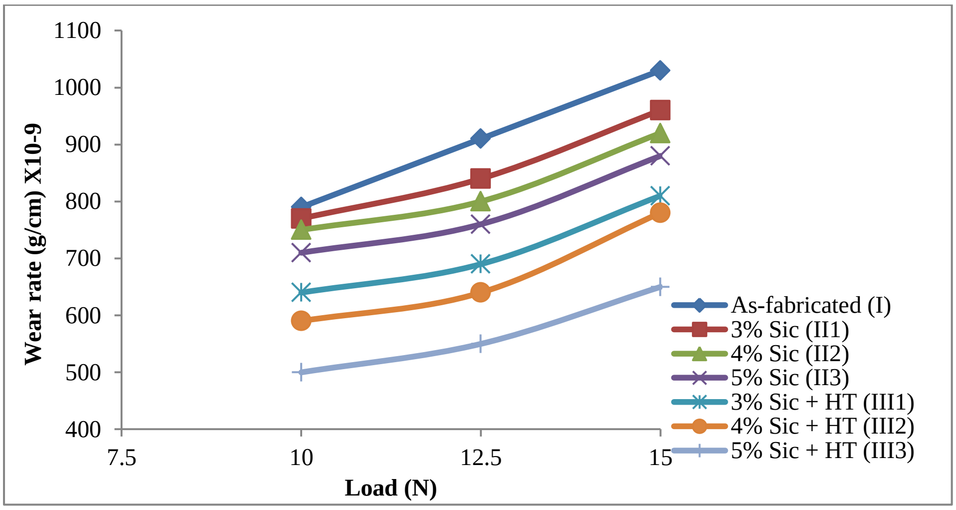

Figure 2 Load against wear resistance of the specimens reinforced with silicon carbide (heat-treated and non-heat-treated) compared with the as-fabricated specimen.

Heat treatment was used to increase the hardness. The wear rate results were related to the microhardness values of the specimens. When the microhardness value was increased, the wear rate decreased. Furthermore, the wear rate of the specimens with load at 10 N for each and reinforced with Sic particles at 3%, 4% and 5% was 640 × 10-9, 590 × 10-9, and 500 × 10-9, respectively. This decrease of the wear rate is attributed to the increase of the microhardness of the specimen. Figure 3 shows the surface friction of the samples. In this figure, high friction strength appears on the surface especially for the areas that contained Sic particles. Thus, it can be seen that some areas have easy plastic deformation (without Sic), while others have hard plastic deformation (with Sic). Figure 4 shows the microstructure of the specimens.

The improvement ratio was calculated for all specimens. It was 2.9% for the specimen with 3% silicon carbide (II1) without heat treatment, while the improvement ratios were 6.1 and 11.1% for the specimens with 4% and 5% silicon carbide (II2 and II3), respectively, at a load of 10 N. The improvement ratios were 12.3%, 13.5% and 16% for specimens III1, III2 and III3, respectively. Therefore, silicon carbide reinforcement followed by heat treatment can be considered the best process.

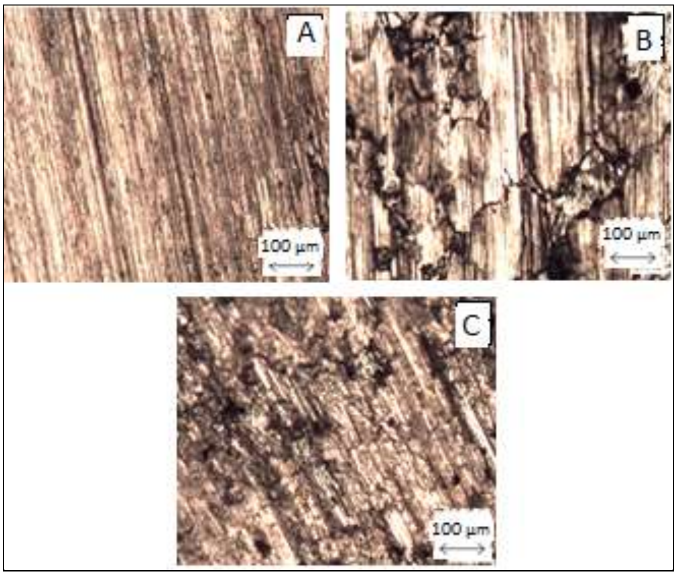

Figure 3 Friction surface area of wear test for different samples: (A) as-fabricated; (B) reinforced with Sic; (C) reinforced with Sic followed by heat treatment.

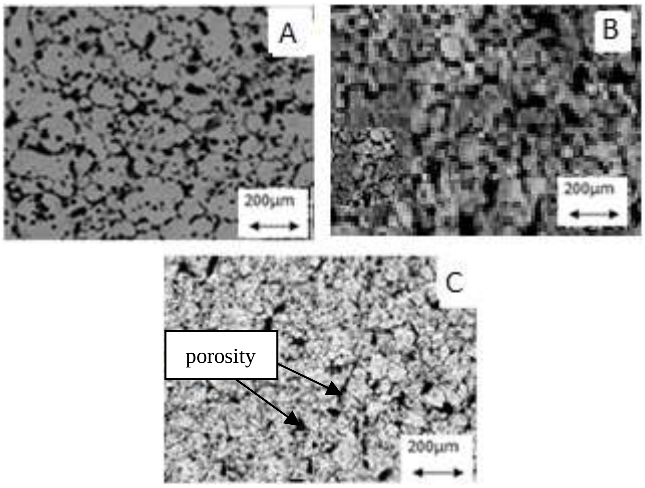

Figure 4 Microstructure of the specimens: (A) as-fabricated; (B) reinforced with Sic; (C) reinforced with Sic followed by heat treatment.

Figure 5 illustrates the improvement ratios of the specimens. Umanath, *et al.* [12] investigated AA6061 alloy reinforced with various volume fractions (i.e. 5% to 25%) of silicon carbide. According to their research, the surfaces of the wear area of the reinforced alloy were rougher than the surfaces of the non-reinforced alloy. The analysis was conducted by SEM.

Figure 6 shows the relationship between the microhardness of the used patterns and the percentage of silicon carbide. It can be seen that the value of microhardness of the specimen reinforced with Sic followed by heat treatment was higher than that of the specimen reinforced with Sic only. On the other hand, the value of microhardness increased with an increased percentage of silicon carbide because the value of hardness of Sic is higher than that of aluminum according to the mixture rule. From this test it can be concluded that the wear rate was related to the microhardness for all the specimens, and therefore when the microhardness was increased, the wear rate decreased.

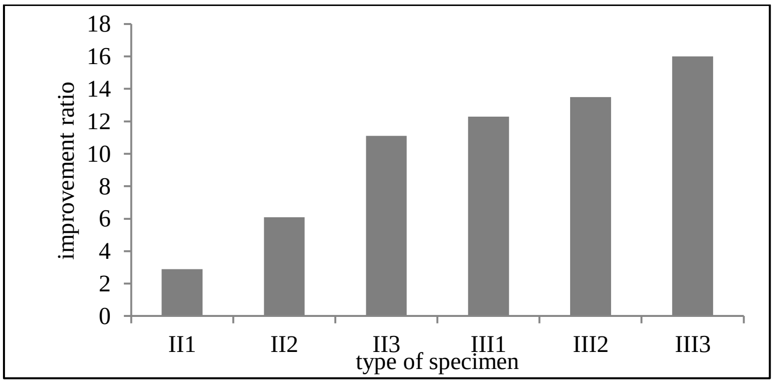

Figure 5 Improvement ratio and type of specimen.

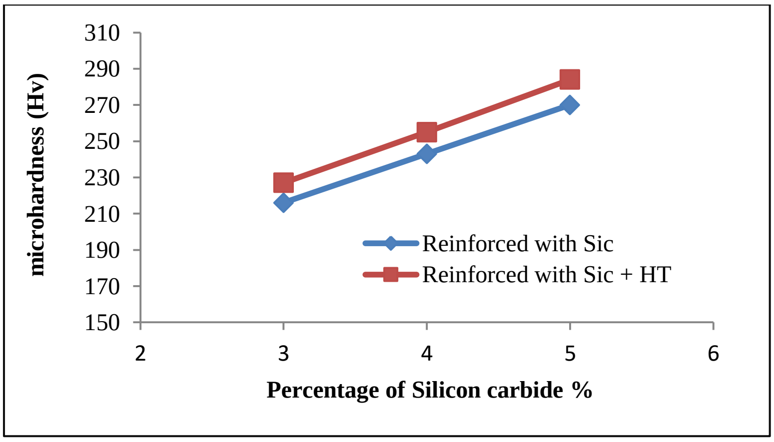

Figure 6 Values of microhardness for the specimens reinforced with silicon carbide powder.

Figure 7 shows the relationship between density and reinforcement with silicon carbide powder followed by heat treatment. It is an inverse relationship, in which density decreases when the percentage of silicon carbide increases. On the other hand, the density decreased upon using heat treatment because of the increased grain size of the aluminum (with temperature increased to 550 °C followed by quenching), therefore, when the volume of the specimen was increased, the density decreased. In addition, a porosity was created between the grains as can be seen in Figure 4(c). Based on the results, the density values for the specimens reinforced with 3%, 4% and 5% Sic were 2.8, 2.795 2.79 Kg/cm^3, respectively, while they were 2.772, 2.767 and 2.76 Kg/cm^3, respectively, for the specimens reinforced with Sic followed by heat treatment.

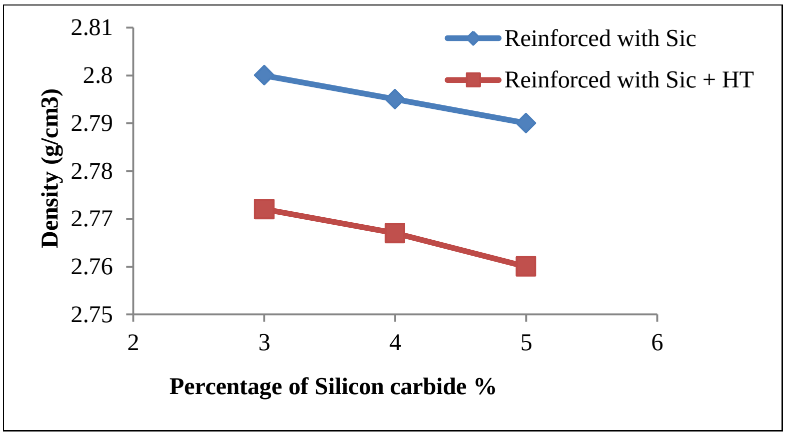

Figure 7 Density and reinforcement with silicon carbide powder.

4 Conclusion

The results of this study revealed the relationship between wear resistance for aluminum 2024 and reinforcement with different percentages of metal (Sic) and heat treatment. A maximum microhardness value of 284 Hv was detected in this study for the specimen reinforced with 5% silicon carbide followed by heat treatment. The minimum value of microhardness was 216 Hv for the specimen reinforced with 3% Sic without heat treatment. Therefore, it can be concluded that the amount of metal reinforcement and heat treatment increased the microhardness value.

By contrast, the reinforced and heat-treated specimens exhibited high wear resistance (a lower wear rate), i.e. 650×10^{-9}, whereas the as-fabricated specimen exhibited low wear resistance (a higher wear rate), i.e. 790×10^{-9}. These results refer to the value of microhardness. Density is related to the heat treatment process. The density value decreased with the increase of the temperature during the heat treatment process. Likewise, the volume of the specimen increased and thus the density decreased. This study on reinforcement of aluminum 2024 by silicon carbide addition and heat treatment was successfully conducted.

Acknowledgments

The author would like to thank Southern Technical University for providing suitable laboratories to complete investigation. In addition, much help was provided by Nasiriya Technical Institute, which included providing of equipment and materials.

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