Electrical conductivity and mechanical properties of Cu-0.7wt% Cr and Cu-1.0wt% Cr alloys processed by severe plastic deformation

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Abstract. As-cast Cu-0.7wt% Cr and Cu-1.0wt% Cr alloys were subjected to equal-channel angular pressing (ECAP), hard cyclic viscoplastic (HCV) deformation and post deformation heat treatment for receiving an ultrafine grained material with a combination of high strength, good wear resistance and high electric conductivity. Samples from Cu-0.7wt% Cr alloy were processed up to six passes and Cu-1wt% Cr alloy samples were processed up to four passes of ECAP via Bc route. HCV deformation of samples was conducted by frequency of 0.5 Hz for 20 cycles at tension-compression strain amplitudes of ±0.05%, ±0.1%, ±0.5%, ±1% and ±1.5%, respectively. During HCV deformation, as-cast Cu-0.7wt% Cr alloy show fully viscoelastic behavior at strain amplitude of ±0.1% while ECAP processed material show the same behavior at strain amplitude of ±0.1%. The Young modulus was increased from ~120 GPa up to ~150 GPa. The results illustrated that specific volume wear decrease with increasing of hardness but the measured coefficient of friction (COF ~ 0.6) was approximately the same for all samples at the end of wear testing. The hardness after ECAP for 6 passes by Bc route was 192HV0.1 and electric conduction 74.16% IACS, respectively. By this the as-cast Cu-0.7wt% Cr alloy (heat treated at 1000 ºC for 2h) has microhardness ~70HV0.1 and electrical conductivity of ~40% IACS. During aging at the temperatures in the interval of 250-550 ºC for 1h the hardness and electrical conductivity were stabilized to mean values of 120±5HV0.1 and to 93.4±0.3% IACS, respectively. The hardness and electric conductivity took decrease by temperature increase over ~550 ºC, respectively. The results of present experimental investigation show that UFG Cu-0.7wt% Cr alloy with compare to Cu-1.0% Cr alloy is a highly electrical conductive and high temperature wear resistant material for using in electrical industry.

1. Introduction
It is well known that by using of severe plastic deformation (SPD) techniques is possible to improve of the mechanical properties and microstructure of plastically deformable metals and alloys [1-4]. During the past two decades the microstructure, mechanical and physical properties of bulk UFG and nanocrystalline (NC) metallic materials are studied in large amount of papers [1-8]. Therefore, the fields for further development related to Cu-Cr alloys span a wide range of different applications [9-11] in the electrical industry. Nevertheless, it is clear that for the fabrication of advanced installations for electrical conduction from Cu-Cr alloys use, there is a need to produce an UFG or NC microstructure with high electrical conduction properties and suitable high wear resistance (WR) and low coefficient of friction (COF) at temperature increase. To date, the tribological properties of UFG Cu [12], Al-Cu
alloys [13], pure Ti [14] and hard coatings [15], etc. have been studied. Unfortunately, the results in [9-15] were inconsistent because the wear tests were conducted using different methods and different parameters. In this investigation, we study the dependence of Cu-Cr alloys tribological properties on its microstructural state as well hardness. One of the goals of this investigation is to study the mechanism of UFG or NC microstructures and properties that form in Cu-Cr alloys during SPD processes, such as ECAP [16] and HCV deformation [17, 18] followed ageing treatment. The Cu-Cr alloys hardening by annealing and softening by deformation are studied in [19-22]. In these investigations are described different mechanisms of hardening via vacancy-assisted deformation and at friction. In this study the SPD processed and heat treated Cu-0.7wt% Cr and Cu-1.0wt% Cr alloys electrical conductivity, micromechanical as well tribological properties and their relationship with various processing parameters will be studied and results compared.

2. Experimental: materials and processing
The conventional Cu-0.7 wt% Cr and Cu-1.0wt% Cr alloys were selected as test materials for the study. The chemical composition was studied by SPECTROLAB (Spectro Analytical Instruments, Germany). The results show that the mean concentration of Cr was 0.664 wt% and it contain also Fe = 0.05 wt% and Si = 0.03 wt%. The second alloy contain 1.072wt% Cr and 0.03wt% Si. The samples from Cu-0.7wt% Cr alloy were subjected to heat treatment at 1000 °C followed cold water quenching. The samples from Cu-1.0wt% Cr alloy was no heat treated before ECAP and HCV deformation. The square samples of 12x12 mm and 120 mm in length were subjected to processing in the ECAP die [19, 20, 23] with channel intersection angle of 90°. The samples from Cu-0.7wt% Cr alloy were processed by ECAP with B\(_c\) route with 6 passes (\(\varepsilon_{VM} = 6.8\)) at room temperature. Part of samples (after ECAP) was at follow treated with HCV deformation and heat treated at temperatures from 250 °C to 750 °C (with step of 100 °C) for 1 h. The Young modulus was measured at tension at least three times before and between each cycling series. The one sample from Cu-1.0wt% Cr alloy was severely deformed by ECAP for 4 passes by B\(_c\) route followed HCV deformation and one sample with stepped cross-section was no ECAP processed and was sent exactly to HCV deformation (Fig. 1a). The extensometer with base length of 10 mm was mounted on the middle part of sample with minimal cross-section. For additional ECAP-processed microstructure improvements, the HCV deformation [13-15] technique was used on the materials testing system Instron-8516. The all materials were studied under tension/compression cyclic loading at strain amplitudes ranging from ±0.05, ±0.2, ±0.5, ±1, and ±1.5 % at a low frequency of 0.5Hz for 20 cycles, respectively. 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. The mechanical properties (tensile strength, elastic modulus, etc.) of samples were studied by means of material testing installation Instron-8516. The tribological behavior of alloy under dry sliding conditions was investigated before and after ECAP, HCV deformation and heat treatment to provide a comparison over a range of material properties as well as collected strain to understand their influence on the coefficient of friction and on the 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 (Al\(_2\)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 as constant parameters. The coefficient of friction (COF) was obtained.
automatically. 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 (MS/m and %IACS) was determined with a measurement uncertainty of 1% for different orientations on flat samples by means of the Sigmatest 2.069 (Foerster), according to NPL standards at 60 and 480 kHz on a calibration area of 8 mm in diameter. The electric conduction was measured at room temperature of 23.0±0.5°C and humidity of 45±5% according to International Annealed Copper Standard (IACS) in the National Standard Laboratory for Electrical Quantities of Estonia.

3. Experimental results and discussion
During followed HCV deformation [18] of sample with stepped cross-section (Fig 1a) or no stepped cross-section (Fig 1b) the microstructure and properties change take place in the test section with length of 10 mm. Sample from Cu-1.0wt% Cr alloy by stepped cross-sections (Fig 1a) was used for study the HCV deformation influence on the stability of tension-compression stress amplitudes, Young module, hardness and electrical conductivity at different strain/stress values. As the cross-section of sample was step-by-step increased (Fig 1a) it provided the inversely proportional decrease of actual stress as well as deformation during HCV deformation. The SEM/EDS investigation of Cu-0.7wt% Cr alloy in initial state show that it contain porous and no-dissolved Cr particles with measures not higher then one micrometer (Fig 2 and Fig 3). During followed ECAP and HCV deformation the microstructure was changed via diffusion processes under cyclic loading at viscoplastic condition. The Cr particles and porous in the SEM micrographs are not presented (Fig 3b). During ECAP processing these porous were compressed under hydrodynamic pressure and Cr particles were dissolved via diffusion into the Cu matrix but the grain size was not significantly refined.

Fig 1. As-cast sample from Cu-1.0wt% Cr alloy with stepped cross-section areas (in mm²) after HCV deformation (a) and ECAP processed for six passes by B₅ route sample from Cu-0.7wt% Cr alloy for HCV deformation.

Fig 2. SEM/EDS micrograph of as-cast Cu-0.7wt% Cr alloy (a) and microstructure with higher magnification with Cr particles and pores (b).
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. During ECAP for four passes of Cu-1.0wt% Cr alloy the hardness was increased up to 192HV0.1 and electrical conductivity to 74.16 % IACS. 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 of Cu-0.7wt% Cr alloy were choosing after heat treatment at temperature intervals from 250 to 750 ºC with step of 100 ºC. The optimal heat treatment temperatures at ageing treatment for 1h in the interval of 250-550°C were for mean microhardness of 119.8±15HV0.1 and for mean electrical conductivity of 93.3±0.6% IACS, respectively (Fig. 4a). However, heating at temperatures higher than 550°C leads to decreasing of the electrical conductivity due to the decomposition of the supersaturated solid solution [20]. The increasing of heat treatment temperature to 650 °C and 750 °C leads to decrease the microhardness to 95HV0.1 and to 78HV0.1 and electrical conductivity to 87.1% IACS and to 77% IACS, respectively. The microhardness of Cu-1.0wt% Cr alloy after aging for 1h was increased with increasing of accumulated strain for all temperatures but the maximal hardness of 160HV0.05 was achieved at aging temperature of 450°C. The electrical conductivity was increased up to 75.5 % IACS or 43.8 MS/m with increasing of aging temperature up to 450°C. The microhardness after ECAP followed HCV deformation increased compared to the initial state (Fig 4b). After following heating at 450°C the microhardness of alloy stayed unchanged followed by the aging process. The determined optimal treatment for the Cu-1.0wt% Cr alloy after ECAP, ECAP+HCV deformation and a subsequent heating is 450 ºC for 1h. After that the strength is approximately ~1.3 times higher than in the initially deformed samples due to the aging processes. By this the determined optimal interval for Cu-0.7wt% Cr alloy is 250-550°C for strength and for electrical conductivity, respectively.

The specific wear rate and COF measurements show their dependence from sample material chemical composition, sample (surface) hardness as well material wear track surface softening/hardening [21] during wear testing (Fig 5a). Results show that HCV deformed sample in surface was hardened from 77HV0.05 to 90HV0.05 and on the wear track surface from 115 to 126HV0.05, respectively. In this case the surface hardening was induced by cyclic straining and wears track hardening as result of sliding. During HCV deformation of Cu-1.0wt% Cr alloy the specific wear rate (Fig 5b) was decrease from 0.3mm³/min to 0.07mm³/min, respectively.
Fig 4. Electrical conductivity and microhardness of Cu-0.7wt% Cr alloy (for six passes of ECAP) dependence from ageing temperature (a) and microhardness as well electrical conductivity of Cu-1.0wt% Cr alloy dependence form processing mode (ECAP+HCVd and HCVd only) and ageing temperature (b).

During ECAP for 4 passes by Bc route followed HCV deformation the material was hardened but the wear tracks surface was softened slightly (Fig 5a) during wear testing. By this the minimal specific wear rate has sample with maximal hardness (Fig. 5b, sample with cross-section of 46 mm²). During HCV deformation in sample with minimal cross-section of 38 mm² the specific wear rate was increased (Fig 5b) as the material softening takes place. By this at the first stage of testing the Cu-0.7wt% Cr alloy COF was 0.57 and Cu-1.0wt% Cr alloy the COF was increased up to 0.7 with lowering to 0.58 at the end of testing. The COF was higher for as-cast Cu-0.7wt% Cr alloy as it has no dissolved hard Cr particles in the soft Cu matrix. By this in our experiments the Cu-Cr alloys with higher hardness have highest COF but lowest specific wear rate or higher wears resistance.

**4. Conclusions**

In this study the Cu-0.7wt% Cr alloy and Cu-1.0wt% Cr alloy mechanical properties, specific wear rate and electrical conductivity were studied in dependence on cumulative strain and ageing temperature. Cu-1.0wt% Cr alloy show highest hardness beside of test materials, good wear resistance but maximal electrical conductivity (75.5% IACS) was received after ECAP followed HCV deformation and ageing at temperature of 450°C for 1h.

The results of present experimental investigation show that UFG Cu-0.7wt% Cr alloy (with compare to Cu-1.0wt% Cr alloy have high stable mechanical and electrical conduction properties (up to 94% IACS), good wear resistant and low COF after ageing at high temperatures in interval from 250°C to 550°C for 1-2 h and it is suitable material for using in electrical industry.
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