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Friction and Wear of a Zr-Based Amorphous Metal Alloy under Dry and Lubricated Conditions*

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Abstract

The unusual internal structure of amorphous metals has been of interest to the tribology community for several decades, but most of the research on these materials has involved unlubricated experiments or tests in other than ambient air environments. If the suitability of amorphous metals is to be evaluated for engineering applications, a great deal more research is need to assess their behavior under liquid lubricated conditions. Studies in the early 1980's focused on Fe-Co-B-Si compositions. The work reported here focuses on an alloy system based on zirconium. Pin-on-disk tests were performed both dry and with diesel oil lubrication. The disks were composed of polished SAE 52100 steel, and pin specimens of Type 303 stainless steel, commercially-pure nickel (Ni-200), and an amorphous alloy of Zr-Cu-Ni-Ti-Al were used. The amorphous alloy was the hardest of the three pin materials. Friction coefficients and wear rates were measured. Under dry conditions, the amorphous metal alloy performed comparably or slightly better than the other two pin materials, but under lubricated conditions, it had the highest friction coefficient and highest wear rate of the three combinations. Differences in the ratios of dry to lubricated wear rates for the three material combinations are discussed in terms of the compatibility of non-ferrous materials with current engine lubricants. Observations on the nature of amorphous alloy wear particles are linked to a combination of simultaneously occurring wear processes.

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Owing to the tribological possibilities suggested by their unique structure and properties, amorphous or 'glassy' metals have been investigated for more than twenty years. For example, a number of studies of ferrous-based amorphous alloys, mainly having Fe-Co-B-Si compositions, were performed by investigators from the National Aeronautics and Space Administration (NASA) in the early 1980's [e.g., (1-5)]. These investigators found that tribological contact could, under some circumstances, induce a transformation of the material from the amorphous to the crystalline state, and that the surface chemistry and frictional behavior of the materials could be influenced significantly by the temperature and environment. More recent work by Williamson et al. (6) indicated that high-fluence Ti and C ion implantation of Fe to create near surface amorphous layers improved the wear resistance but not the frictional behavior of the Fe. Hiratsuka and Sasada (7) prepared films of amorphous Ta and W alloys by physical vapor deposition and tested them in dry air and vacuum against a range of high purity metals. The amorphous Ta wore most against Fe, Ni, and Ta compared with Cu, Al, Mg and W in vacuum. In air, however, transfer of Cu and Mg to the amorphous metals was increased. In 1998, Scruggs (8) asserted that tribocontact could convert a thermally sprayed deposit of metallic alloy into a wear-resistant, amorphous material. These unusual findings remain to be confirmed by additional research.

While a great deal has been learned about the friction and wear behavior of certain amorphous metals under vacuum or controlled laboratory environments, none of these materials seems to have been tested under liquid lubricated conditions, a situation more common to practical engineering applications. The pin-on-disk experiments reported here were conducted to compare the sliding friction and wear of a Zr-based amorphous alloy to that of both stainless steel and commercially-pure Ni under both air and diesel oil lubricated conditions. The same counterface material was used for the disks: a commercial bearing steel.

Procedure

The pin-on-disk apparatus was described in earlier publications [e.g., (9), (10)]. The cylindrical pin specimens were approximately 20 mm long and had a diameter of 6.35 mm. The ends of the cylinders were rounded to a tip radius of 3.175 mm and finished with 600 grit wet SiC paper and 6 μm diamond paste. The sliding speed was adjusted for each track diameter (23-29 mm) to give an average sliding velocity of 0.25-0.26 m/s, and the normal force was 4.95 N. Tests were run with and without lubrication in room temperature laboratory air having a relative humidity in the range of 35-51% RH. The lubricant was a fully-formulated 15W40 diesel oil (Valvoline………….). Sliding distances were 100 m for unlubricated tests and 1000 m for lubricated tests. Pin wear volumes were calculated in the manner of ASTM pin-on-disk test method G-99 (11), and the disk wear volumes were obtained by multiplying the average wear track cross sectional area by the circumference. Wear rates are reported in units of mm^3/N-m. Friction data were obtained using a load cell mounted on the pin holder and a chart recorder.

Materials

The disk specimen material for all experiments was SAE 52100 bearing steel in the spheroidized and annealed condition (Source: Sullivan Metals………….). It's composition (in wt %) was 1.03 C, 0.36 Mn, 0.009 P, 0.011 S, 0.27 Si, 1.44 Cr, 0.12 Ni, 0.03 Mo, 0.28 Cu, 0.025 Al, 0.002 Ti, 0.0007 O, balance Fe. It was finished to a final polish using 6 mm diamond paste. Three materials were used as the pin specimens: Type 303 stainless steel, Ni-200 (commercially-pure nickel), and a Zr-based amorphous metal that was specially prepared by C. T. Liu, Oak Ridge National Laboratory. The latter was arc-melted in inert gas and drop-cast into a Cu mold. The final specimen was approximately in 7.0 mm diameter and 60 mm long. The amorphous alloy's composition (at%) was 17.9 Cu, 14.6 Ni, 5.0 Ti, and 10.0 Al, with the balance, Zr. A further discussion of the structure and properties of Zr-based amorphous materials, including the composition used in this work, can be found in the paper by Liu et al. (12).

The Vickers microindentation hardness numbers for the four test specimen materials are compared with those reported for other materials in Table 1. The amorphous alloy is harder than Stellite 6B, a well-known Co-based alloy used for severe wear applications, and significantly harder than the 52100 disk material. The type 303 stainless steel is very similar in hardness to the disk material, but the Ni-200 is softer. From the standpoint of relative hardness alone, the potential for resistance to wear of the amorphous alloy seemed favorable. However, other alloy characteristics, such as the tendency of the material to adhere to the opposing surface, can overwhelm the potential benefits of its higher hardness, particularly if the wear mode is other than abrasion. Therefore, actual wear tests were needed to evaluate whether the tribological benefits of the amorphous alloy exceeded those of the softer materials.

Results and Discussion

Pin-on-disk friction and wear data are summarized in Tables 2 and 3. In the unlubricated condition, both the pin wear and average sliding friction coefficient of the amorphous alloy were slightly lower than the other two materials, but this was not the case under lubricated conditions. Values of sliding friction coefficient in the range of 0.18-0.20 indicated the presence of a boundary lubrication regime. In addition, the lubricated disk specimen that was slid against the amorphous alloy showed more visible wear damage than the disks slid against the other pin materials. Profilometry indicated that the track produced by the amorphous pin had material displaced both above and below the original plane of the disk surface suggesting plastic deformation, abrasive grooving, and interfacial transfer. None of the lubricated disk wear tracks was deep enough to measure its cross-section to obtain a wear rate.

Debris particles collected from the dry test with the amorphous alloy exhibited a range of sizes and shapes, ranging from metallic flakes to cutting chips (see Fig. 1). This observation suggested that several wear debris formation processes had operated in the interface: cutting, delamination, and classical 'adhesive wear.' The tip of the amorphous pin specimen displayed fine abrasion marks, supporting the abrasive removal process. All the disk specimens worn under dry conditions showed tearing, grooving, and transferred patches of material symptomatic of 'adhesive wear.'

The ratios of the dry wear rates of the pin specimens to their lubricated wear rates (fourth column in Table 3) indicated that the friction- and wear-modifying additives in the diesel oil lubricant worked better with the stainless steel and Ni pins than with the amorphous alloy pins. This implies that different additive formulations might be required in order to improve wear behavior of the current amorphous alloy under oil-lubricated conditions. The slightly higher friction coefficient and the presence of more prominent disk wear damage for the lubricated amorphous alloy test reinforces the conclusion that a different lubrication formulation would be required if this material were to be considered for sliding contact applications.

In summary, preliminary pin-on-disk test results for a Zr-based amorphous alloy sliding against type SAE 52100 bearing steel did not indicate improved friction and wear behavior when compared to the responses of austenitic stainless steel and commercially-pure Ni. Despite its higher hardness, its wear behavior was significantly worse than the two other combinations when tested under oil lubricated conditions. While not encouraging, these preliminary pin-on-disk results should not rule out the use of Zr-based amorphous alloys in other types of tribosystems. Rather they suggest that a great deal more research is needed in order to establish both the potential and the limitations of amorphous alloys being considered for wear applications. In light of the findings of this and previous investigations, additional studies should focus on applications-oriented testing in which higher sliding speeds or elevated temperatures might promote thermally-induced microstructural phase changes and surface chemistry changes in these materials.

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Table 1. Vickers Microindentation Hardness Numbers of Selected Materials
(current specimen materials in **bold** type)

Material	**HV**, GPa [normal force in N (Ref. no.)]
Diamond	98.7 [1.96 (1)]
Tungsten carbide	22.1 [0.98 (2)]
Silicon nitride, hot-pressed, type NT-551	16.1 [1.96 (3)]
Steel, stainless, type 440C	12.6 [0.98 (2)]
Steel, tool steel, type M-50	9.08 [0.98 (2)]
Glassy metal, Zr-Cu-Ni-Ti-Al	**5.77 [0.98 (4)]**
Co-based superalloy, Stellite 6B	4.65 [1.96 (3)]
Steel, AISI 52100, annealed, as-rec'd	**3.67 [0.98 (4)]**
Steel, AISI 303 Stainless	**3.46 [0.98 (4)]**
Nickel, Ni-200	**2.31 [0.98 (4)]**
Nickel, high-purity polycrystal	1.01 [0.98 (1)]
Copper, high-purity annealed	0.42 [0.98 (1)]

Table references:

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4. Specimen materials used in this study.

Table 2. Friction and Wear Data from Unlubricated Tests
(sliding distance 100 m)

Pin Material	Steady State Friction Coeff.	Pin Wear Rate (mm^3/N-m)	Disk Wear Rate (mm^3/N-m)	Ratio of Pin to Disk Wear
303 St. Steel	0.94	4.99×10^{-4}	5.91×10^{-4}	0.84
Ni-200	1.11	1.07×10^{-3}	9.82×10^{-4}	1.09
Amorphous alloy	0.74	4.68×10^{-4}	4.54×10^{-4}	1.03

Table 3. Friction and Wear Data from Lubricated Tests
(15W40 diesel oil, sliding distance 1000 m)

Pin Material	Steady State Friction Coeff.	Pin Wear Rate (mm^3/N-m)	Pin Wear Ratio (dry/lubricated)	Disk Wear Observations
303 St. Steel	0.17	4.73×10^{-9}	1.1×10^{5}	fine scratch
Ni-200	0.17	1.39×10^{-8}	7.3×10^{4}	fine scratch
Amorphous alloy	0.20	8.01×10^{-7}	5.8×10^{2}	roughened track*

* Material was displaced above and below the plane of the disk surface. This was substantiated by profilometry, but there was no clearly measurable wear groove cross-sectional area, and therefore no wear rate could be obtained.

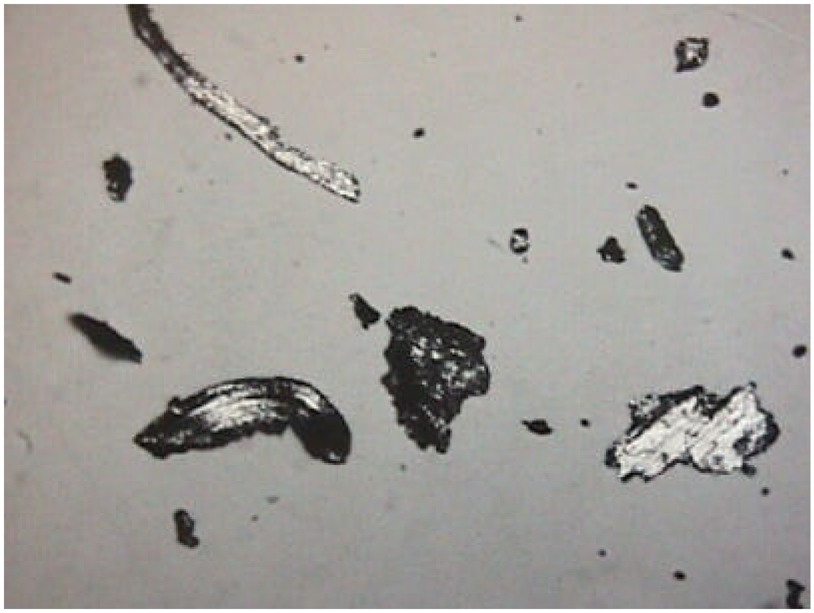

Fig. 1 Optical photomicrograph of wear particles from test of the amorphous alloy against 52100 steel. Morphology suggests cutting, delamination, and fine-scale fracture. The longest chip, at the upper left, is approximately 26.5 μm long.