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Size effect on friction and wear mechanisms of bulk metallic glass

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ABSTRACT

This paper investigates the effect of sample size on the friction and wear of a bulk metallic glass (BMG), $Ti_{40}Zr_{25}Ni_3Cu_{12}Be_{20}$. The sliding tests were conducted on a pin-on-disk tribometer and the microstructural analyses were carried out by SEM and TEM. It was found that friction and wear of BMG change with sample size. The fracture strength and plasticity of BMG play a central role in the mechanism variation of friction and wear. When the pin diameter is 5 mm, the wear track showed typical abrasive morphology (without noticeable ductile features) containing shear bands which resulted in maximum wear under this condition. With the decrease of sample size, ductility and fracture strength of BMG increased, resulting in higher wear resistance and friction for smaller samples. The paper also concluded that the observed variations in mechanical and tribological properties of BMG with sample size are not due to the cooling rate effect or geometric instability or tilting of the specimen.

1. Introduction

Bulk Metallic Glasses (BMGs) have exceptional strength to density ratio, high wear resistance and low friction [1–3]. These properties make them a promising class of materials for critical mechanical components subjected to contact sliding. However, the microstructural transformation of a BMG can occur easily during contact sliding, which leads to the variation of wear mechanism [3,4]. Our previous studies showed that temperature rise due to frictional heating plays an important role in the microstructural transformation of BMG [3–6]. Depending on the interface temperature rise superplastic deformation or phase transformation took place in the BMG [3,4]. Because of such microstructural change the wear mode experienced a brittle-ductile-brittle transition[3].

However, the dimension of a BMG specimen affects its ambient temperature strength and deformation mechanism [7,8]. Two postulates e.g. 'free volume concentration' and 'plastic zone size' have been used to explain this size dependent deformation mechanism of BMG. A smaller sample experienced a faster cooling rate which creates more free volume in the smaller sample of same composition [7,8]. Higher free volume means more sites for the nucleation of initial shear bands, thus according to free volume model smaller sample exhibits better plasticity [7,8]. On the other hand, Wu et al. [9] reported that substantial reduction in exothermic heat for structural relaxation, ΔH_r (ΔH_r is proportional to the annihilation of excess free volume) did not change malleability of the annealed samples and small samples were more malleable under both conditions (as-cast and annealed). They [9] then concluded that higher malleability of smaller samples was due to the effects of sample size differences rather than free volume differences and explained the mechanism using 'material's plastic zone size'. When sample size is larger than the material's plastic zone size, shear bands propagate rapidly and the metallic glass failed catastrophically [9–11]. Whatever the underlying mechanism is the compressive plasticity of BMG changes with specimen dimensions and change of plasticity alters the wear resistance of BMGs [12]. It is also worthwhile to note that the size-dependence of fatigue life and endurance limit of BMG have been observed in fatigue studies [13]. The formation of multiple share bands in a small-sized BMG sample enhances ductility but decreases its flexural strength. This effect alters the failure mechanism when the sample size changes [13].

Durability of BMG components in tribological applications was found much better than that made by conventional materials. However, the superior performance of BMG components varied from case to case. For instance, the durability of a Ni-based BMG micro-gear was found 313 times better than that of conventional SK-steel [14], whereas, the durability of Zr-based BMG roller (ϕ7.5 mm by 7.5 mm) was found only two times better than that of conventional GCr15 steel roller [15]. This indicates that a systematic study on the effects of sample size on tribological behaviour of BMG is essential for assessing their proper application field e.g. nano-, micro- or macro-scale applications.

The relationship between sample size and tribological

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behaviour of BMG has not been investigated yet. Under a constant applied load, higher wear rates were reported for smaller BMG samples and that the wear mechanisms were explained using local structural relaxation/ atomic ordering [16]. It is important to note that under a constant applied load (10 N) varying the sample size (2 to 5 mm) [16] also vary the nominal contact stress. Thus the reported wear rates in Ref [16]. are also a consequence of the contact pressure. However, during uniaxial compression test, small sample made from same large stock (i.e. same cooling rate) [7] and annealed sample (reduced free volume) [9] showed better plasticity. This means more studies are necessary for better understanding of sample size – tribology relationship of BMG.

The objective of this paper is to understand the friction and wear mechanisms of a Ti-based BMG by varying the sample size. To eliminate possible effect of cooling rate, smaller pin will be prepared from large sample (pin).

2. Experiment

The Ti-based bulk metallic glass with a nominal composition of $Ti_{40}Zr_{25}Ni_3Cu_{12}Be_{20}$ (at. %), was prepared by arc melting of the pure elements with a purity of 99.9% under a Ti-gettered argon atmosphere. To assure the homogeneity of the elements, the ingot was melted for three to four times. Then the master alloy was remelted and cast into a copper mould to obtain cylindrical samples of 5 mm diameter. The mechanical, physical and thermal properties of the BMG and EN26 steel have been reported in [5,7,8,17] and have been listed in Table 1. The pin-on-disk experiment was performed on a CETR UMT – 2 tribometer (CETR/ Bruker, USA) in the open air under dry condition, by pressing a Ti-based BMG pin to slide against a rotating EN26 steel disk. The pin surfaces were polished using a series of grinding/polishing sand paper/disk on a StruersTegraPol 15 system by applying sufficient coolant. The smaller pins (ϕ0.8, ϕ1.9 and ϕ3.5 mm) were prepared by reducing the diameter of cast cylindrical samples (ϕ5 mm) on TegraPol 15 system. Fig. 1 shows the schematic of a pin with reduced diameter of contacting end and pin holder. The surface roughness (Ra) of the polished pins and disk before testing was 0.1 and 0.2 μm, respectively. It was confirmed by X-ray diffraction (XRD) analyses that the pin materials were indeed amorphous before the sliding tests (Fig. 2).

In a pin-on-disk test, a BMG pin was pressed onto the rotating disk under a constant nominal stress of 1.5 MPa. The applied loads were varied with sample size (diameter) accordingly to maintain the constant nominal pressure. The sample size (diameter) was varied from 0.8 to 5 mm. The sliding speed used was 0.13 m/s and the sliding duration was two hours. The surface roughness was measured by a 3D surface profiler – ZygoNewView700 (Zygo, USA). The microstructure of a pin was examined by a scanning electron microscope (SEM), Hitachi 3400I/3400X and transmission electron microscope (TEM), Phillips CM200. The TEM samples were prepared by focused ion beam, using XT Nova Nanolab 200/ xP200. The X-ray diffraction was performed using a PANanalytical Xpert Materials Research Diffractometer with a Cu Kα radiation and $\lambda=0.15406$ nm. After a sliding test, a pin was cleaned ultrasonically and the weight of the pin was measured on a high-precision digital scale, Semi-Micro Analytical GH252, whose resolution is 0.01 mg. The weight loss was quantified by deducting the weight after a sliding test from that before sliding. The wear rate was calculated as (weight loss of material/ total sliding distance).

Table 1
Properties of the BMG and EN26 steel.

Material	Density (kg/m³)	Young's modulus (GPa)	Poisson's ratio	Microhardness, HV(kg/mm²)
BMG [7]	5384	93.3	0.35	504
EN26 steel [17]	7860	203.8	0.3	311

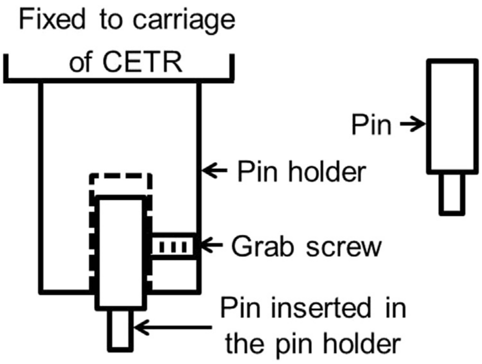

Fig. 1. A schematic of the pin and pin holder.

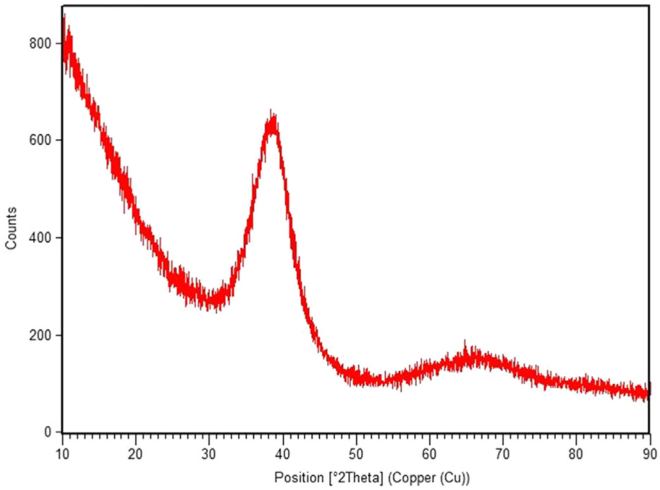

Fig. 2. The XRD pattern of a polished BMG pin.

3. Results and discussion

3.1. Friction coefficient and wear rate

Fig. 3 shows the typical variation of friction coefficient with time after sliding with pin diameters of 5 and 1.9 mm. It can be seen that the friction values reached a steady state after certain duration. However the running-in period is longer for a smaller pin. Fig. 4

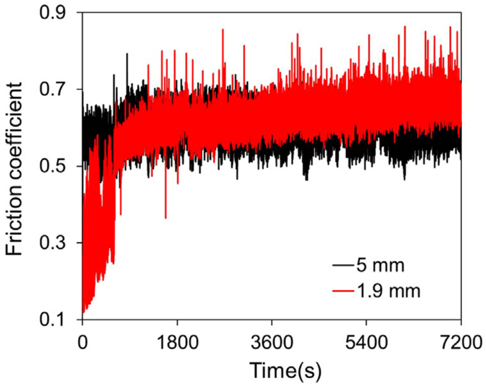

Fig. 3. Variation of friction coefficient with time.