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Dry reciprocating sliding wear behavior and mechanisms of bulk metallic glass composites

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The dry sliding wear behavior and mechanisms in a bulk metallic glass composite, $Ti_{48}Zr_{20}V_{12}Cu_5Be_{15}$, composed of *in situ* crystalline dendrites in an amorphous matrix, was studied in reciprocating mode against a WC counterface loaded at 5 N and 10 N. The composite showed higher wear rates but lower coefficient of friction compared to a monolithic fully amorphous glass. Nanomechanical characterization was done to map the hardness and modulus of the crystalline and amorphous constituents of the composite. Nano-scratch test was done on each phase to evaluate the coefficient of friction. The observed hardness values scale according to Archard's relationship for sliding wear behavior. No tribolayer formation was seen for the composite in sharp contrast to that of the monolithic metallic glass.

1. Introduction

Bulk metallic glasses (BMGs) exhibit exceptional mechanical properties, high corrosion resistance, and soft magnetic properties due to their structural homogeneity and fully amorphous structure, free from grains and grain boundaries. Due to the high surface hardness, Zr-based BMGs show good wear resistance compared to alloys in the Pd-based, Mg-based, and La-based systems [1]. However, absence of crystalline slip planes and directions severely limit the tensile plasticity in these materials, limiting its wide spread use. Recently developed metallic glass composites (*MGCs*), with in situ crystalline ductile phase, demonstrate a combination of fracture toughness (K_{1C}) and Young's modulus (E) better than most known structural material [2,3]. *MGCs* have been tested under extreme environments including spacecraft shielding [4], and hence understanding their surface degradation behavior is important to extend their range of useful applications.

While there are studies on wear behavior of BMGs [1,5–12], there are no reports that elucidate wear mechanisms in *MGCs* and comparative analysis with respect to a monolith BMG. In this study, we report on the wear behavior of a *MGC*, $Ti_{48}Zr_{20}V_{12}Cu_5Be_{15}$, and compare it to a fully amorphous *BMG*, $Zr_{41.2}Cu_{12.5}Ni_{10}Ti_{13.8}Be_{22.5}$. We have analyzed the materials' response to reciprocating sliding wear. To understand response of each phase, nanomechanical measurements were carried out to obtain hardness and wear of the glassy matrix and in situ crystalline phase in the *MGC*. Similar set of experiments were performed on the monolithic *BMG* to understand the relative performance. White light interferometry (*WLI*) was used to quantify the wear volume loss, and scanning electron microscopy (*SEM*) was used to analyze the wear mechanisms.

2. Experimental

2.1. Bulk and nano-wear studies

The *BMG* and *MGC* samples were cut and polished up to 1200 grit for bulk wear analysis. Reciprocating sliding wear test was performed using Rtec Universal Tribometer (Rtec Instruments, San Jose, CA, USA). A WC ball of 3 mm diameter was used as a sliding counterface. WC was selected to eliminate counterface tribochemical phases, e.g., WO_3, forming in the wear track that could otherwise bias the results. Tests were performed at loads of 5 N and 10 N with a reciprocating frequency of 5 Hz. The initial mean Hertzian contact stresses for these two loads are ~1.0 and 1.3 GPa, respectively. These contact stresses were chosen to be both below and approximately at the 1.3 GPa yield strength of the composite [2]. The stroke length was fixed at 1 mm. The tests were run from 2 min to 20 min with incremental steps of 2 min and conducted in lab air (~50% RH). The wear tracks were sufficiently spaced apart to avoid effect from neighboring wear areas. The total sliding distance was calculated from the wear time, frequency of reciprocation and stroke length. Interferograms of the wear tracks were captured with 10× objective using white light. Wear volume

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loss was calculated using Gwyddion image processing software. The alloy samples were polished up to 1 μm finish for nano-mechanical studies. Hysitron TriboIndenter TI-750L (Hysitron, Inc., Minneapolis, MN USA) was used to study the hardness and nano-wear behavior of both the alloys. Nanoindentation was performed using a Berkovich tip at 10,000 μN under load control mode comprising of 5 s loading, 2 s holding and 5 s unloading cycles. Nano-scratch was done at 3000 μN load with a displacement of 5 μm.

2.2. Materials characterization

The microscopy was performed using FEI Quanta environmental scanning electron microscope (SEM). All the microstructures reported have been recorded in un-etched condition. Chemical changes on the samples were measured using energy dispersive X-ray spectrometer (EDS) in built with the SEM.

3. Results and discussion

The back scattered electron images of *MGC* and monolithic *BMG* at the same magnification are shown in Fig. 1(a) and (b). The monolithic glass is homogeneous without any microstructural features. The amorphous matrix and crystalline dendrites are marked for the composite. A phase contrast is produced due to the atomic weights of the constituent elements, because of which the amorphous matrix appears bright and the crystalline phase appears dark. The metallic glass composite is composed of about 53 vol% amorphous phase with a nominal composition $Ti_{32}Zr_{25}V_5Cu_{10}Be_{28}$ and 47 vol% crystalline phase of composition $Ti_{66}V_{19}Zr_{14}Cu_1$.The crystalline phase area has an average dendritic arm width of about 20 μm. Fig. 1(c)–(f) show SEM and WLI images of the wear tracks of the composite and monolith. Fig. 1(c) and (e) show the wear volume loss for the composite after ~15 m sliding at 5 N and 10 N respectively. Fig. 1(d) and (f) show the wear tracks on the monolith under similar testing conditions. The *WLI* images determined that the wear tracks on the *MGC* are deeper than the *BMG*. Wide and deep grooves can be seen on the *MGC*, while those on the *BMG* are narrow and shallow. The wear volume (W_V) was calculated from the *WLI* images and is plotted against sliding distance (W_S) as shown in Fig. 2(a) and (b) for composite and monolithic BMG. The slope of the curve is a measure of the wear rate (W_R) [13]. The W_V is much lower when compared to conventional structural materials like dual phase steels [14]. The W_V loss for the composite is relatively higher than the monolithic alloy.

The W_R increases almost linearly with increasing sliding distance and load for both alloys follow Archard's relation [15]. The W_R is higher for MGC than BMG at all test conditions. The mean coefficient of friction (*mean-COF)* for each test condition is shown in Fig. 2(c) and (d). The composite alloy exhibits a lower *mean-COF* compared to the monolithic alloy under both loading conditions. Small increments in the *mean-COF* is observed to also

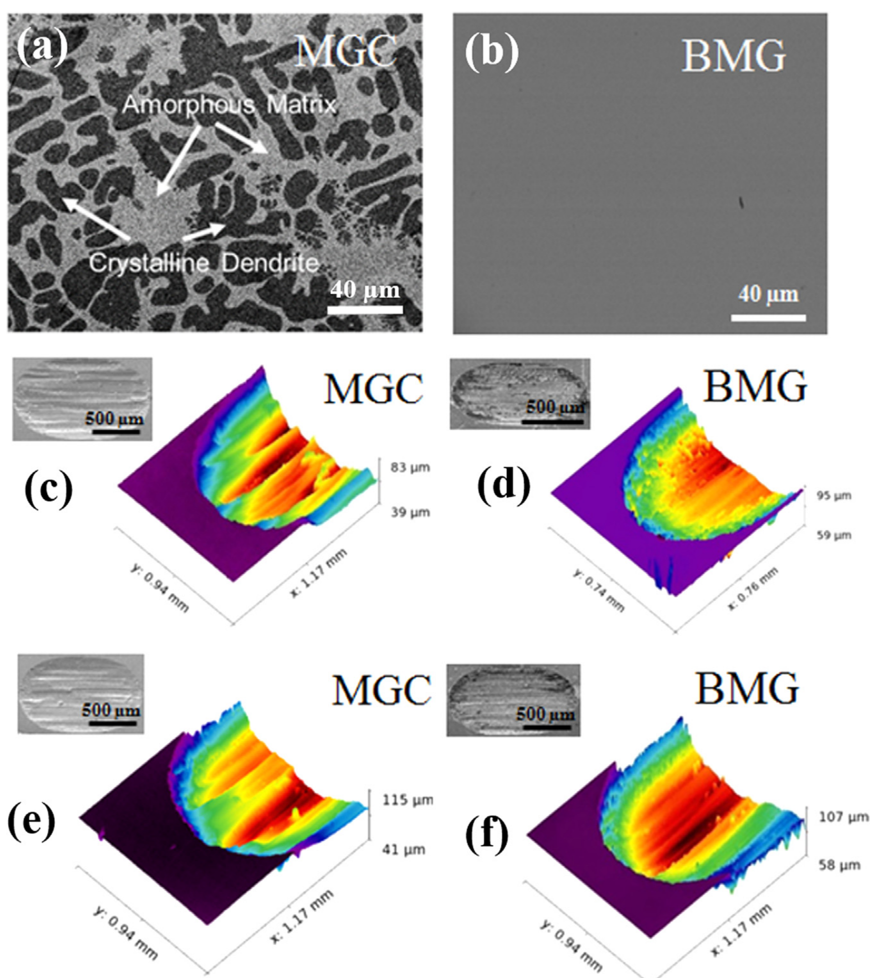

Fig. 1. Backscattered SEM images of (a) MGC and (b) BMG. The WLI and SEM images of the wear tracks generated at 5 N load for (c) MGC and (d) BMG and at 10 N load for (e) MGC and (f) BMG.