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Original Research

Severely deformed copper by equal channel angular pressing☆

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ABSTRACT

Mechanical and microstructural analysis of equal channel angular pressed copper was experimentally investigated. The results showed that the hardness distribution uniformity was rapidly decreased after the first pass and gradually improved at the following passes. Also, the bottom region of the pressed material experienced lower Vickers hardness magnitude irrespective of pass number. Furthermore, the addition of 0.1% magnesium to the pure copper had a considerable effect on the distribution uniformity. In addition, the material fracture mode changed from ductile to brittle by the alteration of the dimples to cleavage planes mechanism. Moreover, the formability index was dramatically reduced after the first pass and slowly improved at the succeeding passes. Eventually, ECAP process led to the increment of low angle grain boundaries and the decrease of high angle grain boundaries at the initial passes and vice versa at the subsequent ones.

1. Introduction

Demand for copper and its alloys have been vastly grown in the past two decades due to the various industrial, architectural and biological applications and also transportation and musical instruments. Its prominent merits include better mechanical properties, high electrical and thermal conductivity, acceptable corrosion resistance, suitable ductility, attractive appearance and antibacterial feature. It has been confirmed that the best circumstance of obtaining above properties is reliant on the purity condition which contains up to about 0.3% impurities even though it has low strength in comparison with the alloying situation. On the other hand, among different strength mechanisms such as solid solution, precipitation and dispersion hardenings which are based on the adding alloying elements, strain hardening seems the only way to improve the mechanical properties of pure metals without the alteration of chemical compositions [1,2].

Although there are several conventional techniques such as rolling, drawing, extrusion and forging for the enhancement of materials' strength, these mechanical improvements are usually accompanied by the sample shape change. On the other hand, recently, severe plastic deformation (SPD) method has enticed materials engineers' attention due to the imposing extremely large plastic strain without any significant changes in the sample's dimensions. This feature leads to repeat the process up to the wanted strain to obtain the desired properties [3–5]. Equal channel angular pressing (ECAP) process as one of the only few SPD techniques with the advantage of scaled up for industrial application imposes intense simple shear plastic strain through a die composing of two equal cross-sectional channels intersected at the angle of Φ with the arc of curvature, Ψ [6,7].

Up to now, there are several experimental works investigating the capability and potential of ECAP samples on the aspects of grain structure, mechanical properties, superplasticity, fatigue behavior, corrosion, wear and etc. [8–13]. The high yield and ultimate strengths, relatively low elongation to failure, the modest strain hardening value and the onset of the deformation localization at a low plastic strain have been attained at the tensile behavior of ultrafine grain (UFG) aluminum processed with the ECAP technique at the ambient temperature carried out by Ivanov and Naydenkin [14]. The study by Torre et al. [15] on the microstructure and mechanical properties of Cu samples subjected to between 1 and 16 ECAP passes indicated a transition from a microstructure dominated by lamellar boundaries to an equiaxed grain structure. Additionally, the maximum hardness, yield and ultimate tensile strengths (YS and UTS) are achieved in the fourth pass sample. From 4–16 passes, the material strength decreases and the uniform elongation increases, which have been associated to the recovery phenomenon that decreases the boundary volume and the total dislocation density. Investigation by Dobatkin et al. [16] about the influence of ECAP route and strain on the oxygen free Cu properties revealed that the strength improves by a factor of 1.6 and remains virtually constant after the fifth pass for all the routes. The maximum YS and UTS values belong to the route B_C. Furthermore, the ductility decreases after the first pass and increases after the tenth pass,

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especially for the route B_C. Moreover, the minimum grain size and the maximum fraction of high angle grain boundaries are respectively related to the final pass of route B_C and route A which are equal to 230 nm and 77%. A new ECAP route with a rotation angle of 60 ° (B_{60}) in the same direction between the consecutive passes was proposed and experimented by Salimyanfard et al. [17]. The results implied that the grains are more equiaxed by route B_{60} while the microstructure consists of the elongated grains in route B_C. For route B_{60}, the texture is saturated after the fourth pass, whereas the saturation in route B_C takes place after the sixth pass. In addition, the tensile strengths reach their maximum magnitudes after the eight passes during the ECAP process with both routes. Also, the fracture surface morphology of the initial and ECAP samples is similar. The temperature effect on the mechanical behavior of ECAPed copper was performed by Tao et al. [18]. The results pointed out that the flow stress of UFG Cu expresses much larger sensitivity to testing temperature than that of coarse grained (CG) one which can be related to the activation volume decrease due to the grain refinement. However, the temperature sensitivity of UFG copper to the both true strain and strain hardening rate is comparatively lower than that of CG one. The study by Zheng et al. [19] on the tensile testing of the cast Mg-Zn-Y alloy processed by ECAP method up to the eight passes at the 523 and 623 K showed the enhanced ductility in the ECAP sample with the maximum elongations of about 200% and 600%, respectively. The grain size of the as-cast alloy is also reduced from 120 µm to 3.5 µm after the final pass. The feasibility of commercial purity titanium for the dental implants after the fourth pass ECAP process at the room temperature was evaluated using cyclic bending loads by Figueiredo et al. [20]. The results indicated that despite this process improves the fatigue life as well as the yield stress and the ultimate tensile strength, the fatigue behavior of grade 1 CP Ti is slightly less satisfactory than the commercial implants fabricated by higher grade titanium alloys. Corrosion study by Mostaed et al. [21] on the multi-pass ECAP process of ZK60 Mg alloy at the different temperatures revealed, an improved corrosion resistance of the UFG alloy in comparison with the extruded one causing a shift of corrosion regime from the localized pitting at the as-received sample to a more uniform corrosion mode with the reduced localized attack at the deformed alloy. The effect of ECAP process on the wear properties of eutectic Al-12Si alloy surveyed by Kucukomeroglu [22] showed that this process decreases the wear resistance of the alloy in spite of the improvement of the strength and ductility. This phenomenon is mainly attributed to the tribochemical reaction leading to the oxidative wear with the abrasive effect in the Al-Si alloy during sliding. The oxide layer plays a dominant role in determining the wear resistance of the sample before and after the process and it masks the effect of sample strengthening on the wear resistance. The report by Nagasekhar et al. [23] stated that although strength and hardness of pure gold are increased after the ECAP process up to the four passes, following passes do not have a sizeable effect on the enhancement. In addition, the main microstructure of pressed sample is low angle grain boundaries and shear bands up to the eighth pass and equiaxed grains with high angle grain boundaries are only achieved after the twelfth pass.

By regarding the previous works, there is no complete investigation on the mechanical and microstructural properties of pure copper with and without magnesium element processed by ECAP method and in fact, this paper has been motivated by this omission.

2. Experimental material and procedure

The used pure copper for this study was in two different compositions including oxygen-free high thermal conductivity copper (Cu-OFHC) and 0.1% magnesium addition (Cu-0.1%Mg) prepared at the ER-BAKIR™ company. Accordingly, all material compositions are the same except Mg element to compare the effect of the addition of 0.1% Mg to the pure copper. The chemical composition of the Cu-OFHC material which was carried out by the spark light emission spectrometer has been listed in Table 1 in accordance with the ASTM B49 (2008) after the surface grinding for removing any oxide, oil and residues. These samples were prepared with the cylindrical shape of a 20 mm diameter and 140 mm length. Furthermore, all samples were annealed at 660 °C for 3 h which was succeeded by the furnace cooling to obtain a fully annealed material before the ECAP operation.

Table 1
Chemical composition of OFHC copper in ppm.

Cu	S	Ag	Fe	Ni	Pb	Sb
Balance	8.3	6	5	1	0.6	0.5
Cu	As	Se	Te	Cd	P	Zn
Balance	0.5	0.4	0.4	0.3	0.2	0.2
Cu	Bi	Sn	Co	Cr	Mn	Si
Balance	0.1	0.1	0.1	0.1	0.1	0.1

The ECAP process was carried out at the ambient temperature by the punch velocity of 2 mm/s and a die with the channel angle and outer corner angle of 90° and 17°, respectively. By considering the imposed equivalent plastic strain magnitude of 1.0675 for a single pass through the mentioned die, the deformation process was accomplished up to the four passes corresponding to the maximum plastic strain magnitude of 4.27 via route B_C in which the sample is consecutively rotated by 90° in the same direction and also, by use of MoS_2 as a lubricant to lessen the frictional force between the sample and the die interface [6,7]. The UFG structure of the deformed Cu samples in both Cu-OFHC and Cu-0.1%Mg conditions were then exposed to the various experimental evaluations, including hardness measurement, tensile properties, impact test and microstructure observation to obtain the capability of the UFG structure compared to their coarse grain (CG) counterparts in both circumstances.

Vickers micro-hardness (HV) measurement was performed according to ASTM E92 on the cross-section of the Cu samples before and after the ECAP process up to the four passes with the force and dwell time of 300 g and 20 s, respectively. At least, fifty measurements were carried out for each pass for evaluation of hardness distribution. In addition, tensile testing samples with the gauge length of 3 mm and cross-sectional area of 2 mm×1.5 mm were prepared via wire cutting machine with their tensile axis perpendicular to the pressing direction as can be observed in Fig. 1. The Applied standard for tensile testing was ASTM E8. All samples have been pulled up to the failure by means of the Instron universal test machine with the constant rate of cross-

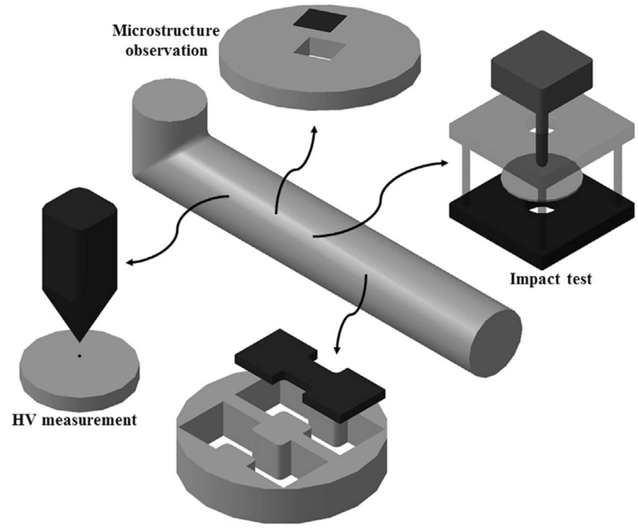

Fig. 1. Schematic representation of experimental tests on the ECAPed Cu-OFHC and Cu-0.1%Mg billets.