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Effect of Equal Channel Angular Pressing Process on Impact Property of Pure Copper

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Abstract**—**Ultrafine grained (UFG) and nanostructured (NS) materials have experienced a rapid development during the last decade and made profound impact on every field of materials science and engineering. The present work has been undertaken to develop ultrafine grained pure copper by severe plastic deformation method and to examine the impact property by different characterizing tools.

For this aim, equal channel angular pressing die with the channel angle, outer corner angle and channel diameter of 90°, 17° and 20mm had been designed and manufactured. Commercial pure copper billets were ECAPed up to four passes by route B_C at the ambient temperature. The results indicated that there is a great improvement at the hardness measurement, yield strength and ultimate tensile strength after ECAP process. It is found that the magnitudes of HV reach 136HV from 52HV after the final pass. Also, about 285% and 125% enhancement at the YS and UTS values have been obtained after the fourth pass as compared to the as-received conditions, respectively. On the other hand, the elongation to failure and impact energy have been reduced by imposing ECAP process and pass numbers. It is needed to say that about 56% reduction in the impact energy have been attained for the samples as contrasted to annealed specimens.

Keywords**—**SPD, ECAP, Pure Cu, Impact property.

I. Introduction

VARIOUS metals and alloys are desired to have enhanced mechanical properties for practical and industrial applications. One strategy of achieving this is techniques which are based on the mechanism of microstructural refinement by plastic deformation. The most important feature of these techniques is the ability for producing ultrafine grained (UFG) and even nanostructured (NS) materials. There are several size scales that all exhibit different amounts of strengthening based on grain size [1]. Fig. 1 shows the terminology that corresponds to different ranges of grain size for the microstructure of fine grained materials.

Severe plastic deformation (SPD) is an efficient method for producing ultra-fine grain (UFG) or nano-structure (NS) materials [2]. Number of SPD technique for fabrication of UFG or NS materials have been developed; these are: equal channel angular pressing (ECAP) [3], [4], cyclic extrusion compression (CEC) [5], high pressure torsion (HPT) [6], accumulative roll bounding (ARB) [7] and so on. It is generally accepted that NS materials have high mechanical and super-plasticity properties [8].

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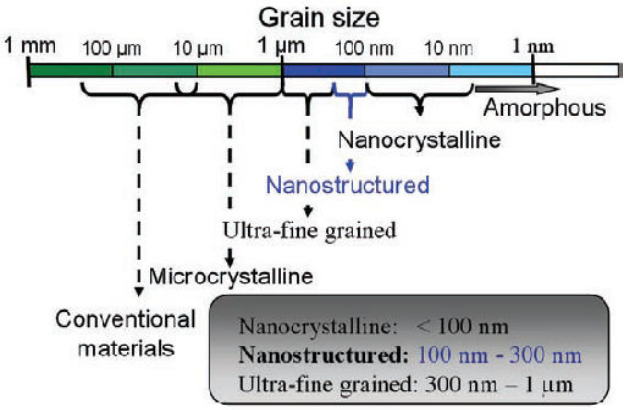

Fig. 1 The terminology and grain size ranges used to describe the microstructure of UFG and NS materials [1]

Among various SPD techniques, equal channel angular pressing is an especially attractive processing technique for several reasons. First, it can produce fairly large billets for a wide range of structural applications. Second, it is a relatively simple procedure as shown in Fig. 2, a sample is pressed through a die with two intersecting channels equal in the cross-section with a die channel angle of 90°. Third, reasonable homogeneity is attained through most of the ECAPed billets provided the pressings are continued to a sufficiently high strain. Forth, the process has the potential to be scaled up for use in commercial metal processing procedures [9]-[14].

Fig. 2 ECAP die set-up used in this research

There are four fundamental routes in the ECAP process as is shown in Fig. 3. These are: route A; the sample is repetitively pressed without any rotation, route B_A; the sample is rotated by 90◦ in alternative direction between each pass, route B_C; the sample is rotated in the same sense by 90◦ and route C; the sample is rotated by 180◦ between each pass [15]. These routes create different slip systems during the pressing

operation so that various microstructure and mechanical properties can be achieved [16], [17].

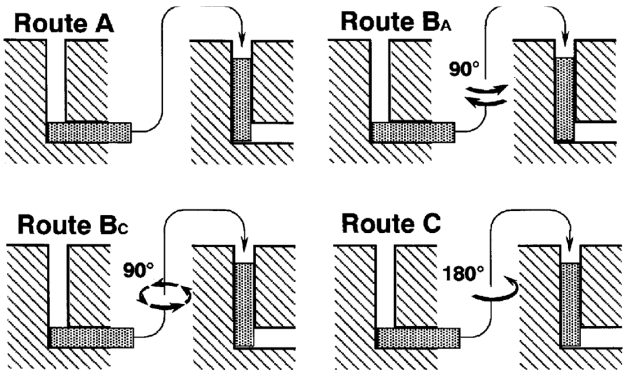

Fig. 3 Four fundamental processing routes during ECAP process [3]

In this research, ECAP die with the channel angle of 90°, outer corner angle of 17° and channel diameter of 20mm has been designed and manufactured. Then, commercial pure copper have been pressed up to four passes by route B_C. Afterwards, the effect of severe plastic deformation by equal channel angular pressing method has been investigated on the mechanical properties of deformed samples. Hardness measurement, tensile strength and impact test have been employed to evaluate mechanical properties of ECAPed specimens.

II. Experimental Procedure

ECAP die set up was designed and manufactured from three steel blocks assembled according to the drawing shown in Fig. 2 where also, a photo of the die can be seen. The die angles are: $\Psi = 17^\circ$ and $\Phi = 90^\circ$. The die material is H13 tool steel heat treated to hardness Rockwell C (HRC) of about 45. The ECAP operation caused flashing along the longitudinal axis of the billet. The flash was removed using a lath machine. Water coolant was used to reduce the heat induced during, because the temperature may cause the changes in the microstructure of the specimen. Four passes of ECAP process were done using route B_C to achieve roughly homogeneous structure. The Copper billets were prepared from extruded rod. After cutting, 30 billets possessing circular cross-sections with the nominal dimensions of 20mm × 140mm were ready to be pressed. Table I shows the different parameters of the ECAP deformation. Prior to operation, the pressing tool components and billets were lubricated in order to minimize friction during process. The copper billets were easily ECAPed at room temperature, because of the excellent ductility of materials with a punch speed of about 2mm/s.

Microhardness was measured in the samples before and after ECAP process using the Vickers scale. Vickers microhardness (HV) measurements were conducted using a Buehler Micromet II microhardness tester on the transverse, flow and the longitudinal planes. A load of 500g and a dwell time of 15s were used. Different samples were ground at 600 and 800 grits and followed by a rough polishing using a 3μm diamond paste. Tensile specimens were prepared with nominal dimensions of 100mm × 12mm in the gage section as can be seen in Fig. 4. The annealed and deformed samples were cut using a wire Electrical Discharge Machining. Two tensile tests were conducted for each ECAP passes and the average values were taken for discussions. Tension test was performed at room temperature using 250 tone servo-hydraulic MTS testing machine Fig. 5.

TABLE I
Conditions of ECAP Process

Lubricant	MoS_2
Ram speed (V)	2mm/sec
Temperature	Room temperature (25 ± 2°C)
Die channel angle	90°
Outer corner angle	17°
Channel diameter	20mm
Route	B_C

True stress σ and true strain (ε) are calculated from their corresponding engineering strain (e) and engineering stress S values according to the following equations.

$$\sigma = F/A \quad (1)$$

$$S = F/A_0 \quad (2)$$

$$\sigma = S(1+e) \quad (3)$$

$$\varepsilon = Ln(1+e) \quad (4)$$

where A and A_0 are respectively the instantaneous and initial cross-sections of the tension specimens. These relationships are valid only up to σ_{UTS} where necking occurs. Charpy impact tests were performed according to ASTM E23. The samples dimensions were 55mm×10mm×2mm; see Fig. 4. The long axis of the impact sample is parallel to the pressing direction. A 45° groove was machined on the longitudinal plane in the middle of the sample with a depth of 2mm and a radius of 0.25mm at the root. The tests were performed on an impact tester with maximum impact energy of 450J and an accuracy of ±1J, See Fig. 6. Each impact experiment was also repeated on three subsequent samples.

III. Results and Discussions

The ultimate aim of the present research is to improve the mechanical properties of commercial pure copper. For this reason, ultrafine grained Cu was fabricated using a technique known as equal channel angular pressing process. Subsequently, mechanical tests have been carried out and the obtained results have been investigated here one by one.

A. Hardness Evaluations

The variations of average Vickers micro hardness (HV) versus the number of ECAP passes up to 4 using route BC have been listed in Table II. As can be observed, the HV magnitudes of pure Cu is 53 HV before ECAP process. Applying severe plastic deformation technique known as equal

channel angular pressing on the as-received billets leads to significant improvements at the HV values. It is found that about 162% enhancements after the fourth pass have been achieved for Cu specimens as compared to the annealed condition. It can be seen that there is a sharp increase in hardness values after the first pass for the sample; see Fig. 7. In addition, it can be said that the increase in hardness magnitude diminishes with the number of passes. These increases at the HV magnitudes by imposing ECAP process after the first pass are considered to be caused by the formation of the ultrafine grained structure and increase in the dislocation density as mentioned above. Furthermore, HV values of the specimen have been slightly increased by adding pass number due to the saturation of the strengthening.

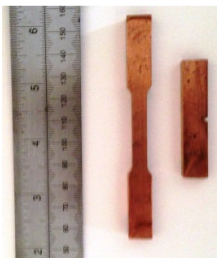

Fig. 4 Tensile and impact test specimens

Fig. 5 Commercial pure copper sample during tensile test

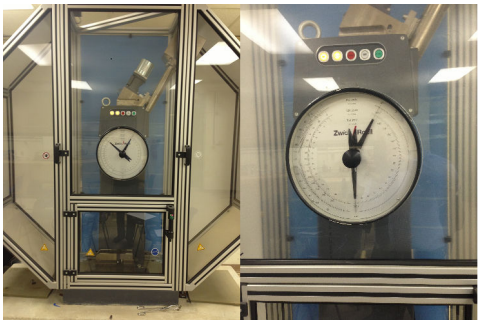

Fig. 6 Impact test machine using in this research

TABLE II
HV MAGNITUDE OF COMMERCIAL PURE COPPER SAMPLES BEFORE AND AFTER ECAP PROCESS UP TO FOUR PASSES BY ROUTE BC

Pass number				
0	**1**	**2**	**3**	**4**
53	111	119	127	138

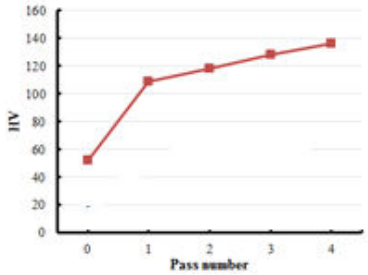

Fig. 7 Hardness measurements versus ECAP pass number for Cu billets

B. Tensile Evaluations

Tensile tests were carried out at room temperature on the samples before and after ECAP process up to four passes in a direction parallel to the pressing one. Generally, it can be found that the as-received samples have a more ductile behavior when compared with ECAP processed samples and the strengths of the samples are observed to be increased with ECAP process. Table III lists the yield strength, ultimate tensile strength and elongation to failure of commercial pure aluminum and copper before and after ECAP operations up to four passes by route B_C. Yield strength of the as-received pure copper sample is increased by about 162% from 112MPa to 292MPa in the first ECAP process and increased by about 285% to 427MPa after the fourth pass as seen in Table III. It can be seen that the both yield and ultimate strengths remain constant at the third and fourth passes. Ultimate tensile strengths show similar behaviors with yield strength but have lower increasing rates. As can be calculated, about (154% & 125%) increments have been achieved after the first and fourth passes as compared to the annealed condition. Finally, it can be concluded that these results are consistent with HV test results in terms of the changes in mechanical behaviors. Similar to hardness results, the reason of this behavior is caused from the decrease in the grain size due to the formation of the ultrafine grained structure and increase in the dislocation density. These results are also consistent with literature results [18]-[21].

Ductility of the metals is known to be decreased with plastic deformation but ductility of severely deformed materials decreases much less when compared with conventional materials. Results obtained by this study shows that the ductility values of the samples are decreased by imposing ECAP passes with inversely proportional by strength values. As can be seen, the decrease in elongation is very large after the first pass; however, there is not much difference in elongation with further ECAP operation; see Fig. 8. This indicates a pronounced loss of formability after the first pass of ECAP process.

C. Impact Evaluations

For impact testing, samples were cut from longitudinal (pressing) direction. The in-plane specimen dimensions are 10mm × 55mm with a 2mm deep, 45° V notch having a 0.25 mm tip radius at the center of the specimen which is prepared according to the ASTM E23. Fig. 9 shows the impact energy as a function of the number of ECAP passes. It is observed that the impact energy of the annealed samples decreases by adding pass numbers. Impact energy of starting bulk annealed sample is about 65J. The first pass is about 49J which is 25% less than the annealed condition. After four passes, the impact energy is 28.5J which is 56% less than that of the un-ECAPed state.

TABLE III
MECHANICAL PROPERTIES OF COMMERCIAL PURE COPPER SAMPLES BEFORE AND AFTER ECAP PROCESS UP TO FOUR PASSES BY ROUTE B_C

Property	Pass number				
	Pass 0	Pass 1	Pass 2	Pass 3	Pass 4
σ_{yp} (MPa)	112	292	358	399	428
σ_{UTS} (MPa)	216	397	418	453	483
El(%)	28	19	18	18	17

IV. CONCLUSIONS

In this work, equal channel angular pressing die set-up with the channel angle of 90°, outer corner angle of 17° and channel diameter of 20mm was designed and manufactured. Then, commercial pure copper had been pressed up to four passes by route B_C. Afterwards, microstructural and mechanical tests had been carried out to investigate the effects of ECAP process on the grain size, tensile properties, hardness measurements and impact energy of specimens. The following conclusions can be drawn.

It was observed that the mechanical properties of ECAPed samples were enhanced in terms of Vickers microhardness, yield strength and UTS due to the formation of the ultrafine grained structure and increasing of the dislocation density. The HV records showed that hardness value have been increased by about 161%, after the fourth ECAP passes as compared to the annealed state. In addition, about 285% enhancement in yield strength have been achieved after the final pass compared with the as-received conditions. Also, it is found that despite these huge increases in the yield strength, ultimate tensile strength has lower increase than the un-ECAPed specimens. There is about 125% increasing at the UTS value is obtained. Furthermore, it was observed that the highest increase at the mechanical properties is occurred after the first ECAP process. On the other hand, the impact test results indicated that the impact energy decreased by adding pass number. About 56% reductions at the impact energy value have been obtained by imposing four passes of ECAP process as compared to the annealed condition.

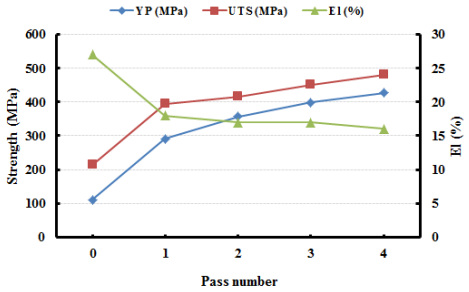

Fig. 8 Trend of yield strength, ultimate tensile strength and elongation to failure changes during ECAP process

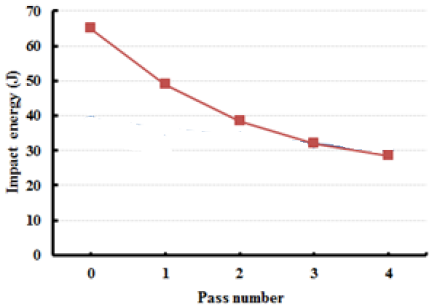

Fig. 9 Impact energy of commercial pure Cu before and after ECAP process up to four passes

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