Composites Part B 157 (2019) 131–139

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Gas-atomized copper-based particles encapsulated in graphene oxide for high wear-resistant composites

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ARTICLE INFO

Keywords:
Metal-matrix composites (MMCs)
Wear
Surface analysis
Powder processing

ABSTRACT

A novel architecture of graphene oxide wrapped copper spheres (Cu/GO) is proposed for fabricating high wear-resistant Cu-based composites. Tribological results indicate that GO shell layers present an exceptional strengthening efficiency surpassing conventional nanoparticle, fiber and nanosheet reinforcements for Cu-based materials reported to date. The friction torque of the composites shows a load-insensitive behavior stabilized at 0.26–0.41 Nm. Such good tribological performance is ascribed to integrated effects including strong metal/GO interfacial coupling, uniform distributed GO, and the GO-assisted tribofilm formed on ridges and asperities of wear tracks. The fabrication strategy is convenient, low cost, easily scalable, and can be expanded to the preparation of other metal/GO materials.

1. Introduction

A good control of wear and friction is crucial for improving the energy efficiency not only in macro-scaled moving assemblies including pumps, compressors and turbines [1], but also in micro/nano-scaled technologies such as micro/nano-electromechanical systems [2–4]. In these devices, mechanical stability is also a fundamental requirement to enhance the lifetime of parts, and to maintain their functionalities [5]. Copper and copper-based alloys have commonly been used in these devices [6–8], which often suffer from substantial tribological problems and subsequent mechanical durability owning to the wear damage.

Nanostructure engineering and hybridization of particles with graphene oxide (GO) shell layers might show the potential to address these problems [9,10]. The flexibility and the high surface area of the two-dimensional (2D) nanostructured functional derivative from graphene enable a good bonding of its hybrid materials, allowing it to attach well with the dispersed particles while avoiding agglomeration during hybridization [11]. GO systems with excellent electrical, thermal conductivity and considerable mechanical strength, have inspired the development of hybrid materials for various applications, such as optoelectronics [11,12] and electrodes [10,13,14]. Nevertheless, to the authors' best knowledge, thus far in the literature no study has been reported to evaluate the anti-wear performance of parts fabricated from the hybrid nanostructures of Cu-based particles encapsulated in GO.

Herein, we made an effort on the synthesis of gas-atomized (GA) Cu-based particles encapsulated in GO for the fabrication of Cu/GO composites with enhanced tribological properties. The gas atomization process offers many advantages including a high sophericity that is beneficial for the Cu/GO interface bonding, control of contamination, grain refinement and avoidance of composition segregation [15]. It has been demonstrated that nano-precipitation could present in GA powders, and remain in the materials after subsequent fabrication processes [16,17], thus providing extra wear resistance and mechanical strength. In addition, the gas atomization technique enables the large-scale production of powders (2 kg/min) with a uniform microstructure due to rapid solidification [18,19], which is favorable for engineering applications of our Cu/GO composites. Anti-wear properties of samples from blank GA powders without GO were also tested to highlight the benefit of the Cu/GO hybridization routing. As demonstrated in fretting wear measurements, the as-prepared GO wrapped spherical Cu-particle composite exhibited exceptional anti-wear performance and distinct stable friction torque. The GO shell layers showed remarkably higher strengthening efficiency than those of conventional nanoparticle, fiber and nanosheet reinforcements for the Cu matrix, and also considerably higher than their hybrid structured reinforcements reported so far.

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https://doi.org/10.1016/j.compositesb.2018.08.125
Received 14 July 2018; Received in revised form 23 August 2018; Accepted 27 August 2018
Available online 28 August 2018
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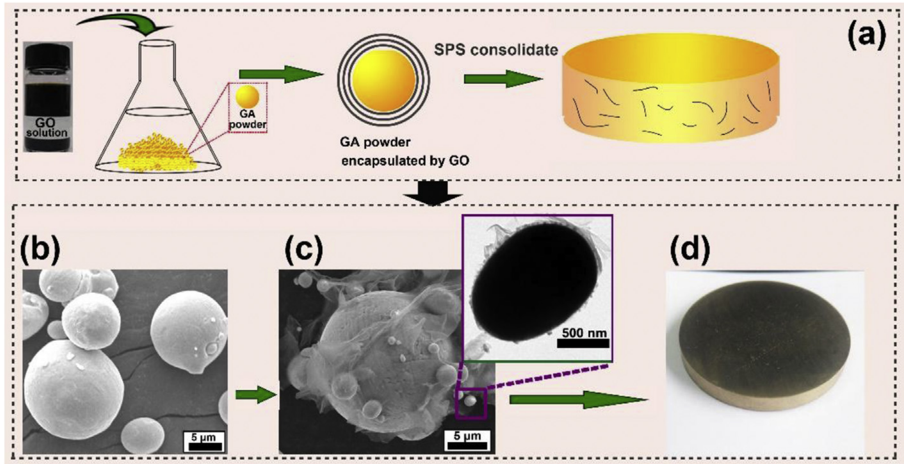

Fig. 1. (a) Schematic illustration of fabrication of GO wrapped Cu spherical particles; (b) SEM image of GA Cu spherical particles; (c) SEM and TEM images of Cu/GO composites showing good Cu/GO interface bonding; (d) The digital photograph of the consolidated Cu/GO composite.

Table 1
Typical composition of GA Cu-based powders in this work.

Element	Cu	Al	Ni	Fe	Mn	Impurity
Content (wt.%)	Balance	9.5	4.2	4.0	1.2	< 0.5

2. Materials and methods

2.1. Synthesis of Cu/GO samples

Fig. 1a schematically depicts the synthesis strategy of Cu/GO samples. Spherical GA powders with an average particle diameter of 7 ± 6 μm (Fig. 1b) supplied by Metal Products Trade Co. Ltd. China, were used as initial particles for the encapsulation. The chemical composition of the powder is shown in Table 1. In a typical preparation process, the Cu/GO powders were obtained from GO wrapping modified-GA powders by the electrostatic adsorption method. Fig. 1c clearly displayed that GA powders were well encapsulated inside thin GO nanosheets. After the hybridization process, a cylindrical graphite mold loaded with Cu/GO powders was put into an spark plasma sintering apparatus (LABOX-1575, SINTER LAND, Japan) and then heated up to 800 °C at a rate of 100 °C/min and a pressure of 40 MPa for 10 min under an argon gas flow. After the apparatus was completely cooled, the product was taken out and the Cu/GO powders were consolidated

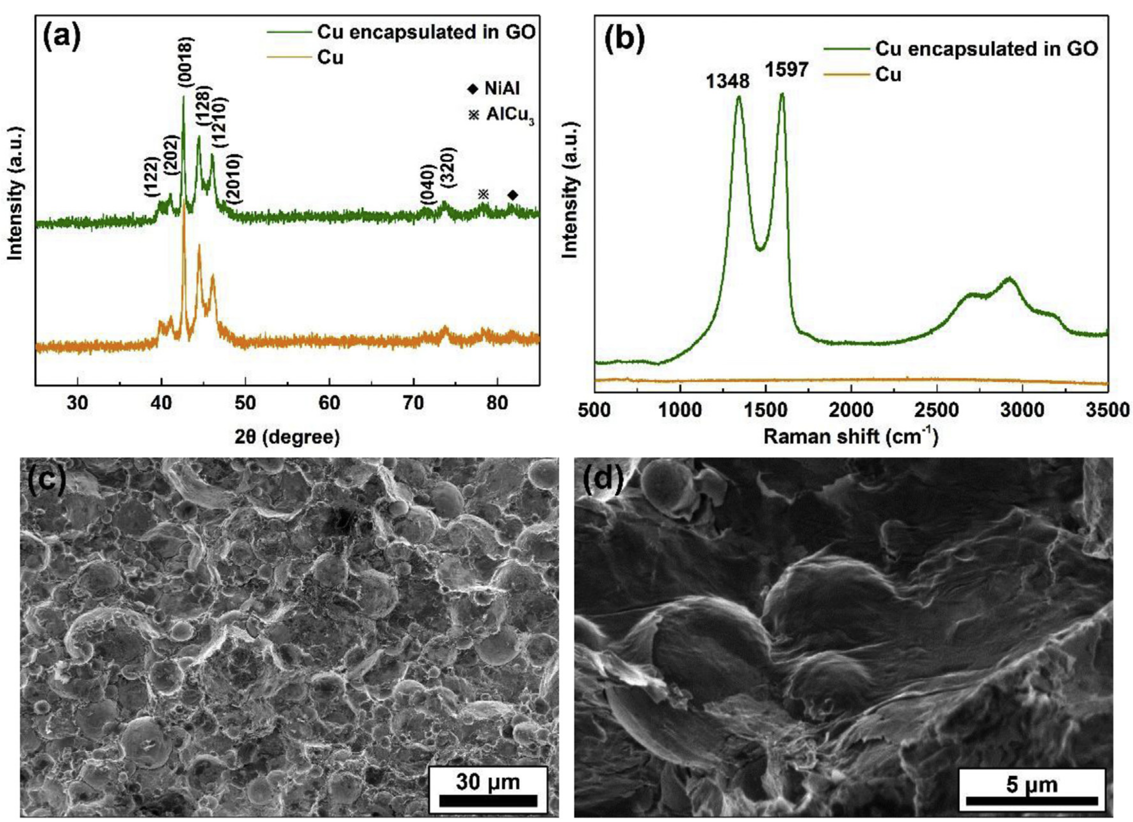

Fig. 2. (a) XRD patterns and (b) Raman spectra of blank Cu matrix and Cu/GO powders; (c and d) FESEM images of the cross-section of the consolidated Cu/GO composite showing good interfacial bonding between the Cu particles and GO after the SPS consolidation process.