Wear 320 (2014) 77–86

Contents lists available at ScienceDirect

Wear

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

On the estimation of interface temperature during contact sliding of bulk metallic glass

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ARTICLE INFO

Article history:
Received 2 April 2014
Received in revised form
19 August 2014
Accepted 20 August 2014
Available online 27 August 2014

Keywords:
Metallic glass
Contact sliding
Interface temperature
Surface parameters
Microstructural analyses

ABSTRACT

This paper investigates an approach to estimate the interface temperature during the contact sliding between a bulk metallic glass (BMG) pin and a steel disk. The Greenwood–Williamson statistical asperity model was used to calculate the real contact area, number of contacts and contact stresses. The Jaeger moving heat source model was used for the heat partition between the BMG pin and the rotating disk in the pin-on-disk wear tests. Transmission electron microscopy studies were conducted to examine the microstructures of the BMG corresponding to the estimated interface temperatures. It was found that the worn BMG surfaces do not follow the general trend of ‘decreasing summit density with roughness’, and that the summit density of a worn BMG surface is controlled by the deformation mechanism of the material. The dimensionless surface parameter, σNR of a BMG surface during contact sliding is not a constant. As such, assuming a constant σNR could bring about misleading results. Using the initial surface parameters will significantly underestimate the interface temperature. The paper concluded that a proper way to estimate the interface temperature is to use the parameters of a worn BMG surface under the threshold of 0.5% and $0.05 < \sigma NR < 0.4$.

1. Introduction

Due to its exceptional strength, hardness and fracture toughness at ambient temperature [1,2] and super-plasticity at high temperature [3], bulk metallic glass (BMG) has become a promising class of materials for making critical mechanical components, some of which may be subjected to contact sliding. Some superior tribological properties of BMGs have also been observed in ambient environment [4]. However, a BMG is prone to microstructural changes in contact sliding, which can cause variations of its tribological properties. Such sliding-induced microstructural changes in BMGs vary from case to case. Both phase transformation (nano-crystals) [5,6] and no phase transformation (sustain amorphous structure) [7–9] have been observed. But direct evidence for the possible mechanisms is not yet available. In addition, the reported effect of nanocrystals on the tribological behaviour of BMGs is controversial. Some claimed an increase in wear resistance of BMGs [10] but some concluded a decrease [11] due to the emergence of nanocrystals.

It is the fact that all engineering surfaces are rough on the microscopic scale. When two engineering surfaces are brought into contact, they interact only at some discrete summit tips. As such, the real area of contact can be only a fraction of the nominal area of contact [12–14]. In a tribological application, the real area of contact influences the friction, wear and thermo-mechanical properties of the mating surfaces. Frictional heating in contact sliding is inevitable, which, when sufficiently high, may alter the material properties and hence the friction and wear mechanisms. Under a sliding contact, a BMG surface would experience a temperature rise due to frictional heating [15] as well as local plastic deformation [16,17]. When the temperature is sufficiently high, a change in the wear mode and microstructure in the BMG may take place [18,19]. However, there are many difficulties in the estimation of the interface temperature when a BMG pin is in contact sliding with a counterpart material.

First, there are no generally acceptable models that could define the load carrying summits. Based on Nayak's [20] terminology, Greenwood [21] suggested a 3-point peak for a 2D profile and a 5-point summit for a 3D surface. For a three-dimensional surface, Poon and Bhushan [22] defined a summit as a point higher than its four adjacent points by a pre-set threshold (the height difference between the central point and its four nearest surrounding points). It was suggested that if the root mean square roughness (R_q) of a surface is less than 0.05 μm, the threshold should be 10% of R_q. However, if R_q is greater than 0.05 μm, the threshold should be less than 10% of R_q [23,24]. Pogačnik and Kalin [25] measured the roughness of different surfaces using a stylus-tip profiler and analysed the 2D profiles. However, even for their roughest surface

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http://dx.doi.org/10.1016/j.wear.2014.08.009
0043-1648/

(R_a=0.64 μm), they did not find any asperity-peak when the threshold was set to be 5% or higher. They then concluded that the peak threshold suggested by [23] was too general, and that a roughness measurement, such as R_a, R_q, summit density or summit would be affected strongly by the spatial resolution of an instrument (e.g., the stylus size or magnification of the objectives lens), the scan length, and the sampling interval [21,22,26]. Greenwood [21] concluded that it is unreasonable to describe a roughness value without clarifying the sampling interval used. Bhushan et al. [26] reported that the number of summits of a magnetic tape increased from 370/mm^2 to 180,100/mm^2 when the sampling interval decreased from 2 μm to 0.2 μm. It should be noted that the statistical analysis of surfaces mainly depends on the correlation length and bandwidth parameter [20,27,28]. A surface could have different statistical parameters depending on these parameters.

A few models [29–31] have been used to calculate the interface temperature of materials during sliding [15,32,33]. Kong et al. [15] claimed that the flash temperature [29] during sliding could reach several hundreds of Kelvin while the bulk temperature of the material remains close to ambient temperature. Guha and Chowdhuri [34] reported that the interface temperature changes with the centre line average (CLA) roughness. Their study was based on the assumption that there is a constant dimensionless surface parameter, σNR, where σ is the standard deviation of the summit heights, N is the summit density, and R is the summit radius. As a matter of fact, however, both summit density and summit radius change with the CLA roughness so the σNR of a worn surface cannot be constant [35]. Chen et al. [36] derived a model to estimate the temperature rise during the polishing of polycrystalline diamond composites, considering the initial surface parameters and parabolic heat source. However, because of the material removal, the load bearing summits change during polishing; thus an estimation based on the initial surface topography might not reflect the interface temperature variation throughout the polishing operation. In reality, the variation of interface temperature of two surfaces during contact sliding depends on the thermo-mechanical properties of the mating materials, the real area of contact, and the number of contacts [37–39]. In the case involving a BMG, phase transformation and superplastic deformation of the material would bring about further complexity to the interface temperature rise in contact sliding [40,41]. A rational characterisation needs to involve not only the essential surface parameters, but also the microstructural changes.

This paper will investigate the temperature variation at the contact sliding interface between a BMG pin and a steel disk, considering the effect of the BMG surface parameters and microstructural changes in the material.

2. Methodology

2.1. Experimental

The BMG used in this study was $Ti_{40}Zr_{25}Ni_3Cu_{12}Be_{20}$ (at%) whose mechanical, physical and thermal properties have been shown in Table 1. The sliding tests were carried out on a CETR pin-on-disk tribometer, in which a BMG pin of 5 mm in diameter was pressed onto a rotating EN26 steel disk under a nominal pressure of 0.25 MPa. The tests were run at environmental temperatures of 295 K (room temperature), 373 K and 473 K. The sliding speeds were 0.13 m/s, 0.52 m/s and 0.90 m/s, and the sliding duration was an hour. The tests under 373 K and 473 K were conducted in a heating chamber in which the temperature was maintained constant. The CETR tribometer has a two-dimensional force sensor for the measurement of friction and for the control of the normal load to apply. The coefficient of friction can be calculated automatically by the system software as the ratio of the frictional force to the normal force applied. The material wear was quantified by measuring the weight loss on a high-precision digital scale, Semi Micro Analytical GH252, whose resolution is 0.01 mg.

The surface topographies of the BMG pin and the EN26 steel disk before and after a sliding test were examined on a 3D surface profiler (Zygo NewView 700) equipped with an optical microscope and a digital camera. The magnification of the standard objective lens used was 10, which provides a fixed scan size of 0.94 mm × 0.7 mm and sampling interval of 1.47 μm. The high speed digital camera has a resolution of 640 × 480 pixels. The measurement and analysis were carried out according to the microscope application and advanced texture application of Zygo NewView 700. A summit is defined as a point that is higher than its four nearest surroundings by a preset threshold. As shown in Fig. 1, for example, summit height Z_0 is greater than its nearest four surroundings, Z_1, Z_2, Z_3 and Z_4, by ΔZ_i. The summit radius is the radius of curvature of the best-fit sphere to the summit based on the four adjacent pixels to a given summit. The default threshold of the equipment is 0.01 nm. In other words, if the height of a point is 0.01 nm higher than the four points surrounding it, this point was considered as a summit and the value would be termed as 0% threshold. In the present investigation, seven different thresholds, 0% (default) to 10% of the root mean square roughness (R_q) were used. The R_q was from a scanned area of 0.94 mm × 0.7 mm. However, in the calculation of surface parameters (e.g., summit density, radius and standard deviation of summit heights), we took the average of six R_q from randomly selected scanning area over the sample surface.

2.2. Modelling the temperature rise

It was found that the summit heights of the BMG and EN26 steel surfaces (polished) before a sliding test and those of the worn BMG surfaces follow approximately Gaussian distributions, $\varphi(z) = (1/\sigma\sqrt{2\pi})e^{-z^2/2\sigma^2}$ (more details in Section 3.1.3), where σ is the standard deviation of the distribution. This allows us to use the statistical asperity model proposed by Greenwood–Williamson (G–W) [45] to calculate the real contact area and stress. This model assumes (i) that all asperities, at least near their summits, are spherical, (ii) that all asperity summits have the same radius R, (iii) that their heights vary randomly, i.e., the probability that a particular asperity has a height between z and $z+dz$ above a reference plane is $\varphi(z)dz$, and (iv) that all contacts are deforming elastically (no plastic deformation is considered). The behaviour of an individual asperity during contact can be found from the Hertzian equations [46]. If the BMG pin and steel disk come together until their reference planes are separated by a distance d, then there will be contact at a summit whose height was originally greater than d. Thus, the probability of making contact at

Table 1
Properties of the BMG and EN26 steel.

Material	Density (kg/m³)	Young's modulus (GPa)	Poisson's ratio	Microhardness, HV (kg/mm^2)	Thermal conductivity (W/mK)	Specific heat (J/kgK)
BMG	5600 [42]	93.3 [43]	0.35 [43]	504 [43]	9.15 [42]	614 [42]
EN26 steel [44]	7860	203.8	0.3	311	34.75	494