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Tribological behavior of Fe-based bulk metallic glass[†]

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Abstract

The unlubricated tribological characteristics of coating layers containing an Fe-based amorphous matrix have been investigated in air using an alumina ball with a diameter of 3.1 mm. From the ball-on-disk test system, the friction coefficient could be measured for up to 3,000 seconds. The temperature changes on the worn surfaces were also simultaneously measured using an infrared thermometer. Three different types of coating layers having an Fe-based amorphous matrix, an Fe-based amorphous matrix with embedded Ni-based self-fluxing alloy particles, and an Fe-based amorphous matrix with embedded WC particles were prepared through a high velocity oxy-fuel (HVOF) process. Although the coating layers have certain levels of porosity, unique frictional characteristics attributed to the amorphous matrix were observed during the friction tests. Compared with conventional bearing steels such as AISI 521000 (Hv=840), excellent tribological and wear characteristics were obtained, demonstrating that an Fe-based bulk metallic glass powder is a viable engineering material for practical anti-wear coating applications.

Keywords: Bulk metallic glass; Friction coefficient; Tribological properties; Wear rates

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1. Introduction

Different classes of materials are used in mechanical components in which adhesion, friction, wear, and lubrication are involved. The most significant class of these materials is the metallic alloy [1]. Among the metallic alloys, bulk metallic glasses with amorphous structures are of great interest. The first metallic glass was reported by Duwez et al. in Caltech, USA in 1960, which was fabricated by rapid quenching, while the bulk metallic glass (BMG) was reported by Chen et al. in 1974 [2-3]. In recent years, the rapid progress in BMG research has been performed such that Fe-based BMGs were cast in bulk form with a critical sample thickness as large as 25 mm in Fe-Cr-(Co)-Mo-Mn-C-B systems and Fe-Cr-Mo-C-B systems in 2004 [4-6]. Consequently, there has been a revival of early interest its mechanical properties. While metallic glasses can be multifunctional owing to their magnetic and good wear-resistance, and they can be exploited as corrosion and wear-resistant coatings, the capability to make bulk components has stimulated interest in their larger-scale structural applications [7].

On the basis of this background, Whang and Giessen reported that wear in these glassy alloys is similar to or slightly inferior to their crystalline counterparts in terms of the friction and wear of some binary Ti alloy glasses [8]. Miyoshi and Buckley determined the surface chemistry, microstructure, and tribological properties of some ferrous-based amorphous alloys [1]. Braham Prakash et al. [9] studied the sliding wear behavior of some Fe-, Co- and Ni-based metallic glasses rubbing against bearing steel.

In accordance with these research trends, there has been increasing interest in the use of the high velocity oxygen fuel (HVOF) thermal spray for depositing protective coatings. J. C. Perron et al. [10] suggested that some additive elements within the Fe_3Si matrix can lead to easier amorphization. M. Cherigui et al. succeeded in making a structure of amorphous iron-based coatings processed by HOVF thermal spraying [11]. The HVOF thermal spray process makes it possible to obtain very hard coatings with excellent cohesion and adhesion [12]. Due to the high-strength steel and its cheap cost as compared to other amorphous alloys such as those that are Zr-based and so on, Fe-based amorphous alloys show good potential as engineering materials. The purpose of this study is to examine the tribological characteristics of different kinds of BMGs developed for application in tribo-systems.

2. Experiment details

2.1 Specimen preparation

Using the powder mixtures listed in Table 1, mild steel

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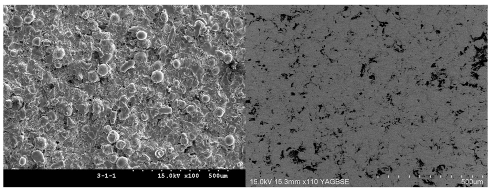
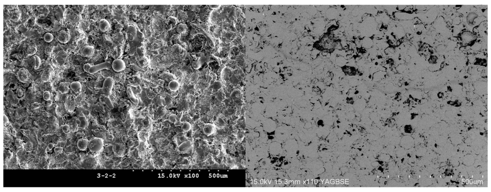
plates with three different coating layers were prepared through a high velocity oxy-fuel (HVOF) process. The as-sprayed plates were cut into pieces with a dimension of L35 mm x W45 mm for friction tests. Fig. 1 shows the back-scattered electron (BSE) images of the original surfaces for each plate after polishing with diamond-paste. Many pores were observed on the surfaces (dark regions). WC particles with bright contrast attributed to the high atomic number of the W element can be observed in Fig. 1(c). The X-ray diffraction patterns from the coating layers are shown in Fig. 2(a). BMG1 and BMG2 revealed a typical halo pattern for amorphous structures. Any peak corresponding to oxide inclusions were undetected on the surface of the BMG coatings. On the other hand, the XRD pattern from BMG3 exhibited the existence of both amorphous structures and WC crystalline particles on the coating layer. A ball specimen made from a hard ceramic (Al_2O_3) with a diameter of 3.1 mm with Hv1500 was used as a counterpart.

2.2 Experimental setup

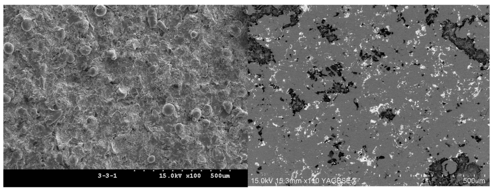
A ball-on-disk apparatus was used to obtain the friction coefficient and wear amount data of three kinds of BMG coatings, and AISI 304, and AISI 52100 bearing steel disks as shown in Fig. 2(b). A normal load applied by dead weights acted to press the stationary test specimen onto the rotating lower disk. The friction coefficient exerted on the contacting material during sliding was measured by a force transducer placed on the ball holder with an adjustable rotational radius. The force transducer had a maximum load range of 3 kgf with a sensitivity of 1 mV/V±1%.



(a) BMG1



(b) BMG2



(c) BMG3

Fig. 1. SEM micrographs on the left side and BSE images on the right side for (a), (b) and (c) polished with diamond-paste.

The counter body was driven by a DC motor rotating at 10 ~ 600 rpm to reach 0.5 m/s sliding speed. A laser infrared non-contact thermometer connected to an A/D converter (NI cDAQ-9172) was used to measure the surface temperatures.

3. Results and discussion

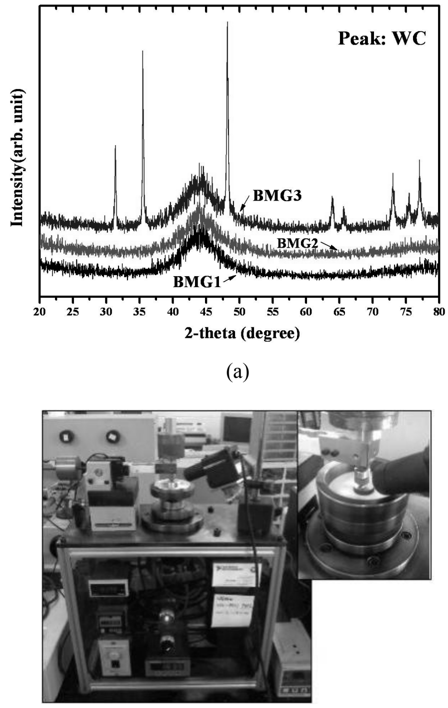
3.1 Friction coefficients

The plot of friction coefficient vs. time under the normal load of 1.4 kgf and sliding speed of 0.1 m/s is shown in Fig. 3. The friction coefficient value for BMG1 was stabilized in the range of 0.35~0.4 after around 1,200 sec. For BMG2 and BMG3, much lower values ranging from approximately 0.08 to 0.15 were obtained up to 2,500 sec, while, for the crystalline materials, AISI 304 and AISI 52100, the average friction coefficient values were in the range of 0.35~0.5 regardless of the material's hardness values. In the initial stage of the friction test (i.e., < 1,000 sec), large fluctuations in the friction coefficient values for AISI 52100 with Hv300 were observed, implying that surface asperities form in the initial stage of the test.

Table 1. Chemical composition of Fe based BMGs.

Alloy designation	Nominal composition (wt.%)
BMG1	$Fe_{73.97}C_{9.60}$ $Si_{1.82}P_{5.81}Cr_{2.57}$ $Al_{0.81}Mo_{5.23}$
BMG2	BMG1+ 50%Ni-base self-flux alloy*
BMG3	BMG1+ 25%Ni-base self-flux + 25%WC

*Ni(bal.)-16Cr4Si4B3Cu3Mo2.5Fe



(a)

(b)

Fig. 2. (a) X-ray diffraction patterns of BMG alloy coatings and (b) Photograph of the ball-on-disk test setup.

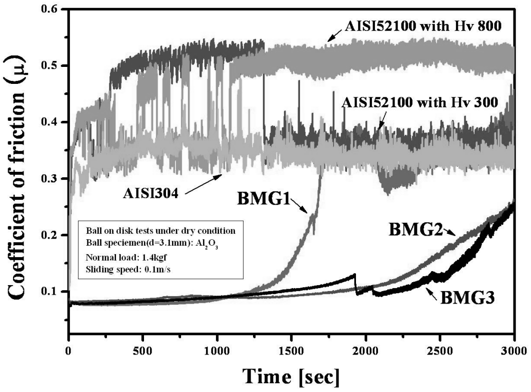
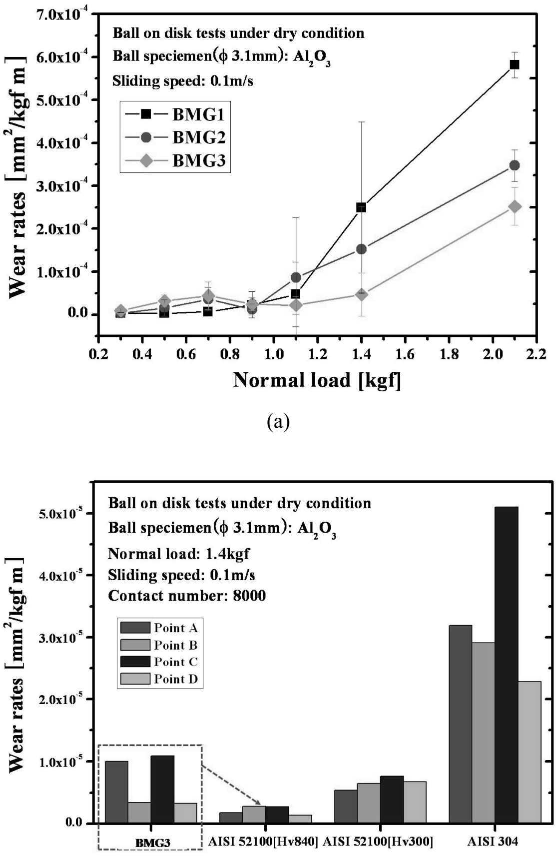


Fig. 3. Variation in friction coefficients at 1.4 kgf and 0.1 m/s.



(a)

(b)

Fig. 4. (a) Wear rate vs. normal load for three kinds of BMGs and (b) Comparison of BMG3, AISI 52100 and AISI 304 materials.

These surface asperities preferentially deformed to form overlapping tongues on the surface after the initial stage as shown in Fig. 5(d). In the meantime, for samples including BMG, significant fluctuations in the friction coefficient were not observed, implying that the formation of surface asperities was effectively suppressed during the friction test [13]. However, as can be seen from the images of worn surfaces (Fig. 5), the wear mechanisms for the BMG samples are considered to be different from one another. That is, the worn surface of BMG1 reveals some detached areas, while those of BMG2 and BMG3 exhibit relatively sound morphologies. It is suggested that the strong particles in BMG2 and 3 may change the deformation characteristics of the amorphous matrix during the friction test, leading to relatively gradual increases in friction coefficient. Meanwhile, the increases in surface temperatures of the crystal line alloys during the friction test were measured and found to be higher than those of the BMG alloys, indicating that much more frictional heat was generated during the friction of crystalline alloys than during that of the BMG samples.

3.2 Wear rates

The wear rates of the BMG samples were measured and found to be much lower than those of AISI304 under the test conditions in this study (Fig. 4). For bearing steel AISI 52100, the wear rates strongly depended on hardness. That is, AISI 52100 with Hv300 exhibited a higher wear rate, while AISI 52100 with Hv840 exhibited a lower wear rate than BMG3. However, it should also be pointed out that the BMG 3 sample can have high porosity since the sample was prepared through a thermal processing method using powder. Thus, the wear rates can be different from position to position. Indeed, as can be seen in the Fig. 4(b), the wear rates of BMG 3 changed significantly as the measuring position changed. The wear rates of BMG3 can be improved to the level of AISI 512000 with Hv 840 through the optimization of thermal processing conditions. At low normal loads (< 1 kgf), a distinct wear rate difference could not be correctly resolved due to the vibrations observed during the friction test.

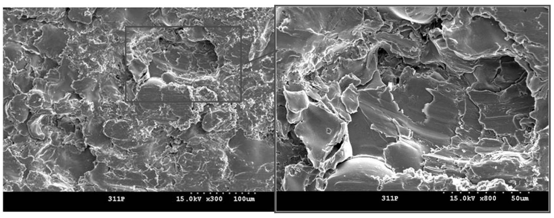
3.3 Worn surfaces

Fig. 5(a) shows the SEM micrographs of the worn surface of BMG1 with pit and material flow after the friction tests. The morphology of the wear track indicates that the material experienced severe plastic deformation in the wear direction. It was found that large wear particles escaped from the worn surface of BMG1 (not shown here). On the other hand, for BMG3, the worn surface experienced plastic deformation without any material flow as shown in Fig. 5(b)

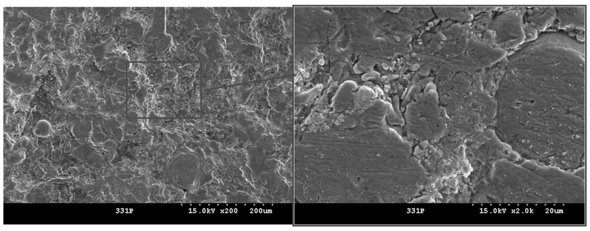
Fig. 5(c) indicates the typical ductile material fracture topography with fine abrasion marks, including plowing, and tearing all over the worn surface. There are also typical evidences of river-like vein patterns due to highly inhomogeneous shear deformation.

4. Conclusions

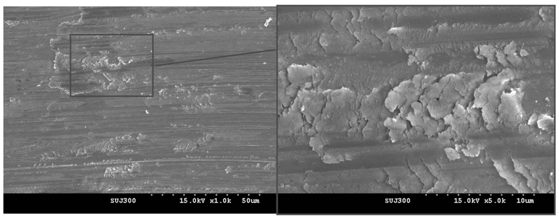
The beneficial friction characteristics of the BMG coating layers under various normal loads were demonstrated in comparison with those of the bulk AISI 304 and AISI 52100 samples. Very low friction coefficients ranging from approximately 0.08~0.2 could be obtained through a relevant design of a coating layer comprising WC particles within an Fe-based amorphous matrix.



(a) BMG1



(b) BMG3



(c) AISI 52100 with Hv300

Fig. 5. SEM micrographs of the worn surface; (a) BMG1, (b)BMG3, and (c) AISI 52100 with Hv300 at 1.4 kgf and 0.1m/s.

Acknowledgment

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