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Influence of prior cold working on the tribological behavior of Cu–0.65 wt.%Cr alloy

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ABSTRACT

The influence of prior cold working on the friction and wear behavior of Cu–0.65 wt.%Cr alloy under dry sliding against a steel disk was investigated on a pin-on-disk wear tester. The worn surfaces and debrises of Cu–Cr alloy were analyzed by scanning electron microscope (SEM) and energy dispersive X-ray (EDX) spectrum. The results indicated that prior cold working and aging had an effect on the hardness and wear resistance of Cu–Cr alloy; in other words hardness and wear rate increased with the amount of cold working. At constant aging temperature, the wear rate of Cu–Cr alloys increase with cold working and reached maximum at 50% cold working. At constant amount of cold working aged specimens at 500 °C shows higher wear resistance than 450 °C. Crack initiation and propagation in the tribolayer and at the interface of subsurface and tribolayer was the dominant mechanism during the sliding process.

1. Introduction

The combination of heat treatment and cold deformation on materials remain a topic of great interest due to development of commercial alloys with wide range of application. Cold deformation is often carried out between the solution treatment and aging treatment in the thermomechanical processing of a precipitation-hardenable alloy [1].

Precipitation-hardened copper–chromium (Cu–Cr) alloy which possesses a combination of high strength and high electrical conductivity is widely used in electrical applications. The high strength of the aged Cu–Cr alloy is caused by very small coherent chromium-rich particles which precipitate in a dispersive manner from a supersaturated copper matrix [1–5]. In some applications of Cu–Cr alloy, factors such as wear resistance must be taken into account. Qi et al. [4] and Tu et al. [5] investigated the wearing behavior of Cu–Cr–Zr alloy against brass but there was no report on the effect of prior deformation on the wearing behavior of Cu–Cr alloy against steel. They concluded that peak aged Cu–Cr–Zr alloy exhibited a high Vickers hardness as a result of a fine scale precipitate dispersion. In addition adhesive wear, abrasive wear and arc erosion were the dominant wear mechanism under unlubricated condition. Friction coefficient tended to decrease with increase of normal load. They show the wear rate of the Cu–Cr–Zr alloy increased with the increase of the normal load and electrical current.

In this study, a Cu–0.65 wt.%Cr alloy was first solution annealed and cold rolled to various strains. After aging the predeformed alloy at 450 °C and 500 °C, the wearing test was carried out on a pin-on-disk wear tester with Cu–Cr alloy pin then the effects of the aging temperature and amount of prior cold working on wear performance were studied. The wear mechanism of the alloy was investigated, as well.

2. Experimental procedure

A copper alloy with the composition of Cu–0.65Cr was prepared in a vacuum induction furnace. The ingots were homogenized at 1050 °C for 30 min and then hot extruded into a rod of 15 mm diameter. This rod was machined into a cube with a size of 10 mm × 10 mm × 10 mm. The cube samples were solution treated in air atmosphere at 1000 °C for 45 min and then quenched in cold water. Subsequently, the alloy cold rolled to total reduction of 0%, 10%, and 50%. All the cold-worked specimens aged at 450 °C and 500 °C for times from 1 h to 4 h in an electric furnace and subsequently cooled in air. Finally, samples with a size of 5 mm × 5 mm × 10 mm for wear test were machined from the solution, cold rolled and aged cubes.

Hardness measurement was carried out on cubes using the ESEWAY DVRB.M Vickers hardness testing machine at 30 kg, and the mean values of at least three measurements conducted on different areas of each sample was considered. Dry sliding pin-on-disc wear tests were carried out in a laboratory atmosphere at 50–60% relative humidity and the temperature around 25 °C with the Cu–Cr alloy pin rubbing against an AISI/SAE 52100 steel disk with hardness of 60 HRC. Friction coefficient measurements were made using a transducer to measure the deflection of the pin holder caused by the disc rotation. The system calibrated by applying known tangential loads and noting pin deflection. The schematic view of the wear test apparatus is shown in Fig. 1. The steel disk was 40 mm in diameter and 5 mm in thickness. Wear test was carried out at a sliding speed of 0.3 m s^{-1}, normal load of 40 N and sliding

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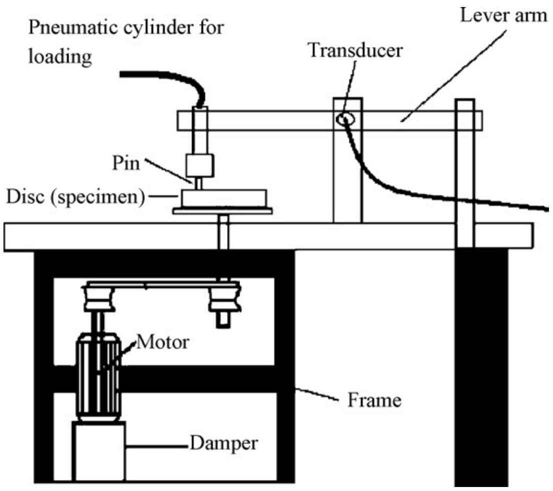

Fig. 1. The schematic view of the wear test apparatus used in this study.

distance of 1000 m. The wear rates of the specimens after wear test were measured by weighing the specimens. Before wear, the specimens were polished with 800 grit emery papers and cleaned ultrasonically in acetone. The worn surfaces of the specimens were examined using MV2300 CamScan scanning electron microscope (SEM) equipped with an energy dispersive X-ray (EDX) analyzer.

3. Results and discussion

3.1. Effect of prior cold working and aging treatment on hardness

Fig. 2 shows the variation of Vickers hardness of Cu–0.65 wt.%Cr alloy in the non-cold-worked and cold-worked state as a function of aging time at 450 °C and 500 °C.

It is obvious that aging at 450 °C results in higher hardness than 500 °C and in each case the hardness increases with time until it reaches to a peak, then the hardness decreases along increasing time. In precipitation hardening, second-phase particles act in two distinct ways to retard the motion dislocations. The particles either may be cut by the dislocations or the particles resist cutting and the dislocations are forced to bypass them. A critical parameter of the dispersion of the particles is the particle spacing λ. A simple expression for the linear mean free path is:

$$\lambda = \frac{4(1-f)r}{3f} \qquad (1)$$

Where f is the volume fraction of spherical particles of radius r. when the particles are small and soft, dislocations can cut and deform the particles. λ is the function of aging time and the temperature [6]. The alloy hardness is dependent on both the aging time and the temperature, but the latter has a more significant influence on the hardness. According to previous studies during the age hardening of copper–chromium alloy system, very fine and coherent Cr-rich precipitates appear in the early stage. They change and grow into incoherent body-centered cubic (bcc) Cr precipitates with increasing time and temperature [1–3]. On the other hand, growth leads to the increase of the interparticle spacing. Large interparticle spacing between precipitates weakens their role as obstacles to the dislocation motion, thus contributing to a decrease in hardness [7].

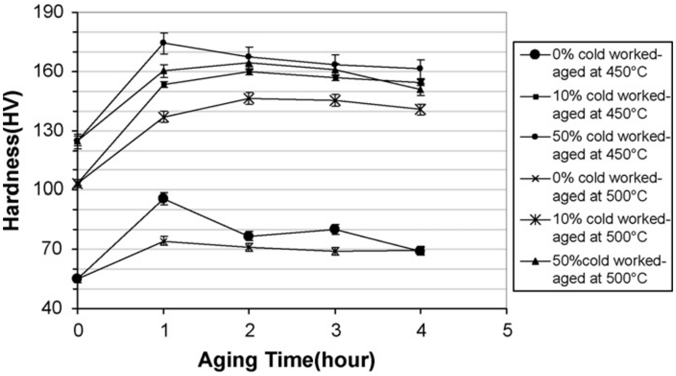

Fig. 2. The hardness of the Cu–0.65 wt.%Cr alloy performed to different cold working as a function of aging time and temperature.

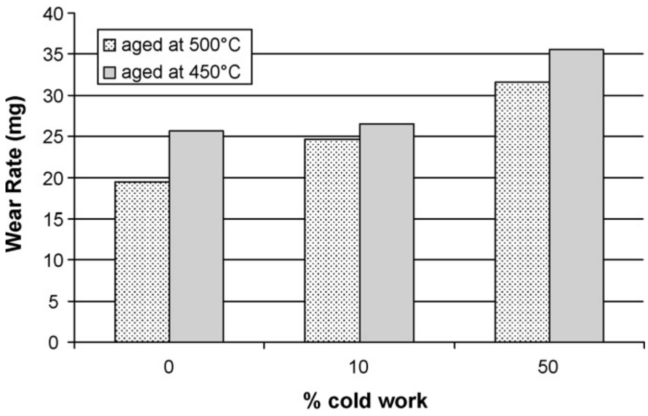

Fig. 3. Variation of wear loss of Cu–0.65 wt.%Cr alloy as a function of amount of cold working and aging temperature.

According to Fig. 1, the overall hardness of the cold-worked specimens is higher than that of the non-cold-worked specimens during aging. The more heavily deformation prior to aging is, the higher is the overall hardness obtained after aging.

A more detail investigation on the influence of prior cold working on the age hardening of phosphorous containing Cu–0.61 wt.%Cr by Gao et al. [1] showed that the total hardness variation (ΔHV_{tot}) of the cold-worked alloy during aging can be formulated according to equation (2):

$$\Delta HV_{tot} = \Delta HV_{def} + \Delta HV_{pre} - \Delta HV_{rec} \qquad (2)$$

Where ΔHV_{def} and ΔHV_{pre} are the hardness gains arising from prior deformation and precipitation, ΔHV_{rec} is the hardness loss caused by recovery and recrystallization during aging. In fact recovery is an unavoidable process which occurs in the beginning of aging and results in a slight decrease in the hardness of cold-worked alloy, but precipitation and recrystallization have their own incubation time, showed by t_P and t_R, respectively [1]. These depend on the amount of prior deformation. Thus there is a competition between recrystallization and precipitation processes. The lightly predeformed alloy with a low density of dislocation (prior strain <0.5) shows a delayed recrystallization process ($t_R \gg t_P$) [1]. In this case the presence of dislocation can enhance the precipitation. In addition, the pinning effect of precipitates can reduce the mobility of dislocations and hinder the rearrangement of dislocations. So the predeformed Cu–Cr alloy is prevented from the softening due to recrystallization and efficient hardening obtained by aging.

3.2. Friction and wear behavior peak aged Cu–Cr alloys

From Fig. 2 it is evident the value of hardness for the Cu–Cr alloy reached the peak hardness after aging for 1 h approximately. According to Fig. 3 in spite of higher hardness of specimen aged at 450 °C with respect to 500 °C, their wear rate behavior is inversed and this is a trend that can be seen with amount of cold working in a way that the wear rate of specimens increase along increasing the amount of cold working.

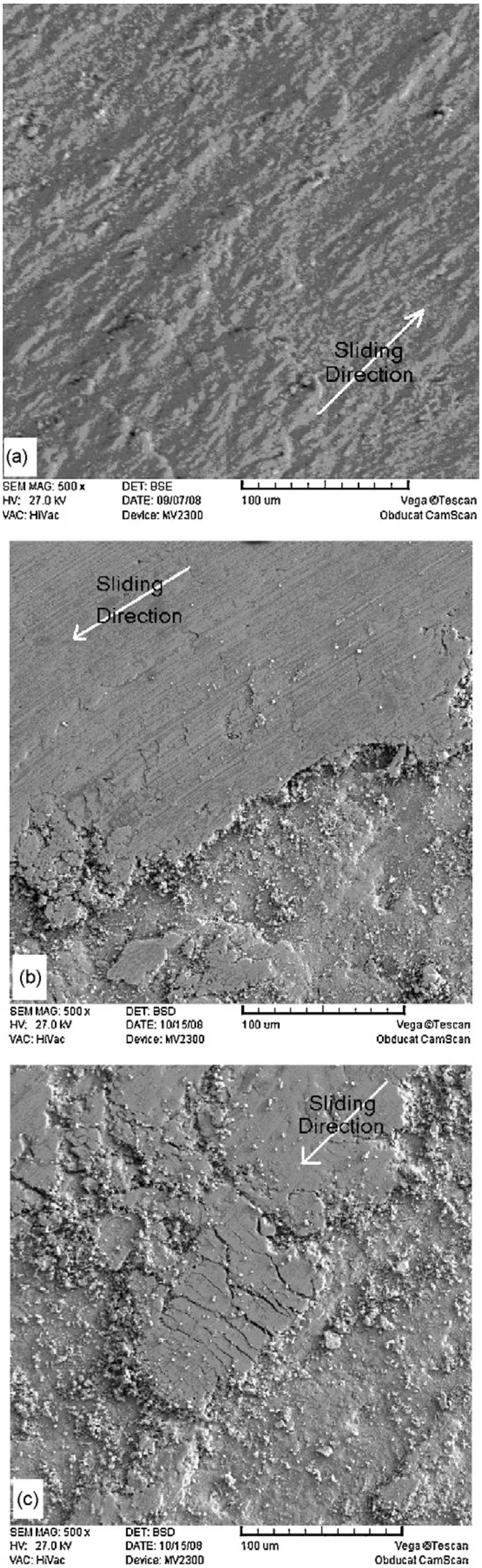

Fig. 4. SEM micrographs of worn surfaces of specimens (a) 0% cold-worked, (b) 10% cold-worked and (c) 50% cold-worked.

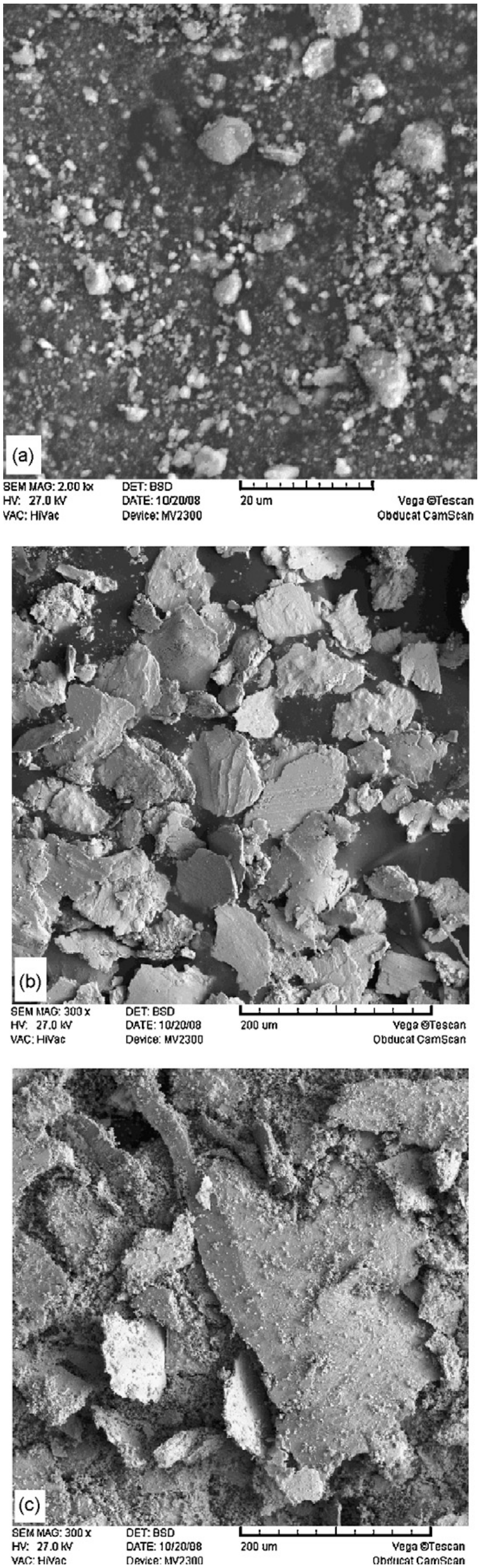

Fig. 5. SEM micrographs of the debris of specimens (a) 0% cold-worked, (b) 10% cold-worked and (c) 50% cold-worked.

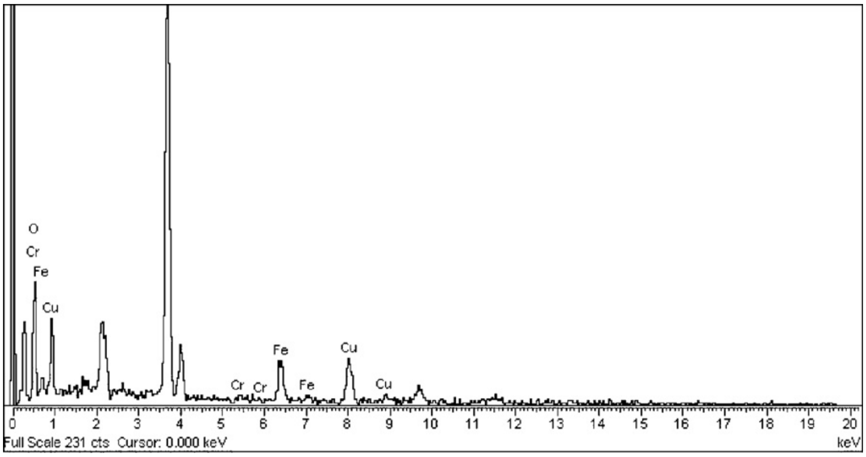

Fig. 6. EDS result of fine particles of Fig. 4a.

This is a conclusion contrary to Archard equation predicting the decreasing trend of wear rate with an increase in hardness [8]. An increase in hardness results in a decrease in the deformation capability of surface asperities, thus due to direct contact between the surface asperities of pin and disk, asperities are detached so the wear rate increases along the increasing of hardness. Fig. 4a–c shows SEM micrographs of worn surfaces of the pins with various amounts of prior cold working that has been aged at 500 °C for 1 h.

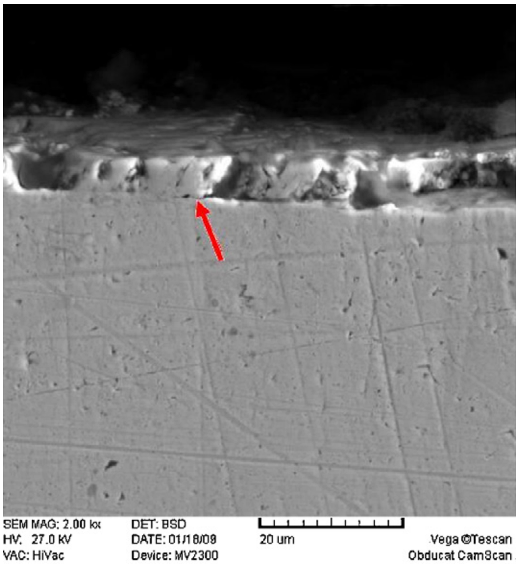

Fig. 7. SEM micrograph of cross section of worn specimens.

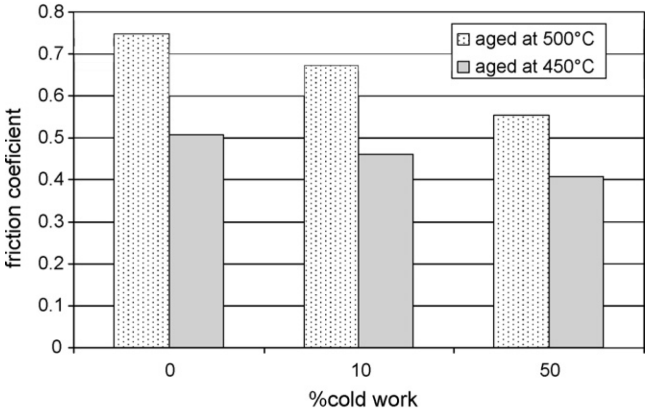

Fig. 8. Variation of friction coefficient with amount of cold working and aging temperature.

Fig. 5a–c shows the SEM micrographs of the debrises of these specimens respectively. According to Fig. 4a, the worn surface of non-cold-worked specimen is smooth and it is mostly covered by a continuous deformed tribolayer. In fact the rate of material removal was lower than that at which the tribolayer was formed, creating the provision for a stable layer. Fig. 5a illustrates the debris of non-cold-worked specimen. The debrises detached from this specimen are fine and mostly consist of oxide particles. From the EDS analysis in SEM, it is concluded that fine particles are copper or iron oxide (Fig. 6).

The presence of these particles is caused by a local increase in temperature at the tip of the asperities, the formation of oxide and their detachment in the wear process [5].

Cold-worked specimens do not show a continuous deformed tribolayer (see Fig. 4b and c). Fig. 4b and c shows some micro cracks on the tribolayer. In addition Fig. 5b and c shows the presence of plate-like debrises. Therefore in these cases, delamination of tribolayer was found to take place inside the tribolayer and below the surface. In this mechanism, cracks nucleated below the surface, where high shear strains are present (Fig. 7), then these cracks joined together and plate-like debris formed [8].

An Increase in the amount of cold working results in the increase of hardness, so that the asperities' capacity for plastic deformation decreases. Therefore in cold-worked specimens the possibility of crack formation below the surface and wear rate increases due to increasing of contact stress caused by decreasing of real contact area. Thus specimens subject to cold work show higher wear rate than non-cold-worked specimens. The variation of friction coefficient with the amount of cold working and temperature of aging are represented in Fig. 8. It can be seen that the friction coefficient show a general trend of decreasing with the increase of hardness. Due to the lower hardness of specimens aged at 500 °C in comparison to those aged at 450 °C, the capability for plastic deformation and hence the real contact area between pin and disk increased. The wider the real contact area between the pin and the disc is the greater is friction coefficient because the force for shearing the contact between pin and disc increases with increasing the real contact area. In the specimens subject to cold work there is no continuous tribolayer and the real contact area, so the real contact area and adhesion of the surfaces between the pin and the disk decreases, and therefore the friction coefficient also decreases.

4. Conclusion

The following conclusion can be drawn from investigation on the influence prior cold working on the sliding wear behavior of Cu–0.65 wt.%Cr.

1. Hardness increased with aging time, temperature and the amount of cold working and attained a maximum when the alloy aged for 1 h at temperature of 450 °C with 50% prior cold working. All the cold-worked alloys had an overall hardness than the non-cold-worked alloys. Aging at 450 °C caused higher hardness than 500 °C.
2. During dry sliding wear, the wear rate increased with increasing amount of cold working. The Cu–0.65 wt.%Cr alloy aged at 500 °C for 1 h with 0% prior cold working exhibited the best wear resistance in the present work.
3. The friction coefficient tended to decrease with increasing amount of cold working. In the specimens subject to cold work there is no continuous tribolayer, so the real contact area and adhesion of the surfaces between the pin and the disk decreases, and therefore the friction coefficient also decreases.
4. From the examination of the worn surfaces and wear particles of specimens, it was found that the crack initiation and propagation in the tribolayer and at the interface of matrix and tribolayer was the dominant mechanism during the sliding process.

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