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Response of copper to Equal Channel Angular Pressing with different processing temperature

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Abstract

Structural property relationship indicates the significance of Ultra Fine Grain (UFG) for attainment of enhanced strength without any chemistry alteration. Ultra fine grain structure can be produced by Equal Channel Angular Pressing (ECAP) by proper selection of die geometry, route (method specimen rotation for each number passes) and processing temperature. The present study illustrates the significance of processing temperature on attainment of higher strength with ductility. Compared to room temperature, processing with 200^{0}C, results in significant contribution of ECAP by way of structural-strengthening. However, both the processing indicates a critical value of 3, passes, for attaining the desired results.

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Keywords: UFG, ECAP, Strength, ductility, processing temperature, strain hardening

1.Introduction

In last few years ultra fine grained [UFG] materials are attracting the people in the area of structural applications due to its high strength [1]. According to the Hall–Petch relationship, $\sigma_y=\sigma_o+k_y d^{-1/2}$, where the yield strength σy varies with the reciprocal of the square root of the grain size, d, σ_o is the friction stress and ky is constant. Many researchers and engineers have studied about various techniques for reducing the grain size of the material and severe plastic deformation (SPD) technique is one of the promising,viable technique [2]. In this, material is experiencing higher magnitude of strain by introducing flow constriction. Among the various SPD

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techniques for attaining bulk UFG material [2,11,12], the Equal Channel Angular Pressing (ECAP) is the most

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preferable method. Since, in this process the shape of material is mostly maintained unlike conventional methods like forging, extrusion [3]. In the ECAP method the material is fed in to the die which contains two channels of equal in crossection, intersecting at an internal angle of 'φ' and external angle of 'ψ' influencing the strain and consequent grain refinement [2]. During the ECAP process, higher magnitude of plastic strain is imposed on the bulk materials which results in the ultra-fine grain structure through by disintegrating the original texure[4]. The grain refinement, mechanical properties of the material not only depends on level of induced plastic strain and also on the no of passes (the billet material is fed in to the die), processing route and processing environment(high temperature, warm temperature, room temperature) [5,6,8]. Copper with medium stacking fault energy, good formability and low cost, is an ideal material to study the microstructure changes and consequence mechanical behavior [3]. Regarding ECAP of copper, Only limited work has been carried out to study about especially concerning the effect of processing environment and no of passes on the microstructure and mechanical properties. Hence, the main objective of the present work is to understand the effect of processing environment and number of passes on the microstructure, mechanical behavior of ECAP processed commercial purity copper. In addition, threshold limit for the enhancement of strength without affecting the ductility is also highlighted

2.Experimental details

In this work, the commercial purity copper was used as processing material. ECAP method was used to produce UFG structured copper. Before performing the ECAP process, the specimens were annealed at 600°C for 1hr to homogenize the microstructure. The ECAP processing was performed at room temperature and warm temperature of 220°C using hydraulic press with a capacity of 60tons. The ECAP die used in this process having a inner channel angle of φ=90° and outer channel angle of ψ=20°; effecting high triaxial equal strain of 1.0 per passage [7]

The diameter of the specimen was 12mm and the initial length of 65mm each specimen was pressed through four passes using route C, (which means the specimen was rotated by 180^0 in the same direction between subsequent passes). Microstructure of UFG copper (UFG-Cu) was examined using a optical microscope (OM) and scanning electron microscope(SEM).

After completion of the ECAP process, tensile specimens were prepared(along the processing direction/texure) to a crossection of 3mm X 5mm and gauge length of 14 mm [9]. The tensile test was performed using INSTRON mini tensile/compression testing machine which is operated at a constant rate of crosshead displacement maintaining a strain rate of about 5×10^{-4} S^{-1}. Further, the Vickers hardness of ECAPed samples was also evaluated.

3.Results and Discussion

3.1 significance of room temperature processing

The outcome of the ECAPing of copper in terms of physical properties and hardness are presented in this section.Typical results from the ECAPing of copper at room temperature are reported in table.1. It is seen that up to 3 passes, the material experiencing progressive strengthening; however certain deviation in hardness/% of elongation can be attributed to possible surface flaws generated after certain number of passes (possibly due to variation in strain rate during ECAP).

material	No of ECAP process	Ultimate tensile strength (Mpa)	Yield strength(Mpa)	Elongation (%)	Vickers hardness (Hv)
Copper	0	205	140	41	82
Copper	1	398	353	19.5	145.5
Copper	2	450	360	15	131.3
Copper	3	460	390	13	149.3
copper	4	420	405	9.6	144.6

Table.1 route c room temperature

3.1.1 Stress-strain characteristics

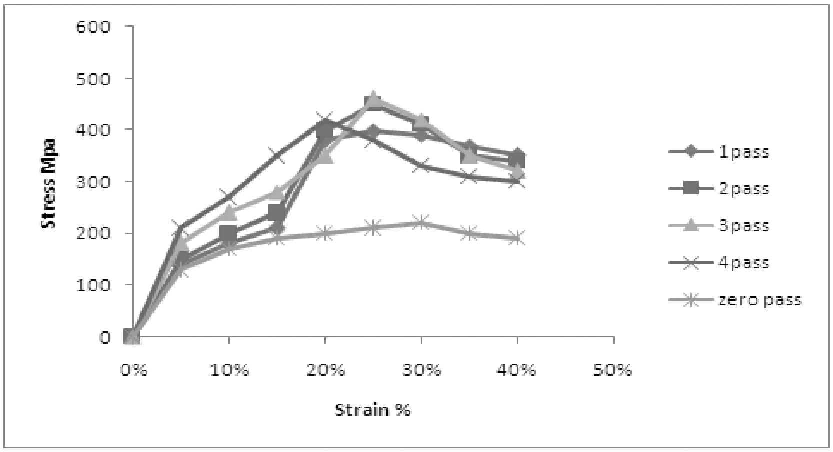


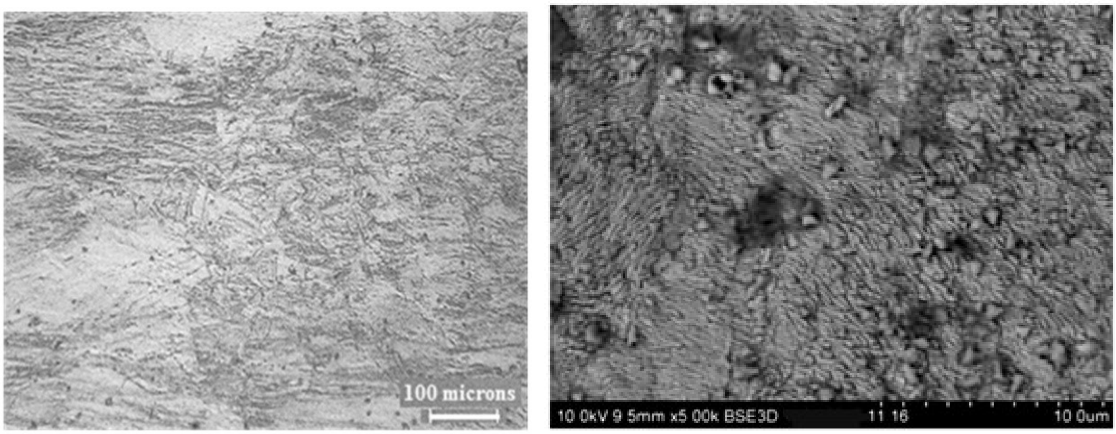
Fig.1. stress-strain graph for room temperature

The ECAPed copper specimens were evaluated for their physical /strength properties. Typical stress-strain characteristics of commercial purity copper exposed to equal channel angular pressing through route C (feeding)at room temperature is shown in figure.1

It is seen that unstressed copper specimen exhibits a stress-strain proportional up to 10%, followed by a load hold, elongation up to 30% results in to strain hardening, followed by a dip, indicating material failure.

3.1.2 Observations with number of passes

After 1pass of ECAP deformation, exhibit proportional stress-strain characteristics up to around 15-20% strain; after 2 passes, the material exhibits almost an identical stress-strain characteristic, however with higher stress (around 400 Mpa). It is seen that up to 2 passes, the material mostly experiences normal work/strain hardening. After 2nd and 3rd passes the yield and ultimate strengths increases but it is not significant compared with first pass. The rate of strength increase is higher only after first pass. Also with increasing number of passes, dynamic recovery combined with strain hardening occures. However elongation is significantly reduced beyond third pass.

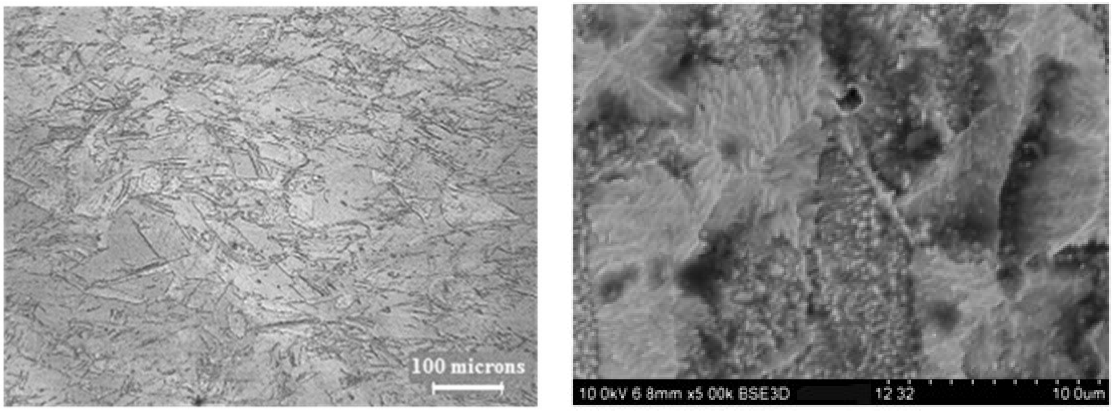


(a) Optical image (b) SEM image

Fig.2. microstructure after 2 passes

Typical microstructure of the material after 2 passes is shown in figure.2. The microstructure presents highly deformed grains, elongated in the direction of material flow; also discrete formation of slip bands can be seen. This can be attributed to the nature of material feeding between passes. Moreover, the deforming material exhibits discrete voids around second phase particles/impurities.

After attaining a threshold of straining/dislocation density, the material experiences recrystalization due to development of dislocation cell structure. With progressive/cumulative straining interaction of dislocation is induced due to localized shear band formation. The dislocation walls leads to formation of new grain boundaries (subgrain within coarser grain).



(a) Optical image (b) SEM image

Fig.3. microstructure after 4 passes

Typical microstructure of copper after 4 pass of ECAP processing is shown in figure.3. Formation of new grains with both low and high angle boundaries can be seen. Formation of ultra fine grain (UFG) in the shear band of copper can be seen.

The microstructure of the heavily deformed copper consists of relatively finer sized, mere ellipsoidal grains separated by low angle boundaries. This is also reflected in the variation of microhardness (after 4 passes, Fig.4)

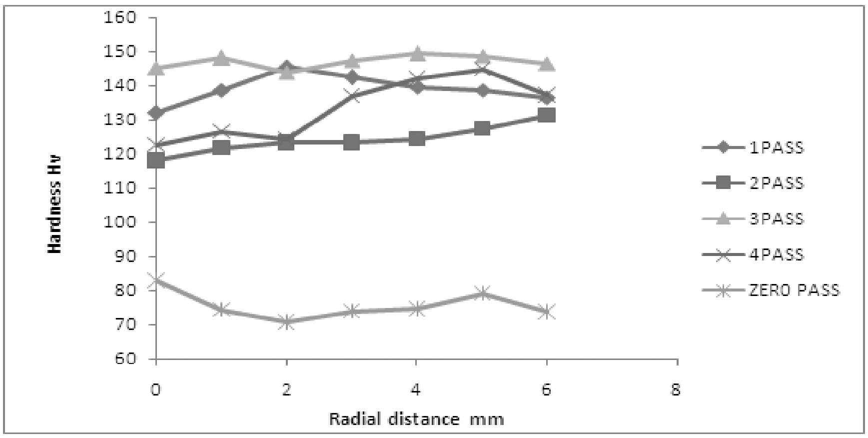


Fig.4.The variation of micro hardness with radial distance for room temperature

Typical microhardness across the crossection of ECAPed copper is shown in figure.4. It is seen that compared to the hardness of annealed copper(80/90Hv), ECAPed material exhibits enhanced hardness(range of 120-150Hv) depending on the number of passes. After 1st pass, the ECAPed copper exhibits progressive increase in hardness (sub structure) up to certain depth from the surface, followed by a mild drop. This indicates the strain hardening of the material after 1st pass. After 2 passes, the material exhibits a fairly an significant hardening (across the section), indicating the on-set of recrystallization. Also, beyond 2 passes, the material attains threshold limit of work hardening, exhibits initiation of dynamic recrystallization. This is reflected in a mild drop in hardness in surface region, but with a progressive rise in hardness across the section. After 3 passes, the material undergoes enhanced strengthening. This is attributed to dynamic recrystallization (with increasing number of passes, strain get accumulated and followed by formation of subgrain within coarse grain (i.e.,formation of dual microstructure)). Further, referring to illustration on hardness of ECAPed copper(Fig.4). it is that the material gets hardened especially upto 3 passes.After 4 passes,the material exhibits a reduction in hardness in surfacial region,followed by a rise in substructure. This could be attributed to possible softening of the material due to frictional heating (possibly due to less absorption of the solid lubricant)

1.1. Significance of warm temperature processing

Typical results from the ECAPing of copper at 200^0C is shown in below table.2.

Tabl.2. route c 220 degree

material	Number of passes	Ultimate tensile strength (Mpa)	Yield strength(Mpa)	Elongation (%)	Vickers hardness (Hv)
Copper	0	205	140	41	82
Copper	1	360	320	24.7	143.7
Copper	2	380	360	17.4	129.8
Copper	3	460	393	13.1	147.2
Copper	4	480	401	11.4	135.8

It is seen from table.2, after first and second passes,the material exhibits sudden increase (75%) in strength and hardness. This is due to strain/work hardening experienced by the material during initial and alternate number of passes. Also, reversing of strain path during alternate number of passes in route C [13]. As a consequence of this, material recovers the initial crystal structure after every second pass.

After third pass, hardness, tensile strength and yield strength are not significantly improved compared with first and second passes. Because material attains the steady state (saturation of strength) and followed by dynamic recovery [8, 10].

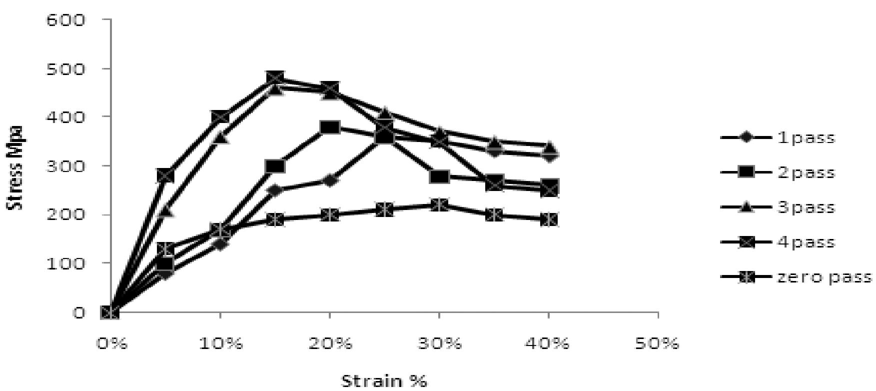


Fig.5. stress-strain graph for 220 degree temperature

Typical stress-strain characteristics of commercial copper subjected to equal channel angular pressing at 220^0c is illustrated in fig.5. It is seen that unlike the case of room temperature pressing, the stress-strain characteristics exhibits a distinct yield drop indicates strengthening of copper associated with ductility. Upto 2 passes, the ECAPed copper exhibits strain hardening above 15% of strain, attaining a peak stress of around 450Mpa. With 3 passes, the characteristics shows strengthening of copper with reduction in ductility. With 220^0c pressing, the material exposed to ECAP, experiences dynamic recrystallization with 3passes. With 4 pass, the stress-strain graph indicating deterioration of material characteristics.

Referring to Fig 1 and Fig 5, a distinct change in stress-strain charecteristics of ECAPed samples (during tensile loading) can be seen. While with room temperature processing, the specimen exhibits a progressive stress-strain charecteristics upto around 7% (strain),followed by a low hardness (upto ≈ 157) with an increased stress. However with 4 passes,the material exhibits a progressive stress-strain charecteristics upto a peak stress of 420Mpa,followed by a drop . With route C,at room temperature,3paases can be a limit for achieving desired results. However,with 220^0C, processing,upto 2passes,the material exhibits fair amount of ductility as seen in the stress-strain charecteristics. Beyond 2 passes,the material exhibits the significance of ECAP by way of enhanced strengthening(Fig.5).

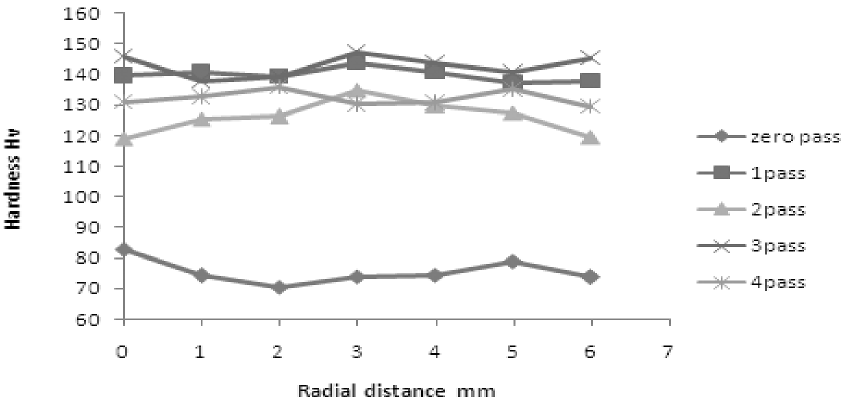
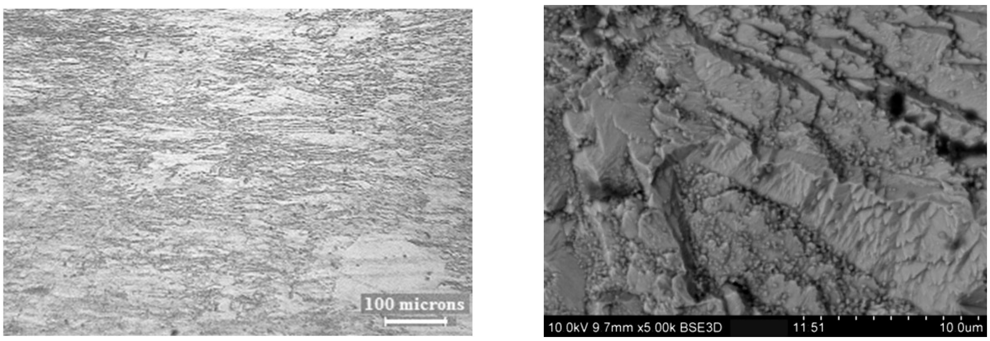


Fig.6.The variation of micro hardness with radial distance for 220 degree

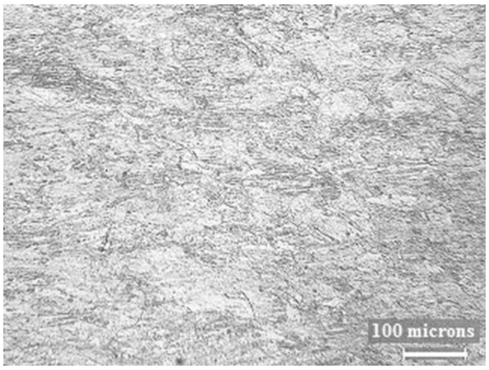
Typical microhardness variation across the crossection of processed copper is shown in fig.6. Unlike the case of room temperature processing, at 220^0c, the material exhibit appreciable hardening after 1 pass, followed by a reduction with successive passes. This indicates that processing at 220^0c,the material continues to undergo strain hardening. The absence of any visible gradient in hardness across the section, also supplements this.



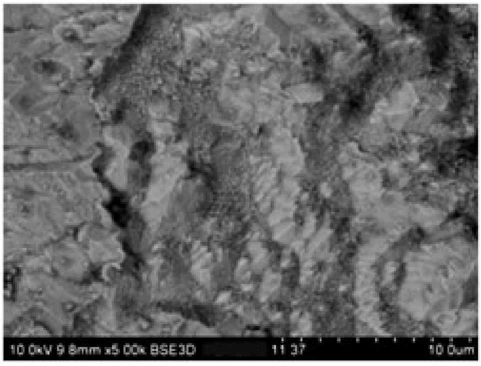
(a) Optical image (b) SEM image

Fig.7. 2PASS at 220 degree

Typical microstructure of a copper after 2 passes (220^0c pressing) is shown in fig.7. Microstructure clearly shows fairly uniform elongated grains/streaks forming a texture along the extrusion direction. The microstructure comprises multi oriented deformed grains in contrast to microstructure after 2 passes with room temperature. This indicates higher order strengthening due to close packed texture.



(a) Optical image



(b) SEM image

Fig.8. 4PASS at 220 degree

Typical micrograph pertaining to ECAPed copper after 4 passes is shown in fig.8. Which comprises elongated shear bands sandwiching relatively fine sub-grains can be seen. The wider separation of shear bands also indicates material deterioration (fig.5).

Generally the grain refinement achieved by ECAP in three stages. First the slip systems are created by severe plastic (shear) deformation of ECAP. Which forms dislocation cells within parent grain.secondly,the above mentioned dislocation cells generates sub-boundaries with low-angle misorientation, identified by deformation bands(with boundaries and dislocation walls). Final one is, with increase in misorientation angle, the new high-angle grain boundaries are formed[6]. Which is consistent with current results.

2. Conclusions

1. Commercial quality copper exhibits varied response to equal channel angular pressing depending on processing temperature, with room temperature, the material experiences mostly strain hardening up to 2 passes.
2. The appreciable change in stress-strain characteristics (with higher peak stress). After 3 passes, indicates a threshold of strain; accumulated and initiation of dynamic recrystallization.
3. Unlike the case of room temperature process, processing at 220^0C ,resulting the stress - strain characteristics with more ductility, indicated by the presence of visible yield-dip.
4. The limitation of ECAPing with 90^0 die geometry is reflected in the micro-structure refinement up to 3 passes; irrespective of the number of passes.
5. Depending on the number of passes, the micro-structure illustrates texturing, localized void formation and formation of shear bands encompassing fine grain structure.
6. The ECAP copper exhibits a progressive rise in structural hardness,with number of passes, with a gradient across the section.
7. Microhardness evaluation shows that with 220^0C processing, the material exhibits hardening, with a close variation between passes. Absence of gradient in hardness across the structure indicates continuous strain hardening. This is also reflected in the microstructure.

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