DOI: 10.1002/adem.200900184

Tribological Studies of a Zr-Based Glass-Forming Alloy with Different States**

By *Feng Jiang**, *Jun Qu*, *Guojiang Fan*, *Wenhui Jiang*, *Dongchun Qiao*, *Matthew W. Freels*, *Peter K. Liaw* and *Hahn Choo*

The tribological characteristics of a glass-forming alloy, $Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10.0}Ti_{5.0}$, in atomic percent (at.%, Vit 105), with different microstructural states have been investigated. Friction and wear studies were conducted using a ball-on-flat reciprocating sliding apparatus against an AISI E52100 bearing steel under dry condition. The observed wear resistance in an ascending order is: the deformed, creep-tested, and as-cast states. Wear analyses suggested that the wear processes of glass-forming alloys involved abrasion, adhesion, and oxidation. The differences in hardness, free volume, and brittleness in different states significantly affected the friction and wear behaviors of the glass-forming alloys.

Introduction

Metallic glasses are characterized by their disordered structures and possess many unique properties, compared to traditional crystalline materials, such as higher hardness and strength, superior resistance to corrosion and better magnetic properties.[1–4] So far, most of the efforts on metallic glasses focused on Zr-based bulk-metallic glasses (BMGs) because these alloys have a high glass-forming ability and exhibit a combination of various good mechanical properties. Especially, due to their high hardness, they are considered to be potential candidates for wear applications.[5] In the literature, there are conflicting results on the wear resistance of as-cast BMGs, relaxed BMGs, and their crystalline counterparts. For example, some studies reported that metallic glasses have higher wear resistance than their crystalline counterparts.[6–8] In contrast, there are also reports indicating that the wear performances of metallic glasses is significantly inferior to their relaxed state[9,10] and crystalline state.[11] Those discrepancies show that wear behavior is a complex processes, and hardness alone may not determine the wear resistance. In this paper, the other natures of glass-forming alloys will be investigated to contribute to the analysis of the wear process. For example, plastic-deformation ability and brittleness may play the important roles on the wear performance of them as well. It is well known that plasticity in amorphous alloys is largely affected by free volume. If the excessive free volume is introduced by plastic deformation, a less dense randomly-packed structure will be obtained, leading to less restriction on the shear-band movement and decrease in hardness of the amorphous alloys.[12] In some cases, the free-volume reduction and annihilation by annealing the samples below the glass-transition temperature (T_g) and above T_g, respectively, may result in brittleness due to the reduced or absent propensity for the shear-band formation.[13–16]

Thus, the change of the free volume and crystallization may yield different deformation and flow behaviors that may influence the wear performance of glass-forming alloys. Until now, although there is a fair amount of literature research on the relationships among hardness (referred to the resistance to ploughing and cutting), free volume (referred to the ability of the plastic deformation of glass-forming alloys), and brittleness (referred to the extent of the crack initiation and propagation), little research has systematically studied their effects on friction and wear behaviors. The purpose of this

[*] *F. Jiang, Dr. G. Fan, Dr. W. Jiang, Dr. D. Qiao, M. W. Freels, Dr. P. K. Liaw, Dr. H. Choo*
Department of Materials Science and Engineering, The University of Tennessee Knoxville, Tennessee 37996-2200, USA
E-mail: fjiang3@utk.edu
Dr. J. Qu, Dr. H. Choo
Materials Science and Technology Division, Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831-6063, USA

[**] *F. J. is grateful to Peter J. Blau for his comments on the paper. The present work was supported by the National Science Foundation (NSF) International Materials Institutes (IMI) Program (DMR-0231320). A portion of this research was sponsored by the US Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Vehicle Technologies Program, as a part of the High Temperature Materials Laboratory User Program, under contract DE-AC05-00OR22725 with the UT-Battelle LLC.*

 © 2009 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

investigation is to compare tribological characteristics of a Zr-based glass-forming alloy with different states of crystallinity under the same testing conditions and to try to address the effect of hardness, free volume, and brittleness on the wear behavior.

Experimental

Sample Preparation

The master alloy of $Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10.0}Ti_{5.0}$ (at.%) was prepared by melting a mixture of high-purity Zr [99.9 weight percent (wt%), Cu (99.999 wt%), Ni (99.99 wt%), Al (99.999 wt%), and Ti (99.99 wt%)] in a purified argon atmosphere. In order to obtain the compositional homogeneity, the alloy ingots were remelted several times before being cast into a water-cooled copper mold using an in situ suction-casting facility.[17] The resulting rectangular samples have a cross-section of 4.75 mm × 4.75 mm and 30 mm in length. The rectangular samples with different height–diameter ratios (H/D) of 0.75 and 2 were cut for compression and creep experiments, respectively. The thermal stability of the as-cast ingots was examined using a differential-scanning calorimeter (DSC) with a heating rate of 20 K min^{-1} in flowing argon. The DSC scan indicated that the glass transition occurred at 673 K. A uniaxial compression test was conducted at room temperature with a strain rate of $5 \times 10^{-4}\,s^{-1}$ on the specimens with a cross-section of 4.75 mm × 4.75 mm and 3.5 mm in length. The bar ends were polished in a specially-designed fixture to ensure parallelism. The plastic strain of the specimens after deformation is around 10%. Those specimens are denoted as deformed Vit 105. A uniaxial compression-creep test was performed at the stress level of 250 MPa at 733 K for 10 h on the specimens, which are denoted as creep-tested Vit 105. The structure of the creep-tested Vit 105 was investigated with high-energy [115 keV (0.01078 nm)] synchrotron X-ray scattering performed at the beam line, 11-ID-C, of the Advanced Photon Source at the Argonne National Laboratory. Table 1 summarizes the treatments of the three kinds of specimens described above.

Hardness Test

Vickers microindentation-hardness tests were conducted under a load of 200 g (1.96 N) using a Buehler Micromet® hardness tester. Seven indentations were performed on each specimen.

Table 1. $Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10.0}Ti_{5.0}$ glass-forming-alloy specimens in different states.

Specimen designations	Treated states
As-cast Vit 105	As-cast by quenching in an arc-melter
Deformed Vit 105	Deformed about 10% at the strain rate of $5 \times 10^{-4}\,s^{-1}$ with the H/D ratio of 0.75
Creep-tested Vit 105	Creep-tested at the stress level of 250 MPa and the temperature of 733 K for 10 h

Wear Test

The specimens with different states were cut to the pieces of 4.75 mm (length) × 4.75 mm (width) × ~2 mm (thickness) and were wet polished to an 800-grit finish to produce a consistent initial surface condition. Tribological tests were performed using a ball-on-flat reciprocating sliding apparatus.[18] Every test was run for 1280 s. The normal force was 5 N, and the oscillation frequency was 5 Hz with a 2.35 mm stroke (the average sliding speed was 0.0235 m s^{-1}). The slider was an AISI 52100 bearing steel ball with a diameter of 9.525 mm. Tribological experiments were conducted in room-temperature air without lubricant. Friction coefficient was monitored in situ by a load cell-based force-measurement system. Wear volumes of the flat samples were determined by measuring the depth profiles of wear scars. Three measurements were performed on each wear track. The ball wear was measured using the profilometry technique described in an earlier paper.[19] The morphologies of the wear scars were examined using a scanning-electron microscope (SEM) equipped with the capability for the energy-dispersive spectroscopy (EDS).

Results and Discussions

Hardness

The hardness results of the Vit 105 glass-forming alloy with different states are shown in Figure 1. The ascending order of the hardness is as follows: the deformed, as-cast, and creep-tested states, which seems to be related to the amount of the free volume in those specimens. In the Figure 2 of DSC results, the exothermic reactions of the deformed and the as-cast specimens signifying the structural relaxation can be clearly discerned just below T_g. However, it cannot be observed for the creep-tested specimens due to the crystallization. The structural relaxation exothermic heat (ΔH_0) for the deformed and the as-cast samples are 9.4 and 4.8 J g^{-1}, respectively. In principle, the amount of the escaped free

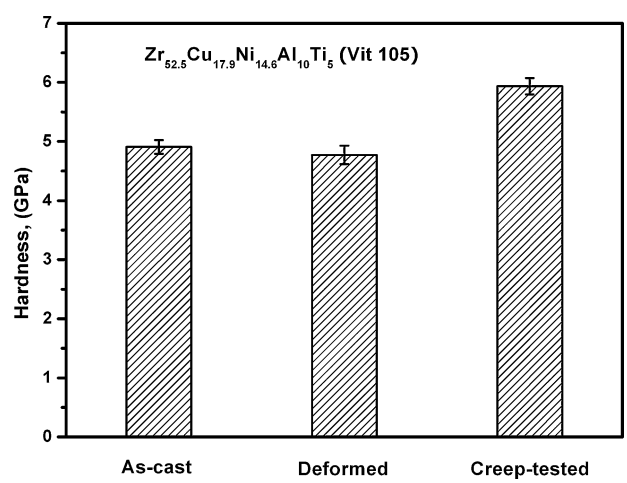


Fig. 1. Hardness for the as-cast, deformed, and creep-tested Vit 105 glass-forming alloys.

 © 2009 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

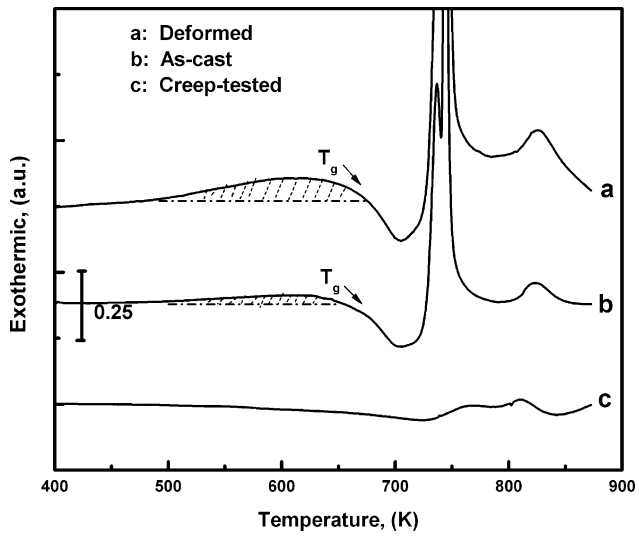


Fig. 2. Enlarged portion of the structural relaxation before the T_g in the DSC traces of (a) deformed, (b) as-cast, and (c) creep-tested Vit 105 glass-forming alloys at a heating rate of 20 K min^{-1}.

volume during heating is proportional to the exothermic heat of structural relaxation.[20] By this reason, the DSC results demonstrated that the deformed Vit 105 had more free volume than the as-cast Vit 105. It is well known that plastic deformation can introduce the excessive free volume into the amorphous matrix by shear banding. Indeed, the excessive free volume accommodates the movement of shear bands. Thus, it is reasonable that the hardness of the deformed specimen will decrease. There is no free volume in the creep-tested specimen due to the crystallization. Figure 3 of the X-ray result shows that a largely developed set of peaks formed in the region, where the first and second diffuse halos were positioned after a creep test for 10 h. It indicates that some crystalline phases develop in the amorphous matrix. Some of them correspond to the face-centered cubic (FCC) and quasicrystalline nanocrystalline phases (marked by solid circles and open squares, respectively), which were also observed by Pekarskaya *et al*.[21] The *d*-spacings obtained from the most prominent peaks are 2.53, 2.34, 2.03, 1.49, and 1.31, which correspond to the nanocrystalline phases. Then, after long-time annealing, the amorphous alloy finally became fully crystalline of the mixture of two FCC and quasicrystalline nanocrystalline phases. Based on the crystallization study of Pekarskaya *et al*.[21] on the as-cast Vit 105, the decomposition process occurs in the early stage of isothermal annealing, which leads to two nanocrystalline phases. However, there is very limited growth of nanocrystals even after long-time annealing (e.g., 900 min.) What are really happening in the long-time annealing is an increase in the volume fraction and/or further ''ordering'' of the quasicrystalline phase.[21] This may help explain the higher hardness of the creep-tested Vit 105 than the as-cast Vit 105.

Friction Coefficient

The friction coefficient as a function of time is shown in Figure 4 for the Vit 105 glass-forming alloy with different states. Previous research indicated that the tribological process occurring in the samples of glass-forming alloys can be divided into three distinct regions[22]: running-in, transition, and steady-state. In the running-in stage, a transient peak-friction coefficient quickly falls down to and temporarily stabilizes at a lower value. The friction coefficient could stay in the low level from seconds to minutes before transitioning to a higher level. This transition stage usually causes an oxide-based transfer layer to form. Eventually, the friction coefficient reaches a steady-state value (third stage). The friction transition in the second stage is crucial to the wear resistance of metallic glasses. The oxide film formed in this transition provides a protection to the contact area of glass-forming alloys and reduces wear rate to some extent.

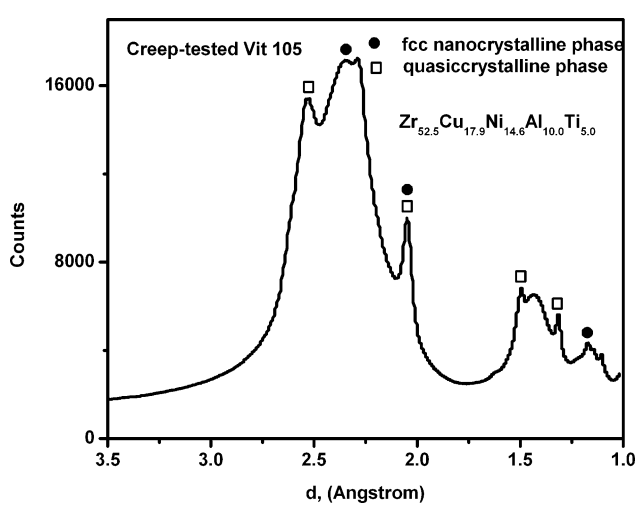


Fig. 3. High-energy synchrotron X-ray diffraction profiles from the creep-tested specimens. The solid circles indicate peaks from the FCC nanocrystalline phase, and open squares indicate the quasicrystalline phase.

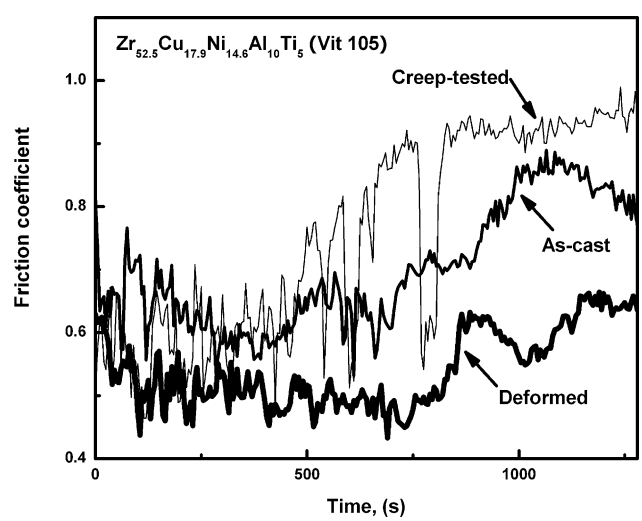


Fig. 4. The friction coefficient as a function of time of tribological tests for the as-cast, deformed, and creep-tested Vit 105 glass-forming alloys.

 © 2009 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

It can be seen in Figure 4 that there are three stages for all kinds of the Vit 105 glass-forming alloy with different states. The as-cast and creep-tested Vit 105 started the important transition stage early at around 450 s, followed by the deformed Vit 105. The ascending order of the steady-state friction-coefficient values is: the deformed, as-cast, and creep-tested states. Many previous studies indicated that the micromechanism of wear in glass-forming alloys is abrasive wear, with high-oxygen-containing tribolayers acting as the abrasive medium.[9] Therefore, the transfer film with oxidation is crucial for explaining the present results. Compared to the as-cast Vit 105, the creep-tested Vit 105 has a higher friction coefficient. Obviously, some drop-offs can be observed from the transition stage of the curve of the friction coefficient versus time of the creep-tested Vit 105. It indicates that the transfer layer is not stable. This is reasonable, considering that the crystalline specimen after creep is very brittle, and the surface is easily ploughed off and scored to the layer of the debris. In addition, according to the oxidation research by Kai *et al*.[23] the oxidation will become severe for the amorphous state, compared to the annealed state above the T_g because the crystalline phases, such as Zr_2Cu and Zr_2Al occurring in the crystalline state help improve the oxidation resistance. In other word, the elements, such as Zr and Ti, are not easily prone to oxidation in the crystalline material after creep, compared to the amorphous state. As a consequence, the oxidation film is not easy to form on the surface of the creep-tested Vit 105. As we know, the presence of the oxide layer inhibits the glass-pin contact, which may lubricate the wear process of the materials. Fu *et al*.[24] reported that for a given load, sliding in air gave a lower friction coefficient and lower fluctuation amplitude, compared with sliding in vacuum for BMGs. This trend may be due to the role of oxidation occurring in the process of sliding. Based on the discussion above, the fact that the creep-tested Vit 105 has the highest friction coefficient is due to the absence of the stable transfer layer and oxide film, which can prevent direct glass-pin contact. The absence of the transfer layer of the creep-tested Vit 105 can be confirmed with SEM observation of the surface after the wear test, which will be discussed later. It is very interesting that the steady-state friction coefficient of the deformed Vit 105 is the lowest. The inhomogeneous shear is believed to be one of the wear mechanisms for metallic glasses.[25] The inhomogeneous plastic flow is characterized by the formation of localized shear bands, which lead to work softening.[26] Thus, there is a soft layer with a low friction coefficient developing on the surface of the deformed sample during sliding of the wear test. Therefore, the increase in the free volume in the deformed Vit 105 enforces its ability of accommodating the plastic deformation, which eventually leads to a low friction coefficient.

Wear Scar and Wear Rate

Transverse profiles of representative wear scars are shown in Figure 5. The wear-scar depth is the greatest for the deformed Vit 105, and the smallest for the as-cast Vit 105.

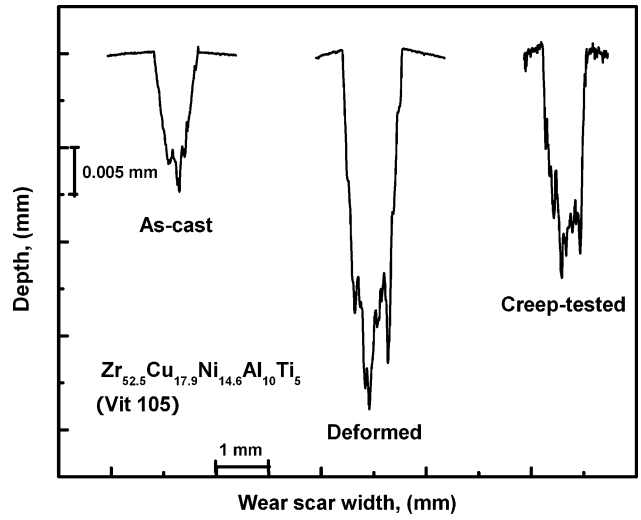


Fig. 5. Wear scars for the as-cast, deformed, and creep-tested Vit 105 glass-forming alloys.

Accordingly, wear rates for different specimens after the tribological tests are summarized in Figure 6. The as-cast Vit 105 had the lowest wear rate, compared to the creep-tested and deformed Vit 105. The creep-tested Vit 105 became a fully crystalline phase after it was heated above the crystallization temperature. Although it possesses the highest hardness, which can impede the material removal by normal ploughing and cutting, the creep-tested sample is usually brittle like ceramics.[27] Gilbert *et al*.[28] observed a dramatic decrease in the fracture toughness for both partially and fully crystallized metallic glasses. This brittleness is associated with the structural relaxation and the annihilation of the quenched-in free volume before crystallization. They are, therefore, susceptible to microfractures under a high load. The crack initiation occurs in the crystalline phases as well as propagates through them.[27] This phenomenon of brittleness helps explain the high wear rate of the creep-tested Vit 105.

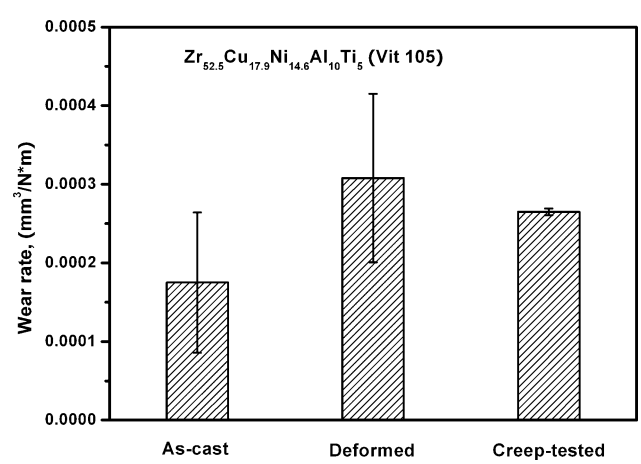


Fig. 6. Wear rates for the as-cast, deformed, and creep-tested Vit 105 glass-forming alloys.

 © 2009 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

More interestingly, in our study, it could be the first time that wear experiments were performed on deformed BMG specimens. Results showed that deformation increased the wear volume of BMG due to the increase in free volume. It is well known that at lower temperatures and higher stresses, the plastic flow of BMGs is markedly inhomogeneous, being concentrated into shear bands.[29,30] These planar shear bands form in orientations close to the planes of maximum resolved shear stress. The shear-band formation is a plastic instability in which the flow causes a reduction in the density of the alloy,[31] and the reduction in density lowers the flow stress. Hence, the result is work softening, leading to a continuing flow on the same plane for the localized deformation.[29] Therefore, a less dense, randomly-packed structure in the amorphous sample was achieved due to the increase in free volume after plastic deformation. This fact leads to a less restriction on the shear-band movement in the deformed amorphous alloy, which results in the decrease in the wear/friction properties of the deformed Vit 105.

The wear scars were examined by SEM, as shown in Figure 7. It was observed that the wear scars have two kinds of distinct regions, the abrasion region (light gray area) and adhesion region covered by transfer material (dark gray area) for the as-cast and deformed Vit 105. However, no dark gray area was clearly observed on the surface of the creep-tested Vit 105. Further chemical analyses by EDS, as shown in Figure 8, indicate the presence of a large amount of oxygen in the dark area, suggesting that an oxidation processes occurred during tribological tests. This observation was also reported by Jin *et al*.[9] that an oxide film was present on the worn surfaces of the as-cast and relaxed Zr-based BMGs and absent on that of a crystalline alloy. Therefore, oxidative wear is believed to be one of the predominant wear mechanisms for as-cast and deformed Zr-based BMGs. This phenomenon is reasonable, considering that the high chemical affinity of Zr and Ti with oxygen to form respective oxides. The formation of high-oxides-containing tribolayers and their subsequent debonding under the action of a reciprocating steel ball constitute the main mechanism of wear in as-cast and deformed alloys. In our studies, the worn surfaces of the as-cast and deformed samples look similar, while the crystallized crept alloy exhibits the different wear-scar morphology with a smoother surface and absence of a protective oxide film, which confirm our discussion in the part on the friction coefficient. This observation further explains why the creep-tested Vit 105 had a higher wear rate than that of the as-cast Vit 105.

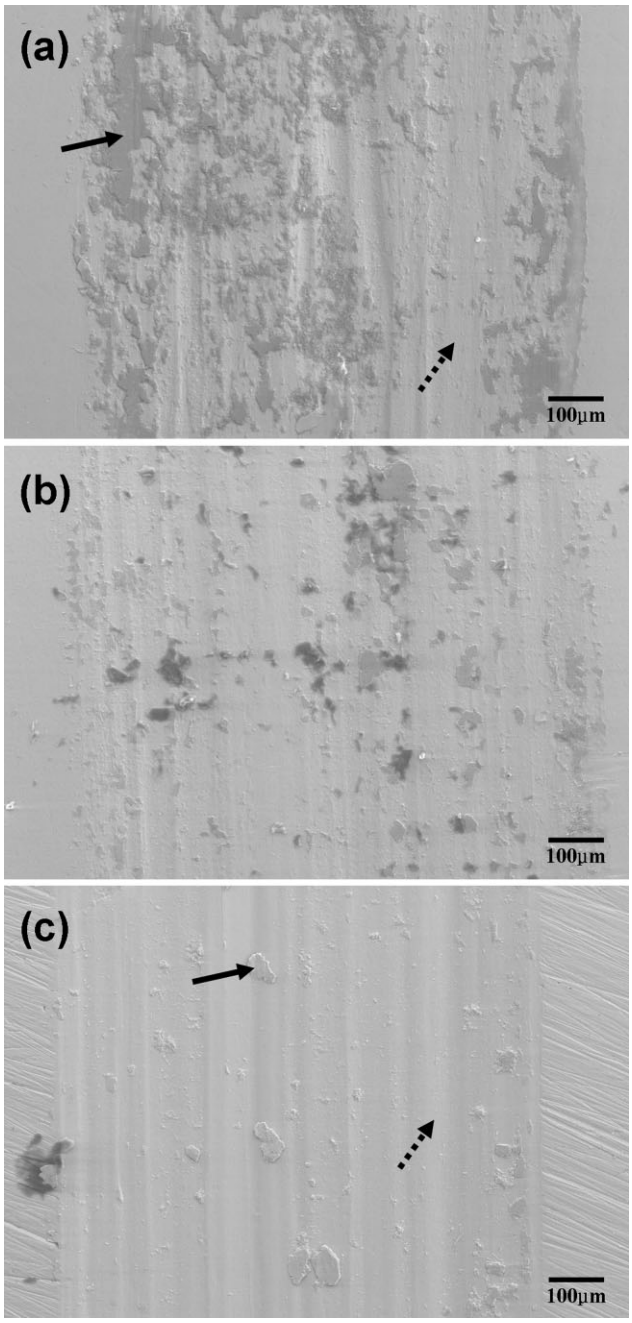


Fig. 7. SEM images for (a) as-cast, (b) deformed, and (c) creep-tested Vit 105 glass-forming alloys after the tribological test.

Conclusion

The tribological behaviors of the Zr-based Vit 105 glass-forming alloy in different states have been investigated using a ball-on-flat test at a fixed load, speed, and sliding time. The following conclusions may be drawn from this investigation.

(i) The ascending order of the hardness is as follows: the deformed, as-cast, and creep-tested states, which seem to be related to the amount of free volume in those specimens.

(ii) The ascending order of the steady-state friction-coefficient values is: the deformed, as-cast, and creep-tested states, which is believed to be related to the different natures of layers formed between the pin and samples.

(iii) The ascending order of the wear resistance (represented by the depth of the wear scar and wear rate) is as follows:

 © 2009 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

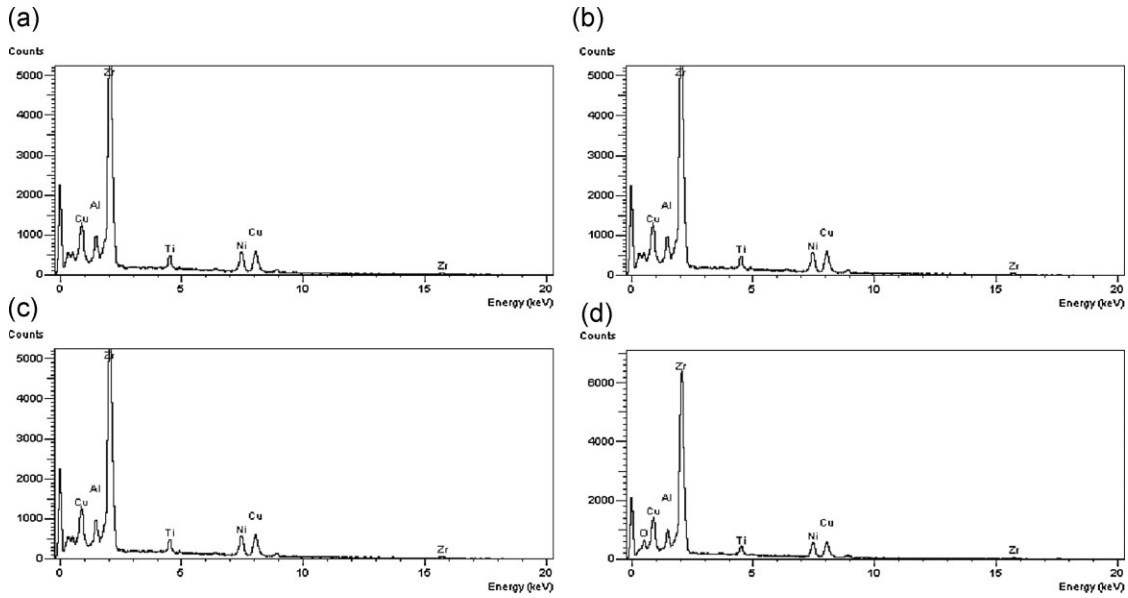


Fig. 8. EDS of (a) white gray area [marked with a dashed arrow in Fig. 7(a)] and (b) dark gray area [marked with a solid arrow in Fig. 7(a)] for the as-cast Vit 105 glass-forming alloy, and EDS of (c) the scratch area [marked with a dashed arrow in Fig. 7(c)] and (d) the debris area [marked with a solid arrow in Fig. 7(c)] for the creep-tested Vit 105 glass-forming alloy.

the deformed, creep-tested, and as-cast states. The deformed sample has the greatest amount of free volume, which accommodates the best plastic-deformation ability and decreases the wear resistance, compared to the as-cast sample. The creep-tested sample is very brittle, which prevents the formation of a stable transfer layer and decreases the wear resistance as well, compared to the as-cast sample. It concludes that besides hardness, other factors, such as the plastic-deformation ability (i.e., free volume) and brittleness of the glass-forming alloys, can also significantly affect the friction and wear characteristics of them.

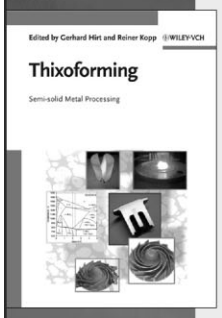
Received: June 23, 2009
Final Version: July 16, 2009
Published online: September 11, 2009

[1] B. Prakash, *Wear* **2005**, *258*, 217.
[2] W. L. Johnson, *MRS Bull.* **1999**, *24*, 42.
[3] A. Inoue, *Acta Metall.* **2000**, *48*, 279.
[4] A. Inoue, B. Shen, N. Nishiyama, in: *Bulk Metallic Glasses*, (Eds: M. K. Miller, P. K. Liaw), Springer, Berlin **2001**, Ch. 1.
[5] A. M. Hodge, T. G. Nieh, *Intermetallics* **2004**, *12*, 741.
[6] M. Anis, W. M. Rainforth, H. A. Davies, *Wear* **1994**, *172*, 135.
[7] T. Gloriant, *J. Non-Cryst. Solids* **2003**, *316*, 96.
[8] T. Imura, K. Hasegawa, M. Moori, T. Nishiwaki, M. Takagi, Y. Kawamura, *Mater. Sci. Eng, A* **1991**, *133*, 332.
[9] H. W. Jin, R. Ayer, J. Y. Koo, R. Raghavan, U. Ramamurty, *J. Mater. Res.* **2007**, *22*, 264.
[10] J. Bhatt, S. Kumar, C. Dong, B. S. Murty, *Mater. Sci. Eng, A* **2007**, *458*, 290.
[11] G. Li, Y. Q. Wang, L. M. Wang, Y. P. Gao, R. J. Zhang, Z. J. Zhan, L. L. Sun, J. Zhang, W. K. Wang, *J. Mater. Res.* **2002**, *17*, 1877.
[12] A. Concustell, G. Alcalá, S. Mato, T. G. Woodcock, A. Gebert, J. Eckert, M. D. Baró, *Intermetallics* **2005**, *13*, 1214.
[13] P. Murah, U. Ramamurty, *Acta Mater.* **2005**, *53*, 1467.
[14] U. Ramamurty, I. M. L. Lee, J. Basu, Y. Li, *Scr. Mater.* **2002**, *47*, 107.
[15] N. Nagendra, U. Ramamurty, T. T. Goh, Y. Li, *Acta Mater.* **2000**, *48*, 2603.
[16] J. Basu, N. Nagendra, Y. Li, U. Ramamurty, *Philos. Mag.* **2003**, *83*, 1747.
[17] J. J. Wall, C. Fan, P. K. Liaw, C. T. Liu, H. Choo, *Rev. Sci. Instrum.* **2006**, *77*, 033902.
[18] ASTM Standard G 133-05, Standard Test Method for Linearly Reciprocating Ball-on-Flat Sliding Wear, Annual Book of ASTM Standards, Vol. 03.02, **2005**.
[19] J. Qu, J. J. Truhan, *Wear* **2006**, *261*, 848.
[20] A. Slipenyuk, J. Eckert, *Scr. Mater.* **2004**, *50*, 39.
[21] E. Pekarskaya, J. F. Löffler, W. L. Johnson, *Acta Mater.* **2003**, *51*, 4045.
[22] U. S. Kishore, N. Chandran, K. Chattopadhyay, *Acta Metall.* **1987**, *35*, 1463.
[23] W. Kai, H. H. Hsieh, T. G. Nieh, Y. Kawamura, *Intermetallics* **2002**, *10*, 1260.
[24] X. Fu, T. Kasai, M. L. Falk, D. A. Rigney, *Wear* **2001**, *250*, 409.

 © 2009 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

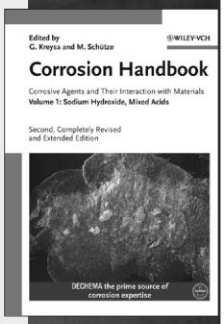
[25] C. Y. Tam, C. H. Shek, *Mater. Sci. Eng, A* **2004**, *384*, 138.
[26] A. L. Greer, W. N. Myung, in: *Mater. Res. Soc. Symp. Proc*, Vol. *644*(Eds: A. Inoue, A. R. Yavari, W. L. Johnson, H. Dauskardt), Mater. Res. Soc, Warrendale, PA **2001**, p. L10.6.
[27] R. C. Y. Tam, C. H. Shek, *J. Non-Cryst. Solids* **2004**, *347*, 268.
[28] C. J. Gilbert, V. Schroeder, R. O. Ritchie, *Metall. Mater. Trans. A* **1999**, *30*, 1739.
[29] A. L. Greer, K. L. Rutherford, I. M. Hutchings, *Int. Mater. Rev.* **2002**, *47*, 87.
[30] F. Spaepen, *Acta Metall.* **1977**, *25*, 407.
[31] A. S. Argon, J. Megusar, N. J. Grant, *Scr. Metall.* **1985**, *19*, 591.

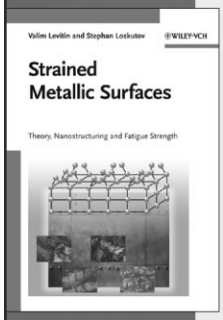
Wiley-VCH BOOK SHOP



G. Hirt / R. Kopp (eds.)
Thixoforming
Semi-solid Metal Processing
Offering a sound technological overview, while also covering the basics, this book summarizes first-hand experience gained from 12 years of collaborative research on the four vital aspects of this field: materials science, modeling of flow behavior, tool and systems engineering.
474 pp, cl, € 139.00
ISBN: 978-3-527-32204-6

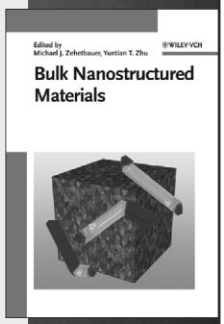
G. Kreysa / M. Schütze (eds.)
Corrosion Handbook
Corrosive Agents and Their Interaction with Materials
13 Volume Set
This DECHEMA Handbook provides a comprehensive collection of knowledge which is unique both in scope as well as content.
approx. 6500 pp, cl, € 4520.00
ISBN: 978-3-527-31217-7





V. Levitin / S. Loskutov
Strained Metallic Surfaces
Theory, Nanostructuring and Fatigue Strength
Providing students, engineers and researchers with a must-have insight into the complexities of surface structure and behavior, this book extends beyond the usual introductory texts to present concise knowledge on the topic, connecting fundamentals with real applications.
258 pp, cl, € 109.00
ISBN: 978-3-527-32344-9

M. J. Zehetbauer / Y. T. Zhu (eds.)
Bulk Nanostructured Materials
The processing and mechanical behaviour of bulk nanostructured materials are one of the most interesting new fields of research on advanced metallic systems. The book focusses on techniques and the outstanding properties of materials with ultrafine grained structure, and also considers the basic understanding behind.
736 pp, cl, € 199.00
ISBN: 978-3-527-31524-6



You can order online via **http://www.wiley-vch.de**
Wiley-VCH Verlag GmbH & Co. KGaA · POB 10 11 61 · D-69451 Weinheim, Germany
Phone: 49 (0) 6201/606-400 · **Fax:** 49 (0) 6201/606-184 · **E-Mail:** service@wiley-vch.de

WILEY-VCH

BS_0903_M1_1c_1-1h_gu

 © 2009 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim