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THEORY AND PROCESSES OF FORMING AND SINTERING OF POWDER MATERIALS

Mechanical and Tribological Behavior of Powder Metallurgy Processed Aluminum–Graphite Composite

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Abstract—In this research, the mechanical and tribological behavior of aluminum–graphite (Al–Gr) composite has been investigated in order to determine the optimum composition of reinforcement. The materials were fabricated by a powder metallurgy process and three different weight percentages of Gr were chosen as a reinforcement in pure Al at 3, 5 and 7 wt % to identify its potential for self-lubricating property under dry sliding conditions. The mechanical properties examined included hardness, tensile strength and flexural strength. The wear tests were conducted by using a pin-on-disc tribometer to evaluate the tribological behavior of the composite and to determine the optimum content of graphite for its minimum wear rate. The results show that the mechanical properties decreased with the addition of Gr. However, 3 wt % Gr reinforced composite offers better mechanical properties as compared to that of other compositions. The wear rate and coefficient of friction also decreased with the addition of Gr and reaches its minimum value at 3 wt % Gr. A smooth graphite layer was observed in the worn surface of the 3 wt % Gr reinforced composite demonstrates superiority in terms of wear properties as compared to base material and other composites compositions.

Keywords: metal-matrix composites (MMCs), mechanical properties, wear, powder metallurgy

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1. INTRODUCTION

Recently, demand for high strength and lightweight components has increased significantly, mainly for aerospace and automotive applications. This provides the motivation to study and develop new materials that can satisfy this demand. Nowadays, Aluminum Matrix Composites (AMCs) have evoked a keen interest owing to their excellence in mechanical properties and strength to weight ratio as compared to the monolithic aluminum. In AMCs, Aluminum (Al) or its alloys are reinforced by dispersion of hard ceramic particles, substantially improving the different mechanical and wear properties as required in the service condition, making them attractive for structural applications [1].

The difficulty of using aluminum alloys in engineering applications is that they offer low wear resistance under insufficient lubricating conditions and may absorb the lubricating film on the sliding surface, which limits their use in tribological applications [2]. To improve the tribological properties, researchers have incorporated different materials in the Al matrix which have the self-lubricating properties. Among those, Graphite (Gr) is one of the most popular choices, and has been used widely to develop self-lubricating composites [3, 4]. Previous studies have reported a general trend of metal–graphite composite that the composite composed of small amount of graphite exhibit superior wear properties over the base material. Under dry sliding conditions, the metal/Graphite composites develop a continuous layer of solid lubricant on the tribosurface [5–8]. This layer forms due to the shearing of graphite particles present underneath the sliding surface of the composite, helping to reduce the magnitude of shear stress, diminish the plastic deformation in the subsurface region, prevent metal-to-metal contact, and act as solid lubricant between two sliding surfaces. Therefore, reducing friction and wear resistance of the composite [2]. Consequently, formation and retention of this tribolayer on the sliding surface controls the wear behaviour of the material. This depends on the nature of the sliding surface, environment and graphite content in the composite. Suresha and Sridhara [9] observed that wear resistance improved in Al–Gr composite with increase in speed due to the presence of the supporting tribolayer in between the worn surface and the disc. However, wear decreased with an increase in load and sliding distance due to the reduction in tribolayer. Moreover, Bansal and Shini [10] observed that the wear resistance of the Al359 alloy increased with graphite reinforcement for higher loading, sliding velocities and sliding distance conditions. It has been reported that an increase in graphite content in the aluminum alloy leads to a decrease in the wear rate of a composite [8]. Leng et al. [11] noticed around 20–50% reduction of tool wear with an increase in graphite content in SiC/Al composites. Additionally, Ames and Alpas [12] compared the wear properties of Al–SiC–3% Gr composite with Al–SiC composite at different loading conditions and observed that the addition of 3% Gr to the Al–SiC composite exhibits low wear rate over entire load range. Besides, Riahi and Alpas [13] studied the formation and role of tribolayer on the A356 Al–10% SiC–4% Gr and A356 Al–5% Al_2O_3–3% Gr composites and compared the behaviour with non-graphite reinforced composite. They found that more stable tribolayers formed on the contact surfaces of graphitic composites, which exhibited a higher transition from mild-to-severe wear at different loading conditions as compared to aluminum A356 alloy and non-graphite composite. However, many researchers have contradicted the results explained above. Baradeswaran and Perumal [2] investigated the wear properties of graphite reinforced Al7075 alloy. They varied the Gr content from 5–20 wt % and found that lower graphite content produces minimum wear rate. Guo and Tsao [4] also found that the wear resistance of 2 vol % Gr reinforced Al–SiC composite is superior as compared to 5 and 8 vol % Gr. These researchers explained that higher volume of Gr degrades the fracture toughness of the composite, hence affecting the friction coefficient.

Previous research has reported that the uniformity of the reinforcement particles in a fine-grained matrix improves the mechanical and tribological properties of the MMCs [14–18]. In general, the AMCs reinforced with ceramic particles or whiskers are fabricated by the liquid metallurgy or powder metallurgy [19–21]. However, AMCs produced by liquid metallurgy exhibit poor wettability of reinforcing particles with aluminum and form intermetallic compounds, accompanied by porosity at the particle-matrix interfaces [21–23]. Another drawback of these composites is their non-uniform particle distribution. Due to the non-uniformity of the particles, particle clustering occurs in the surface and cracks initiate in these clustering areas during conventional loading process [24]. Therefore, these composites usually show low mechanical and wear properties in service condition [19, 25]. To achieve the desired uniformity and avoid the formation of intermetallic compounds, powder metallurgy is an effective alternative process, as this technique offers more uniform dispersion of the reinforcing particles and ensures better wettability of the reinforcing particles with matrix metals. Components produced by this technique require minimal finishing and offer both technical and economic advantages, making them attractive for many applications in industry. Though this technique provides tremendous advantages, the effects of graphite addition in the tribological behaviour of the pure monolithic aluminum composite produced by powder metallurgy have rarely been studied. Hence, this study aims to evaluate this tribological behaviour. The effect of graphite content on the mechanical and tribological behaviour of the Al–Gr composite has been studied. The wear rate and friction coefficient under dry sliding conditions has been investigated and the optimum amount of graphite addition in Al has been evaluated.

2. MATERIALS AND METHODS

In this study, pure aluminum powder (99% purity) and flakes type graphite powder (99% purity) were used to fabricate an Al–Gr composite. The Al powder was used as the matrix material and Gr was used as reinforcement to act as a solid lubricant during wear by producing a thin layer between the contact surfaces. The average particle size of Al and Gr was 70 and 20 μm respectively. To investigate the effects of the quantity of the reinforcement graphite, three different compositions of the composite have been chosen (97% Al + 3% Gr, 95% Al + 5% Gr and 93% Al + 7% Gr). The raw powders were then mixed in a high energy ball mill (type RETSCH PM 100) for 2 hours. Polyvinyl Alcohol (PVA) was added (2% of the powder mass) to the powder mixture as a process control agent in order to avoid the agglomeration of the powder and prevent powder deposition on the walls of the vial and balls. The rotational speed of the ball mill was maintained 300 rpm to ensure the uniformity of the mixture. To check the uniformity of the mixture, microstructural analysis of the pure raw powders before mixing and after the milling process was conducted via Scanning Electron Microscopy (SEM JOEL model 6390) as shown in Fig. 1. After the milling process, a homogeneous distribution of the graphite particles was observed in the Al matrix as shown in Fig. 1c. The Al–Gr powder mixture was then compacted at room temperature. Compaction was performed in a single-die uniaxial hydraulic press (TOYO: Model TL30, capacity: 300 kN) with a nominal force of 250 kN. The load on the powder mixture was maintained for 30 s and then released. Subsequently, the green compact specimen was prepared. These specimens were very fragile due to their low cohesive strength; however, the materials were compacted strongly enough so that these can handle and transport to the sintering furnace.

The heat treatment of the green samples was carried out in a vacuum sintering furnace (BSO-1200G). The sintering temperature 630°C was used, based on the melting temperature of the aluminum. A heating rate of 5°C/min was maintained to set the temperature to its maximum value. Once the temperature reached its maximum value, a holding time of 120 minutes was maintained to stabilize the heat on the specimens. The samples were then cooled in the furnace until they reached room temperature. The schematic diagram of the compaction and sintering process is shown in Fig. 2. Sintered specimens were then polished to reduce the machining scratches and prepared for different mechanical testing and characterization.

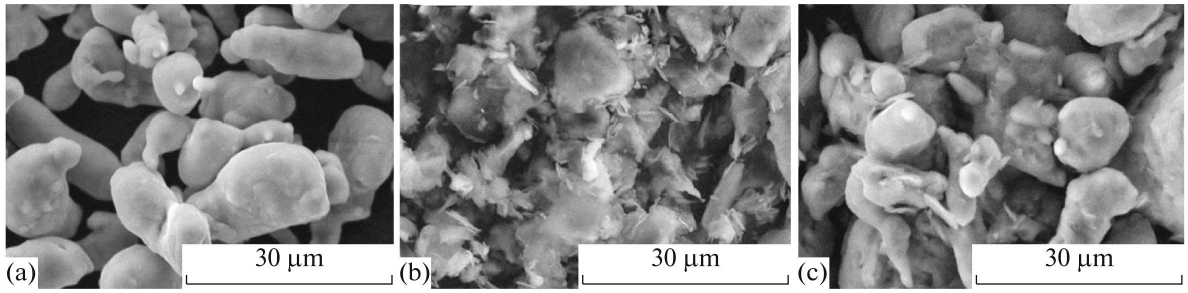

Fig. 1. SEM micrograph of the raw powders used to fabricate the composite (a) pure Al (b) graphite powder (c) Al–Gr powder mixture.

Microstructural analyses of the samples were carried out using a metallurgical microscope (OLYMPUS BX51M, Japan). The densities of the pure Al and the Al–Gr composites with three different percentage of Gr were measured in accordance with ASTM B-325, while hardness was measured on Vickers hardness tester (Wilson Hardness: Model 402 MVD, Made in USA). The load of 300 gf was applied for a duration of 30 s on all the specimens. The test was conducted at room temperature along the longitudinal axis. Ten measurements were taken on each specimen with an interval of 1 mm to avoid any effects of neighboring indentations. Finally, the mean value was taken as the Vickers hardness (HV) number. Uniaxial tension tests were carried out at room temperature in a universal testing machine (INSTRON 3369) as per the ASTM 08-8 standard. A 100 kN load cell was used to perform the experiment and the displacement rate was maintained at 0.016 mm/s. Moreover, the flexural strength of the Al–Gr composite was determined by using the conventional 3-point bending test to find the maximum load withstanding ability of the composites. The wear characteristics of the prepared composite samples were investigated using a pin-on-disc apparatus. A schematic diagram of the pin-on-disc wear test is shown in Fig. 3.

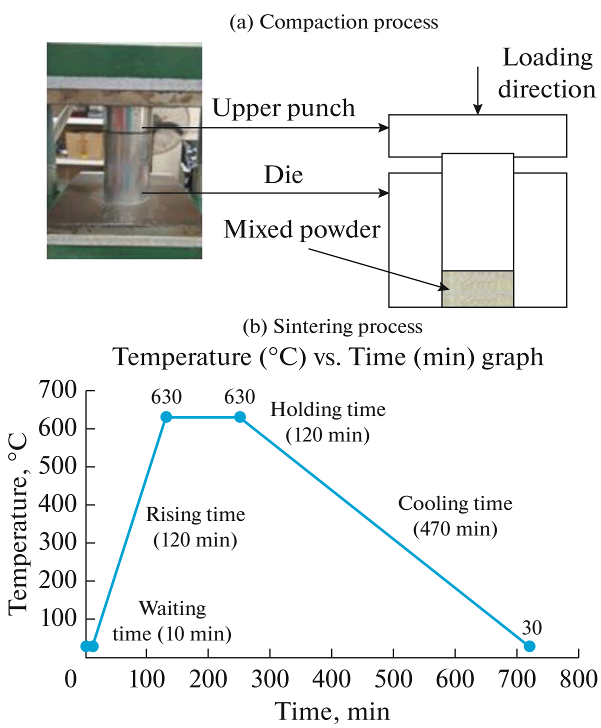

Fig. 2. Schematic diagram of (a) compaction process and (b) sintering process.

The tests were performed at room temperature following the guidelines of ASTM G99-95. Pins with 6 mm diameter and 50 mm height were used for the wear test. The pin surface was polished and rotated against an OHNS (Oil Hardened Nickel Steel) disc. The specimens were cleaned with ethanol before and after each run of the wear test. The tests were conducted with different sliding speed and different loading condition to investigate the relationship of wear rate with different load and sliding speed. 0.5, 0.8 and 1 m/s sliding speed and 10, 20 and 30 N loads were used for the process. A weight loss method was used to determine the wear rate. The weight of each specimen was measured using an electronic weighing balance with resolution of ±0.1 mg. The morphology of the worn surfaces was analyzed by SEM.

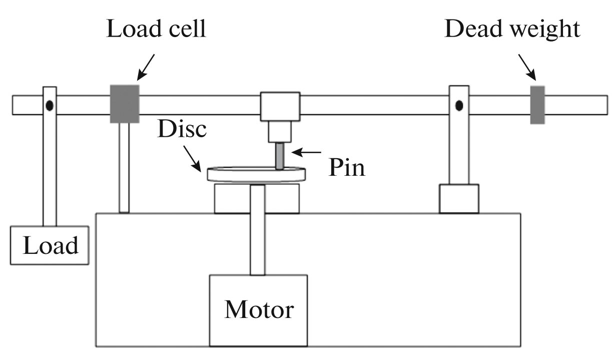

Fig. 3. Schematic diagram of Pin-on-disc wear test.

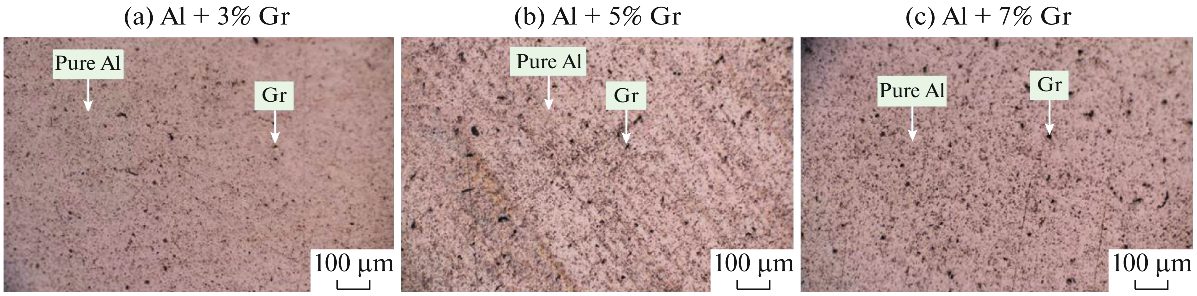

Fig. 4. Optical micrograph of composites (a) Al + 3% Gr, (b) Al + 5% Gr and (c) Al + 7% Gr.

3. RESULTS AND DISCUSSION

An optical micrograph of the microstructure of the Al–Gr composite with varying wt % of Gr is shown in Fig. 4. The white area of the figures represents Al matrix and the black spots represent Gr particles as indicated in the figures. A uniform distribution of Gr particles is observed in the aluminum matrix in all the samples. The uniform distribution of the reinforcing particles contributes to improved mechanical and tribological properties of the composites. No significant pores and surface cracks are found in the samples, which indicates reasonably proper bonding of Al matrix with the reinforcing particles during the fabrication process. Therefore, it can be concluded that the strong particle-matrix interfacial bonding is achieved during the fabrication of nanocomposites by powder metallurgy technique. Additionally, the variation of the density of the prepared composite samples is shown in Fig. 5. The results revealed that the addition of Gr particles to the Al matrix decreases the density of the composite; the higher the wt % of the Gr, the lower the density of the composite. Densities vary from 2.78 g/cm^3 at 0% Gr addition to 2.31 g/cm^3 at 7% Gr addition indicates 17% decrement of density from the pure Al.

This decrease in density of the composites is due to the low theoretical density of the Gr particles. The theoretical density of the Gr particle is 2.2 g/cm^3. Therefore, once it is added to the metallic aluminum matrix, it decreases the overall density of the composite. This phenomenon of density is in line with the study of Prashant et al. [26]. Moreover, in Fig. 6, the hardness values of the composite samples are presented. The Vicker's micro-hardness value (HV) declines as the content of Gr particles increase in the Al–Gr composites, and the lowest hardness is observed in the 7 wt % Gr reinforced composite. Around 41% reduction of hardness is noted in the Al + 7% Gr composite as compared to the pure Al. Graphite is soft and has low density and hardness values (25.49 HV) as compared to the hardness of pure Al (49.5 HV) and creates a weak bonding with Al.

Thus, the incorporation of higher weight percentage of Gr reinforcement results low hardness value of the Al–Gr composite. The same tendency of hardness was also observed by Hasan et al. and Akhlaghi et al. [27, 28]. Furthermore, to understand the tensile behavior of the prepared composites, a stress-strain diagram of pure Al and Al–Gr composites with different wt % of Gr reinforcement is presented in Fig. 7. It is observed from the diagram that tensile strength significantly reduces with an increase in the content of Gr reinforcement from 147.5 MPa at 0% addition of Gr particles to a minimum of 133 MPa at 7% addition of Gr particles. The presence of soft Gr particles act as

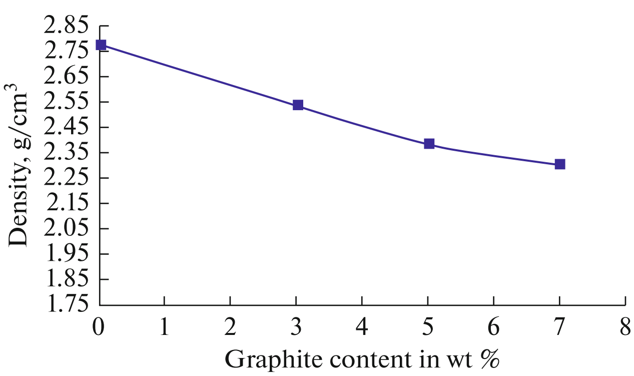

Fig. 5. Variation of density with different wt % of graphite.

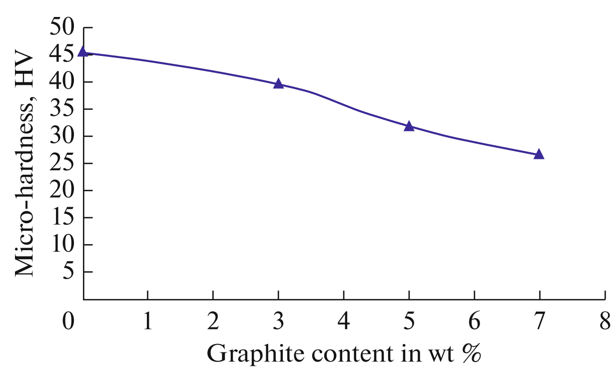

Fig. 6. Vicker's micro-hardness (HV) of composite with different wt % of graphite content.

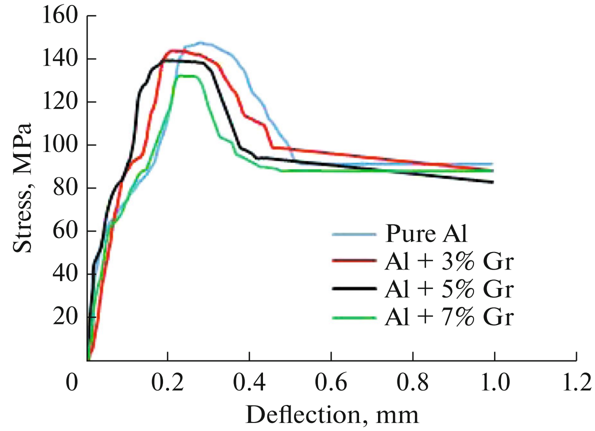

Fig. 7. Stress-strain diagram of pure Al and Al–Gr composite with varying wt % of Gr.

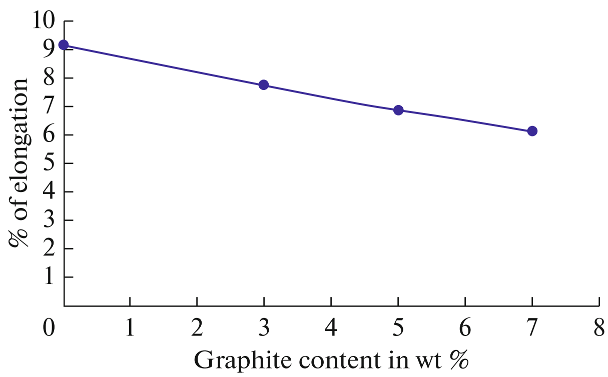

Fig. 8. % of elongation of the composite with different wt % of Gr.

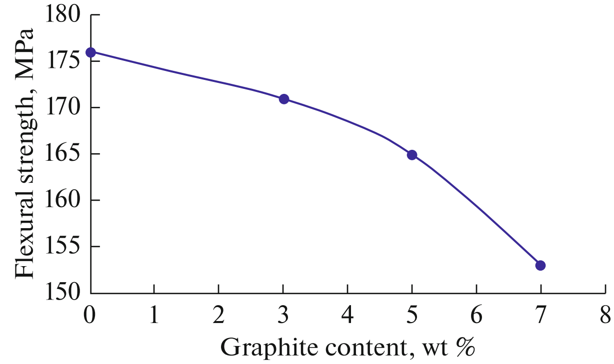

Fig. 9. Flexural strength of Al–Gr composite with varying wt % of Gr.

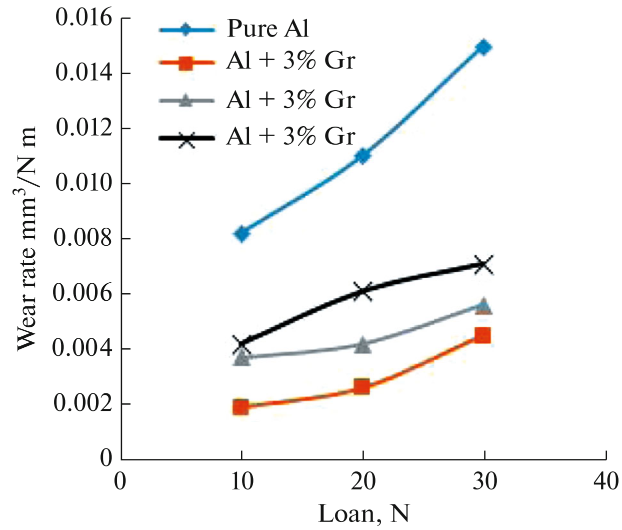

Fig. 10. Variation of wear rate with varying applied load.

an impurity and creates a weak bonding between matrix and reinforcement, reducing strength. Additionally, the elongation percentage as shown in Fig. 8 decreases with the addition of Gr in the composite. The brittle nature of the reinforcing particles (Gr) plays a significant role in decreasing the ductility of the composite. Graphite particles are soft but brittle in nature, thus integrating Gr particles in the Al matrix intensifies the brittleness of the composite which in turn drops the ductility of the composite. Moreover, as the content of Gr particles increases in the composite, it resists the flow ability of aluminum matrix and reduces the ductile aluminum alloy matrix content which results in the decrease in the percentage elongation of the composites. The flexural strength of the pure Al and Al-Gr composites are shown in Fig. 9. In this case also it is observed that the flexural strength decreases with increasing Gr content. The addition of Gr causes an increase in the tendency of crack initiation at the interface of graphite and matrix, which in turn deteriorates material properties and reduces strength. These results for tensile and flexural strength are in good agreement with other studies in this field [2].

The wear rate of the pure Al base material and Al–Gr composites with varying graphite content at different load is presented in Fig. 10. The wear rate of the base material decreases once Gr is added to it and the lowest wear rate was found in the composite composed with 3 wt % Gr as compared to other compositions. Beyond 3 wt %, the wear rate increases proportionally with increasing load, but the value remains lower than that of the base Al material. The Gr particles in the composite form a thin layer between the contact surface and act as a lubricant which diminishes metal to metal contact. Therefore, the wear rate decreases. This behavior was consistent with the outcomes reported by several previous researchers [10, 11]. Figure 11 represents the wear behaviors of pure Al and the Al–Gr composites with varying Gr content at different sliding speeds. It is observed that the wear rate of the composites decreases as compared to the base material once Gr is added. In this case, the minimum wear rate was noticed in the 3 wt % Gr sam-

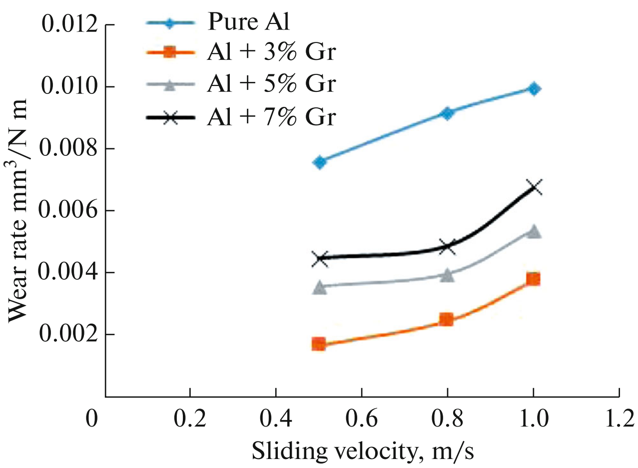

Fig. 11. Variation of wear rate with varying sliding speed.

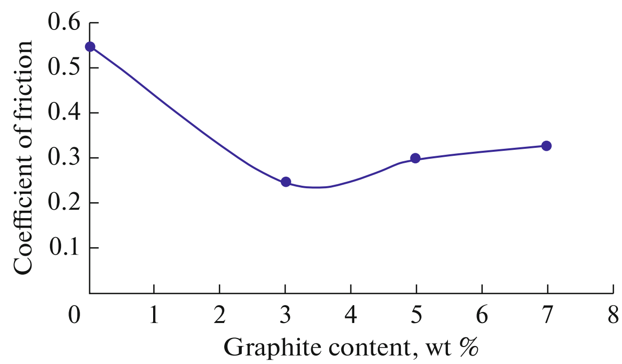

Fig. 12. Coefficient of friction with varying Gr content.

ples. Beyond 3 wt % Gr content, the wear rate increases; thus, it may be concluded that the 3 wt % Gr is the optimum value to obtain good wear behavior in the Al–Gr composites. The relationship of coefficient of friction of the base material and the composites with varying Gr content is shown in Fig. 12. The composites show low coefficient of friction as compared to the base material. The average coefficient of friction under dry sliding conditions of the composite with 3 wt % graphite is about 0.25. However, this value slightly increases for the composites with 5 and 7 wt % Gr particles. Once Gr is added to the composite, it forms a smeared Gr film, which acts as a solid lubricant and decreases the friction coefficient. As the Gr content increases, the thickness of the film increases which leads to the lowering of the friction coefficient. However, if the film becomes more Gr rich, then it forms porosity and cracks on the surface, which eventually restricts the wear properties and increases the friction coefficient of the composites. The composites with 5 and 7 wt % Gr may develop porosity and cracks on the surface, thus increasing the wear rate. To understand the wear mechanism, the worn surface of the wear samples of Al–Gr composite are characterized by SEM and the micrograph of Al-Gr composite with 3 and 5 wt % Gr is shown in Fig. 13. Several grooves and patches are observed in both the cases,

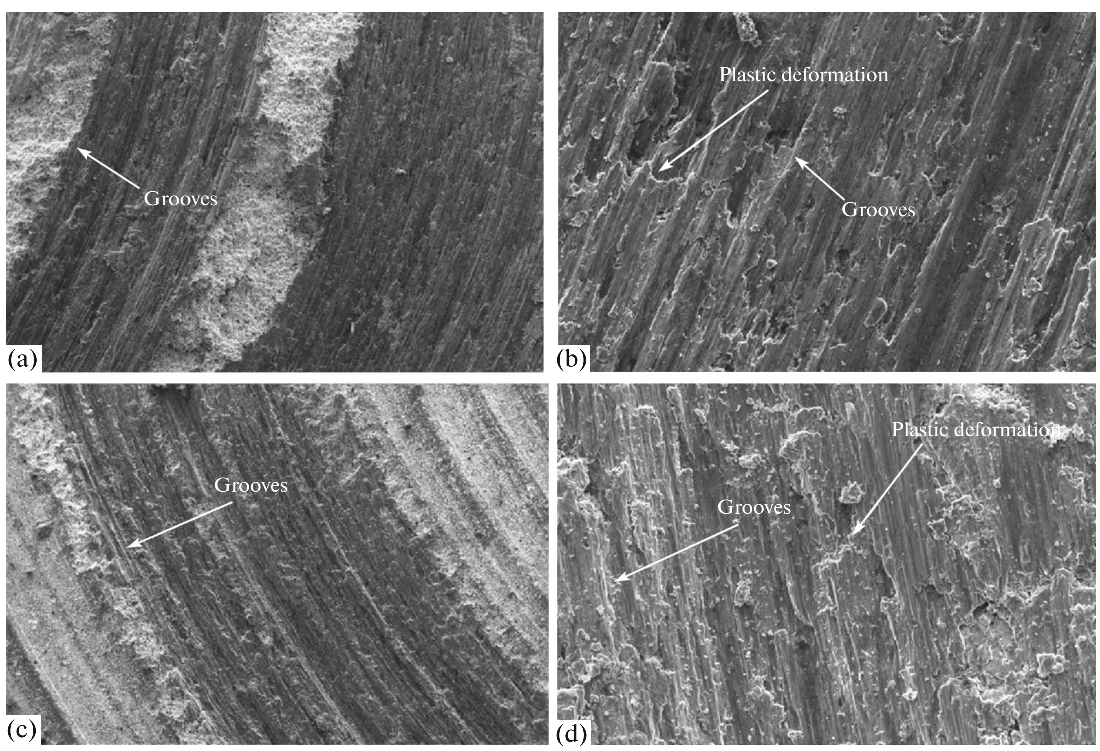

Fig. 13. SEM micrograph of the worn surface of the composite (a, b) Al + 3% Gr, (c, d) Al + 5% Gr.

which indicates that plastic deformation occurred in the composite surface. The morphologies of the worn surface indicate the existence of abrasion and delamination wear mechanism in these composites. However, the grooves present in the 3 wt % Gr reinforced composite are smaller in size as compared to those of the 5 wt % Gr reinforced composite indicates the smoothness of the wear surface. Moreover, a graphite layer is observed in the 3 wt % Gr reinforced composite which uniformly covers the entire worn surface of the composite. Therefore, preventing direct contact between the pin and disc and effectively reduce the friction coefficient. Hence, from the above results, it can be concluded that the addition of graphite to the base material significantly improves the tribological behaviour of the composite. Moreover, the Al–3 wt % Gr exhibits superior tribological properties to other wt % of Gr composites.

4. CONCLUSIONS

The mechanical and tribological behaviors of powder metallurgy processed Al–Gr composites with varying percentages of Gr have been thoroughly studied. In general, the addition of Gr decreases the mechanical properties of the composite as compared to the base material, but improves the wear behaviour. Mechanical properties including hardness, tensile strength, and flexural strength have been found to decrease with increasing Gr content, and 3 wt % Gr reinforced composite possesses superior mechanical properties. Moreover, the wear rate increased with increasing Gr content and the minimum wear rate was found in the 3 wt % Gr reinforced composite. The wear rate increased with increasing applied load and sliding speed. However, this rate was also lower in the 3 wt % Gr reinforced composite, indicating that the wear rate is optimized with the addition of 3 wt % Gr to the base material.

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