

Experimental Study on Mechanical Properties of Commercially Pure Copper Processed by Severe Plastic Deformation Technique-Equal Channel Angular Extrusion

Krishnaiah Arkanti, Ramulu Malothu

Abstract—The experiments have been conducted to study the mechanical properties of commercially pure copper processing at room temperature by severe plastic deformation using equal channel angular extrusion (ECAE) through a die of 90° angle up to 3 passes by route B_c i.e. rotating the sample in the same direction by 90° after each pass. ECAE is used to produce from existing coarse grains to ultra-fine, equiaxed grains structure with high angle grain boundaries in submicron level by introducing a large amount of shear strain in the presence of hydrostatic pressure into the material without changing billet shape or dimension. Mechanical testing plays an important role in evaluating fundamental properties of engineering materials as well as in developing new materials and in controlling the quality of materials for use in design and construction. Yield stress, ultimate tensile stress and ductility are structure sensitive properties and vary with the structure of the material. Microhardness and tensile tests were carried out to evaluate the hardness, strength and ductility of the ECAE processed materials. The results reveal that the strength and hardness of commercially pure copper samples improved significantly without losing much ductility after each pass.

Keywords—Equal Channel Angular Extrusion, Severe Plastic Deformation, Copper, Mechanical Properties.

I. INTRODUCTION

THIS over the last two decades a number of secondary processing methods have emerged, with the primary objective of refining the microstructure to characteristic length scales near or below 1 μm. An important breakthrough in modern materials science was the application of severe plastic deformation (SPD) techniques for producing ultrafine-grained (UFG) structures with an average grain size in the submicron range and improvement of physical and mechanical properties of materials with high strength and high ductility [1]-[3]. Equal-channel angular extrusion (ECAE) is at present one of the most promising techniques that can process UFG materials large enough for industrial applications [4]-[6].

The immediate and future requirements of industrial applications can be light metals with high strength and high

ductility. Despite the fact that copper being a good conductor, corrosion resistant and antibacterial still the industrial use of copper and its alloys are topical. The strength and ductility of materials which determine virtually all facets of its mechanical response are primarily controlled by microstructure, of which the grain size and second phase distribution are important parameters. These in turn are dependent on the processing methods used for the fabrication of these metals and alloys [7]-[14]. A typical schematic diagram of the ECAE process is shown in Fig. 1. Due to the geometric constraints of the die, the workpiece deforms in shear within a small area at the intersection between the two channels.

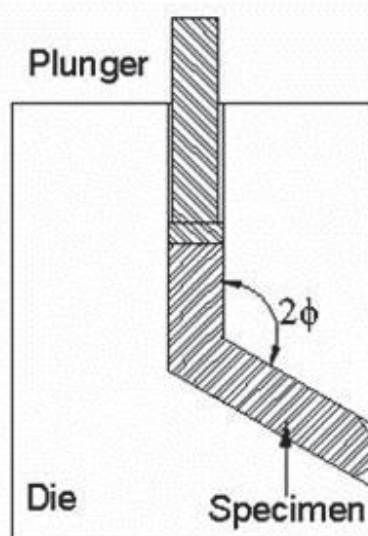


Fig. 1 A schematic diagram of the ECAE Process

Presently, ECAE is one of the well-designed processes for rods and bars to refine the microstructure of various metals and alloys in the modern era. In which very large strains can be imparted onto metal billets by simple shear. The simple shear occurs as the sample passes through the section of an angular die where the entry and the exit channels meet. Since the overall dimension of the billet remains unchanged in this process, the billet can be pressed repeatedly, so that exceptionally high cumulative strains can be achieved. The microstructural development of ECAE is affected by different

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parameters like strain imposed, number of passes and processing routes.

The magnitude of shear strain [15] after one pass of ECAE in the frictionless condition is determined with

$$\gamma = \left[2 \cot \left(\frac{\phi}{2} + \frac{\psi}{2} \right) + \psi \operatorname{cosec} \left(\frac{\phi}{2} + \frac{\psi}{2} \right) \right] \quad (1)$$

Shan et al. [16] reported that there was 15% of the total area found non-uniform deformation occurring in the vicinity of the lower surface of the billet where the material passed through the outer corner of the die.

Increasing the number of passes lead to decrease the grain size and the effect of number of passes on mechanical properties was studied [17]-[21] and observed that the strength of the materials increases abruptly and a massive reduction of grain size occurs at the initial pass and as the number of passes increases, the grains are substantially refined up to the submicron or even nanometer ranges [22] and the sub grains formed with low angles of misorientations subsequently evolve into high angle grain boundaries.

Also, the magnitude of equivalent effective plastic strain (ϵ_{eq}) after N passes is given by the following relationship [15]:

$$\epsilon_{eq} = \frac{N}{\sqrt{3}} \left[2 \cot \left(\frac{\phi}{2} + \frac{\psi}{2} \right) + \psi \operatorname{cosec} \left(\frac{\phi}{2} + \frac{\psi}{2} \right) \right] \quad (2)$$

where, ϕ is the angle of intersection and ψ is the angle of curvature. This is derived for ideal conditions of pressing. In reality, several factors should be taken into account such as the friction in the channel walls, flow localization, material properties etc.

The processing route of ECAE significantly affects effectiveness of grain refinement and grain shape. In the ECAE process, orientation of the sample can be changed from pass to pass in order to develop an ideal ultrafine-grained (UFG) microstructure for high strength and high ductility should have short dislocation-slip path to impede dislocation slip and very low dislocation density to ensure more room for dislocation accumulation [24]. There are four fundamental routes between each repetitive pressing. These are: route A by which the sample is repetitively pressed without any rotation, route B_A by which the sample is rotated by 90° in the alternative direction between each pass, route B_C by which the sample is rotated in the same direction by 90° and route C by which the sample is rotated by 180° between consecutive passes. These routes result in different slip systems in the specimen and so, various microstructures and mechanical properties can be obtained by them.

Iwahashi et al. [25], [26] processed pure Al with ECAE routes A, B_C and C using a die channel angle of 90° and concluded that route B_C is most effective and route A is least effective in grain refinement.

Since the last decade, many theoretical as well as experimental studies have been performed on ECAE to understand the influence of processing conditions and processing routes on the aspects of microstructure, texture and

mechanical properties. The purpose of the present work is to provide a detailed analysis of the changes in strength and ductility of commercially pure copper billets processing at room temperature using ECAE.

II. EXPERIMENTAL PROCEDURES

Commercially pure copper rods are used in the present study. Due to its good electrical and thermal conductivity, workability, antibacterial, corrosion resistance, and strength this material was selected. The chemical composition of the Cu as per ASM standard composition specifications is 99.9% Copper, 0.08% Silver and 0.02% Oxygen. The bar of 20 mm diameter and 600 mm length is made cut into billets with dimension of 20 mm in diameter and 120 mm in length using abrasive cutting machine. Before processing through ECAE, the specimens were annealed at 700°C for about 2 hrs in a muffle furnace thereby metal becomes softer and can be deformed more easily. The annealed specimens were machined with dimension of 19.3 mm in diameter and 120 mm in length using lathe machine in the presence of coolant (mixture of water and coolant oil) to get good surface finish. A 35° taper was also given at one end of the specimen to facilitate the easy start of ECAE.

A 100 ton hydraulic press, a split die of 19.5 mm diameter made of SKD61 with an internal angle of (ϕ) 90° between the vertical and horizontal channels and outer curvature angle of (ψ) 0° and molybdenum disulphide (MoS₂) as the lubricant used for conducting ECAE. A split die with two splits to facilitate not only easy removal of specimen but also the safety of the operator and three split punches enable to prevent buckling of the punch. Extrusions were carried out at room temperature. For this die configuration, the effective strain achieved on a single pass is 1.1547 [15].

Before inserting the billet into the die assembly, lubricant MoS₂ is applied to the die cavity as well as the billet. The process of ECAE is started only after ensuring the assembly is properly done and dies are aligned correctly. Punch is accurately positioned above the billet and then gradually applied load with the hydraulic press. A repetitive pressing of the same billet was attempted by using B_C route [23] for all three passes. After each pass, the billet was machined to the diameter of 19.3mm and used for the next pass consequently. Microhardness and tensile tests were carried out to evaluate the strength and ductility of the ECAE processed specimens of each pass.

Tensile testing is the most common type of test used to measure the mechanical properties of a material and it is widely used to provide basic design information on the strength of materials and is an acceptance test for the specification of materials. Ductility is the degree of plastic deformation that material can withstand before fracture. The major parameters that describe the stress-strain curve obtained during the tension test are the Ultimate Tensile Strength (UTS), Yield Strength (YS) and Ductility can be expressed either in terms of percent elongation or percent reduction in area.

Tensile testing was carried out on a 50kN DAK, universal testing machine (UTM). In order to conduct this test, the specimens were prepared for gripping into the jaws of the testing machine. The specimen used is approximately uniform over a gauge length (the length within which elongation measurements are done). Three specimens were prepared for each pass.

The equipment used for hardness testing was Vickers micro-hardness tester. The load applied was 300g for a period of 15 sec. Samples from the solution zed billet and samples after each ECAP pass were cut by silicon carbide abrasive cutting wheel and polished by metallographic sample preparation procedure using 1/0, 2/0, 3/0 and 4/0 emery papers and then polished on an alumina powder rotating disc. The samples are also polished using diamond paste to obtain fine mirror finished surface. The polished samples were kept on the Vickers microhardness tester. The hardness values are measured along the transverse section. The samples are to be checked, so that the surface opposite to the surface being measured is exactly parallel to the former one. This ensures the machine's safety as well as accuracy of the readings. The values obtained are noted down for each sample.

III. RESULTS AND DISCUSSION

The main objective of the present study is to understand the changes in strength, hardness and ductility of commercial pure copper. For this reason, ultrafine grained Cu was produced using a severe plastic deformation using equal channel angular extrusion process. Successively, mechanical tests have been carried out and the obtained results have been examined here one by one.

A. Microhardness

The variations of Vickers microhardness (HV) in transverse section of commercially pure copper is presented in Fig. 2. The average values of each samples as a function of the number of ECAE passes up to 3 passes using route B_C.

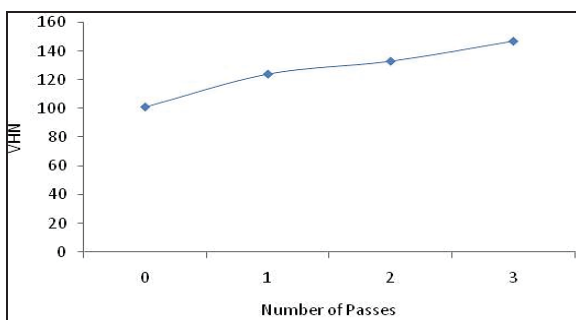


Fig. 2 Vickers hardness variations with number of passes

It is seen that briefly a high value of hardness will be achieved by ECAE processing. As can be observed, the HV magnitude of commercially pure copper is 101 HV before ECAE process. It is found that about 146% enhancements after the third pass have been achieved for Cu specimens as compared to the annealed condition. It is observed that there is a sharp increase in hardness values after the first pass for the

sample. In addition, it is found from the results that the increase in hardness magnitude diminishes with the number of passes. These increases at the HV magnitudes by imposing ECAE process after the first pass are considered to be caused by the formation of the ultrafine, equiaxed grained structure with high angle grain boundaries 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. After three passes, the hardness reaches the maximum value (147).

B. Tensile Behaviour

Tensile tests have been conducted at room temperature on the commercially pure copper billets before and after ECAE process up to three passes in a direction parallel to the pressing. Generally, it can be found that the annealed billets have a more ductile behaviour when compared with ECAE processed billets and the strengths of the billets are observed to be increased with ECAE pressings. Table I lists the yield strength, ultimate tensile strength and elongation to failure of commercial pure copper before and after ECAE operations processed up to two passes by route B_C.

TABLE I
TENSILE STRENGTH PARAMETERS OF COPPER

Strength	Annealed	Pass one	Pass two
Yield Strength (MPa)	145	262	300
UTS (MPa)	251	344.5	393
Elongation (%)	44	19	18

Fig. 3 shows the average values of true stress–strain curves obtained from the tensile tests of samples subjected to 1–3 passes. For comparison, the flow stress–strain curve of an annealed (Zero Pass) Cu specimen is also plotted.

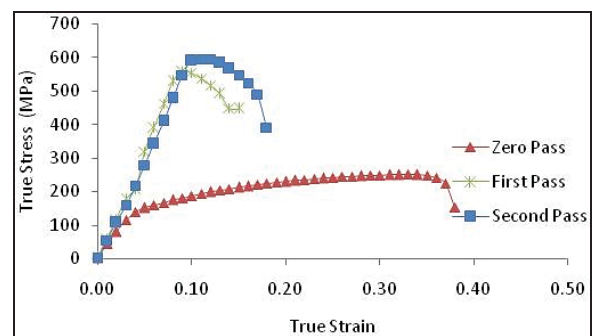


Fig. 3 True stress Vs True strain of Cu specimens

Fig. 4 shows the tensile and yield strength results of Cu as a function of the ECAE pass numbers. These results show that: (i) a high value of yield strength is obtained by ECAE process; (ii) the yield strength of the material varies in a similar trend like hardness as a function of ECAE pass numbers; (iii) the rate of strain hardening of ECAE processed material is very low as compared to annealed material. Yield strength of the annealed pure copper billet is increased from 145MPa to 262.3MPa in the first ECAE process and after second pass it was reached to 300MPa as seen in Table I.

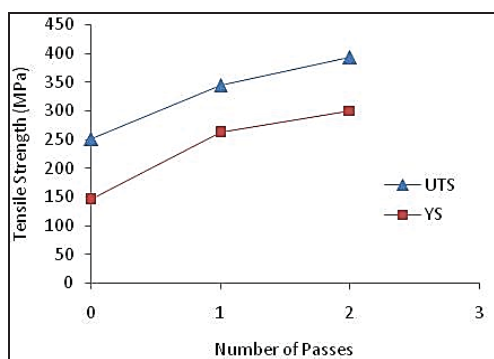


Fig. 4 Tensile properties of Cu with number of passes

The tensile strengths show similar behaviour with yield strength but have lower increasing rates. The ultimate tensile strength results are also plotted in Fig. 4 as a function of the ECAE pass numbers. These results show that: (i) a high value of UTS is obtained by ECAE process; (ii) the ultimate tensile strength of the material varies in a similar trend like hardness as a function of ECAE pass numbers; and (iii) the rate of strain hardening of ECAE processed material is very low as compared to the annealed material. The tensile strength is increased from 251MPa to 344.5MPa in the first ECAE pass and after second pass it was reached to 392.53MPa as seen in Table I.

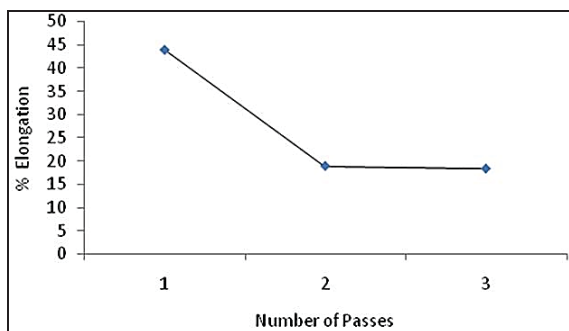


Fig. 5 Percent elongation of Cu with number of passes

Finally, it can be concluded that these results are consistent with HV test results in terms of the changes in mechanical behavior. Similar to hardness results, the reason of this behaviour is caused from the decrease in the grain size due to the formation of the ultrafine, equiaxed grained structure with high angle grain boundaries and increase in the dislocation density. Ductility of the metals is known to be decreased with plastic deformation but ductility of ultra-fine grained materials decreases much less when compared with conventional materials. Results obtained by this present study shows that the ductility values of the billets are decreased by imposing ECAE passes with inversely proportional by strength values. The % of elongation (ductility) results is plotted in Fig. 5 as a function of the ECAE pass numbers.

IV. CONCLUSIONS

Commercially pure copper billets have been pressed at room temperature through ECAE up to 3 passes by route B_C in the present study. The changes in the tensile properties and micro hardness were investigated. From this study, the following conclusions can be drawn.

1. The tensile strength and the yield strength of the material have been increased significantly after first and second passes of ECAE. UTS is increased from 251 MPa to 344.5MPa in the first pass and then to 392.53MPa in the second pass. YS is increased from 144.58 MPa to 262.3MPa in the first pass and then to 300MPa in the second pass.
2. There is a significant reduction in percentage of elongation after the first pass of ECAE (43.7 to 18.99), but lesser reduction in percentage of elongation after the second (18.42).
3. The micro hardness of the material has been increased significantly after first pass of ECAP in transverse (101 VHN to 124 VHN) section.
4. Almost there is a constant increase in micro hardness after the second and third passes of ECAP in the transverse section.

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