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Wear 263 (2007) 636–642
WEAR
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Short communication

Friction and wear of nanostructured metals created by large strain extrusion machining

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Received 31 August 2006; received in revised form 7 November 2006; accepted 17 November 2006
Available online 26 March 2007

Abstract

Tribological behavior of nanocrystalline oxygen-free high conductivity (OFHC) copper and commercially pure titanium produced by large strain extrusion machining (LSEM) is compared with the coarse grained counterparts. Friction and wear of these materials have been determined using a pin-on-disk tribometer, sliding against AISI 52100 steel pins. Although friction coefficients are very similar, microstructure refinement reduces wear factors for these conditions. Wear mechanisms are discussed from optical microscopy and SEM observation of wear tracks, wear debris morphology and transfer tribolayers.

Keywords: Wear; Friction; Nanocrystalline structure; Copper; Titanium

1. Introduction

Ultra-fine grained (UFG) and nanostructured materials are often harder, stronger and more wear-resistant than their coarse grained counterparts [1].

Developments in the fabrication of UFG materials have focused on the use of large strain or severe plastic deformation (SPD). There has been a recent development at Purdue University of a low-cost manufacturing process, using principles of shear deformation by machining, for the production of nanostructured metals and alloys. It is the focus of this paper to investigate into the wear characteristics of the materials processed by this new method. The chips produced during common machining of a variety of pure metals, steels, and other alloys, are shown to be nanostructured with grain (crystal) sizes between 100 and 800 nm. The hardness of the chips is found to be significantly greater than that of the bulk material [1–4]. A potentially exciting opportunity resides in the creation of material systems which could show enhanced wear performance.

In the present study, the machining method is used in the preparation of nanostructured oxygen-free high conductivity (OFHC) copper and pure titanium chips of high hardness [1–4]. We report here the influence of the microstructure refinement on the wear resistance of these materials.

The authors have previously reported [5] a wear reduction of a polymer–matrix composite reinforced with nanostructured Al 6061 particles with respect to the conventional microstructured reinforcement.

The wear performance of the materials, sliding against AISI 52100 steel pins, are studied using a pin-on-disk tribometer. The predominant wear mechanisms in each case are discussed.

2. Experimental

Oxygen-free high conductivity (OFHC) copper and commercially pure titanium were deformed by LSEM [6] to obtain a nanostructured microstructure. For the copper samples, three different shear strains (γ) were imposed by appropriately changing the opening between the constraining edge and the cutting

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doi:10.1016/j.wear.2006.11.040

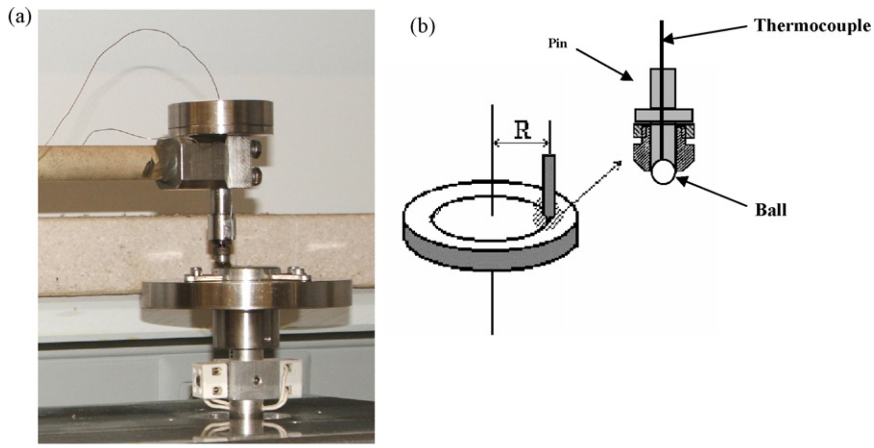

Fig. 1. (a) Pin-on-disk test machine and (b) scheme showing the thermocouple embedded in the steel pin.

Table 1
Materials designation, grain size and hardness values

Designation	Hardness HV (kg/mm^2)	Microstructure	Grain size
Cu-micro	97	Equiaxed grains	~150 μm [6]
Cu-nano $\gamma = 7.4$	158	Equiaxed grains	~250 nm [6]
Cu-nano $\gamma = 4.3$	157	Mix of elongated and equiaxed grains	~300 nm [6]
Cu-nano $\gamma = 2.2$	148	Elongated grains	~300 nm[a] [6]
Ti-micro	144	Equiaxed grains	~60 μm [9]
Ti-nano	230	Elongated grains	~200 nm[a] [9]

[a] In the narrow direction.

edge of the especially designed extrusion and machining tool [6]. The chosen values of γ were 2.2, 4.3 and 7.4. By varying the level of strain imposed in the material a progressive refinement of microstructure is observed [6]. For titanium, a single shear strain of 3 was imposed using the same method [6]. Machining speeds were kept low to avoid any temperature effects on the processed materials.

Specimens were tested in a pin-on-disk (Fig. 1) test machine (Microtest, Spain), where an AISI 52100 steel ball (0.8 mm spherical radius, hardness 848 HV) rigidly held is used as the pin specimen, according to ASTM G99-05 standard. Tribological tests were carried out in air under a load of 3 N for copper and 1 N for titanium. The following experimental parameters were kept constant for all tests: sliding velocity = 0.01 m/s; radius = 2 mm; sliding distance = 30 m. Friction coefficients were continuously recorded with sliding distance. The "contact" temperature was recorded during the tests by means of a thermocouple embedded (Fig. 1) in the steel pin at a distance of 1.6 mm from the pin–disk interphase. Volume loss was determined using two different methods: from wear track width values according to ASTM G99-05 [7] and from the change of cross-sectional area measured with a profilometer ALPA-SM [8]. Mean friction coefficients and wear factors were obtained after three tests under the same conditions. Optical micrographs of wear track were obtained using a Leica DMRX optical microscope. SEM images and EDS analysis were obtained using a Hitachi S3500N scanning microscope.

3. Results and discussion

As can be seen from Table 1, grain-refinement due to large strain extrusion machining produces nanostructured materials with hardness values at least 1.5 times as high as that of the conventional micro-structured material.

3.1. Copper

3.1.1. Friction

Friction behavior is the same for all samples. Fig. 2 shows the typical friction variation with sliding distance in this case

Table 2
Friction coefficients (standard deviations in parenthesis)

Material	Cu-micro	Cu-nano			Ti-micro	Ti-nano
		$\gamma = 7.4$	$\gamma = 4.3$	$\gamma = 2.2$		
Friction coefficient	0.7 (0.26)	0.7 (0.15)	0.79 (0.03)	0.69 (0.04)	0.42 (0.09)	0.47 (0.07)

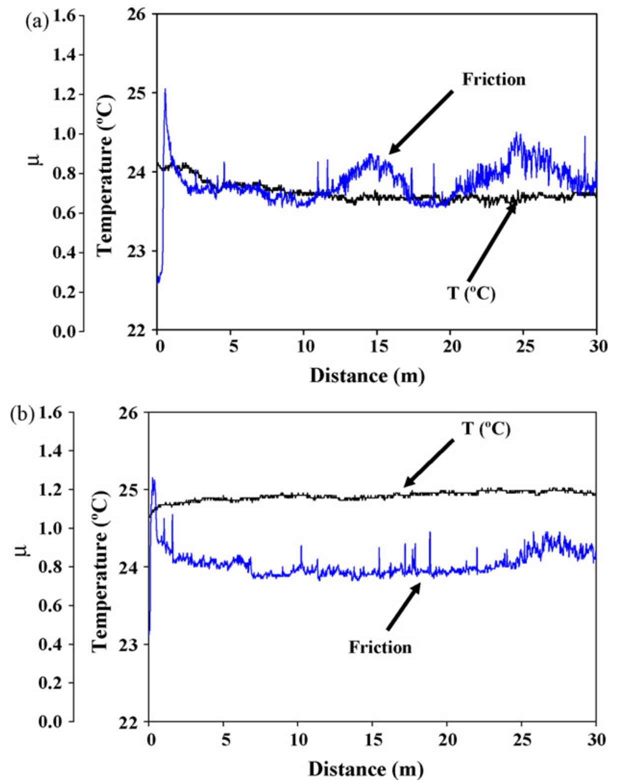

Fig. 2. Friction coefficient and contact temperature vs. sliding distance for (a) Cu-micro and (b) Cu-nano $\gamma = 4.3$.

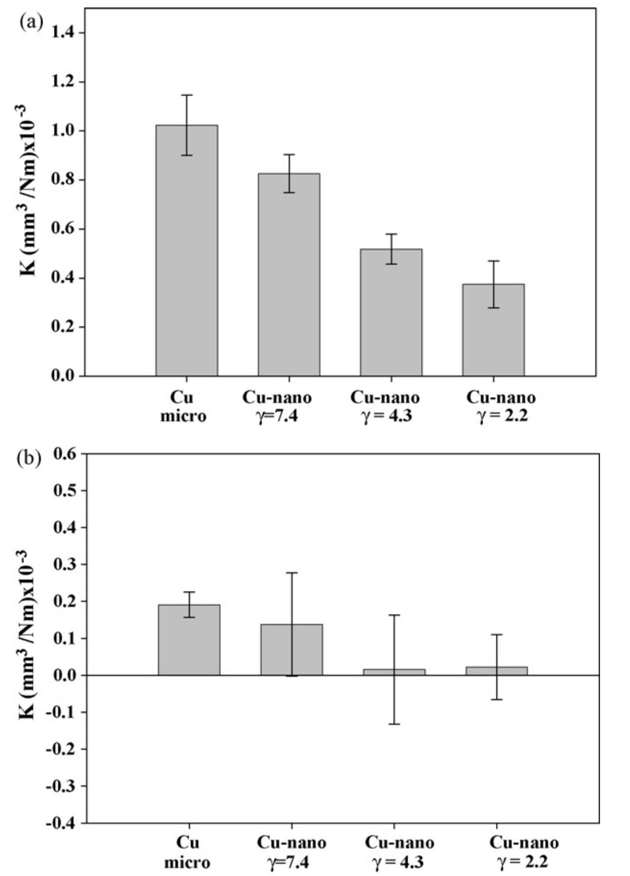

Fig. 3. Wear rates for copper micro and nanostructured: (a) from wear track width and (b) from profilometer.

for Cu-micro (Fig. 2a) and Cu-nano $\gamma = 4.3$ (Fig. 2b). After the break-in period reaching a maximum value of friction of 1.2, a lower friction steady state regime is reached where the mean value of friction coefficient for all samples is approximately 0.7. Mean values considering all friction values for all samples can be seen in Table 2.

3.1.2. Wear measurements

Fig. 3 shows wear rates from wear track width for copper micro- and nanostructured according to ASTM G99-05 (Fig. 3a) and profilometer (Fig. 3b). The wear resistance of Cu-micro, in comparison with the three types of Cu nanostructured, is clearly weaker (Fig. 3). The wear rate for Cu-nano under the low shear strain is around 64% smaller than that of Cu-micro. Wear rate values calculated using the profilometer (Fig. 3b) are in agreement with that obtained from wear tracks. In this case, nanostructured copper under low and medium shear strain values show a wear reduction of 88 and 92% with respect to Cu-micro.

The high deviation of wear values, when the profilometer is used (Fig. 3b), can be explained from the observation of the cross-section of the wear scar (Fig. 4a). In this case, the area of material deformed plastically ($A_2 + A_3$), Fig. 4b, is higher than the wear loss area A_1.

3.1.3. Wear mechanism

SEM micrographs of wear tracks are shown in Fig. 5. Wear tracks show severe wear, particularly for Cu-micro (Fig. 5a and e) with lateral plastic flow inducing accumulation of material on the border and outside the border grooves. The worn surface of Cu-micro (Fig. 5e) and Cu-nano $\gamma = 7.4$ (Fig. 5f) exhibited a higher amount of deformation and fracture in the

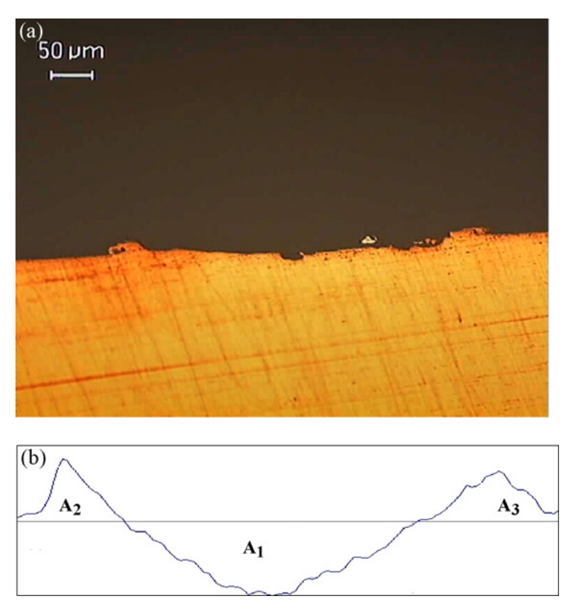

Fig. 4. (a) Optical micrograph of the cross-section of Cu disk and (b) schematic profile of wear scar on disk.

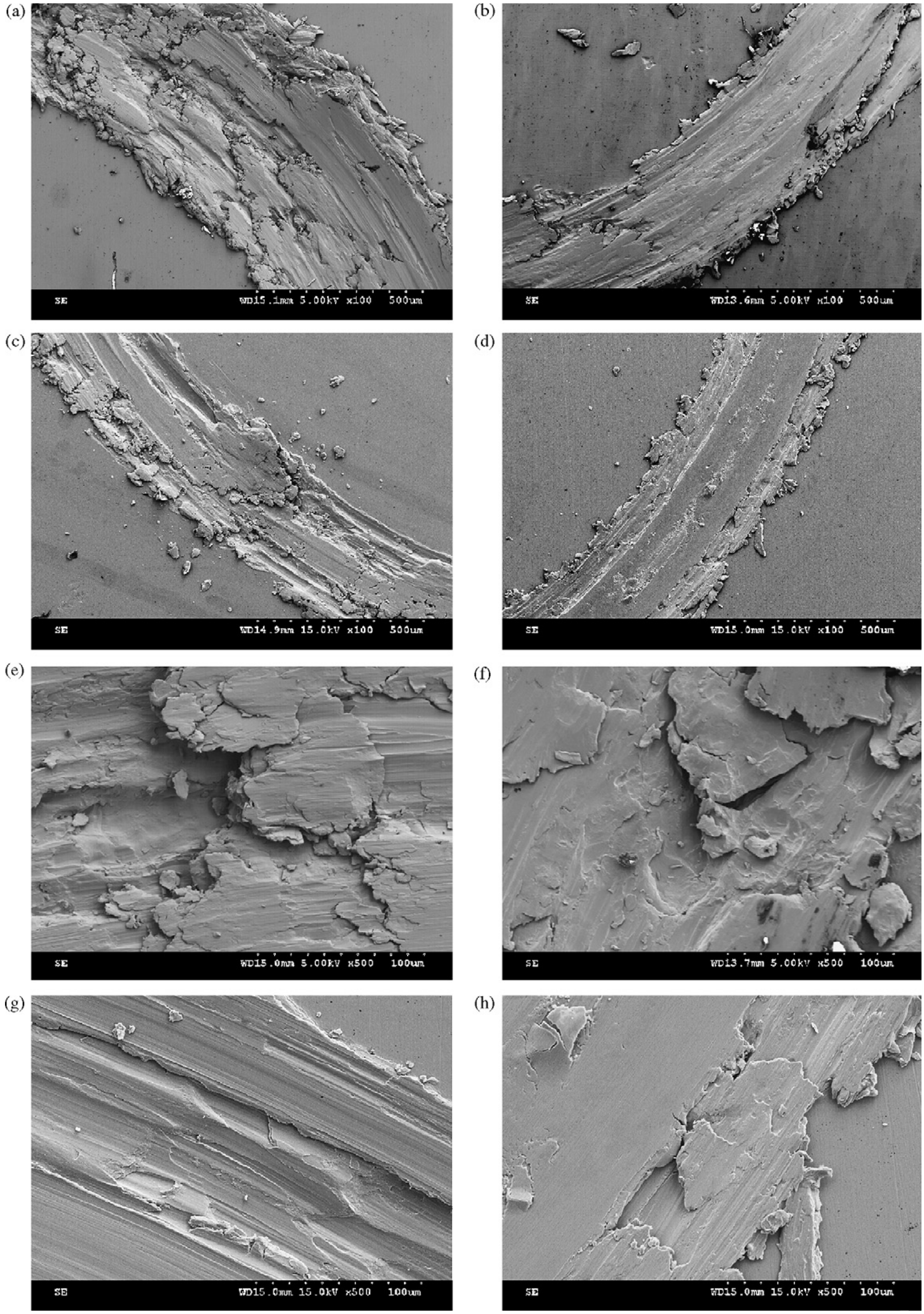

Fig. 5. SEM micrographs of Cu disk wear tracks: (a and e) Cu-micro; (b and f) Cu-nano $\gamma = 7.4$; (c and g) Cu-nano $\gamma = 4.3$; (d and h) Cu-nano $\gamma = 2.2$.

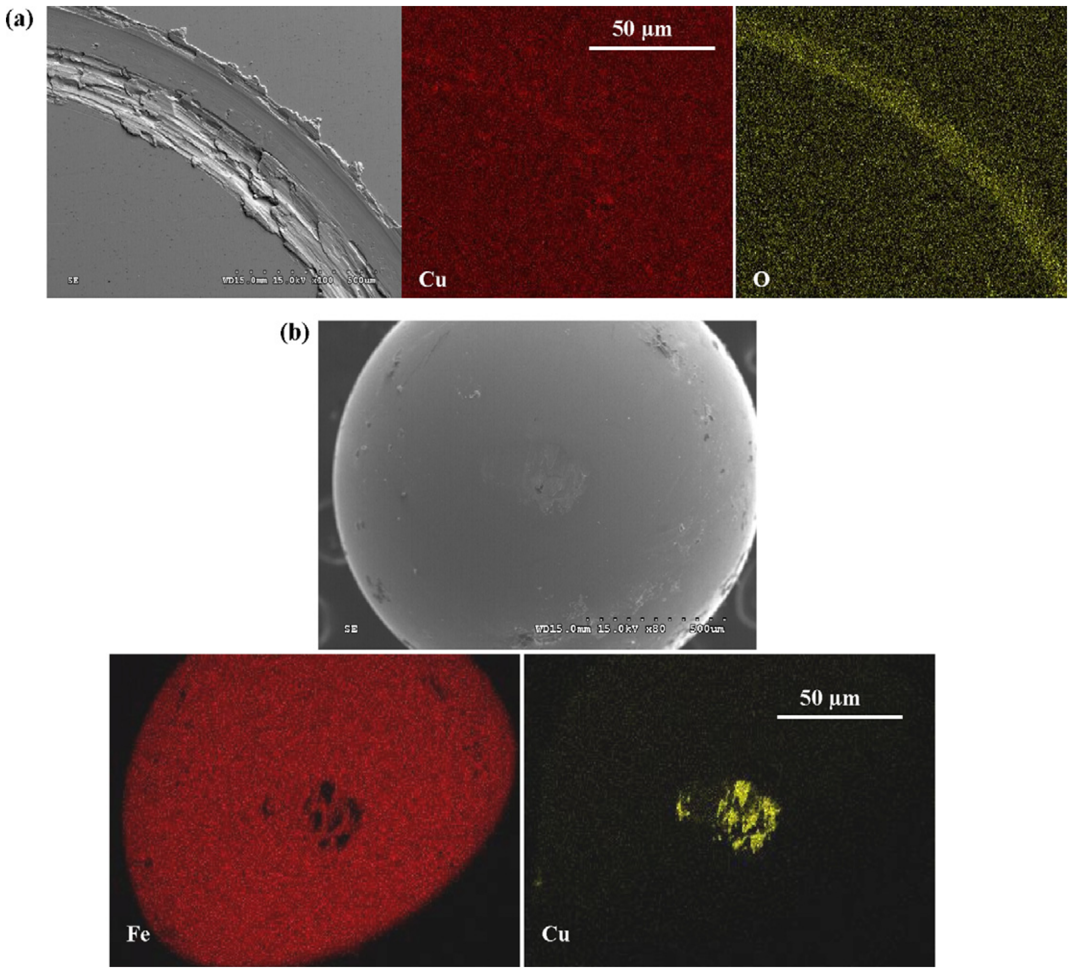

Fig. 6. Cu-nano $\gamma = 4.3$: (a) SEM micrograph of Cu wear track with Cu and O elemental maps; (b) SEM micrograph of steel ball with Fe and Cu elemental maps.

sub-surface and contacting surface as can be seen under higher magnification.

In the case of the more wear-resistant materials (Fig. 5c, d, g and h) a more polished wear track is observed. For these materials the wear path is covered by an oxide layer, as can be seen in Fig. 6a for Cu-nano $\gamma = 4.3$.

Finally an adhesive wear component is observed for all materials by the copper to steel transference shown in Fig. 6b. This transfer layer changes the contact mechanisms from an initial steel–copper pair to a copper–copper tribolayer-steel, thus changing the contact pressure and the real contact area [10].

3.2. Titanium

Fig. 7 shows wear rates for titanium micro- and nanostructured according to ASTM G99-05 and profilometer. Wear of nanostructured titanium is lower than that of microstructured material. Microstructure refinement reduces wear factor up to 30% under these conditions.

Friction coefficients (Table 2) are very similar for both materials. In both cases, the wear mechanism by plastic deformation (Fig. 8a and b) with formation of wear debris as finely divided particles (Fig. 8c and d) can be observed. Under larger magnifications (Fig. 8e and f) the abrasive wear component is pointed out by the ploughed grooves inside the wear tracks.

The adhesive component of the wear mechanisms can be observed by the titanium adhered layer on the AISI 52100 ball surface, as can be seen by the EDS Fe and Ti maps in Fig. 9.

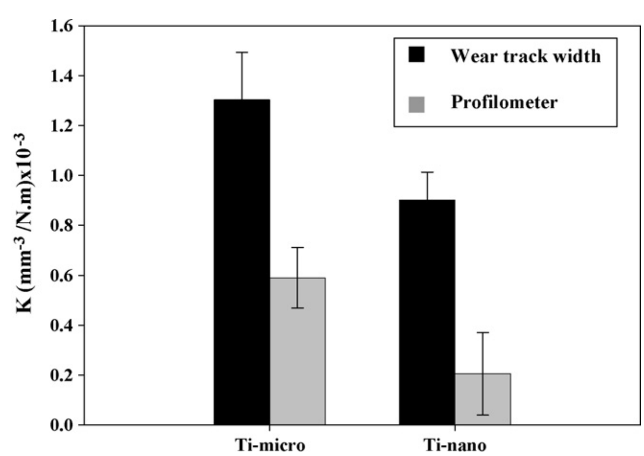

Fig. 7. Wear rates for micro- and nanostructured titanium.

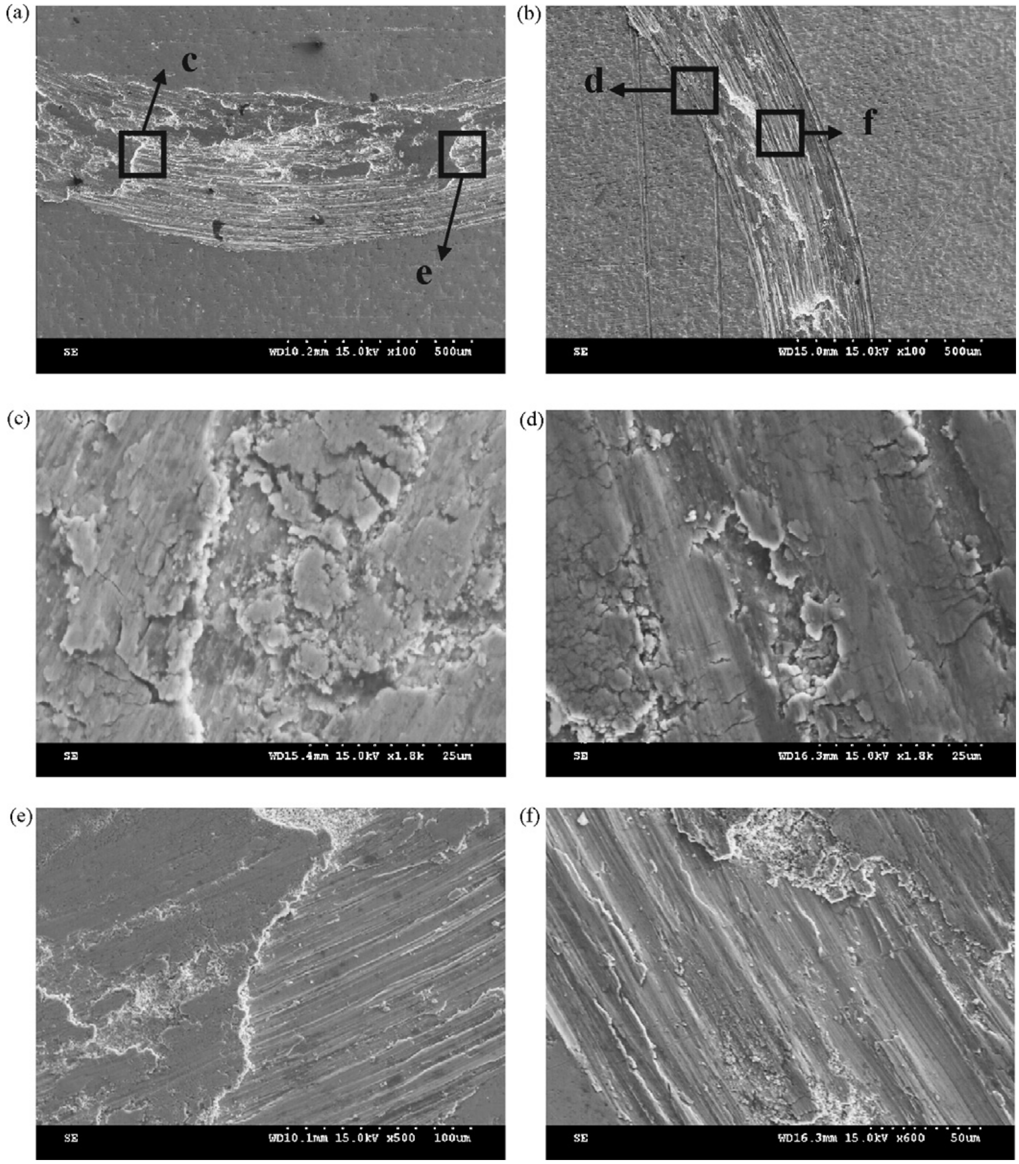

Fig. 8. SEM micrographs of titanium disk wear tracks: (a) Ti-micro; (b) Ti-nano; (c and e) magnifications of details in (a); (d and f) magnifications of details in (b).

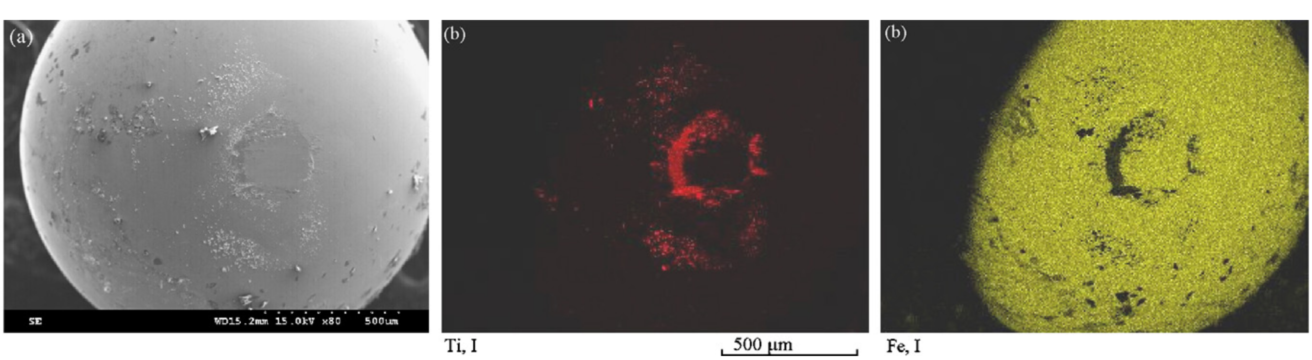

Fig. 9. SEM micrograph of steel pin (a) after the test against Ti-nano, and elemental mapping: Fe map (b) and Ti map (c).

4. Conclusions

Microstructure refinement shows no influence in friction for the materials studied under these conditions.

Wear rates of nanostructured copper and titanium are lower than that of the microstructured materials.

The reduction in wear rate for Cu-nano is particularly important under low shear strain value.

The adhesive wear mechanism of titanium shows an abrasive component. Microstructured copper presents severe plastic deformation and fracture characteristic of adhesive wear, while nanostructured copper shows a milder oxidative wear mode.

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