Tribological behavior of heat treated CuCrZr alloy

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Abstract. Optimal combination of strength, ductility and conductivity in CuCrZr alloy can be achieved by suitable heat treatment involving solution annealing at high temperature to dissolve alloying elements, water quenching to produce a super-saturated solid solution, and an aging treatment at an intermediate temperature to produce fine precipitates giving rise to high strength. In this study, Cu-1Cr-0.1Zr alloy was manufactured as cast material and following hot forging, solution annealing and aging were applied conventionally. In order to enhance the precipitation kinetics, solution annealed and quenched alloy was cold deformed and then aged at the same condition. Specimens obtained after (i) casting, (ii) conventional solution annealing and aging and (iii) aging after cold deformation were investigated in order to determine microstructural features, hardness and tribological properties. The results showed that while heat treatment process increased hardness of cast specimen, it was enhanced further with deformation before aging. Besides hardness, tribological properties of the cast specimen were improved further by deformation before aging.

Keywords: CuCrZr alloys; microstructure; tribology; characterization

1 Introduction

Cu-1Cr-0.1Zr (CuCrZr) alloy is a precipitation-hardened alloy and exhibits high electrical/thermal conductivity, high strength, good ductility, radiation resistance. Optimal combination of strength, ductility and conductivity in CuCrZr alloy can be achieved by suitable heat treatment involving solution annealing at high temperature to dissolve alloying elements, water quenching to produce a super-saturated solid solution, and an aging treatment at an intermediate temperature to produce fine precipitates giving rise to high strength [1-6]. Due to its high strength and high conductivity, CuCrZr alloy is suitable for high loading parts under electrical current such as springs, contact wheel, contact wire of high speed railways etc. [1-5]. It is reported that CuCrZr has already been selected as a base material for the ITER ICRH RF contact louvers' manufacturing and as machine components of ITER. CuCrZr alloys are subjected to both high heat flux and sliding contacts during operation [6]. Therefore, tribological behavior of CuCrZr alloy at room temperature and high temperature under sliding contact becomes important under these service conditions.

CuCrZr alloy has several types of precipitates (Cu_3Zr , Cu_4Zr , Cu_5Zr , $\text{Cu}_{51}\text{Zr}_{14}$, etc.) within α -Cu matrix. As mentioned above, the presence of these precipitates provides precipitation hardening of the material by inhibiting dislocation motion and hence improves the mechanical properties. In order to get highest mechanical properties, size, volume fraction and distribution of these precipitates must be controlled. Therefore, after casting the material should be forged and then heat treated. Literature indicate that, instead of conventional heat treatment, thermomechanical treatment consisting of annealing, cold deformation and aging steps, improves the mechanical properties further, since cold deformation before aging accelerates the precipitation kinetics [7-9]. Therefore, in this study, it is aimed to investigate the effect of cold deformation on hardness and wear properties of CuCrZr

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alloy. Thus, both conventional heat treatment and thermomechanical treatment were applied on cast CuCrZr alloy and their room temperature and high temperature wear behavior were investigated.

2 Experimental study

2.1 Material

Two different treatments were applied to the cast CuCrZr alloy. Initially, solution annealing was applied to all specimens at 980 °C during 30 min. After solution annealing, (i) one specimen, namely the aged one, was peak aged at 450 °C for 24 h and (ii) second specimen, namely deformed + aged one, was deformed with a 30 % strain and then peak aged at 450 °C for 24 h. For microstructural investigation, all specimens were prepared metallographically and etched with a solution (10g FeCl₃, 50 ml HCl, 10 ml HNO₃, 100 ml H₂O).

2.2 Tribological tests and surface characterizations

In order to investigate tribological behavior of heat treated CuCrZr alloy, room temperature and high temperature wear tests were applied to the alloys. Friction coefficient values and specific wear rates were obtained by these tests. Wear tests at room temperature (RT) were performed using a Nanovea model “ball-on-disc” type tribometer and ZrO₂ balls were selected as counterpart. In these tests, sliding speed, normal load and total sliding distance were selected as 0.15 m/s, 10 N and 150 m, respectively. The high temperature (HT) wear tests were carried out at 300 °C using a home-made “block-on-cylinder” type tribometer against 51CrV4 steel. The wear parameters were 0.27 m/s, 50 N and 1000 m.

Wear performance of the samples were evaluated by (i) the variation of friction coefficient as a function of sliding distance, (ii) specific wear rates calculated according to ASTM G-99 standard, (iii) examination of worn surfaces using both light microscope (LM, Olympus BX41M-LED), scanning electron microscope (SEM, Jeol 6060) and optical profilometer (Nanovea PS50).

3 Results and discussion

3.1 Microstructural characterization

The microstructures of the specimens are given in Figure 1. In copper alloys, chromium and zirconium have a low solubility, thus chromium stays in elemental form in the matrix while zirconium forms precipitates with copper (Cu₃Zr, Cu₄Zr, Cu₅Zr, Cu₅₁Zr₁₄, etc.). Among these secondary phases, Cu-Zr based precipitates are responsible for the precipitation hardening. All specimens (cast, aged, deformed + aged) have Cu-Zr based precipitates and elemental Cr phase (blue and in globular form) embedded in α -Cu. This indicates that Cr phase has no solubility in solution annealing process. However, Cu-Zr precipitates are dissolved and finely dispersed within the matrix of aged and deformed + aged specimens (Fig. 1b and c). Since cold deformation provides more nucleation sites, relatively fine dispersed precipitates occur within the matrix of deformed + aged specimen. Although these fine precipitates cannot be observed by LM, this effect is observed in hardness data given in Table 1. While as cast alloy has a hardness value of 80.1 ± 2 HV₃, aged specimen hardness is 233.5 ± 5 HV₃. By means of these fine precipitates obtained by cold deformation, hardness value of deformed + aged specimen reaches at 258.4 ± 7 HV₃.

Fig. 1. LM images of the (a) cast, (b) aged and (c) deformed + aged alloys.

3.2. Evaluation of wear tests

The friction coefficient data obtained by RT wear tests are given in Figure 2 and specific wear rates are given in Table 1. Cast CuCrZr alloy has the highest friction coefficient and the highest specific wear rate due to its low matrix hardness. While heat treated alloys have similar friction coefficient values, deformed and aged specimen exhibits lower specific wear rate because of its relatively higher hardness.

The friction coefficient data of heat treated specimens obtained by high temperature wear tests are given in Figure 3. Deformed + aged specimen has a smooth friction coefficient line while aged specimen shows higher friction coefficient values intermittently. It may be caused due to the higher plastic deformation capability of aged specimen at 300 °C. Deformation before aging provides much more submicron precipitates in the deformed + aged matrix which inhibit its plastic deformation..

Fig. 2. Friction coefficient values as a function of distance obtained by “ball-on-disc” type tribometer at RT.

Table 1. The variation of specific wear rates obtained at RT wear tests and the matrix hardness values of specimens.

Specimen	Specific wear rate ($\times 10^{-5}$, mm ³ /Nm)	Hardness (HV3)
Cast	267,10	80.1 ± 2
Aged	1,37	233.5 ± 5
Deformed+aged	0,81	258.4 ± 7

Fig. 3. Friction coefficient values as a function of distance obtained by “block-on-cylinder” type tribometer at 300 °C.

3.3 Characterization of worn surfaces

LM images of wear tracks are given in Figure 4. It is clearly seen that cast specimen has the widest wear track consisting of dense adhesive layers (Fig. 4a). Heat treated specimens have similar and much narrower wear tracks than the cast specimen. Although aged specimen has some plastically deformed parts near the wear track (Fig. 4b), there is no such observation for the deformed + aged specimen (Fig. 4c). SEM images showing the worn surfaces at higher magnification are given in Figure 5. Even though all worn surfaces have adhesive layers, cast specimen has wider and multilayered adhesive layers (Fig. 5a). Plastically deformed layers can also be observed on the worn surface of the aged specimen that lie from the worn surface to base metal (Fig. 5b). On the worn surface of deformed + aged specimen, only adhesive layers are observed (Fig. 5c). The difference between wear tracks of aged and deformed + aged specimen can be observed clearly by 3D images given in Figure 6. Wear track of aged specimen has deep and globular parts (Fig. 6a) while deformed + aged specimen has smooth deformation.

Fig. 4. LM images showing the worn surfaces of (a) cast, (b) aged and (c) deformed + aged CuCrZr alloys obtained at RT.

Fig. 5. SEM images of the worn surfaces of (a) cast, (b) aged, (c) deformed + aged tested under 10N with a 0.15 m/s sliding speed.

Fig. 6. 3D images of the worn surfaces of (a) aged, (b) deformed + aged tested under 10N with a 0.15 m/s sliding speed.

SEM images showing the wear tracks of specimens tested at 300 °C are given in Figure 7. While aged specimen has adhesive layers with accumulated oxide particles (Fig 7a), deformed + aged specimen shows abrasives tracks with thin adhesive layers (Fig. 7b).

Fig. 7. SEM images showing the worn surfaces of (a) aged and (b) deformed + aged CuCrZr alloys obtained at 300 °C.

4 Conclusion

In this study room temperature and high temperature wear behavior of cast and thermo-mechanically treated CuCrZr alloys are investigated. Results show that (i) matrix hardness of cast CuCrZr alloy increases with heat treatment, (ii) deformation before aging provides higher hardness than only aged specimen, (iii) both friction coefficient values and specific wear rates obtained at RT wear test are affected by hardness, therefore deformed+aged specimen has the lowest specific wear rate, (iv) at high temperature wear tests, deformed+aged specimen has lower friction coefficient due to lower plastic deformation capability at 300 °C.

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