Wear 364-365 (2016) 122–129

Contents lists available at ScienceDirect

Wear

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

# Improving wear performance of $CuSn_5Bi_5$ alloys through forming self-organized graphene/Bi nanocomposite tribolayer

Z.C. Lu [a,c], M.Q. Zeng [b,c], J.Q. Xing [b,c], M. Zhu [b,c,*]

[a] School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou 510640, PR China
[b] School of Materials Science and Engineering, South China University of Technology, Guangzhou 510640, PR China
[c] Key Laboratory of Advanced Energy Storage Materials of Guangdong Province, Guangzhou 510640, PR China

ARTICLE INFO

*Article history:*
Received 25 November 2015
Received in revised form
12 July 2016
Accepted 20 July 2016
Available online 27 July 2016

*Keywords:*
Sliding wear
Non-ferrous metals
Tribochemistry
Bearings

ABSTRACT

The wear and friction behavior of Pb-free Cu–Sn–Bi bearing alloys were improved by adding multi-layer graphene (MLG). An MLG/$CuSn_5Bi_5$ composite was produced by combining ball milling and conventional powder sintering. The composite exhibited increased bulk hardness and improved distribution and refinement of the Bi phase. Addition of MLG to the $CuSn_5Bi_5$ matrix resulted in a significant decrease in the friction coefficient and wear volume. Both adhesive and delamination wear were reduced at a certain MLG content. Despite an increase in the hardness, friction and wear improvements were caused by easy shear of the self-lubricating MLG in the contact interface, a decrease in the peeling of the brittle Bi phase, and the transport and spread of the Bi phase via slippage of the laminated MLG platelets on the worn surface. The self-organizing MLG/Bi nanocomposite tribolayer that forms is proposed to act as a lubricant and to improve the wear behavior significantly.



## 1. Introduction

Owing to their non-toxicity and superior load-carrying capability, Cu–Sn–Bi alloys are important potential alternatives for Pb-free alloys as solid self-lubricating materials for soft tribological applications [1,2]. However, Bi is fairly brittle, and tends to segregate at the grain boundaries of the solid solution of Sn in Cu (denoted as Cu(Sn)), which reduces the strength and ductility of the alloy, and leads to deterioration of the wear performance [3,4]. Various attempts have been made to overcome these drawbacks, including alloying addition [4,5], improvement of preparation methods [6,7], and surface modification [8].

Previous research indicates that the addition of various carbon materials (including carbon fiber, carbon black, and carbon nanotubes), generally results in the formation of a graphite-rich tribolayer on the Cu matrix; this tribolayer prevents sticking or welding during sliding and reduces the frictional force [9,10]. Recently, the excellent solid-lubrication ability of graphene, as well as its outstanding friction and wear properties, has been demonstrated [11–13]. These properties are far superior to those of conventional materials. Owing to its excellent mechanical properties, graphene also constitutes a perfect reinforcement for many types of composites [13,14]. Graphene or multi-layer graphene (MLG) are therefore expected to act as a lubricating and reinforcing phase in Cu–Sn–Bi-bearing alloys, and significantly enhance their mechanical and wear properties.

Furthermore, it has been demonstrated that engineering-scale superlubricity can be realized when graphene or MLG platelets are used in combination with hard nanoparticles, such as nanodiamond and nano-Cu particles [15,16]. Graphene patches at a sliding interface wrap around these hard nanoparticles to form nanoscrolls. Therefore, plate-shaped MLG has the potential to transport and spread soft Bi, Sn, or Ag particles on worn surfaces. As such, the combination of Bi with MLG platelets as a solid lubricant, and the homogeneous dispersion thereof, constitute a new strategy for improving the wear performance of Cu-based bearing alloys.

However, the aggregation of MLG represents a major obstacle to achieving homogeneous dispersion of MLG platelets. Reducing aggregation and improving the wetting of MLG with the metal are therefore essential in MLG/metal composites [17,18]. Various methods have been used to fabricate MLG/metal composites, including electrochemical deposition, metal evaporation, hydrogen reduction of metallic salt–graphite composites, and mechanical alloying [19–23]. In particular, mechanical alloying is considered an effective method of dispersing MLG and preventing Bi from segregating at the Cu grain boundaries thereby a refined and controllable microstructure can be resulted in this immiscible system [22–24]. These methods enabled effective and uniform dispersion of MLG in the final MLG/metal composites, and

* Corresponding author at: School of Materials Science and Engineering, South China University of Technology, Guangzhou 510640, PR China.
Fax: +86 20 87111317.
*E-mail address:* memzhu@scut.edu.cn (M. Zhu).

http://dx.doi.org/10.1016/j.wear.2016.07.014
0043-1648/

Please cite this article as: Z.C. Lu, et al., Improving wear performance of $CuSn_5Bi_5$ alloys through forming self-organized graphene/Bi nanocomposite tribolayer, Wear (2016), http://dx.doi.org/10.1016/j.wear.2016.07.014

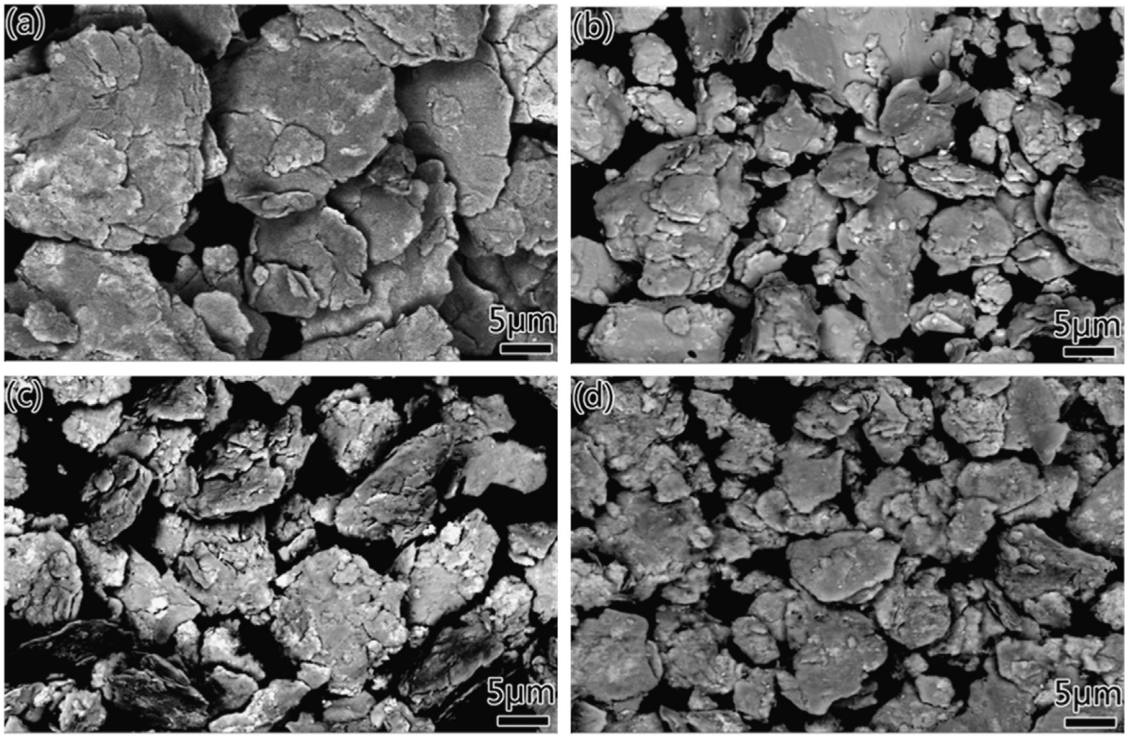


**Fig. 1.** Backscattered electron images of 40-h milled $CuSn_5Bi_5$ alloy powders with MLG content of (a) 0 wt%, (b) 0.5 wt%, (c) 1.0 wt%, and (d) 2.0 wt%.

graphene impeded dislocation movements and hence increased strength of metal matrix.

Although these previous works focused on the effect of the monolithic MLG on the mechanical properties and wear properties of composites, the combination role of MLG platelets and soft particles on the wear performance has not been extensively investigated. In this study, a new MLG/$CuSn_5Bi_5$ bearing alloy was produced by combining low-energy ball milling and conventional powder sintering. In a well designed engine, operated under normal conditions, bearings are generally not immune to dry friction. But new bearing alloys cannot be designed or used and existing ones cannot be optimised without precise knowledge of wear damage mechanisms [25]. Therefore, this work will focus on wear mechanisms in MLG/$CuSn_5Bi_5$ when exposed to severe conditions. More importantly, the cooperative wear mechanism between the MLG platelets and the soft Bi phase resulted in an improved wear performance of the MLG/$CuSn_5Bi_5$ composite.

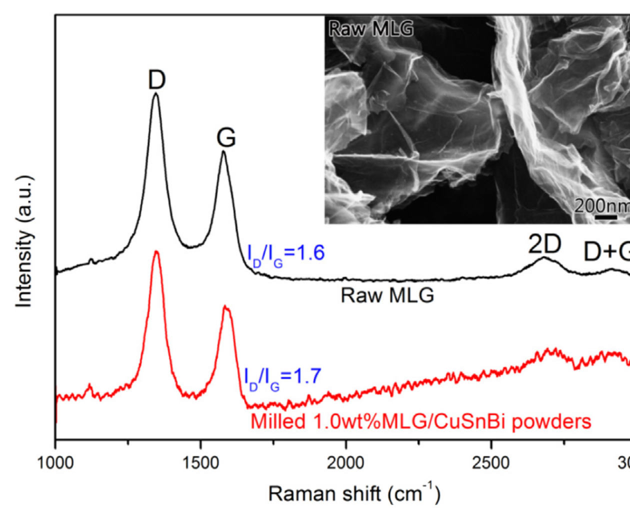


**Fig. 2.** Raman spectra of the as-received MLG and milled 1.0 wt% MLG/$CuSn_5Bi_5$ powder. The inset shows an image of the as-received MLG.

## 2. Experimental

Cu, Sn, and Bi powders (200 mesh size, 99.5% purity) were supplied by Aladdin Chemistry Co., Shanghai, China. The MLG was supplied by Sixth Element Materials Technology Co., Ltd., Jiangsu, China.

Mechanical alloying was used to prepare MLG/$CuSn_5Bi_5$ composite powder. The raw Cu, Sn (5 wt%) and Bi (5 wt%) powders were mixed with 0–2.0 wt% MLG. The mixture was sealed in a stainless steel vial with a powder-to-ball ratio of 1:13 and milled for 40 h at 150 rpm. Prior to milling, 0.5 wt% absolute ethanol was added as a process control agent to inhibit cold-welding. Powder handling and milling was performed under pure argon. To obtain high-density bulk MLG/$CuSn_5Bi_5$, a press–sinter–repress–anneal sequence was used to consolidate the milled powder. The pressing and sintering steps were performed using a uniaxial press at 660 MPa and a vacuum oven at 973 K for 20 min, respectively.

A Philips X'pert MPD X-ray diffractometer (XRD) with Cu-Kα radiation ($\lambda$=0.1541 nm) and a Zeiss SUPRA 40 scanning electron microscope (SEM) equipped with energy-dispersive spectroscopy (EDS) apparatus were used to characterize the microstructure of the composites. The microhardness of the samples at 2.98 N was measured using an HVS-1000 digital hardness tester. The hardness value was the average of at least seven measurements.

Because relatively little information is learned from the oil lubrication sliding interface in most bearing, a severe dry friction case will be used as a reference for the experiment. Thus, wear and