Characterization of Aluminum-Graphene-Graphite Hybrid Nanocomposites Synthesized Via Flake Powder Metallurgy

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ABSTRACT

Aluminium matrix composites (AMCs) developed for lightweight applications particularly in aerospace and automobile sectors due to their low density, high strength, acceptable ductility and good corrosion resistance [1, 2]. Graphene nanoplates (GNPs) became an attractive reinforcing agent for AMCs due to their high thermal conductivity, low coefficient of thermal expansion, high damping capacity and excellent self-lubrication properties [3]. Powder metallurgy (PM) is one of the most widely used processes in the fabrication of MMCs. Recently, a novel PM strategy called flake PM developed to fabricate MMCs with nano-laminated or hierarchical architectures. The name ''flake PM'' was derived from the use of flake metal powders, which could benefit the uniform dispersion of reinforcements in the metal matrices and thus result in balanced strength and ductility. Flake PM regarded as a suitable method for dispersion of nano aluminium oxides, carbon nanotubes, GNPs, and micron-sized B_4C particles in aluminium or copper matrix alloys [4].

In this study, aluminum-graphene-graphite (Al-GNPs-Gr) hybrid nanocomposites fabricated through a relatively new technique termed as flake powder metallurgy. In the first stage, In order to produce Al-GNPs powder mixtures containing different amounts (0.25, 0.5, 0.75 and 1.0 wt.%) of GNPs were ball milled along with semi-spherical Al powders for 6h and then cold pressed at 750 MPa and subsequently consolidated through hot extrusion at 480°C. The resultant Al-GNPs composites subjected to SEM and optical microscopy as well as macrohardness and porosity measurements. Then Al-GNPs-Gr hybrid nanocomposites containing different amounts of graphite (3, 5, 7 and 9 wt.%) and keeping 0.5 wt.% GNPs constant were synthesized via the same route as for Al-GNPs composites. A pin-on-disc wear testing tribometer used to carry out the dry sliding wear tests on these samples.

The results confirmed that the Al-GNPs composite containing 0.5 wt.% of reinforcing agent exhibited the maximum macrohardness together with minimum wear rate. SEM and optical microscopy images of composite samples confirmed that the reinforcing particles distributed uniformly within the layered structure (flakes) of the Al matrix. The results of sliding wear tests revealed that Al-0.5 wt.%. GNPs-9 wt.% Gr hybrid nanocomposite showed the minimum wear rate among the hybrid composites. However, Al-0.5wt.% GNPs nanocomposite showed the minimum wear rate among all the composite samples.

OBJECTIVES

In the present study, for the first time, microstructure, hardness and tribological properties of aluminum-graphene-graphite (Al-GNPs-Gr) hybrid nanocomposites fabricated via flake powder metallurgy technique investigated.

It was anticipated that optimized amount of GNPs addition to Al matrix could result in enhanced hardness values because of the hard nature of GNPs and simultaneously improve the tribological behavior of the Al-GNPs composite due to self-lubricating behavior of these particles.

In addition, to improve the tribological properties of composites further, different weight percentages of graphite flakes, added to the composite to serve as another solid lubricating material in the resultant hybrid Al-GNPs-Gr composite. It was predicted that selecting the optimized percentages of reinforcing materials could enhance the hardness as well as the tribological properties of the resultant hybrid Al-GNPs-Gr composites.

MATERIALS AND METHODS

In this research, commercially pure aluminum powder (> 99% Purity) with a semi-spherical morphology in the size range of 53-125 µm was used as the matrix alloy. GNPs (>99.5% purity) with a thickness of 2-8 nm, in 3-6 layers and a diameter of 4-12 µm and flake graphite powder particles in the size range of 44-88 µm were used as the reinforcement materials. GNPs along with as-received Al powders co-milled for 6h (15 min resting time at 1h time intervals to prevent excessive heating) using a two chamber planetary ball mill (PM2400) with stainless steel balls (ϕ=10mm) and a ball-to-powder mass ratio of 15:1 in argon atmosphere at 300 rpm. 1.5 wt.% of stearic acid was used as the Process Control Agent (PCA). The weight percentages of GNPs and Al powders were selected in a way that composite powders containing 0.25, 0.5, 0.75 and 1.0 wt.% of GNPs were produced. For preparation of hybrid composites containing 3, 5 ,7 and 9wt.% graphite, specified amount of graphite flakes were added to 6h ball milled Al-0.5wt.% GNPs and ball milled for another 5min in the same conditions. Ball milled powders (Al flakes with incorporated reinforcements) were heated at 100℃ for 30 min to remove moisture. Then powders stacked in a steel mold using an air column (a glass tube h= 300 mm and ϕ=25mm), to ensure that the flakes are laying on each other by their largest surfaces. Cold pressing performed at 750 MPa on a single acting 45t hydraulic press. The compacts (ϕ=25mm and h=20 mm) were hot extruded at 480 °C (heating rate of 20 ℃/min) at speed rate of 36 mm/min and ratio of 1:11 to obtain 8 mm diameter composite rods. Both the as-received Al powders as well as 6h-milled Al powders cold pressed using the above-mentioned parameters and sintered at 600 °C for 1h in a resistance tube furnace to serve as the reference samples.

Density of samples measured by Archimedes method using a scale with 0.0001g accuracy. The porosity of samples calculated by considering their theoretical density. The density of Al and graphite assumed as 2.7 g/cm³ and 2.2 g/cm³, respectively. Density of the composites calculated using the law of mixtures.

Macrohardness of the samples on their horizontal cross-sections measured using a Vickers macrohardness tester (Innova Test-Nexus 4302) with 5 kgf load. For hardness measurements, the average value of five hardness measurements conducted on each specimen considered.

Dry sliding pin-on-disk wear tests were carried out on the samples using cylindrical pins (ϕ=8mm and h=15 mm) and an AISI 52100 steel disk (ϕ=40 mm and h=5 mm) with about 800 Vickers hardness. The surfaces of samples (pins) and disks were ground with silicon carbide papers, cleaned with acetone in an ultrasonic bath for 10 sec and dried. Samples and disks weights were measured before and after each test and the worn weights were reported. The weight loss measured with an accuracy of 0.1 mg, and then converted to volumetric wear rate using the measured density of each material and the total sliding distance.

RESULTS

Due to the hard nature of GNPs, increasing the weight percentage of GNPs to 0.5wt.% enhanced the macrohardness value of hot-extruded Al-GNPs composites compared to those without GNPs addition. However, adding further GNPs to the matrix reduced this characteristic by increasing porosity and expanding GNP agglomeration within the matrix. Furthermore, the addition of 0.5wt.% GNPs dramatically reduced the wear rate of the composite sample compared to the unreinforced counterpart, owing to its lower porosity and higher macrohardness value.

As Figure 1 shows the porosity of Al-0.5wt.%GNPs-Gr hybrid nanocomposite has decreased with graphite addition. The increased percentage of graphite as a solid lubricant material in the powder mixtures decreased the particles-die wall friction and friction between the particles during cold pressing and subsequent hot extrusion. Therefore, movement and rearrangement of particles facilitated, resulting in increased density and decreased porosity. However, the presence of non-deformable graphite particles in the mixtures can also lead to deterioration of densification as these particles do not deform plastically during consolidation. It seems that by using up to 9wt.% of graphite flakes at the set of experimental parameters used in this study, the lubricating effect of graphite in enhancing densification has been dominant over its negative effects.

Figure 2 shows the effect of graphite addition on the macrohardness values of Al-0.5wt.%GNPs-Gr hybrid nanocomposite samples consolidated by hot extrusion. It could be seen that increasing graphite up to 9wt.%, increases the macrohardness values by a small slope. The decreased porosity of such composites with their graphite content (Figure 1) contributed in increased macrohardness values to some extent.

Wear test results (Figure 3) have shown that addition of only 3wt.% graphite, results in a vast increase in the wear rate of composite. By considering the porosity (Figure 1) and macrohardness (Figure 2) data related to these samples it was expected that Al-0.5wt.% GNPs-3wt.Gr hybrid composite, due to its lower porosity combined with its higher hardness exhibit even lower wear rate than the sample with no graphite addition. This extreme increase in wear rate is probably related to easily detachment of Al flakes from the wearing surface due to presence of graphite flakes located between the Al layers which results in inferior bonding between two adjacent Al layers during consolidation. By only considering this effect, it is expected that the increased graphite content in excess of 3wt.% should result in more wear rate values. However, as seen by increasing graphite content to 5wt.%, a sharp decrease in the wear rate occurred and by further addition of graphite up to 9wt.%, the wear rate values decreased continuously with smaller slope. It is clear that the wear rates of the all the hybrid composites are considerably higher than that of the Al-0.5wt.% GNPs composite with no graphite addition. SEM images of the worn surfaces of Al-0.5wt.% GNPs-Gr hybrid nanocomposites with different graphite contents are shown in Figure 4. The worn surface of composite with 3wt.% Gr (Figure 4-a) is rough and consists of large and clear grooves, which confirms the high wear rate of this sample due to severe plastic deformation occurred during wear test. The graphite present in aluminium matrix acts as a solid lubricant material by smearing on the surface and formation of a solid lubricant-rich film on the tribo-surface, thereby reducing the friction and wear rate by preventing metal-to-metal contact at the sliding surface. The worn surface of Al-0.5wt.% GNPs-5wt.%Gr hybrid nanocomposites (Figure 4-b) is covered with a black film and the grooves are smaller in comparison to the composite with 3wt.% graphite addition. By increasing of graphite content, the thickness and area fraction of this lubricating film on the wearing surface increases (Figures 4 c & d) and the probability of metal-to-metal contact decreased.

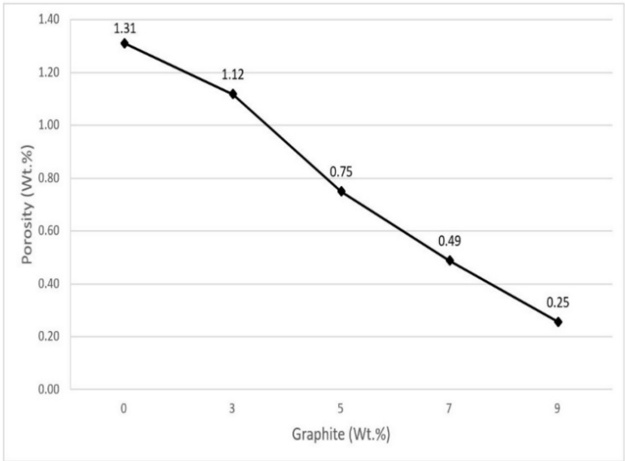

Figure 1: Effect of graphite flakes on porosity of hot-extruded Al-0.5wt.% GNPs-Gr hybrid nanocomposite.

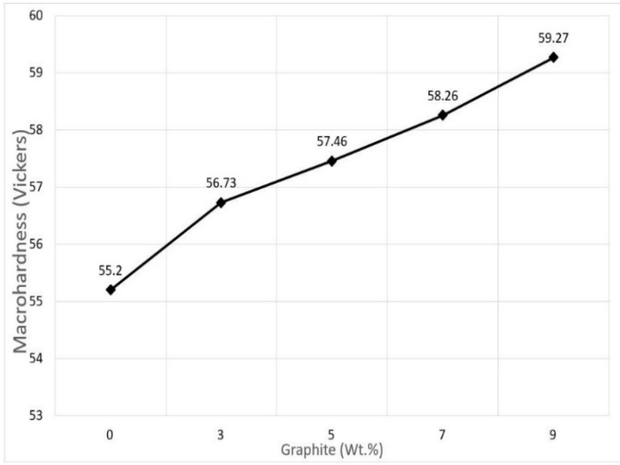

Figure 2: Effect of graphite on macrohardness values of hot extruded Al-0.5wt.% GNPs-Gr hybrid nanocomposites.

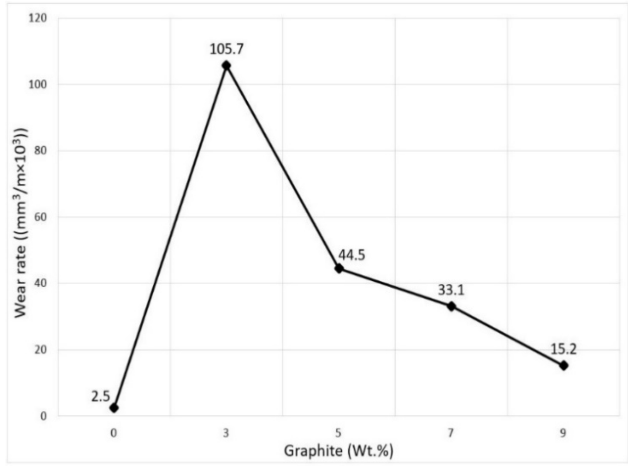

Figure 3: Effect of graphite addition on wear rate of Al-0.5wt.% GNPs-Gr hybrid nanocomposites.

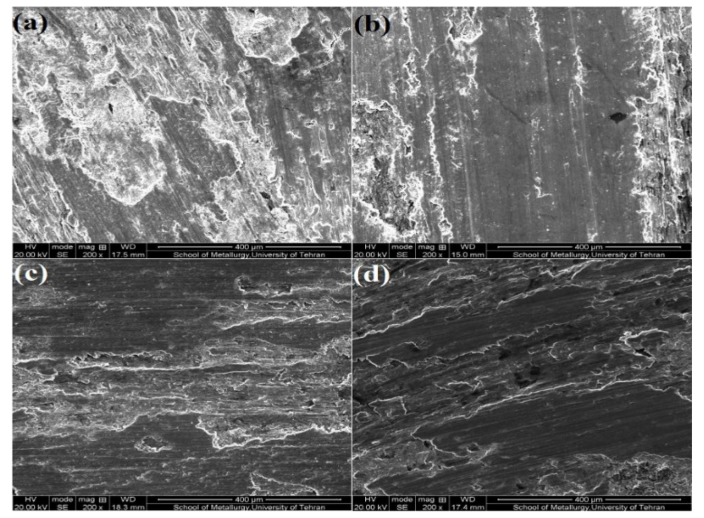

Figure 4: SEM images of worn surfaces of Al-0.5wt.% GNPs-Gr hybrid nanocomposites consolidated by hot extrusion containing (a) 3wt.% (b) 5wt.% (c) 7wt.% and (d) 9wt.% of graphite.

CONCLUSIONS

- Addition of up to 0.5wt.% of GNPs to Al matrix, results in increased macrohardness value of hot-extruded Al-GNPs composites as compared with those with no GNPs addition, attributable to the hard nature of GNPs. However, further GNPs addition deteriorated this property due to increased porosity and extended agglomeration of GNPs within the matrix of these composites.
- The porosity of hot-extruded Al-0.5wt.%GNPs-Gr hybrid nanocomposite decreased gradually with 3-9wt.% graphite addition due to self-lubricating effects of graphite. The decreased porosity of such composites with their graphite content contributed in increased macrohardness values of these composites.
- Addition of 0.5wt.% GNPs significantly reduced the wear rate of the ball milled hot extruded composite sample as compared to its unreinforced counterpart attributable to its lower porosity combined with its higher macrohardness value.
- Addition of only 3wt.% graphite, resulted in a significant increase in the wear rate of ball milled hot extruded Al 0.5wt.% GNPs composite despite of its lower porosity combined with its higher hardness. This attributed to easily detachment of Al flakes from the surface during wearing test due to inferior bonding between the adjacent layers of Al induced by incidence of graphite flakes. However, while all the hybrid composites exhibited higher wear rates than the Al-0.5wt.% GNPs composite with no graphite addition, the increased graphite content in the range of 3 to 9wt.%, resulted in continuous decrease in the wear rate values. SEM studies revealed a self-lubricating layer covering the worn surfaces of hybrid composites that extended by increased graphite content. This effect dominated the detrimental effect of graphite addition to some extent.

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