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Effect of graphite content on the wear behavior of Al/2SiC/Gr hybrid nano-composites respectively in the ambient environment and an acidic solution

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ABSTRACT

Effects of graphite (Gr) content on the dry sliding wear, solid-particle erosion and corrosive wear of Al6061based hybrid nano-composites fabricated via powder metallurgy route containing 2 vol% of SiC nano-particles and 0,2, 5 and 7vol%of micron-sized Gr particles were investigated. The hardness of these composites decreased almost linearly with their Gr content, accompanied with decreased erosion resistance at 90° particle impingement. Also the conductive Gr particles as the micro-cathodes enhanced galvanic effect and resulted in an increase in the corrosion rate and thereby stronger corrosive wear of nano-composites. The Al6061/2SiC/2Gr nano-composite exhibited the minimum wear rate and friction coefficient.

1. Introduction

Aluminum alloys due to their outstanding specific strength and stiffness together with high thermal and electrical conductivities are widely employed in industry [1–4]. However, their poor wear resistance limited their use in high performance tribological applications [5,6]. Aluminum matrix composites (AMCs) containing hard reinforcing particles such as Al_2O_3,TiB_2, SiC, B_4C and Si_3N_4 possess improved wear resistance over the conventional aluminum alloys [5–10]. Characteristics of the matrix material as well as the type, size and volume fraction of the reinforcements together with the quality of bonding at the particle/matrix interface are crucial factors influencing the wear resistance of AMCs [10–12].

Self-lubricating materials such as Al-graphite (Al/Gr) particulate composites in which the Gr particles act as the solid lubricant, offer many improvements over the materials to which lubricant needs to be applied periodically [13,14]. However, the main limitation in using graphite is the resulting loss in the strength of the composites [15]. One strategy to overcome this barrier is using hard ceramic particles such as silicon carbide (SiC) in Al/Gr composites to compensate for the weakening effects of Gr and to improve their mechanical properties. Such materials as a new generation of composites are termed as “hybrid composites” [16–20]. It has been demonstrated that composites reinforced with nanometeric particles are superior to those reinforced with coarser particles [21]. Thus, hybrid composites containing nano-particles can be regarded as a new generation of AMCs.

Uniform distribution of reinforcing particles throughout the matrix is a basic requirement for enhancing the improved properties of composite materials [22]. Nano-sized reinforcing particles are more susceptible to agglomeration and clustering as compared to coarser particles used in composites. Mula et al. [23] ultrasonically dispersed nano-scaled ceramic particles in molten Al and Mg to achieve a uniform distribution of these particles in the matrix alloy. This process is however expensive and difficult to be implemented industrially. Powder metallurgy (P/M) techniques do not have the typical drawbacks of casting routes for fabrication of metal matrix composites [24,25]. However, clustering of nanoparticles in conventionally P/M processed nano-composites is inevitable [25]. Mechanical milling is a useful method for fabrication of nano-composites with a uniform distribution of nano-particles in the matrix [26,27]. This technique is capable for generating nano-crystalline materials with a high thermal stability [28]. This process has been also found to be effective for achieving a homogenous distribution of reinforcing particles not only in micro-composites [29,30] but also in nano-composites [9,26,27]. It must be noted that a problem associated to addition of carbon or phases containing carbon to the aluminum matrix is formation of deleterious phase of aluminum carbide [31,32]. However, due to relatively low temperatures involved in P/M processing routes this problem may not arise.

In recent years, considerable interest has been paid to extend

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the use of AMCs in the marine environments [33]. This demands investigating the corrosion as well as erosion–corrosion characteristics of the composite materials in a simulated marine environment. A few studies have been reported in the literature on corrosive wear behavior of Al alloys and composites [34–37]. Zhang and Li [35] studied the effect of yttria addition on the wear resistance of aluminum under dry and corrosive conditions. They found that the dispersed yttria particles were effective in enhancing both the dry and corrosive wear resistance of the aluminum matrix.

Ramachandra and Radhakrishna [36] reported that the slurry erosive wear resistance in Al/SiC composites increases with increased SiC content. This was attributed to passive layers formed on the surface of the slurry erosive specimens acting as protective layers against the attack of slurry. In another study [37], they also analyzed the slurry erosive wear behavior of Al-2 wt%Si alloy reinforced with fly ash and noticed that the reinforcing particles enhanced the slurry erosion wear resistance of the composites.

Candan and Bilgic [38] reported that addition of SiC particles to Al-4 wt% Mg could improve the corrosion resistance of the composites over that of the base alloy in 3.5 wt% NaCl solution. On the other hand, Kiourtsidis and Skolianos [39] reported the enhanced pitting corrosion of aluminum AA2024/SiC composites in 3.5 wt% NaCl solutions. However, they found that the SiC particles were not directly responsible for deterioration of the corrosion resistance of the material and the pitting attack was initiated from the intermetallic phases surrounding the SiC particles. Saxena et al. [40] examined the corrosion resistance behavior of a cast aluminum alloy (LM-13) containing 3 wt% graphite particles in 3.5 wt% NaCl solutions and attributed the inferior seawater corrosion of the material to the galvanic corrosion between the cathodic graphite particles and active aluminum matrix. However, the same casting alloy (4xx.x series) reinforced with graphite particles displayed excellent corrosion resistance in SAE-40 engine oil at 150 °C. Alaneme et al. [41] reported that Al–Mg–Si alloy matrix hybrid composites reinforced with rice husk ash (RHA) and silicon carbide exhibited improved corrosion resistance in 3.5% NaCl solution. They noticed the higher preferential dissolution of the anodic matrix acting as the primary corrosion mechanism which was reduced around the matrix/RHA/SiC particle interfaces. They also realized that the coefficient of friction and the wear resistance of the hybrid composites were comparable to those of the Al–Mg–Si matrix alloy reinforced with only SiC particles.

The corrosive wear; as compared to ordinary wear; is accompanied with accelerated surface degradation and generally results in more damage due to the wear-corrosion synergy. It is possible that the corrosion products such as oxide scales exist on the surface of material during corrosive wear. Depending on properties of these oxides and their adherence to the substrate they may play a negative role in corrosive wear [42].

Despite the importance of corrosive wear behavior of hybrid nano-composites, studies on Al/SiC/Gr hybrid nano-composites are rather limited. The objective of the current investigation is to study microstructure, corrosion, corrosive wear and abrasive wear, of Al/2SiC/Gr hybrid nano-composites to understand and optimize the materials for improved performance.

2. Materials and experimental procedures

2 vol% of nano SiC particles (25–50 nm, Plasma-Chem Co. Germany) were co-milled with nitrogen gas-atomized Al-6061 powder particles (38–63 μm), having the nominal chemical composition as given in Table 1. Milling was performed using a laboratory planetary ball mill (PM-2400), a hardened stainless steel vial and 10 mm in diameter hardened steel balls in argon for 20 h [43]. The ball to powder weight ratio and the rotational speed were 15:1 and 300 rpm, respectively. Stearic acid (1.5 wt%) was used as the Process Control Agent (PCA). Fig. 1 shows a typical TEM micrograph of the used nano SiC powder particles.

Table 1
Chemical composition (wt%) of 6061 aluminum alloy.

Mg	Si	Fe	Cu	Cr	Al
1.12	0.64	0.48	0.33	0.04	Balance

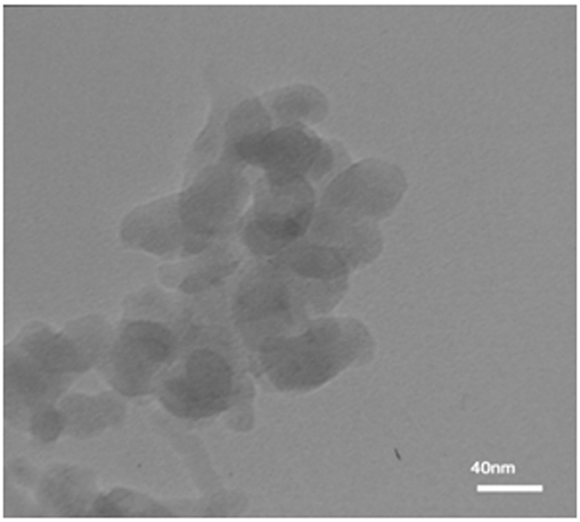

Fig. 1. A typical TEM micrograph of the used nano SiC powder particles.

The Al–SiC nano-composite powders (milled for 20 h) were mixed with 0, 2, 5 and 7 vol% of micron-sized graphite (Gr) powder particles (53–63 μm) and subjected to milling for 15 min under the same milling conditions. The resultant powder mixtures were cold pressed at a constant pressure of 750 MPa in a steel die on a single acting 45 t hydraulic press, while graphite was used as the die lubricant. Dimensions of the compacts were 25 mm in diameter and 15 mm in height. Green compacts were hot extruded at 500 °C, being held for 45 min using a 45-ton hydraulic press at a ram speed of 36 mm/min with the extrusion ratio of 11:1 and resulted in 8 mm diameter extruded bars.

The surfaces of the composites were examined using a Hitachi S-2700 scanning electron microscope (SEM) and a Transmission Electron Microscope (TEM) (Philips CM30, Poland). Hardness of the samples was measured using a Rockwell-B hardness (HRB) tester with a maximum load of 100 kgf (Zwick, Roell ZHR, Germany), and the average value of 5 hardness measurements conducted on each specimen was considered.

The corrosion resistance of the samples was evaluated via the Tafel curves obtained from electrochemical measurements in 0.1 mol/l H_2SO_4 solution. Each specimen was connected to a copper wire and mounted in epoxy resin in such a way that a surface area of 1 cm^2 of the sample could be exposed to the testing solution. This surface was initially ground with silicon carbide papers up to 800-grit, and cleaned with acetone. A saturated calomel electrode (SCE) was used as the reference electrode and a platinum plate having the area of 1 cm^2 was used as the counter electrode. The corrosion current density was determined using the Tafel extrapolation method.

Dry sliding wear tests were performed at room temperature using a CSEM tribo-meter (pin-on-disc). The used pin was a 3 mm diameter Si_3N_4 ball and the test material was a disc with height of 5 mm that was cut from the 8 mm diameter extruded bar using a hand saw. All the tests were performed at a sliding speed of 1 cm/s