Microstructure and Mechanical Properties of Ultra-fine Grained Copper Processed by Equal Channel Angular Pressing Technique

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***Abstract*— The equal channel angular pressing (ECAP) technique is now recognised for achieving very significant grain refinement of ultra-fine grained materials which, at present produce unique mechanical properties. This study reports the results of the tensile tests and the microstructural analysis carried out on the specimens of ultra-fine grained (UFG) copper processed by ECAP technique at room temperature using a die with a 126° between the die channels. The copper samples used in this work were subjected to six and twelve passes during the ECAP processing. Tensile tests were conducted for samples cut out in two different directions; in the parallel and perpendicular direction at room temperature to evaluate the mechanical properties after the ECAP at these two directions. The microstructural characterization was carried out using optical electron microscope (OEM) and scanning electronic microscope (SEM). The results show ECAP technique introducing significant grain refinement and produced ultrafine grains in copper and there is a potential for achieving high ductility in the copper alloy after processing. The tested sample is characterized by significant differences of strength properties depending on the direction.**

***Keywords*— ECAP, copper, tensile properties, severe plastic deformation, ultra-fine grained, microstructure.**

I. INTRODUCTION

The manufacturing and processing of ultra-fine grained (UFG) and nanocrystalline materials have attracted growing scientific and industrial interests in the last decade as a result of the novel and attractive properties of these materials [1]. These materials have mechanical properties that include extraordinarily high yield strength, high hardness, improved toughness and ductility with increasing strain rate [1, 2, 3, 4]. They have also been found to exhibit marked different microstructures and mechanical behaviours from their conventional coarse grained polycrystalline counterparts, thus UFG materials have enhanced super-plasticity deformation at low and high strain rate [3]. Equal channel angular pressing (ECAP) is a processing technique in which an intense plastic strain is imposed on a polycrystalline sample by pressing the sample through a special die in other to produce large fully dense samples containing an ultrafine grain size in the sub-micrometre or nanometre range [5, 6] . The idea of ECAP was the results of the early works of Segal and co-workers which showed the technique of pressing test samples through a die containing two channels, equal in cross section, intersecting at an angle of ϕ. [7, 8, 9, 10]. As a result of the pressing, the sample underwent simple shear but it retained the same cross-sectional area so that it was possible to repeat the pressings for several cycles [11]. To accumulate very large strains, a sample can be forced to pass through the die several times and the strain path can be easily changed by turning the sample around its longitudinal axis between subsequent passes. Four standard routes are often used and they are A, BA, BC, and C [12, 13, 14] . A sample is rotated around its axis to an angle of 0°, 90°, and 180° for the routes A, B, and C, respectively. When using route BA, consecutive 90° rotations have opposite senses, while in route BC the sample is rotated in the same direction. ECAP is currently being widely investigated because of its potential to produce ultrafine grained microstructures in both pure metals and alloys.

The materials processed by ECAP also have the advantage of formation of an UFG structure with mainly high-angle grain boundaries, the absence of macroscopic damages and cracks in the samples, Microstructural homogeneity in the most volume of the samples, and formation of equiaxed grains. The aim of this study is to investigate the tensile properties and formation of structures results in copper produced by ECAP using six and twelve passes. The copper sample employed in this work was subjected to tensile test in perpendicular and parallel directions to obtain information on the mechanical properties of UFG produced by this technique.

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II MATERIALS AND METHODS

A sample of copper alloy obtained as extruded rods was used as starting materials in this study. This material was selected due to its good electrical and thermal conductivity, workability, corrosion resistance, and strength .The copper alloy also shows significant strain hardening, strain rate sensitivity and temperature dependence of plastic flow behaviour. The composition of the copper alloy used for the experiment is shown in Table 1. The ECAP die was constructed using K510 silver quenched and tempered steel. The die was a relatively simple design. It was machined as a two-piece split die, consisting of a highly polished smooth plate bolted to a second polished plate. The angle between the channels is 126o and the external curvature is 0o. The channel section is 14.5 mm in diameter. The die used has the same inlet and outlet channels with nearly identical dimensions. Since the cross-sectional dimensions of the sample remain unchanged on passage through the die, repetitive pressings was used to attain very high strains [15, 16]. The specimens were deformed by passes through the die using routes Bc. Route Bc (samples rotation 1800 after each pass) was chosen because of its tendency to develop a substructure after fewer ECAP passes than the other routes [7] [6, 17, 18]. Six and twelve passes of deformation were carried out at room temperature, with Molybdenum disulfide (MoS2) used as lubricant in 63 tons pressing machine. The material was easily deformed at room temperature, because of its excellent ductility. Each specimen was removed from the die by pressing the next specimen into the die and final specimen inside the die was removed using a dummy specimen which then remains within the die. For the tensile tests, the samples were cut in two directions parallel and perpendicular to the ECAP axis with gauge lengths of 3.75mm and gauge diameter and thickness of 0.74 and 0.60 mm, respectively for tensile testing using an Instron testing machine with tensile velocity 0.00375 mm/s .The microstructures of the UFG and coarse-grained samples were investigated prior to and after the ECAP tests using optical electron microscopy (OEM) and scanning electron microscopy (SEM) was used in this study for measuring grain size, and to examine the crack morphology of ECAP materials to relate the fracture features to the microstructure and mechanical properties.

TABLE I
CHEMICAL COMPOSITION OF COPPER ALLOY USED

Elements	Wt %
Cu	90.77
P	0.61
Sn	1.20
Ti	0.30
Cr	0.49
Mn	0.57
Fe	0.77
Si	0.08

III RESULTS AND DISCUSSION

The stress – strain curves of as-received, six passes, and twelve passes of tensile copper samples tested in parallel direction are shown in Figure 1, while the stress – strain curves of the tensile samples tests in perpendicular directions are shown in Figure 2. From the figures the mechanical strength increases with increasing deformation, the strength is higher in the material subjected to ECAP technique compared to as received samples both in two directions. The specimens subject to six passes have a better strength than the specimen subject under twelve passes. The same results were obtained when the tensile properties were measured in perpendicular direction

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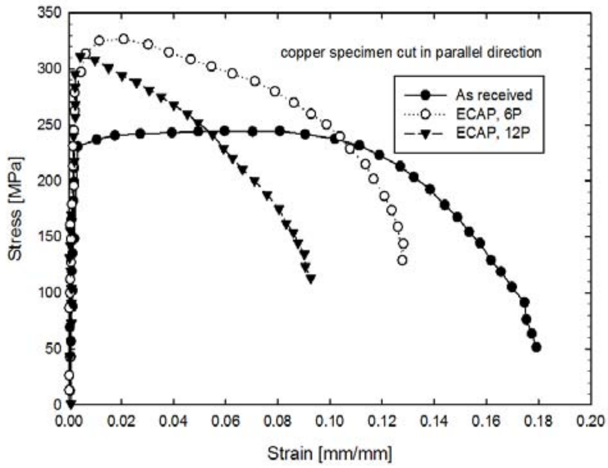

Figure 1: Stress-strain curves for the copper alloy samples cut in parallel direction

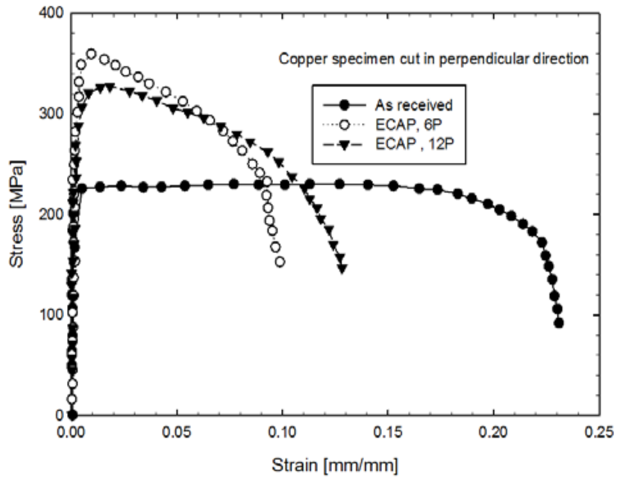

Figure 2: Stress-strain curves for the copper alloy samples cut in perpendicular direction

For the copper specimen processed at six passes, the tensile strength measured in perpendicular direction has an improved strength than in parallel direction as shown in Figure 3, the same observation is visible for the samples processed at twelve passes shown in Figure 4.
Based on the obtained results, one can conclude that the tested samples are characterized by significant differences of strength properties depending on the direction. Samples taken in parallel direction are characterized by clear yield and better mechanical strength related properties than samples taken at perpendicular direction.

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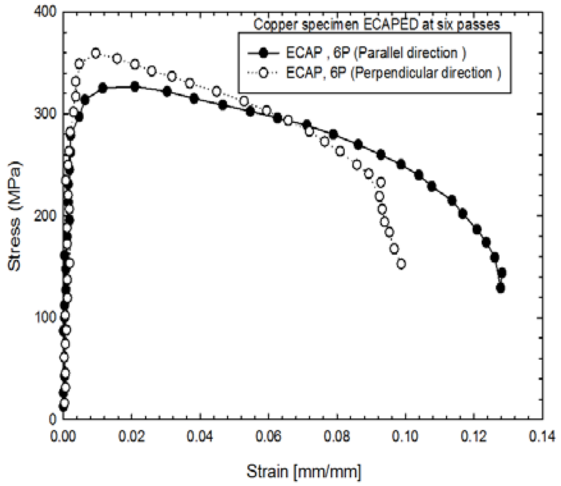

Figure 3: Stress-strain curve for the copper alloy specimen at six passes and cut in parallel and perpendicular directions

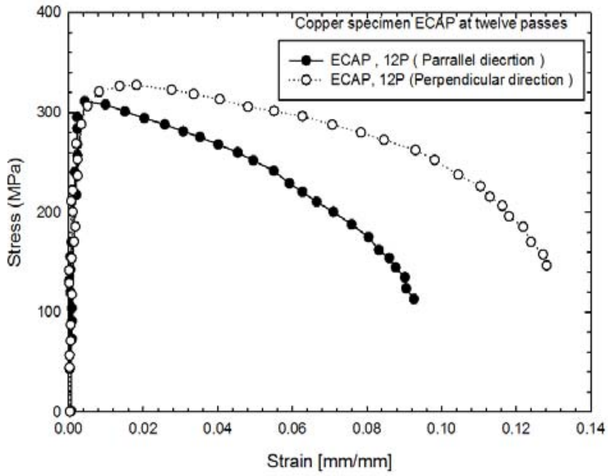

Figure 4: Stress-strain curve for the copper alloy specimen at twelve passes and cut in parallel and perpendicular directions.

Figure 5a shows the Optical microscope image of the as-received copper. While the Optical microscope image of the material copper alloy subjected to ECAP technique at six passes and twelve passes respectively are shown in figure 5b and 5c respectively. The microstructure of copper after processed is greatly reduced and presents relatively homogeneous grain size compare with the as received copper. The copper processed after six passes have the average grain size of about 0.75μm and the copper processed after twelve passes have the average grain size of about 0.34μm. The homogeneous microstructure and grain size refining are due to deformation process.

Figure 6c shows the fracture surfaces of copper when processed. A mixed morphology of shallow dimples and tearing ridges were formed on fracture surface. the size and depth of the dimple of the material depend on plastic deformation capability, and the better the plastic deformation ability of the metal, the more prone the necking is and the greater the size of the micropores.

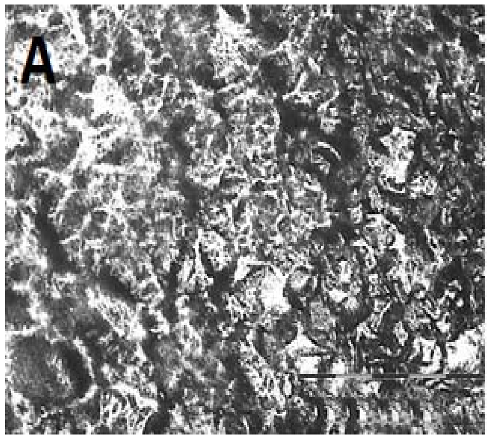

Figure 5A: Optical microscope images of as-received copper

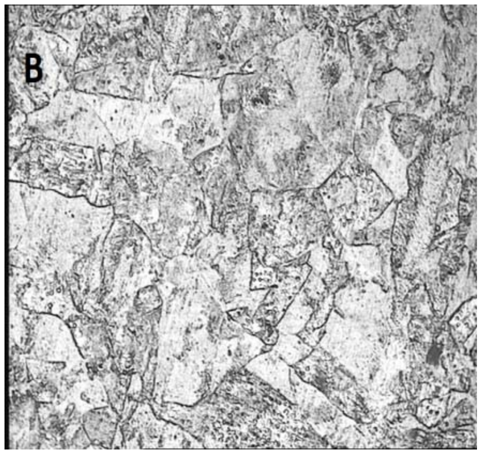

Figure 5B**:** Optical microscope images of the ECAP copper obtained at 6 passes

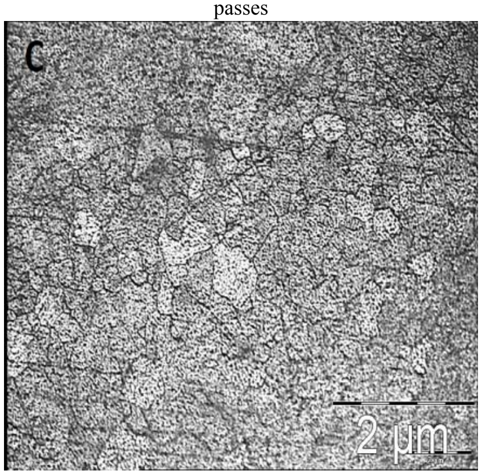

Figure 5C**:** Optical microscope images of the ECAP copper obtained at 12 passes

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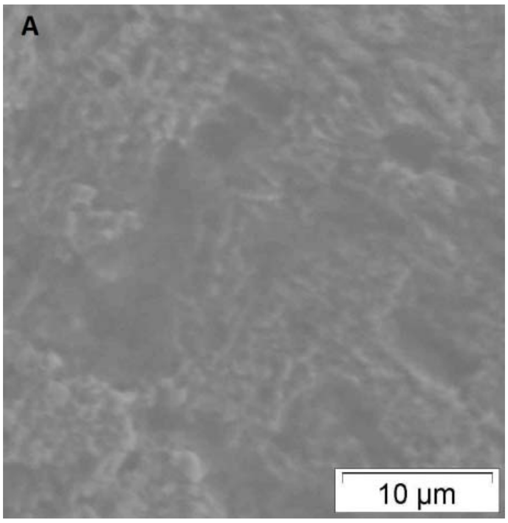

Figure 6a: SEM image of the ECAP copper obtained at six passes

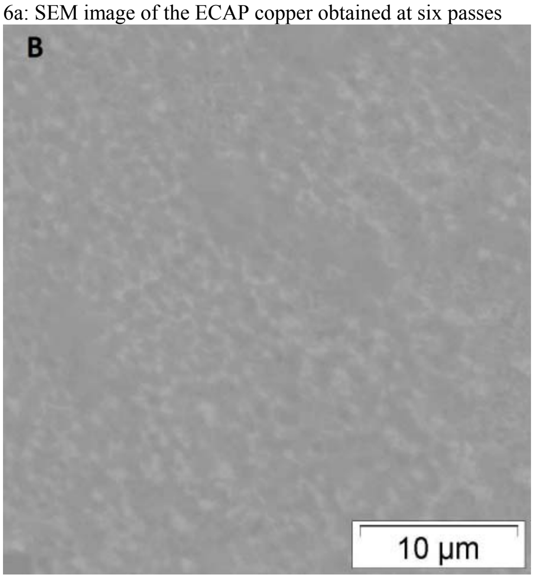

Figure 6b: SEM image of the ECAP copper obtained at twelve passes

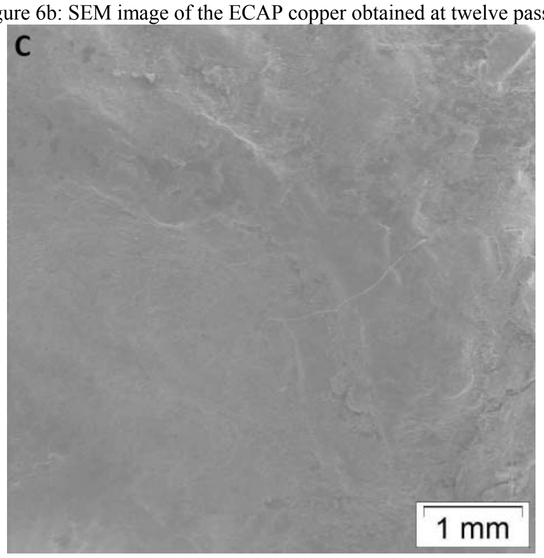

Figure 6C**:** SEM image of Fracture surface of processed UFG copper

IV CONCLUSION

In summary, copper alloy was satisfactorily processed by ECAP technique at room temperature using Bc route and the following conclusions were obtained.

1. Processing by ECAP technique introducing significant grain refinement and produced ultrafine grains in copper.

2. The microstructure of copper after processed is greatly reduced and presents relatively homogeneous grain size compare with the as received copper.

3. These processed copper samples exhibited improved mechanical properties.

4. The tested samples are characterized by significant differences of strength properties depending on the direction.

5. A mixed morphology of shallow dimples and tearing ridges were formed on fracture surface of the sample due to plastic deformation capability.

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REFERENCES

[1] H. Gleiter, “Nanostructured materials: Basic concepts and microstructure.,” Acta Materials, pp. 48-29, 2001.
[2] R. Valiev, “Paradoxes of severe plastic deformation.,” Adv Eng Mater., vol. 5, no. 5, p. 296–300, 2003.
[3] K. Kumar, H. Swygenhoven and S. Suresh, “Mechanical behaviour of nanocrystalline metals and alloys.,” Acta Mater., vol. 51, p. 5743–5774, 2003.
[4] T. Langdon, “Processing by severe plastic deformation: Historical developments and current impact.,” Materials Science Forum, vol. 9, no. 4, p. 667– 669, 2011.
[5] V. Segal, V. Reznikov, A. Drobyshevskiy and V. Kopylov, “Metally,” Russian Metallurgy, vol. 1, no. 115, p. 99, 1981.
[6] Y. Iwahashi, Z. Horita, M. Nemoto and T. G. Langdon, “The process of grain refinement in equal-channel angular pressing,” Acta mater, vol. 46, no. 9, pp. 3317-3331, 1998.
[7] R. Valiev and T. Langdon, “Development in used of ECAP Processing for grain refinement,” Review of advance Materials Science, vol. 13, pp. 15-26, 2006.
[8] V. Segal, “Equal channel angular extrusion: from macromechanics to structure formation,” Materials Science and Engineering, vol. A 271, p. 322–333, 1999.
[9] S. Semiatin and D. DeLo, “Equal channel angular extrusion of difficult-to-work alloys,” Materials and Design, vol. 21, p. 311–322, 2000.
[10] L. Kommel, I. Hussainova and O. Volobueva, “Microstructure and properties development of Copper during severe plastic deformation,” Materials and Design, vol. 28 , p. 2121–2128, 2007.
[11] Y. Iwahashi, J. Wang, Z. Horita, M. Nemoto and T. G. Langdon, “Principle of equal-channel angular pressing for the processing of ultra-fine grained materials,” Scripta Materialia, vol. 35, no. 2, pp. 143-146, 1996.

[12] R. Valiev, R. Islamgaliev and I. Alexandrov, "Bulk Nanostructured Materials from Severe Plastic Deformation," Prog. Mat. Sci, vol. 45, no. 2, pp. 103-189, 2000.

[13] Y. Zhu and T. Langdon, "Fundamentals of Nanostructured Materials by Severe Plastic Deformation," Journal of Metals, vol. 56, no. 10, pp. 58-63, 2004.

[14] V. M. Segal, "Material Processing by simple shear," Mater. Sci. Eng. A, vol. 197, pp. 157-164, 1995 .

[15] Z. Horita, M. Furukawa, M. Nemoto and T. G. Langdon, "Development of fine grained structures using severe plastic deformation," Materials Science and Technology, vol. 16, no. 11-12, p. 1239–1245, 2000.

[16] J. Horita, "Production of ultrafine-grianed structures using equal-channel angular pressing," Journal of the Japan Welding Society, vol. 74, p. 88, 2005.

[17] M. Furukawa, Y. Iwahashi, Z. Horita, M. Nemoto and T. Langdon, "The Shearing Characteristics Associated with Equal-Channel Angular Pressing," Materials Science Engineering A, vol. 257, pp. 328-332, 1998.

[18] R. Z. Valiev and T. G. Langdon, "Development in used of ECAP Processing for grain refinement," Review of advance Materials Science, vol. 13, pp. 15-26, 2006.

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