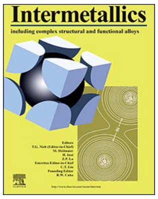
ARTICLE IN PRESS

Intermetallics xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Intermetallics

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



Correlations between the wear resistance and properties of bulk metallic glasses

Zhenlong Liao[a,c], Nengbin Hua[a,b,c,*], Wenzhe Chen[a,b,c], Youting Huang[a,c], Tao Zhang[d]

[a] Department of Materials Science and Engineering, Fujian University of Technology, 350118 Fuzhou, China
[b] Department of Materials Science and Engineering, Fuzhou University, 350116 Fuzhou, China
[c] Fujian Key Laboratory of Advanced Materials Processing and Application, 350118 Fuzhou, China
[d] Key Laboratory of Aerospace Materials and Performance (Ministry of Education), School of Materials Science and Engineering, Beihang University, 100191 Beijing, China

ARTICLE INFO

Keywords:
A. Bulk metallic glasses
B. Wear resistance
E. Elastic modulus
E. Poisson's ratio
E. Correlation

ABSTRACT

The wear, elastic, mechanical and thermodynamic properties of bulk metallic glasses (BMGs) is studied to explore correlations between the wear resistance and properties of BMGs. It is found that the wear resistance of BMGs is dominated by synergistic effects of strength factors, namely the hardness (H), Young's modulus (E), yield strength (σ_y) and glass transition temperature (T_g), as well as toughness factors, like the notch toughness (K_Q) and Poisson's ratio (ν). Moreover, a novel strategy for optimizing the wear resistance of BMGs is proposed from elastic perspective. The wear resistance of BMGs is correlated with chemistry-induced changes to bulk modulus (B) and Poisson's ratio (ν) for the first time. Developing BMGs with high value of $B^{0.5}\cdot[2(1+\nu)/3(1-2\nu)]^{0.25}$ can achieve simultaneously both high strength and good toughness, which provides the elastic opportunities for designing ultra-wear-resistant BMGs.

1. Introduction

Owing to their special disorder microstructures, bulk metallic glasses (BMGs) exhibit unique chemical and physical properties, preceding their crystalline counterparts, making them as promising structural materials [1–3]. The tribological properties is of interest since the generally high hardness values of metallic glasses would make them candidates for high wear applications. For example, metallic glasses have been proposed as coatings in dry bearings for use in space. The viscous flow of metallic glasses has been exploited to make ultrafine mechanical devices, e.g. gear wheels; for these also the friction and wear properties are of direct concern [4]. According to Archard's equation, the wear resistance is proportional to the hardness of the material [5]. However, existing results of wear studies so far often lead to conflicting reports of the wear resistance of BMGs. It has been claimed that Zr-based and W-based metallic glasses exhibit increasing wear resistance as their hardness increase [6,7]. On the contrary, the wear behavior of Fe-based and Cu-based BMGs is inconsistent with the Archard's equation [8,9]. Wang et al. [10,11] studied the crystallization and nanoindentation behavior of a Zr—Al—Ti—Cu—Ni BMG and then used nanoscratch techniques to investigate the wear properties of the Zr-based BMG. The results showed that a lower hardness produces a higher wear and a sample with a mixture of amorphous-nanocrystalline structure is more wear resistant. Nieh et al. reported that the wear resistance of Zr, Pd, Cu and La-based amorphous alloys does not follow the classical Archard's equation, i.e. the wear resistance is not linearly proportional to the hardness. This discrepancy is attributed to different wear mechanisms operating in different materials [12]. Greer et al. [4] compiled a comprehensive review of the wear properties of metallic glasses and related materials, mostly Fe and Al-based. Nevertheless, the large variety of test methods used for assessing the tribological properties of the alloys and incomplete wear data made the task of making a direct comparison among these alloys quite challenging. To date, the relationship between the wear resistance and properties for various BMG systems is unclear.

It has been argued that hardness alone does not determine the wear resistance; in addition to resistance to indentation, crack nucleation and propagation are also responsible for wear [12]. For ductile metallic materials, such as pure metals, the wear resistance is linearly proportional to their hardness [13]. On the contrary, silicon nitride ceramic, with a typical low fracture toughness, has been reported to show an improved wear resistance as its fracture toughness increases [14,15]. To sum up, hardness is the main material parameter that controls wear of tough materials. Fracture toughness, however, is an important factor mostly for brittle wear when the fracture toughness values are less than about 10–20 MPa m$^{1/2}$ [16]. Owing to a lack of microstructure, BMGs

---

[*] Corresponding author. Department of Materials Science and Engineering, Fujian University of Technology, 350118 Fuzhou, China.
E-mail address: flower1982cn@126.com (N. Hua).

http://dx.doi.org/10.1016/j.intermet.2017.10.008
Received 7 August 2017; Received in revised form 12 October 2017; Accepted 13 October 2017
0966-9795/

Please cite this article as: Liao, Z., Intermetallics (2017), http://dx.doi.org/10.1016/j.intermet.2017.10.008

are inherently strong but brittle, and often demonstrate extreme sensitivity to flaws. Accordingly, their macroscopic failure is often not initiated by plastic yielding, and almost always terminated by brittle fracture. Among the various glass-forming systems, Fe—, Mg— and rare-earth-based BMGs exhibit as low fracture toughness as brittle ceramics and glasses. Therefore, it can be assumed that fracture toughness also plays an important role in the wear resistance of those "brittle" BMGs. D. Maddala et al. [9] reported that as the annealing time is prolonged, the hardness of Cu—Hf—Al BMGs increases, whereas the fracture toughness decreases. The wear mechanism turns from hardness-controlled into toughness-dominated as the increase in annealing time.

It was demonstrated that wear properties of metallic crystalline materials strongly depend upon their microstructure. For example, it has been reported that the wear rate of different pure metals is roughly proportional to hardness. However, hardening of individual metals (by cold work, precipitation, etc.) leads to a decrease in wear rate, of less than that expected from the increase in hardness [13]. Metallic glassy alloys, normally regarded as mechanically and physically isotropic, are ideal mode systems for investigating wear behavior. BMGs generally display super-high strength two times or even higher than that of their crystalline counterparts, yet their fracture toughness covers a wide range of over almost three magnitudes [17]. For example, the toughness of Mg-based MGs may equal to that of ideally brittle solids [18], while Pd-based MGs may show outstanding damage tolerance [19]. The availability of various BMG systems, with marked difference in mechanical and physical properties, together with thermodynamic features, makes it possible to establish some correlations among the properties and wear resistance. Nevertheless, the studies on the wear behavior of BMGs are mostly focus on typical single alloy system. A direct comparison among various BMG systems remains quite challenging because of the wide variety acceptable wear tests, which can result in the divergence in wear values depending on test conditions. Consequently, the relationship between the wear resistance and properties for various BMG systems is still inexplicit. To explore correlations between the wear resistance and properties of BMGs, the present study investigates the wear behavior of a variety of BMG systems with the same test conditions such as sliding load, speed and counterpart material to eliminate the discrepancy in wear data caused by various test methods. The results show that the wear resistance of BMGs under dry sliding condition is dominated by synergistic effects of strength factors and toughness factors. Furthermore, a novel strategy for optimizing the wear resistance of BMGs is proposed from elastic perspective for the first time. The conclusions obtained provide the elastic opportunities for designing ultra-wear-resistant BMGs.

2. Materials and methods

Master alloys with nominal compositions (at.%) of $Pd_{40}Cu_{30}Ni_{10}P_{20}$, $Ti_{40}Zr_{10}Cu_{38}Pd_{12}$, $Fe_{41}Co_7Cr_{15}Mo_{14}C_{15}B_6Y_2$, $Hf_{51}Cu_{27.75}Ni_{9.25}Al_{12}$, $Zr_{53}Al_{16}Co_{23.25}Ag_{7.75}$, $Zr_{55}Al_{10}Ni_5Cu_{30}$, $Mg_{65}Zn_{30}Ca_5$ and $Mg_{56.5}Cu_{27}Ag_5Dy_{11.5}$ were prepared in the present study. These alloys were fabricated using various techniques [20–24]. The $Pd_{40}Cu_{30}Ni_{10}P_{20}$ and $Fe_{41}Co_7Cr_{15}Mo_{14}C_{15}B_6Y_2$ alloys (hereafter this text will be abbreviated as PdCuNiP and FeCoCrMoCBY, respectively) were prepared by high-frequency induction melting of pure metal components in a thick-walled quartz in a high-purity argon atmosphere. The $Ti_{40}Zr_{10}Cu_{38}Pd_{12}$, $Hf_{51}Cu_{27.75}Ni_{9.25}Al_{12}$, $Zr_{53}Al_{16}Co_{23.25}Ag_{7.75}$ and $Zr_{55}Al_{10}Ni_5Cu_{30}$ alloys (abbreviated as TiZrCuPd, HfCuNiAl, ZrAlCoAg and ZrAlNiCu, respectively) was prepared by arc melting the mixtures of pure metals under Ti-gettered high-purity argon atmosphere in a water-cooled copper crucible. The alloy ingots were re-melted several times to insure compositional homogeneity. The $Mg_{65}Zn_{30}Ca_5$ and $Mg_{56.5}Cu_{27}Ag_5Dy_{11.5}$ alloys (henceforth referred to as MgZnCa and MgCuAgDy, respectively) were produced by induction melting the constituent elements in a graphite crucible under high-purity argon atmosphere. The Cu—Ag—Dy pre-alloys were prepared by arc melting Cu, Ag and Dy under a Ti-gettered argon atmosphere in a water-cooled copper crucible. The pre-alloys were remelted with Mg to form master alloy of MgCuAgDy.

From the master ingots, cylindrical rods ($\Phi 2 \times 70\,mm^3$) and plates ($2 \times 10 \times 50\,mm^3$) were cast in copper molds. Ball-on-disk reciprocating wear experiments were conducted on the surfaces of BMGs with a Si_3N_4 ball of 6 mm in diameter as the counter-material. The reciprocating speed was fixed at 2 m/min, and the normal load was set at 40 N. The specific wear rate (W_S) was calculated according to the following equation based on the changes in mass (Δm) before and after each test as:

$$W_S = \Delta m/(S \cdot P \cdot \rho) = \Delta V/(S \cdot P) \tag{1}$$

where ΔV is the wear volume loss, S is the sliding distance and P is the applied normal load. Topography of the worn surface and wear debris of samples was observed by scanning electron microscopy (SEM, CS-3400). Microhardness measurement was performed using a THVP-10 Vickers diamond indenter with an applied load of 0.2 kg and a dwell time of 10 s. Notch toughness (K_Q) test was carried out on BMGs rods with a span of 20 mm in a three-point bending mode by a SES-1000 universal mechanical testing machine. The notch with a depth of about 1 mm and root radius of about 200 μm was cut by a slow diamond saw. The fracture energy (Q) was calculated according to Ref. [25]. The morphology of fractured samples was examined with a SEM.

3. Results and discussion

The specific wear rate (W_S), the coefficient of friction (f) and mechanical properties including the hardness (H), the notch toughness (K_Q) and the fracture energy (Q) of nine BMGs were listed in Table 1. For comparison, the wear parameters of $Zr_{61}Ti_2Al_{12}Cu_{25}$ BMG were cited from Refs. [27,28], which have the similar sliding test conditions. The elastic properties and thermal parameters of the investigated BMGs were cited from Refs. [22–24,26–35] and also summarized in Table 1. The elastic properties and thermal parameters of $Mg_{65}Zn_{30}Ca_5$ BMG is unavailable from the literature, thus, those parameters were cited from Ref. [26] with a similar composition of $Mg_{66}Zn_{30}Ca_4$. According to Archard's equation, the wear resistance of materials is related to their hardness (H). Fig. 1(a) presents the W_S vs. H of BMGs. It indicates a general trend that the specific wear rate of BMGs decreases with increasing hardness. Exceptionally, the specific wear rate of PdCuNiP is about 1/38 as large as that of Zr-based BMGs, despite they have similar hardness. Fig. 1(b), (c), (d), (e) and (f) show the relationships between the specific wear rate and the Young's modulus (E), the yield strength (σ_y), the glass transition temperature (T_g), the notch toughness (K_Q) and the Poisson's ratio (ν) of BMGs, respectively. From the available data, no obvious linear relationships between W_S and E, σ_f, T_g, K_Q and ν of present BMGs can be obtained. The above results come to a conclusion that the H, E, σ_f, T_g, K_Q, and ν of present BMGs do not independently exhibit a direct correlation to the specific wear rate. The wear resistance of BMGs may be dominated by the competition of multiple physical parameters.

The morphology of the worn scars of typical PdCuNiP, ZrAlNiCu, FeCoCrMoCBY and MgZnCa BMGs with distinct discrepancy in toughness are shown in Fig. 2(a), (b), (c) and (d), respectively. Under dry sliding wear condition, parallel ploughed grooves with diverse widths and depths are observed on the worn surface of all these BMGs. These are typical features associated with the abrasive wear. However, the PdCuNiP shows a rather smooth worn surface covered with tiny shallow grooves, suggesting that only slight scratch took place. In contrast, wear pits in size around 30 μm reside in the surface of FeCoCrMoCBY, indicating a damage of brittle fracture, as seen in Fig. 2(c). Wear debris particles are spread on the worn surface of MgZnCa because of the plowing and scratching by abrasive particles, as illustrated in Fig. 2(d). Fig. 3 presents the chemical compositions on typical regions (A-H) of worn surfaces for (a) PdCuNiP, (b) ZrAlNiCu, (c) FeCoCrMoCBY and (d) MgZnCa BMGs by EDS analysis. The worn scar of PdCuNiP after dry