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Full Length Article

Nanoscale tunable reduction of interfacial friction on nano-patterned wear-resistant bulk metallic glass

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ABSTRACT

Controllable friction and wear is desired for the structural durability and functional reliability in small-scale moving devices such as MEMS/NEMS. A critical need is to understand the fundamental mechanisms concerning interfacial friction evolution and modulation on the nano-structured surfaces, and to explore the possibility to reduce wear at the nanoscale. Here, we show a novel method to reduce friction by fabrication of nano-groove patterns on wear-resistant Zr-based bulk metallic glass of $Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10}Ti_5$. The tunable level of friction reduction is highly dependent on contact parameters, and the origins of a series of friction phenomena such as Amontonian behavior, friction anisotropy, logarithmic evolution and topography-induced instability are interpreted from the aspects of groove density, normal load, scan velocity, topographical direction and contact area. The exceptional anti-wear performance of glassy metal interface is attributed to the in-situ formation of a 5 nm-thick oxide layer with specific alloying components of ZrO_2, CuO and Al_2O_3. The present findings provide key implications on the use of metallic glass as engineering materials for sustainable and efficient design of miniaturized systems.

1. Introduction

The development of nanotechnology allows modern equipment to be designed in a miniaturizing size [1]. Typically, microelectromechanical systems (MEMS) are micrometer-scale devices comprising of integrated electrical and mechanical components with tailored functionalities for diverse applications [2]. It evolves into nanoelectromechanical systems (NEMS) with dimension further reduced to the nanometer range [3,4]. The large surface-to-volume ratio inherent in these systems renders them sensitive to surface-dominating phenomena such as tribological behaviors [5,6]. Critical issues related to friction and wear significantly affect the performances of MEMS/NEMS devices with moving parts in contact at small scales [7]. The clear understanding of reliability and failure mechanisms therefore is extremely fundamental for developing a highly functional MEMS/NEMS system with precision control.

In general, the geometric characteristic of MEMS/NEMS devices is the presence of various micro- and nano-patterns fabricated in specific shapes. Remarkable efforts have been devoted to exploring the interfacial friction mechanisms dependent on topographic features, material properties and contact-related parameters. Most of these studies focused on understanding the topographic effects on adhesion and friction in different miniaturized systems, such as nanoparticle-textured [8], line-like or Penrose-like polyimide surface [9], micropillar-arrays-assembled polydimethylsiloxane [10], dome- or dimple-textured metal substrates [11,12], microneedle-distributed [13] or Ni nanodot-patterned [14] Si surfaces, and micro-grooved surfaces [15]. A variety of friction phenomena such as Amontonian behavior (namely friction is proportional to applied normal load) [11,13,16], friction anisotropy [9,15], frictional instability or even stick-slip [11] have been observed to rely closely on feature shape and size, topographic orientation, applied normal load and sliding velocity. It should be pointed out that, in light of the contact configuration, an overwhelming majority of these cases reported frictional issues on the micro- and macroscales rather than on the nanoscale, mainly due to the large probing tip size (i.e., from tens of micrometers up to the millimeter scale) used in the experiments [8–10,12–15,17]. Therefore, despite the considerable phenomenological knowledge obtained at these dimensions, the fundamental mechanisms governing frictional interactions on nanostructured surfaces are not fully understood in a more in-depth way, namely at the

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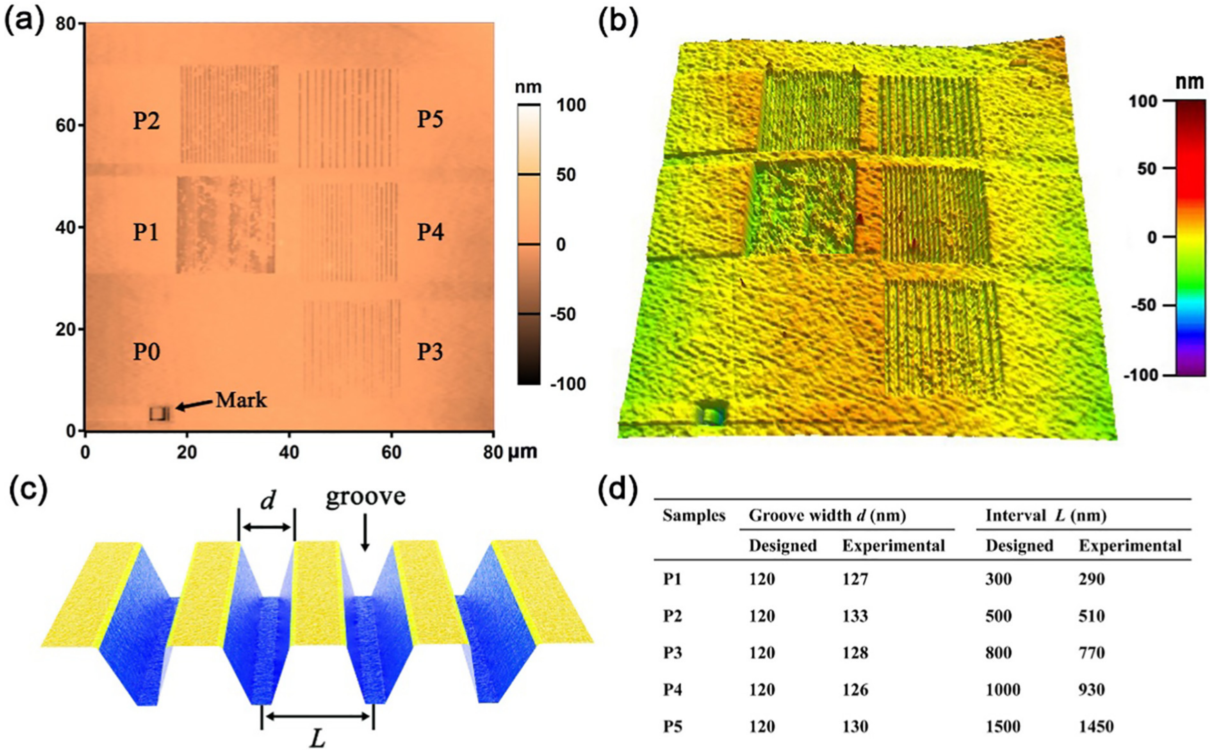

Samples	Groove width d (nm)		Interval L (nm)	
	Designed	Experimental	Designed	Experimental
P1	120	127	300	290
P2	120	133	500	510
P3	120	128	800	770
P4	120	126	1000	930
P5	120	130	1500	1450

Fig. 1. Topographies of the as-fabricated nano-patterns on the mirror-polished Zr-based BMG surface. (a) AFM 2D image showing an overview of the distribution of nano-groove arrays of P0–P5 (P0 indicates the as-polished surface). (b) The corresponding AFM 3D image of (a). (c) Schematic showing the upper-end width *d* of the V-shaped groove and the center-to-center spatial interval *L* between two neighboring grooves. (d) The designed and as-measured values of *d* and *L* for nano-groove arrays of P1–P5. The depth of the grooves was designed to be 75 nm.

length of nanometer scale. To this end, the primary goal of this work is to provide insight into nanoscale friction evolution and modulation, and to explore the possibility for friction reduction.

Wear is another unavoidable phenomenon that is confronted in MEMS/NEMS devices with moving mechanical assemblies [18]. It is a crucial factor that affects not only the durability but also the efficiency. To date, most MEMS/NEMS devices are fabricated by silicon, polymers, metals and ceramics [19,20]. Rapid wear in the form of progressive material loss occurs as a result of harsh mechanical actions associated with rubbing or compacting surfaces, especially in high-friction-bearing Si-based systems. Failure mechanisms generally involve adhesive, abrasion, fatigue and corrosive [19]. For instance, high adhesive forces between Si surfaces easily initiate micro-cracking at stress-concentrated points and yields a large amount of wear debris [21]. The accumulation of these scratching particles further induces third-body wear. Ultimately, the deterioration of surface condition and severe damage lead to failure of the micro- and nano-systems. Metallic glass, also called amorphous alloy, is a novel engineering material with a highly disordered arrangement of atoms [22]. The absence of dislocations and the capability of being tailored in different forms of nanostructures endow metallic glass with superior strength, high hardness, and impressive resistance to corrosion and wear [23,24], because of which it draws increasing attention on design, fabrication and its application in MEMS/NMES systems. The rapid developing metallurgical field of metallic glasses, bulk metallic glasses (BMGs) and relevant alloys can be found in some recent literatures [25–27]. As a concern to wear-resistance application, Browne et al [28,29] have shown that some Zr-Cu-based bulk metallic glass alloys have the requisite mechanical properties to be patterned with micro to nano features on the surfaces, which can be used as resilient tooling for molding of polymers. More recently, Li et al [30] clarified the possibility to tune friction at the macro scale by honeycomb-textured Zr-Ti-based BMG with various pitches, wherein the patterned surface with an appropriate pitch size of 75.5 µm could also achieve a minimum wear rate. To this regard, another aim of this work is to provide a clear understanding of the capacity of being processed as miniaturized components for BMG material, and to reveal the underlying anti-wear mechanisms.

For these purposes, we fabricated a batch of nano-sized grooves with different arrays on zirconium-based amorphous alloy. As one of the most common shapes encountered in MEMS/NEMS devices, these nano-grooves were designed to be distributed in specific arrangement pattern. We presented a clear description of the evolution of interfacial friction, especially the friction reduction behavior, with respect to the patterning nanostructure and the rubbing conditions such as applied normal load, sliding velocity and contact area. Special attempts were implemented to microscopically resolve the tribo-induced interfacial nanostructure, enabling an unprecedented illumination of the anti-wear mechanism in BMG at the nanoscale.

2. Materials and methods

2.1. Nano-groove patterns on Zr-based BMG surface

The Zr-based BMG specimens of $Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10}Ti_5$ (The digitals behind each element representing the nominal atomic compositions of metal powders for alloying) were synthesized by home-built arc-melting apparatus. The Zr-based BMG rod with diameter of 5 mm was prepared using copper mold casting in argon atmosphere. XRD result confirms the amorphous nature of the rod. The glass transition temperature and crystallization temperature of the BMG specimens are 675 K and 738 K, respectively. To achieve mirror-finished surfaces, the specimens were polished by an automatic polishing machine (Metaserv 250, Buehler Company). The specimens were first roughly flattened using water as polishing solution. Then they were polished successively by 6 µm and 1 µm diamond polishing slurries, respectively. Afterwards, mirror polishing was carried out by using 60 nm and 20 nm silicon