MICROMECHANICAL PROPERTIES AND ELECTRICAL CONDUCTIVITY OF Cu AND Cu-0.7wt% Cr ALLOY

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Abstract: Microstructure, electrical conductivity and micromechanical properties of industrial Cu and Cu-0.7wt%Cr alloy after equal channel angular pressing, hard cyclic viscoplastic deformation and followed ageing treatment were studied. The tensile strength of 430 MPa and hardness of 195HV0.05 were arrived. The Young modulus was increased to 125 GPa and the maximal electrical conductivity for Cu was achieved 103% IACS after hard cyclic viscoplastic deformation and 94.5% IACS for Cu-0.7wt% Cr alloy after ageing at 450 °C for 1 h. The Cu-0.7% Cr alloy have high electrical conductivity at operation temperatures from 260 °C to 550 °C while the pure ultrafine grained Cu lost hardness, wear resistance and conductivity at 170 °C, respectively.

Key words: Ultrafine grained microstructure, Electrical conductivity, Micromechanical properties, Young modulus, Copper.

1. INTRODUCTION

By using of severe plastic deformation (SPD) techniques like equal channel angular pressing (ECAP), parallel channel angular pressing (PCAP) or high pressure torsion (HPT) it is possible to change the mechanical properties and microstructure of plastically deformable metals and alloys [1-3]. During the past two decades the microstructure, mechanical and physical properties stability of bulk ultrafine grained (UFG) and nanocrystalline (NC) materials are studied in large amount of papers [1-6]. The fields for further development related to UFG Cu and Cu-base alloys span a wide range of applications [7-9] in the different industries. Nevertheless, it is clear that for electrical conduction the Cu-based alloys with high electrical conduction properties, suitable high wear resistance (WR) and low coefficient of friction (COF) at increased temperatures will be used [10]. To date, the tribological properties of UFG Cu [11, 12] have been studied. Unfortunately, the results in [10-12] were inconsistent because the wear tests were conducted using different methods and as result the properties are not comparable. The Cu-Cr investigations are described alloys hardening by annealing and softening by deformation is studied [13-15]. In these articles also the different mechanisms of hardening via vacancy-assisted deformation are presented. The goal of this investigation is to study the mechanisms of UFG or NC microstructures, mechanical, physical and tribological properties forming in pure Cu and Cu-0.7wt% Cr alloy during ECAP and PCAP followed HCV deformation [16] and ageing treatment. In addition, we examine by tension, nanoindentation [17, 18] and wear testing the micromechanical properties in the sample body and/or inside of wear tracks.

2. EXPERIMENTAL

The commercially pure Cu and Cu-0.7wt% Cr alloy were selected as test materials for the study. The Cu samples were cut to diameter of 15.6 mm and in length of 120 mm, and samples from Cu-Cr alloy were
cut to square 12x12 mm and 120 mm in length, respectively. The samples from Cu were heat treated at 650 °C for 2h. The samples from Cu were processed in PCAP die with two intersection angles of 110° and step-by-step decrease of channel diameter from 16 to 15.5 and to 15 mm, respectively. The samples were routed by 90° and pressing direction was changed to 180° after each pressing. The 12 passes ($\varepsilon_{vM} \sim 22$) were conducted at room temperature. The Cu-0.7wt% Cr alloy was cold water quenching from 1000 °C (for 2h), respectively. The samples from Cu-0.7wt% Cr alloy were subjected to ECAP by the B$_c$ route with 6 passes ($\varepsilon_{vM} = 6.9$) at room temperature in the ECAP die with channel intersection angle of $\Phi = 90$° and $\Psi = 0$° in air with a pressing speed of 5 mm s$^{-1}$ [3]. From received rods were cut off tension/compression test samples with test part of 8 mm in diameter and 12 mm in length. The extensometer base length was 10 mm. The samples were subjected to HCV deformation for 20 tension/compression cycles at strain amplitudes of $\pm 0.05\%$, $\pm 0.1\%$, $\pm 0.5\%$, $\pm 1\%$, $\pm 1.5\%$, and $\pm 2\%$ at a low frequency of 0.5 Hz, respectively. The Young modulus was measured at least three-five times between each series for 20 cycles at constant strain amplitudes. These processed samples from Cu-Cr alloy were subjected to heat treatment at temperatures 250-750 °C (with step of 100 °C) for 1 h and some samples for 2h. The HCV deformation [16, 18] technique was conducted on the materials testing system Instron-8516. The microhardness was measured using a Mikromet-2001 tester after holding for 12 s at a load of 50 and 100 g. The obtained samples' microstructure was studied by optical (Nikon CX) and scanning electron (Zeiss EVO MA-15) microscopy. For SEM imaging a secondary (SE) and backscattered (BE) electrons were used. The accelerating voltage was 20 kV. The micromechanical properties were characterized using the nanoindentation device of the NanoTest NTX testing center (Micro Materials Ltd.). The nanoindentation was conducted for 49 indents on grinded and etched surface of sample under load of 100 mN. The tribological behavior under dry sliding conditions was investigated before and after ECAP, HCV deformation and heat treatment to provide a comparison over a range of material harness and to understand their influence on the electrical conductivity, COF and specific wear rate. The dry sliding wear was studied using a ball-on-plate tribometer (CETR, Bruker, and UMT2) with a counterface ball of alumina ($\text{Al}_2\text{O}_3$) with a ball diameter of 3 mm. The tribological tests were conducted at room temperature in air under normal compression load of 100 g. The sliding distance amplitude was 3 mm at a frequency of 5 Hz, velocity of 20 mm/s, testing time of 10 min and sliding distance of 12 m for all samples. For wear volume calculations, the cross-sectional area of the wear tracks was measured by the Mahr Pertohometer PGK 120 Concept 7.21. The electrical conductivity was determined by means of the Sigmatest 2.069 (Foerster), according to NPL standards. The measurements for different orientations at frequency of 60 and 480 kHz on a calibration area of 8 mm in diameter and room temperature of 23.0±0.5°C and humidity of 45±5 % with an uncertainty of 1% according to International Annealed Copper Standard (IACS) in the National Standard Laboratory for Electrical Quantities of Estonia were conducted.

3. RESULTS AND DISCUSSION

3.1. Microstructure

The SEM/EDS investigation of as-cast Cu-0.7wt% Cr alloy show that it contain porous and no-dissolved Cr particles with measures not higher then one micrometer (Fig 1a). During followed heat treatment at 1000 °C and ECAP for 6 passes by B$_c$ route these inclusions measures were decreased (Fig 1b) and after followed HCV
deformation dissolved via Cr atoms diffusion into the Cu matrix.

The hardness of Cu-0.7wt% Cr alloy (in as-cast condition and after heat treatment at 1000 °C for 2h) was ~75HV₀.₁ and electrical conductivity was 40% IACS, respectively (Fig 2). During ECAP the hardness was increased up to 192HV₀.₁ and electrical conductivity to 74.16% IACS, respectively. By this, during followed HCV deformation the hardness was decreased slightly to 187HV₀.₁ and electrical conductivity increased to 75.52% IACS, respectively.

The optimal parameters of microhardness and electrical conductivity were choosing after heat treatment at temperatures in the interval from 250 to 750 °C with step of 100 °C. The optimal ageing temperatures in the interval of 250-500 °C for 1h were the mean microhardness of 120±10HV₀.₁ and the mean electrical conductivity of 93.3±0.6% IACS. However, heating at temperatures higher than 650 °C leads to decreasing of the electrical conductivity due to the decomposition of the supersaturated solid solution [9]. The increasing of heat treatment temperature to 650 °C and 750 °C leads to decrease in the microhardness to 95HV₀.₁ and to 78HV₀.₁ and electrical conductivity to 87% IACS and to 77% IACS, respectively.

The electrical conductivity of pure Cu was decreased by increase of equivalent von Mises strain higher than ~4 εᵥM (Fig 3). As is shown the electrical conductivity at ~11 εᵥM to ~14 εᵥM strain decrease sharply and by cumulative strain increase to ~22 εᵥM it was decreased to 58.95% IACS measured at frequency of 60 kHz and to 51.05% IACS measured at frequency of 480 kHz, respectively. At the frequency of 60 kHz the depth of measure is 3-3.5 mm and at frequency of 480 kHz it decreases to ~1 mm. This result shows that dislocation density has very large influence on the results of electrical conductivity measure as the dislocations have obstacle to electrons mowing in the material [6]. By this, in other works [7, 9, 10] is shown that the electrical resistivity/conductivity depends on hardness of material and the correlation is shown.
3.3. Strength and thermal stability of UFG Cu and Cu-Cr alloy

The UFG pure Cu was lost its strength properties at temperature of 170°C. After PCAP for 6 passes the strength was $R_m = 430$ MPa, after ageing treatment at temperature of 170 °C the $R_m = 355$ MPa and at 200 °C this parameter was decreased to 264 MPa.

The results of HCV deformation show that at strain amplitude increases (from ±0.1% to ±1%) the stress amplitude and Young module increase, respectively. At the increased strain amplitudes of ±2% (Fig 4a) the stress amplitude decrease at 15 cycle’s from 339.7 MPa to 265.3 MPa and the Young modulus (Fig 4b) was sharply decreased from 130 GPa to ~100 GPa at these some strain amplitude. This result depend on the test material grain size before HCV deformation [16] and show the phenomena of NC metals [14] as softening by slight deformation. According to our speculative opinion the Young modulus was decreased (Fig 4b) as the interatomic interaction was decreased by cumulative strain or cycles number of HCV deformation increase (see Fig 4a). But these standpoints need detailed investigations in future.

The results of nanoindentation for UFG Cu-0.7wt% Cr are presented in Fig 5. The mean (from 49 indents measured under 100 mN load) nanohardness of sample N1 was $H_N = 3.84$ GPa and indentation modulus $E_r = 538.5$ GPa, respectively. The ageing time increase to 2h (sample N2) leads to decrease of hardness but increase of indentation modulus.
Fig 5. Nanohardness (HN) and Young/elastic modulus (EM) of Cu-0.7Cr alloy after 6 passes measured in cross-section of sample by nanoindentation. Definitions: N1 – ageing at 450 °C for 1 h; N2 – 450 °C for 2h; N3 – 450 °C for 2h+HCV; N4 – 550 °C for 1h; and N5 – 550 °C for 2h.

The minimal indentation modulus Er = 437 GPa was measured for hardest HN100= 3.89 GPa Cu-0.7wt% Cr alloy (sample N3) after HCV deformation. The ageing time increase to 550 °C (sample N4 for 1h and sample N5 for 2h) leads to increase of hardness (from HN = 3.02 GPa to HV = 3.59 GPa) but decrease of indentation modulus.

The specific wear rate and COF measurements show their dependence from chemical composition of sample material, sample surface hardness as well material surface softening/hardening during wear testing. Results show that HCV deformed sample in surface was hardened from 77HV0.05 to 90HV0.05 and on the wear track surface from 115HV0.05 to 126HV0.05, respectively. In this case the wear track surface hardening was induced by cyclic straining as result of sliding. The specific wear rate was decrease from 0.3 to 0.07 mm³min⁻¹, respectively. The minimal specific wear rate has sample with maximal hardness. By this, during cycling (Fig 4a) at strain amplitude of ±2% the stress amplitude and Young modulus (Fig. 4b) were sharply decreased as the interatomic interaction was lowered [18]. At that time the rate was increased. The results show that the pure Cu has lowest COF equal to 0.32 at the end of wear testing. By this at the first stage of testing the annealed Cu has slightly higher COF equal to 0.38 and Cu-0.7wt% Cr alloy COF was 0.57 at the end of wear testing. The COF was higher for Cu-0.7wt% Cr alloys as these have no dissolved hard Cr particles in soft Cu matrix. By this in our experiments the Cu-0.7wt% Cr alloys with higher hardness have highest COF but lowest specific wear rate.

4. CONCLUSIONS

In this study the pure Cu and Cu-0.7wt% Cr alloy the physical, mechanical and micromechanical properties, electrical conductivity, specific wear rate and COF were studied in dependence on cumulative strain and ageing temperature. The UFG pure Cu (after ECAP+HCV deformation) have best electrical conductivity (~103% IACS) and low COF as well low specific wear rate but lowest thermal stability by temperature increase over 170 °C. The UFG Cu-0.7wt.% Cr alloy after ECAP show highest microhardness, good wear resistance but low electrical conductivity (74.16% IACS). During followed HCV deformation the electrical conductivity was lightly increased (75.52% IACS). The ageing treated at 250-550 °C UFG Cu-0.7wt% Cr alloy have highly stable mechanical, tribological and electrical conduction (~94% IACS) properties and will be used as material for electrical energy industry.

5. ACKNOWLEDGEMENTS

The work was supported by the Ministry of Education and Science of the Estonia, Project No. IUT19-29 and EU ERA.Net RUS STPObjects-219.

6. REFERENCES


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