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Wear Behavior of Nanocrystalline Cu-Zn Alloy

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The wear behaviors of nanocrystalline Cu-Zn alloy were investigated. Sliding wear tests were performed on a pin-on-disk test machine under dry conditions. Results indicated that nanocrystalline Cu-Zn alloy annealed at 300 °C exhibited better wear resistance and high load-bearing capacity than those in the as-pressed state. A surface film almost covering the entire worn surface was formed for nanocrystalline Cu-Zn alloy annealed at 300 °C at a load range from 2.1-5.6 MPa. The surface film effectively improves the wear resistance of nanocrystalline Cu-Zn alloy.

Keywords nanocrystalline Cu-Zn alloy, surface film, wear resistance

1. Introduction

Nanocrystalline metal materials have received intense attention owing to their attractive mechanical, physical, tribological, and other properties. However, little research has examined the study of tribological behaviors of nanocrystalline metals, perhaps owing to the difficulty in producing bulk samples suitable for friction and wear tests.[1] The wear of copper and its alloy with submicrocrystalline structure obtained by severe plastic deformation has been studied,[2,3] in which the results still could not completely reflect the tribological properties of nanocrystalline materials because their grain sizes are larger than 100 nm. The metal wear is a complicated process. It is suggested that the nanocrystalline metal can have some specific tribological characters due to its special structures.

In the present work, a nanocrystalline Cu-Zn alloy layer is fabricated on the surface of coarse-grained copper using powder compacting process to obtain bulk samples suitable for friction and wear tests. It can solve the difficulty of fabrication of bulk nanocrystalline materials, and the information of tribological behaviors of the nanocrystalline surface layer can be also obtained.[4] The structure, hardness, and wear resistance of nanocrystalline Cu-Zn alloy were investigated.

2. Experimental Details

Nanocrystalline Cu-40 at.%Zn alloy powder was synthesized by the wire explosion method. Transmission electron microscope (TEM) observation showed that the grain size to be 30-50 nm. The nanopowder surface can be partially blunted owing to the presence of absorptive inert gas during synthesis. The obtained nanocrystalline Cu-Zn powder uniformly covered the commercially pure copper powder. The average grain size of pure copper powder was 45 μm. The composite powders were compacted together under 1.6 GPa pressure at room temperature into disk-shaped samples with a diameter of 15 mm and a thickness of 8 mm, then annealed at temperatures ranging from 200-600 °C for 30 min. The thickness of nanocrystalline Cu-Zn alloy layer of samples was up to 100-200 μm. The cross-sectional view of the sample is shown in Fig. 1.

The microstructures of nanocrystalline Cu-Zn alloy were examined by H-800 TEM. The microhardness of nanocrystalline Cu-Zn alloy surface layer was measured by Vicker's method under a load of 100 g and duration of 20 s. The density was determined in distilled water by the Archimedes method, which had a relative error of less than 2%.

Sliding friction and wear tests were carried out under dry sliding conditions employing a pin-on-disk test machine (MG-2000) in an ambient environment (room temperature 20 °C to 25 °C and humidity 40-50%). Pins were cut from the prepared specimens to a dimension of 6 mm diameter and 8 mm thickness. The rotating disks were made of plain carbon steel (0.45 wt.%C) with a hardness of HRC42-45. The applied load was varied in a range of 0.35-7.0 MPa whereas sliding speed and total sliding distance were kept constant at 0.628 m/s and 376.8 m, respectively. Prior to testing, the pins and disks were polished to a roughness less than 0.2 μm, and cleaned with ac-

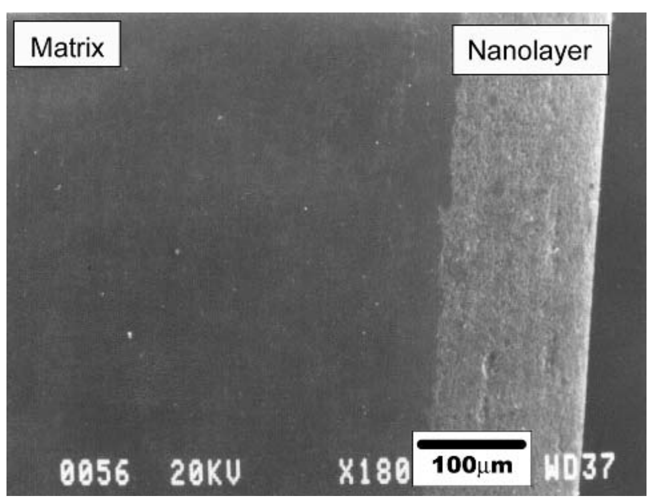

Fig. 1 Cross-sectional SEM view of the nanocrystalline Cu-Zn alloy surface layer

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etone. The specimens were weighed in air before and after the testing with an accuracy of 0.1 mg to determine the mass loss. The worn surface morphologies were examined using a JSM5310 (JEOL LTD., Tokyo, Japan) scanning electron microscope (SEM) attached with energy dispersive spectrometer (EDS) and x-ray diffraction system.

3. Results and Discussion

3.1 Structure and Hardness

The nanocrystalline Cu-Zn alloy surface layer of samples pressed under 1.6 GPa had a relative density of 93% and a mean microhardness value of 182 HV. The subsequent annealing processing did not result in a measurable density increase. Microhardness varies with annealing temperature of nanocrystalline Cu-Zn alloy (Fig. 2). It can be seen that the microhardness value of nanocrystalline Cu-Zn alloy displays a peak at around 300 °C annealing temperature. The microhardness can be up to 290 HV.

Figure 3 shows the TEM images of nanocrystalline Cu-Zn alloy at different temperature annealing. Some residual pore defects can be observed in the as-pressed nanocrystalline Cu-Zn alloy (Fig. 3a). No grain growth was observed in samples annealed below 300 °C (Fig. 3b). When the annealing temperature was elevated to 400 °C, abnormal grain growth occurred (Fig. 3c), which resulted in the decrease of microhardness of samples. Annealing twins marked with the arrow can be found in the grown coarse grain.

3.2 Wear Behavior

Figure 4 shows steady-state specific wear rate of nanocrystalline Cu-Zn alloy surface layer with annealing temperature at an applied load of 1.4 MPa. The nanocrystalline surface annealed at 300 °C processes a higher wear resistance due to its high microhardness. The variations of specific wear rate with applied load for nanocrystalline Cu-Zn alloy as-pressed and annealed at 300 °C are shown in Fig. 5. For the as-pressed nanocrystalline Cu-Zn alloy, the wear rate increases with the increase of the applied load, and there is a sudden acceleration

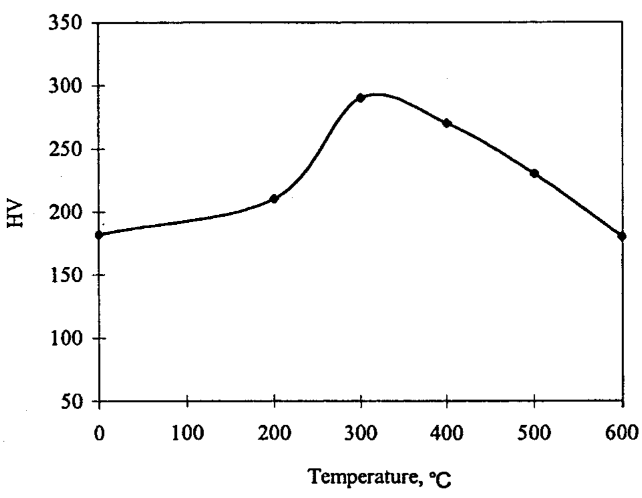

Fig. 2 Variation of microhardness of nanocrystalline Cu-Zn alloy with annealing temperature

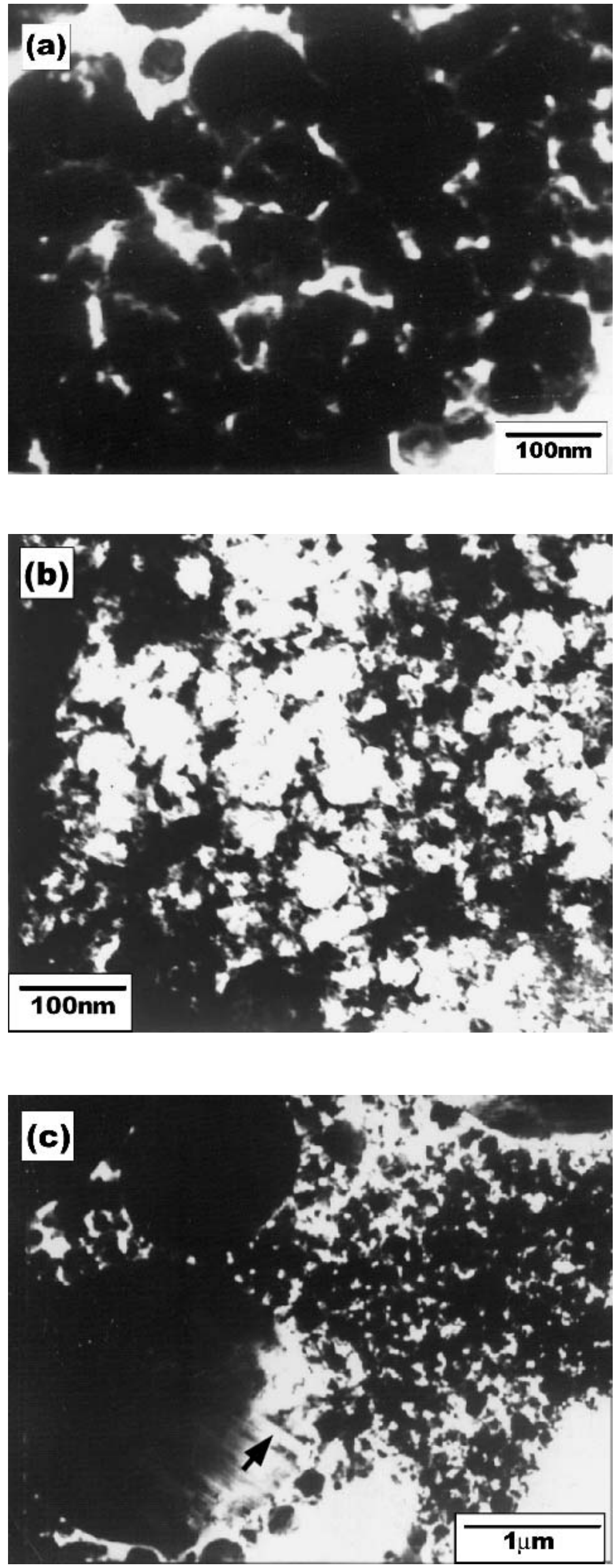

Fig. 3 TEM images of nanocrystalline Cu-Zn alloy at different temperature annealing: **(a)** as-pressed; **(b)** annealed at 300 °C; **(c)** annealed at 500 °C

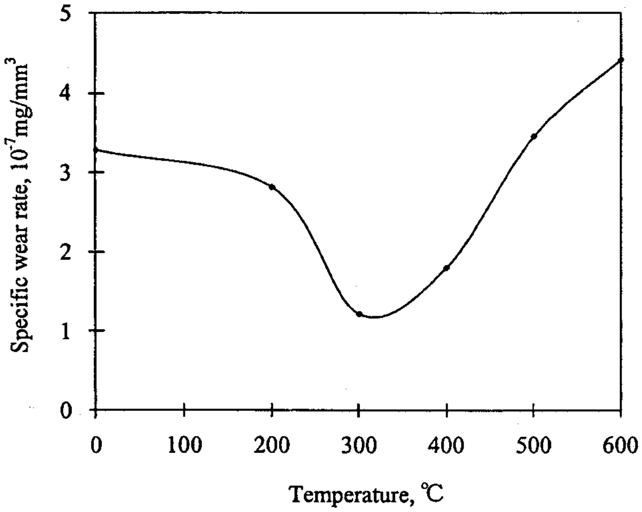

Fig. 4 Variation of specific wear rate of nanocrystalline Cu-Zn alloy with annealing temperature at an applied load of 1.4 MPa, sliding speed of 0.628 m/s, and sliding distance of 376.8 m

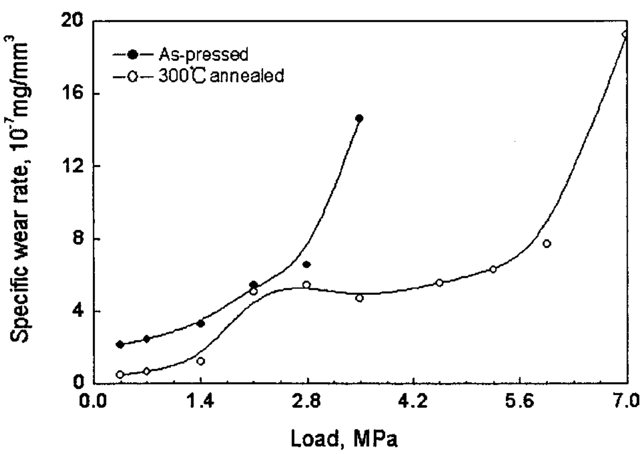

Fig. 5 Variation of specific wear rate of nanocrystalline Cu-Zn alloy as-pressed and annealed at 300 °C with applied load at constant sliding speed of 0.628 m/s and sliding distance of 376.8 m

at applied load above 2.8 MPa. This transition marks the onset of a severe wear regimen. For nanocrystalline Cu-Zn alloy annealed at 300 °C, the wear rate increases with load at applied loads below 2.1 MPa, but there is little increase in wear rate at loads from 2.1 to 5.6 MPa and the wear rate level off to a stable value. It suggests that at loads from 2.1 to 5.6 MPa, a significant change occurs in the wear nature of the nanocrystalline surface, giving rise to a substantial reduction in the wear rate. Above 5.6 MPa a steep increase in wear rate for nanocrystalline Cu-Zn alloy is observed. The load-bearing capacity of the nanocrystalline surface is remarkably improved, compared with that in the as-pressed state.

3.3 Worn Surface Morphology and Wear Mechanism

3.3.1 For As-Pressed Nanocrystalline Cu-Zn Alloy. The SEM micrographs of worn surfaces of as-pressed nanocrystalline Cu-Zn alloy are shown in Fig. 6. At low loads (1.4 MPa;

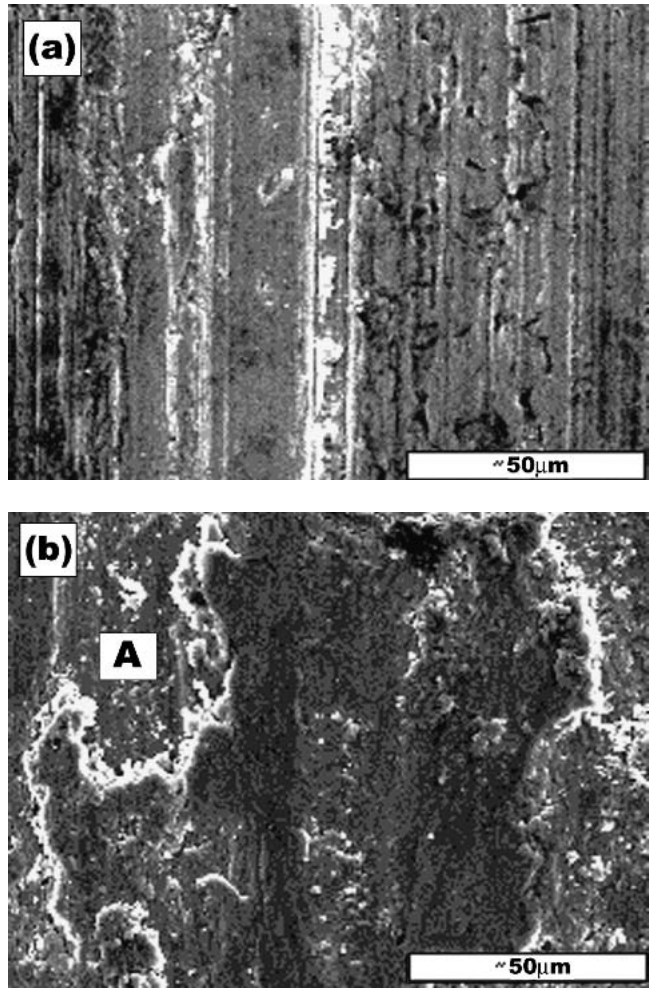

Fig. 6 SEM morphologies of worn surfaces of as-pressed nanocrystalline Cu-Zn alloy: **(a)** 1.4 MPa; **(b)** 2.8 MPa

Fig. 6a), the worn surface shows ploughing, local fatigue crack and peeling off. At loads above 2.8 MPa (the transition load), severe adhesion and plastic deformation are observed in the worn surface (Fig. 6b), which results in extensive damaged regions and materials delamination, as marked in Fig. 6(b) as A regions. It indicates that severe wear occurred.

3.3.2 For Nanocrystalline Cu-Zn Alloy Annealed at 300 °C. The SEM morphologies of worn surfaces of nanocrystalline Cu-Zn alloy annealed at 300 °C at different loads are shown in Fig. 7. At low loads (1.4 MPa; Fig. 7a), the worn surface is smooth and no ploughing, and slight adhesion is observed. Very fine particles are presented in wear scar, and wear debris is generated. At the load range from 2.1 to 5.6 MPa, the contacting surface apparently develops a thin surface film (Fig. 7b-d). At the higher load of 3.5 and 5.6 MPa, this surface film was found to cover almost the entire worn surface and be continuously supplied in the steady-state wear process. As seen in Fig. 7(c), there is little uncovered zone marked with arrows. In Fig. 7(d), microcracks of surface film at an angle with the sliding direction can be observed, as marked with arrows. EDS analysis indicates that the surface film comprise elements from both the sliding counterparts, including Cu, Zn,

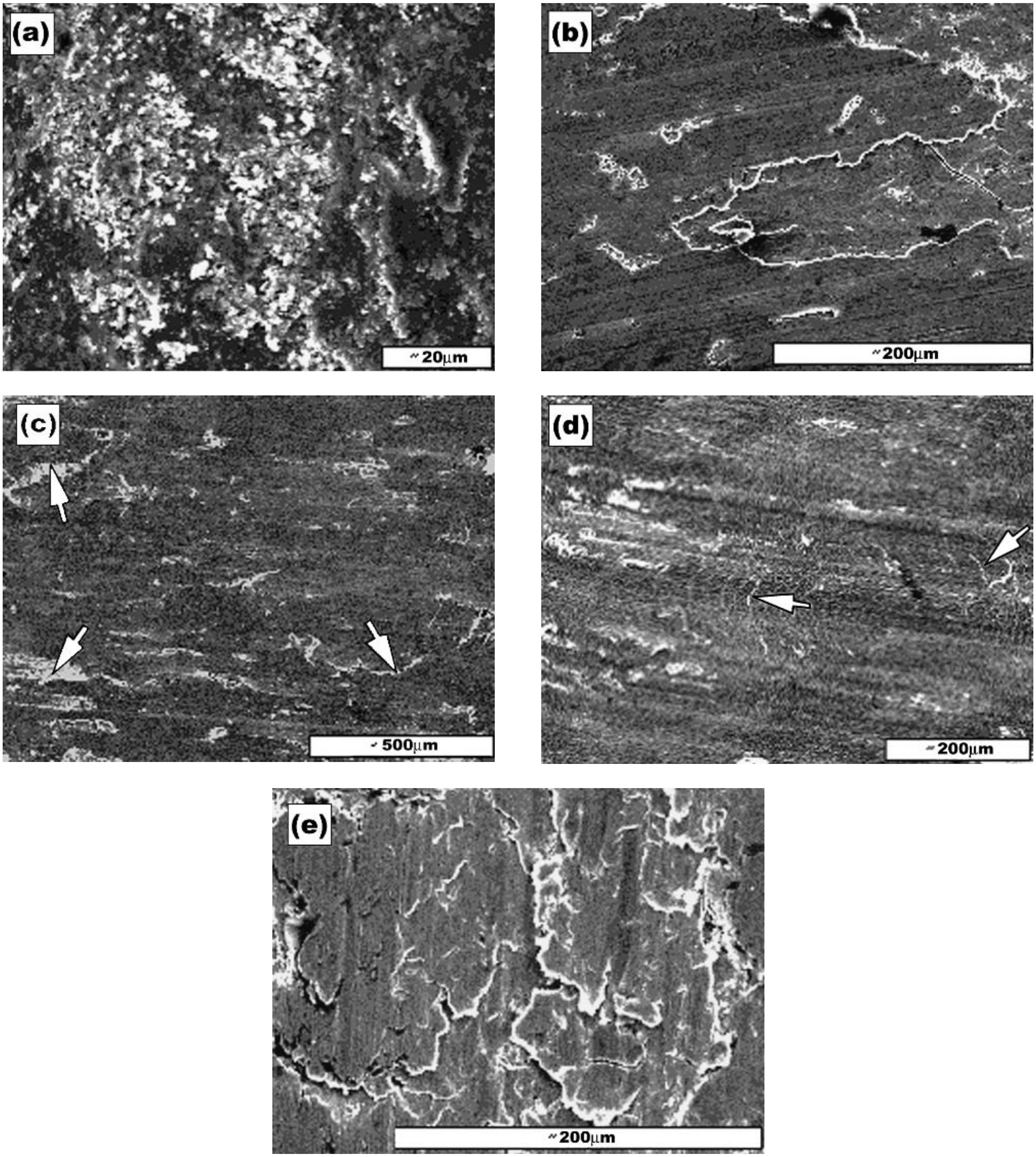

Fig. 7 SEM morphologies of worn surfaces of nanocrystalline layer annealed at 300 °C: **(a)** 1.4 MPa; **(b)** 2.1 MPa; **(c)** 3.5 MPa; **(d)** 5.6 MPa; **(e)** 7.0 MPa

O, and Fe (Table 1). There is high content of oxygen in the surface film, implying that this film is an oxide film. During this period, the tribological behaviors of nanocrystalline Cu-Zn alloy depend on the function of the surface film formed on the worn surface. The wear resistance is remarkably improved owing to the effective protection of the surface film, which separates the sliding surfaces of sliding counterparts and avoiding the direct metal-metal contact of sliding surfaces. The wear rate of nanocrystalline Cu-Zn alloy is determined by the rates of forming and peeling of the surface film.

Table 1 EDS Analysis of the Surface Film Formed on the Worn Surface of Nanocrystalline Cu-Zn Alloy Annealed at 300 °C

Element	Mass %	at.%
O	15.80	42.59
Fe	8.93	6.89
Cu	45.55	30.91
Zn	29.71	19.60
Total	100.00	100.00

At the load 7 MPa, excessive load will result in the surface film breaking off and a continuous and effective surface film cannot be formed, causing severe plastic deformation and material removal on the worn surface (Fig. 7e).

4. Conclusions

The wear resistance of nanocrystalline Cu-Zn alloy varies with the annealing temperature. The nanocrystalline Cu-Zn alloy annealed at 300 °C exhibits better wear resistance and high load-bearing capacity. A surface film almost covering entire worn surface was formed at a load range from 2.1 to 5.6 MPa. The surface film effectively improves the wear resistance of nanocrystalline Cu-Zn alloy.

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