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MECHANICAL AND TRIBOLOGICAL PROPERTIES OF AA2124-GRAPHENE SELF LUBRICATING NANOCOMPOSITE

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Abstract

In this paper AA2124/graphene self-lubricating nanocomposites with different graphene addition of 0.5,3 and 5%wt. were prepared using P/M technique. A combination of cold compaction and hot extrusion (H.E) at ~0.45Tm were employed for fabrication of the nanocomposites. Addition of graphene significantly increased the compressive strength and hardness of the composites, while poor results were obtained for the ductility at room temperature. The microstructures of the composites were studied using OM and SEM. The effects of graphene addition on the friction and wear performances of the nanocomposites at room temperature in air in sliding against plain AA 2124 were investigated for the HE conditions using a pin-on-disk tribometer. Results showed that the wear rates of AA21224 could be remarkably reduced when 3wt% graphene is added and when cold compaction followed by HE at relatively low temperature was employed.

I. Introduction

Graphene, the first truly two-dimensional crystalline material recently identified and analyzed, is a single atomic layer of carbon where sp2 hybridized carbon atoms are arranged in a hexagonal lattice structure [1]. Since its isolation in 2004, it has been studied for several applications due to its unique physical properties, which attracted the attention for area related to electronics [2,3]. One promising field in the application of nanoscale materials such as graphene is their extraordinary strength and light weight, which made them suitable reinforcement candidates for ultrahigh strength nanocomposites [4]. Considered to be the thinnest and strongest material discovered, graphene addition to the various matrices is expected to improve the composites performance and reliability due to the enhanced mechanical properties and hence cost effectiveness compared to other conventionally reinforced composites. Due to the ease of fabrication and the promising results, graphene has been investigated as reinforcement in polymer matrix composites [5, 6]. Only few researches investigated the effect of graphene in metal matrix composites due to the complex microstructure and difficulties in dispersion. Aluminum alloy 2xxx series are used in high technology areas such as the construction of the internal structure of aircrafts and tank trucks due to their high specific strength and Young's modulus [7]. Ultrahigh strength/tough AA2xxx series alloys are also used for cryogenic tanks on space shuttles [7]. Conversely, Aluminum alloys have low resistance to the wear. Jingvuve wang *et al*., reported the fabrication of aluminum composite reinforced with graphene nanosheets [8], where Al flakes, modified by polyvinyl alcohol, were added to it graphene oxide via mechanical stirring. The composite powders were heated to decompose the poly vinyl alcohol and reduce the graphene oxide nanosheets to graphene. The graphene/Al composite powders were consolidated a conventionally in Argon atmosphere at 580 ^{o}C for 2 h, followed by hot extrusion at 440 ^{o}C. The 0.3wt.% addition to Al matrix resulted in 62% enhancement in tensile strength compared to the unreinforced matrix. Stephen F. *et al*., fabricated Composites of graphene platelets and powdered aluminum using ball milling, hot-isostatic pressing and extrusion [9]. The Al/graphene composite showed decreased strength and hardness compared to Al/CNT composites due to the formation of aluminum carbide with the graphene filler.

Due to technical and economical factors, manufacturing areas require self lubricant material, which can work under harsh sliding conditions. Many groups of researchers studied the influences of graphite particles addition on the tribological properties of aluminum alloys. Aluminum 6061 was cast with 5, 10, 15 and 20wt.% graphite followed by heat treatment (T6 condition) [10]. A Dry tribological test was conducted at 0.12 MPa for 250 meters and velocity 0.5m/s. The results showed that graphite addition decreased the wear rate (mm/mm^3) since it provided a solid layer between the two contacting surfaces. Self lubricating material as produced via employing milling technique to attain a homogeneous dispersion for the graphite particles in the Aluminum 6061 matrix [11]. The milled powders were compacted then extruded. Tribological property investigation revealed the increasing in wear resistance with increasing in milling time due to the fine dispersion of graphite in the aluminum matrix.[11]

In the current work fabrication of graphene/AA2124 nanocomposites was conducted to evaluate the influence of graphene percentages on the mechanical and tribological behavior. Milling of mixed AA 2124/graphene powders followed by cold compaction and hot extrusion techniques were employed for consolidation at the lowest temperature possible to achieve the highest relative densities. The wear rate and weight loss in mg were investigated and compared to the plain aluminum alloy 2124 fabricated and tested at the same parameters.

2. Experimental Procedure

AA 2124 powder with average particle size of 45μm and average crystallite size of 87 nm was supplied by the Aluminum Powder Company limited (APC). The AA 2124 powder chemical composition is Al-3.9 Cu-1.5 Mg-0.65 Mn-0.1 Si-0.1. Graphene platelets supplied by SkySpring Company (USA) with average particle size of 15μm and monolayer thickness between 5-10 nm were employed as a filer in the Al-matrices. Mixing AA2124 powder with the graphene nanosheets was carried out in a turbula mixer at maximum speed of 96 rpm for 60 minutes. Graphene layers were stabbed into AA2124 particles forming clusters. High energy mechanical milling in Retsch 400MA was then carried out in steel jars containing steel balls of variable diameter between 8.5 and 10 mm and 15:1 ball to powder ration (BPR). The Milling speed used is 400 rpm for 2 hours. Ethanol was added as process control agent (PCA) with 0.2 wt.%. The powders were enclosed in argon atmosphere to prevent contamination. Figure 1a shows scanning electron images for AA2124 powder particles and graphene platelets investigated in the study in the as received condition and mixed for one hour using turbula mixer. Figure 1b shows an image for the milled composite powders which shows the disappearance of the graphene nanosheets and the formation of nonuniform particles of aluminum covered by graphene layer. The milled powders were consolidated via conventional cold compaction in a heat treated tool steel die with a bore diameter 10 mm at pressure 525 MPa using a 100 ton ARMSTRONG hydraulic press. Samples were cold compacted under pressure 525 MPa followed by sintering at 305°C then extruded with an extrusion ratio of 2:1.

Density measurements were conducted using a Mettler Toledo XS 205 digital densitometer. The hardness test was done for samples that were hot compacted and those that were extruded at load 9.8 N by Vickers macro hardness and Mitutoyo MH Series 810-128A. The sliding wear test was carried out using a pin-on-disc testing machine with 73mm diameter stainless steel disc. Sliding speed was 300 rpm the sliding distance covered was 1000 meter under 100 N applied load. Specimens were 7.5mm in diameter and 10 mm in length. The specimens' surfaces were ground (400-1200 grit/cm^2) and polished before testing. Structural evolution of the consolidated discs was investigated using optical and scanning electron microscopy. A field emission scanning electron microscope (FESEM) (LEO supra 55) was used. The extruded samples, after being mounted, ground, polished and etched in Keller solution, were imaged using the Leica optical microscope. Wear tested samples were also investigated using optical and SEM.

3. Results

As mentioned in the experimental section, two methods for mixing of AA2124 with graphene were investigated to achieve the best dispersion for graphene in aluminum matrix. The graphene nanosheets can be clearly distinguished in between the particles of AA2124 mixed powders via turbula mixer at 96 rpm for 1 hour, while milling of the powders at 400 rpm for 2 hours produced clustered Al particles wrapped with the graphene sheets as shown in Figure 1a and b, respectively. The milled, AA2124/graphene average particle size was about 22.4 μm.

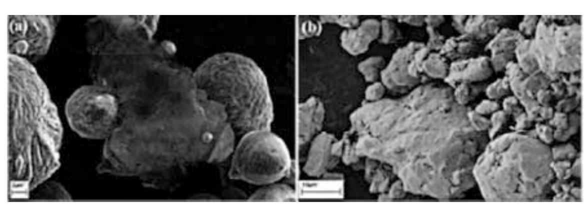

Figure 1. AA2124/Graphene nanosheets mixture after (a) Mixed and (b) milled.

Cold compaction followed by hot extrusion at 305°C produced highest density for the plain AA2124 alloy consolidates, while density of the extrudates decreased with increasing graphene content. The relative densities of the 0, 0.5, 3, and 5 wt % graphene – AA 2124 nanocomposite are represented in Figure 2. Coating the individual aluminum particles with graphene layers during milling hindered the fresh metallic surfaces of the aluminum particles from diffusion which explains the deteriorated density measured with increasing graphene content.

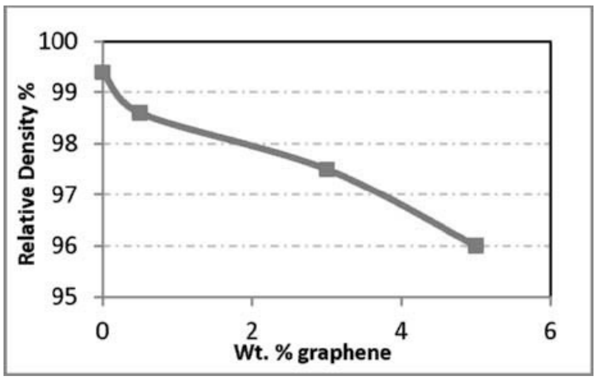

Figure 2 Relative density variations as a function of graphene addition to AA 2124 nanocomposite.

On the other hand increasing graphene content influenced the hardness variation so that the highest hardness occurred at 3wt.% graphene compared to lower or higher graphene content including the plain milled AA2124 powders. Figure 3 shows the variation VHN as a function of increasing graphene-content. 3 wt.% graphene composite produced 47.5 % increase over the plain AA 2124. Structural investigation is necessary to understand the current observations.

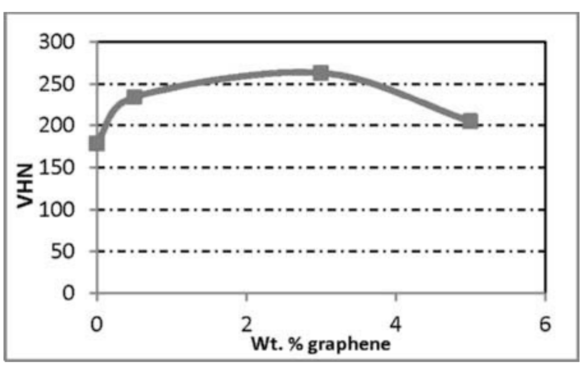

Figure 3. Vickers macrohardness variation as a function of graphene content in AA2124 matrices

As shown from Figures 3 and 4, the 3 Wt % graphene – AA2124 composite displayed the lowest wear rate and the lowest weight loss in the dry wear test, respectively. Samples of the same composite tested under 50N loads, 20 HZ frequency, S of 2mm and tested in paraffin for 5 hrs, reported 0.23 mg weight loss compared to 0.33mg for the plain matrices. 5wt% graphene composite extrudates suffered most from wear rates and weight loss, respectively.

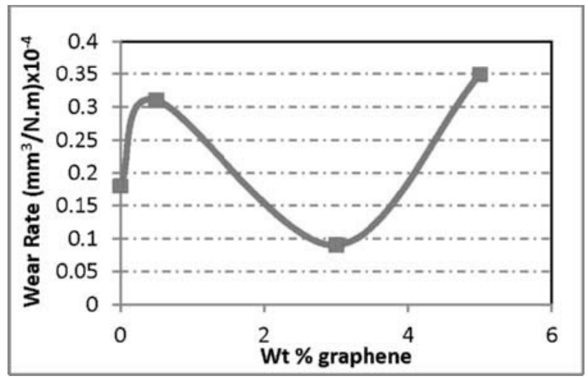

Figure 4. Wear rate variation as a function of graphene content in AA2124 matrices.

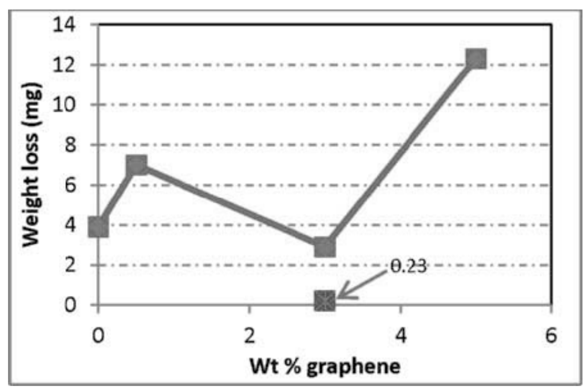

Figure 5. Dry Weight loss variation as a function of graphene content conducted compared to wet weight loss of the 3 wt % in AA2124 matrices.

Figure 6 shows optical micrographs for the AA2124 with and without graphene addition post hot extrusion on sections cut parallel and perpendicular to the extrusion direction. It clear that the elongated grains in the plain AA2124 (Fig. 6b) are decorated with fine dark particles aligned along their boundaries in the extrusion direction. Those particles are suggested to be the fragmented Al_2O_3 films formed on the Al-particles' surfaces during the milling operation. On the other hand, thicker dark black films are observed encasing the elongated Al-grains representing graphene [12].

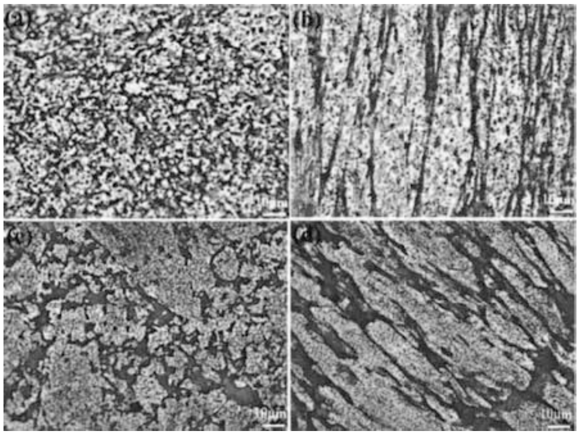

Figure 6. Optical micrographs showing the hot extruded sections cut perpendicular and parallel to the extrusion direction for (a, b) AA2124 and (c, d) AA2124-3wt.% graphene composite.

Figure 7 shows representative SEM images for the worn surfaces of the AA2124 matrices containing 0.5, 3 and 5wt% graphene compared to the plain ones. Longitudinal grooves can be observed clearly on the worn surfaces due to the ploughing effects [13] Mild scratches can be observed on the surface of the 3wt% graphene composite worn surface (Fig. 7c) compared to sever scratches, craters, delamination and microploughing especially for the plain 2124 matrices and 0.5wt.% graphene composite (Fig 7a, b, respectively).

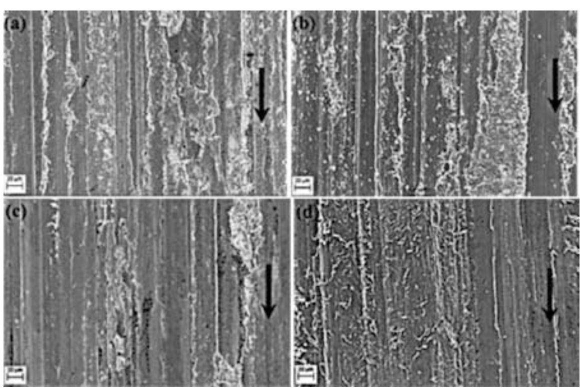

Figure 7. SEM micrographs for AA2124 worn surfaces (a) 0, (b) 0.5, (c) 3 and (d) 5 wt.% graphene nanocomposite.

Relatively shallow parallel grooves and ridges formed on the worn surfaces of the AA21124-5% graphene is an indication of microplouging and sever plastic deformation wear mechanism.

Figure 8 shows higher magnification SEM images for the worn surfaces of AA2124- 0, 3 and 5wt% Graphene nanocomposite. Plain AA2124 matrices (Fig. 8a) suffered clearly from the formation of debris entrapped in between delaminated surfaces which was absent in the worn surfaces of the nanocomposite (Fig 8 b, c). Such debris could be alumina fragmented films or strain hardened particles from the heavily milled consolidated powders which were detached under the load during the wear test [14].

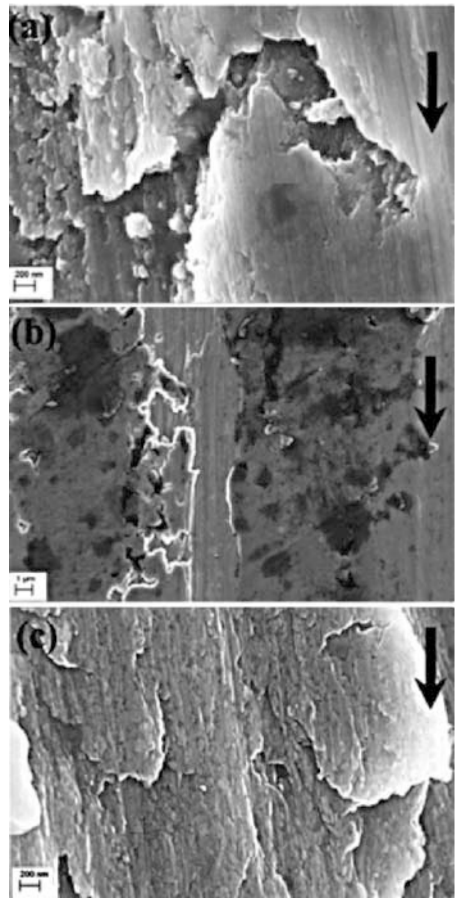

Figure 8. SEM micrographs for the worn surfaces of AA2124- 0, 3 and 5wt% graphene nanocomposite

The worn composite surfaces with the high graphene content of 5wt% (Fig 8c) show sever delamination in the direction of sliding which explains the significant increase in wear rates and weight loss observed in Figures 4 and 5, respectively. Conversely, 3 wt.% graphene composite show very smooth surfaces covered with graphene lubricating layer. The formed layer reduced friction and wear. The worn surface of graphene-containing composite also shows the ploughed grooves due to the relatively soft nature of the lubricant film [15].

4. Conclusions

AA212-graphene nanocomposite mixed and milled powders were successfully consolidated into discs. Milled and hot extruded nanocomposite powders were tested for their hardness and tribological properties. Density of the consolidated discs decreased with increasing content of graphene-content, while the VHN was reported highest for the 3 wt.% graphene nanocomposites. This was reflected on the enhanced tribological properties, where the lowest weight loss and wear rate were achieved. Plain AA2124 matrices suffered from the formation of debris entrapped in between delaminated surfaces. Shallow parallel grooves and ridges formed on the worn surfaces of the AA21124-5% graphene is an indication of microplouging and sever plastic deformation wear mechanism. Severe delamination was also observed on the worn surfaces of the 5 wt.% graphene nanocomposite. Conversely, 3 wt.% graphene composite show very smooth surfaces covered with graphene lubricating layer. The formed layer reduced friction and wear.

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