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Chapter 7

Tribological Aspects of Graphene-Aluminum Nanocomposites

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Abstract

Graphene is a new class of material in carbon group with strong $sp^2$—hybridized 2D-sheet like nanomaterial. In order to make an effective utilization of their astounding properties, they are currently used in the form of reinforcements in various proportions in metals and its alloys to fabricate the nanocomposites. Graphene is incorporated in oil and grease at nano range that results in higher load-carrying capacity compared with that of raw grease and oils without additives, which shows that graphene possesses self-lubricating capacity. Graphene is a planar sheet-like structure (2D), with more contact surface area in the developed composites that can make them suitable for industrial applications with well-established tribological performance. The novelty of this work focuses on the role of graphene addition in enhancing the wear performance aluminum composites to replace the conventional materials by graphene composite combinations. The current chapter explains the processing and tribological performance of graphene-aluminum composites and its effect with various hybrid combinations of MWCNT/SiC/Al$_2$O$_3$. Dispersion of graphene is carried out through ultrasonic liquid processor followed by ball-milling aluminum powder. Thus prepared precursors are vacuum-pressed and microwave-sintered. Graphene in the nanocomposites has resulted in significantly improving the tribological properties, where it gives the wear resistance by creating a solid, lubricant layer between the sliding surfaces.

Keywords: graphene, aluminum, nanocomposites, tribology

1. Introduction

Recent research advancements in the field of materials, development of strengthened materials without compromising weight factor, are very much fascinating. Due to evolution
in the materials and processing methods, it is required to study the new class of materials and its unusual blends to improve the properties [1–3]. The significance of composites materials technology is the conglomeration of important features of base metals/matrix and the reinforcements. The technology enables achieving high-strength materials without losing the ductility and density, besides, overcoming the drawbacks of base materials by providing viability to add one or more high-strengthened particles and platelets. The necessity for mending the various properties and improved tribological performance will be governed by its applications in addition to various operating conditions [4, 5]. Most of the metal matrix composites are fabricated through ductile materials such as titanium, copper, aluminum, nickel, and its alloy. Such composite materials are extensively taking a role in miniature components of automobile, defense, and huge aerospace structural applications [6, 7]. Ceramic particulates such as silicon carbide, alumina, and boron nitride are the commonly employed reinforcements for the metal matrix composites (MMCs) [8, 9]. The particulate reinforcement trend gave rise to enhanced material properties under appropriate contents that are processed through advanced fabrication techniques compared with its monolithic [10]. Further, MMCs can be sorted out according to the type of reinforcements, namely whiskers (fibers), platelets, or particulates and its physical form with continuous and orientation configurations. In general, whiskers-reinforced and continuous fiber MMCs with advanced fabrication techniques become a promising cost-effective and light-weight engineering material from the past decades [11, 12]. In the recent years, the trend of research is on combinations of advanced materials and new forming methods to synthesis metal matrix composites (MMCs). However, substantial improvement of the aluminum and its alloy-based composites has conquered various manufacturing and industrial sectors. Further, these composites have been widely adapted in various aerospace and automobile industries because of light weight and high strength to weight ratio with improved thermal and electrical properties that are processed through the classical ingot (casting) route [13, 14].

Currently, demands for alternate materials are massive, mainly in various engineering sectors and military applications to facilitate higher payloads and more economical [15, 16]. In order to attain successful fabrication of this material with enriched properties, various permutations of new and advanced materials with cutting-edge processing method are to be adopted [17, 18]. Particulate technology (powder metallurgy) is one such feasible technology that provides the integration of various novel and new combination of reinforcements that can fuse through innovative processing method. The principal element in any composite material assimilating with nanoparticles comprises homogeneous distribution, type of boundary bond, and the interaction of nano reinforcement [19–21].

The materials' research field had been abstracted to find various carbon and its allotropes as reinforcements. Graphene being 2D-sheet like nanomaterial is endowed with extreme strength (tensile strength 130 GPa) in a carbon group that was coined by Andre Geim and Konstantin Novoselov experimentally during 2004 [22, 23]. Further, graphene is an elementary building block for several graphitic materials such as three-dimensional material graphite, single and multiwalled carbon nanotubes (CNTs, one-dimensional), fullerenes (C60, zero-dimensional) [24]. It is strong sp²-hybridized 2D-nano scale material (sheet like morphology) that is well recognized for its extreme strength. Moreover, it got inspiring attention because of its exceptional physical and
mechanical properties, which includes elastic modulus (up to 0.5–1 TPa); thermal conductivity (up to 5.3 \times 10^3 \text{ Wm}^{-1}\text{ K}^{-1}); tensile strength (up to 130 GPa) in the field of research [25]. Figure 1 shows a distinctive molecular model of single-atomic-layer graphene flake with many other graphitic forms. Carbon nanotubes (CNTs) also have emerged as materials with unique properties greater than those of any available conventional material [26]. Carbon nanotubes (defect-free), both multiwalled nanotubes (MWNTs) and single-wall nanotubes (SWNTs) have superior tensile strengths (~90 GPa) and elastic moduli (~0.6 TPa). Carbon nanotube (CNT), graphite, and fullerenes were used in base metals such as Al, Cu, Mg, and their alloys [27, 28]. Some of the results are found to have significant improvement in the mechanical properties on CNT-reinforced MMCs. But these composites subjecting to various challenges, including uniform distribution of CNTs in the matrix materials, lower surface contact area, and wettability, have been among the major concerns [29].

Initially, graphene preparations are carried out by breaking the graphite into graphene through a liquid phase exfoliation or mechanical cleavage method. An other equally common method is chemical vapor deposition (CVD) [30]. Compared to other physical forms of carbon materials such as CNTs and graphite, graphene has been anticipated to outperform its competitors due to its distinctive properties and has great latent in developing the nanocomposites. So the requirement was limited to microscale aggregate without concerning about mechanical properties and strengths. But the excellent mechanical properties of carbon-based graphene are yet to be taken advantage of in metal and its alloy matrix composites [31, 32]. The challenges in synthesis and production of its alloy—graphene composites remain similar to that of ceramic-graphene system or polymer-graphene systems, which have poor dispersion, agglomeration, and individually exfoliated graphene in the matrix. An additional challenge for metal and its alloy—graphene composites could be the unusual reactions at the interfaces [33]. Aluminum-graphene and various aluminum/CNT/SiC/Al$_2$O$_3$ combination composites are fabricated through advanced processing techniques such as spark plasma sintering (SPS), mechanical alloying, powder metallurgy (PM), hot press and extrusion [34, 35], melt-blending [36], and hot isostatic pressing (HIP) [12]. But the important factor is the mechanism of various planar/tubular/spherical-shaped structured reinforcement bonding, specific surface area (SSA), and its proposed structural and tribological performances [37]. Further, hybrid combinations of graphene are combined with other reinforcements, and its effect on various mechanical and tribological performances of aluminum matrix is not addressed so far. The current chapter deals with the composite made out of aluminum reinforced with the graphene and its hybrid combinations with CNT/SiC/Al$_2$O$_3$ that are processed through ultrasonic liquid processor, ball milling, and consolidated through vacuum hot press followed by microwave sintering. Thus developed composites are

Figure 1. Structure of allotropes of carbon: (a) Graphene; (b) Graphite; (c) MWCNT; (d) SWCNT; (e) Fullerenes.
tested for its tribological potential. Comparison and analysis are carried out to explore the effect of friction, wear, and structural damage on the added carbon allotropes during various testing conditions.

2. Processing and fabrication technique of graphene-aluminum composites

Figure 2 shows the morphology of aluminum, SiC, Al₂O₃, MWCNT, and graphene, which is characterized through scanning electron microscope. Figure 2(a) and (b) shows the TEM micrographs of graphene and MWCNT, respectively. Graphene is in flake form, single-layered morphology in which the layers are stacked upon each other. Figure 2(c–e) shows the aluminum, SiC, Al₂O₃, respectively. Aluminum powders that are produced through gas atomization method were procured commercially with a density of 2.7 g/cm³. Also, SiC particles with a density of 3.20 g/cm³, Al₂O₃ particles with a density of 3.8 g/cm³, CNT with a density of 1.6 g/cm³ and graphene with average platelets (flake) size >10 μm, and a density of 1.5–2.0 g/cm³ are considered for the fabrication as reinforcements. Aluminum-graphene nanocomposites with hybrid combinations are produced through a number of ways. At the first step, dispersion of graphene is carried out through an ultrasonic dispersion method with various weight percentages. SiC/CNT/Al₂O₃ was added separately to a solvent containing graphene that is dispersed in acetone. Dispersion (ultrasonication) is carried out until it turns to complete block solution indicating that no graphene sediments were left in the beaker also; all flakes are individually exfoliated. Further, graphene mixtures are dried in hot air oven and subjected to ball milling. Ball milling is carried out for 90 min with the ball mill ratio 16:1 at 200 rpm rotating speed for hybrid combination graphene weight fraction precursor. Encapsulation and homogeneous dispersion of graphene on SiC/Al₂O₃ and homogeneity of mixture are achieved at optimized processing parameters. Figure 2(f–h) shows the portion of the ball-milled graphene-SiC/Al₂O₃ powder mixtures that confirm the encapsulation of SiC and Al₂O₃, respectively. Apparent density of aluminum, SiC, Al₂O₃, MWCNT, and graphene is listed in Table 1, which are measured according to ASTM B703-10 using Arnold density meter, and tap density is carried out according to ASTM B527-14 by tapping apparatus giving 250 taps under dry conditions. Aluminum metal powder is added parallel to ball-milled hybrid-graphene precursors, and ball-milling process is continued with the same milling ratio for another 30 min. After this, the precursor (mixture of graphene and its hybrid combinations) is dried in hot air oven for 24 hours. Further, precursors are consolidated in vacuum hot press at 240 N/mm² in chromium hot-work tool steel (40–48 HRC die case, at 480°C). Boron nitride spray (Momentive Performance Materials Inc. USA) type lubrication is used as a lubricating agent between the precursor and the die walls. Thus prepared compacts are (each comprising two sets) subjected to microwave sintering at 510°C in a nitrogen inert gas (flushing) atmosphere for 30 min followed by furnace cooling to attain room temperature. The process followed for the synthesis of aluminum-graphene and its hybrid combinations is illustrated in Figure 3.
Figure 2. TEM image of (a) Graphene (b) CNT; SEM image (c) Aluminum powder morphology (d) SiC and (e) Al$_2$O$_3$; Ball-milled aluminum with (f) MWCNT (g) SiC and (h) Al$_2$O$_3$; precursors.

<table>
<thead>
<tr>
<th>Material</th>
<th>Apparent density ($\rho_a$)</th>
<th>Tap density ($\rho_t$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphene</td>
<td>$0.088 \pm 0.002$</td>
<td>$0.071 \pm 0.002$</td>
</tr>
<tr>
<td>AA 6061</td>
<td>$1.118 \pm 0.05$</td>
<td>$0.95 \pm 0.05$</td>
</tr>
<tr>
<td>SiC</td>
<td>$2.600 \pm 0.06$</td>
<td>$1.9 \pm 0.04$</td>
</tr>
<tr>
<td>CNT</td>
<td>$0.076 \pm 0.002$</td>
<td>$0.069 \pm 0.002$</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>$2.580 \pm 0.06$</td>
<td>$2.0 \pm 0.04$</td>
</tr>
</tbody>
</table>

Table 1. Measured apparent and tap density values.
6. Conclusion

One of the common engineering research challenges in materials is to determine ways and means to improve the wear resistance between any coupling surfaces, thereby reducing the energy and wear losses. In the current research work, aluminum with graphene is processed separately through vacuum hot press (gives high improved density compacts >98%) followed by microwave sintering successfully. Addition of graphene will provide more number of nucleation’s regions. Aluminum-graphene composites are observed to be superior in hardness compared to monolithic material owing to uniform dispersion and higher dispersion strengthening mechanism. Graphene exhibits more grain refinement, which improves the fracture toughness of the composite. This feature has reduced wear losses, and therefore, graphene-reinforced composites are suitable for various tribological applications. The significant differences in the friction coefficients due to high protective nature of graphene will lower the shear force and reduce the material losses. Further, graphene and MWCNT combinations in composite become a sacrificial layer which smeared (dry lubricant) on the wearing surface and enable the self-lubricating properties of aluminum-graphene/MWCNT composites. Graphene/MWCNT (flattened–ball-milled) combination is a favorable tribological application, coupled with improved hardness, strength, and surface roughness values compared to individual MWCNT or graphene/MWCNT (tubular)-reinforced aluminum composites applications, where the component is exposed to wear and friction. Addition of graphene in SiC/Al2O3 and encapsulation enables significant improvement in hardness compared to base aluminum. Microwave sintering method can
efficiently increase the diffusion of ions in the composite and thus gear up the sintering process, leading to finer grain growth and the densification. Also, combination of SiC/Al₂O₃ and graphene in the nanocomposites has resulted in significant improvement on tribological properties, where it gives the wear resistance by creating a solid lubricant layer between the sliding surfaces.

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