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# Hardness Inhomogeneity and Microstructure Stability in Aluminum-copper Alloys Processed by Equal Channel Angular Pressing

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**Abstract** Three alloys; Al- 2Cu, Al- 2Cu- 0.5Ag and Al-2Cu- 0.5Mg (composition in wt.%) were casted from high purity metals into rods of 14 mm diameter and 80 mm long, using chill casting. Samples of 11 mm diameter and 70 mm long were machined, solution treated and overaged at 350℃ and then subjected to equal channel angular pressing (ECAP) processing, for one pass and two passes (route A) at room temperature. The microhardness of ECAP processed specimens was measured along a diametral direction from the top to bottom surface at room temperature (RT). The results indicate homogeneous deformation with hardness values fluctuating around mean value with standard error of ± 5 HV. The thermal stability and recovery process of ECAP processed samples, were investigated by isochronal aging in the temperature range of 200-375℃ for half an hour. Hardness values were compared and showed gradual decrease with increasing aging temperature for one-pass ECAP processed samples. For two-pass processed samples hardness tends to increase, after initial decrease, with increasing annealing temperature above 300℃. Mechanical testing showed high increase in tensile properties with number of passes as compared to overaged samples. Two-pass samples exhibited high tensile strength, high strain hardening and high ductility.

**Keywords** Aluminum Alloys, ECAP, Hardness, Mechanical Properties

## 1. Introduction

The ultrafine-grained (UFG) materials have been attracting great interests in recent years because of their unique properties as compared with conventional materials [1-4]. This interest is due to various reasons. First, the mechanical properties of UFG materials are expected to have high strength and good low temperature toughness according to the Hall–Petch relationship, $\sigma_y = \sigma_o + k_y d^{-1/2}$, where the yield strength $\sigma_y$ varies with the reciprocal of the square root of the grain size, $d$, $\sigma_o$ is the friction stress and $k_y$ is constant. Second, the utilization of an ultrafine grain size at high temperatures, in the regime where diffusion-controlled processes become important, offers the potential for achieving high strain-rate superplasticity because the rate of flow in superplastic deformation is inversely proportional to the square of the grain size [5, 6]. On the other hand, the low uniform ductility of UFG materials severely limits their practical utility. Therefore, the basic idea to improve the ductility of UFG materials is to regain the work hardening, dislocation accumulation capability, which is often accompanied with sacrifice of strength [7]. As a result, enhancement of ductility has been demonstrated for ECAP processed commercial purity Al, as well as post-ECAP heat treated Al alloys [8, 9].

The ECAP die contains two channels, equal in cross-section, intersecting at an angle near the center of the die. The die defines two internal angles, Φ and Ψ, delineating the curvature associated with the two channels [10]. During the ECAP process, it is believed that only simple shear is introduced into the specimen [7, 10, 11]. It is possible to define four distinct processing routes [10, 11]. Among these, route A in which the sample is not rotated between repetitive pressings. The shear plane in route A is exposed to successive monotonic increase in shearing strain.

The current work focuses on studying the effect of ECAP processing up to 2 passes, using the route A, on modifying hardness and mechanical properties of tested alloys and the thermal stability of produced microstructure. The effect of addition of 0.5 Ag or 0.5 Mg on the mechanical properties of Al-2Cu alloy is investigated in detail.

## 2. Experimental Work

Three alloys; Al- 2Cu (base alloy), Al- 2Cu- 0.5Ag (alloy 2) and Al-2Cu- 0.5Mg (alloy 3) (composition in wt.%) were casted from high purity metals into rods of 14 mm diameter and 80 mm long, using chill casting and homogenized at 540℃ for 24 hrs. Samples of 11 mm diameter and 70 mm long were machined, solution treated and overaged at 350℃ before ECAP processing, for one pass and two passes (route A) at room temperature. The die used is of 11.2 mm diameter channel, with a channel intersection angle Φ of 120$^o$ and sharp outside intersection angle Ψ of 0$^o$. The equivalent engineering strain in each pass is 0.67 [7]. The microhardness of ECAP processed specimens was measured along a diametral direction from the top to bottom surface at room temperature (RT) on two parallel lines spacing 0.5 mm. The measurements procedure is similar to that reported elsewhere [12]. The results indicate homogeneous deformation with hardness values fluctuating around mean value with standard error of ± 5 HV. The thermal stability and recovery process, of ECAP processed samples, were investigated by annealing in the temperature range of 200-375℃ for half an hour.

Tensile tests were also performed using 3385H Instron machine with data acquisition system, at a constant speed of 1 mm/min corresponding to initial strain rate of $10^{-3}$ $s^{-1}$. Standard cylindrical tensile specimens of $(L_o/D_o) = 4$, where $L_o$ is the gage length and Do is the diameter, were machined from the ECAP proceeded samples, where the tensile axis parallel to the extrusion direction. The turning process of tensile samples was carried out under coolant and at low feed rate to avoid any change of developed substructure in ECAP processed samples. It is expected that the machining process will not influence the true stress-strain response of the tested samples. True stress-strain diagrams were plotted and corrected for the machine compliance.

## 3. Results and Discussion

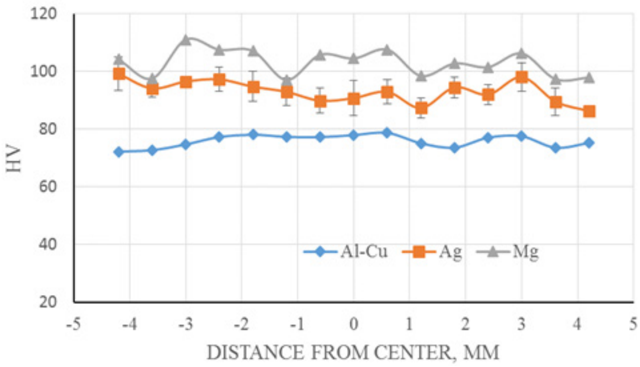

**Figure 1.** Microhardness data for various Al-2Cu alloys. Values of standard error are added for alloy with 0.5 Ag addition (alloy 2).

**Microhardness after One Pass.** Fig. 1 shows values of microhardness as measured as function of distance from center where top part is on left and bottom is on right. The microhardness values did not suggest increasing trend toward the center of cross section as reported for pure Al [12]. The reason may be attributed to the use of different die angles; in Al experiments [12] Ψ = 0$^o$ and Φ = 90$^o$ as compared to Ψ = 0$^o$ and Φ= 120$^o$ in present experiments. The amount of equivalent normal strain [7] achieved in each case is 1.15 and 0.67, respectively. The values exhibited are almost constant within ± 5 to 10 HV. The average hardness value increases from 76 to 93 to 103 for base alloy, alloy 2 and alloy 3, respectively.

**Microhardness after Two Passes.** The second pass using route A increased the deformation strain to 1.34. Fig. 2 shows microhardness values after two passes using route A. While the values for base alloy and alloy 3 showed slight increase in hardness value after two passes, alloy 2 did not exhibit any pronounced change and the hardness value fluctuating around average value similar to one pass specimen.

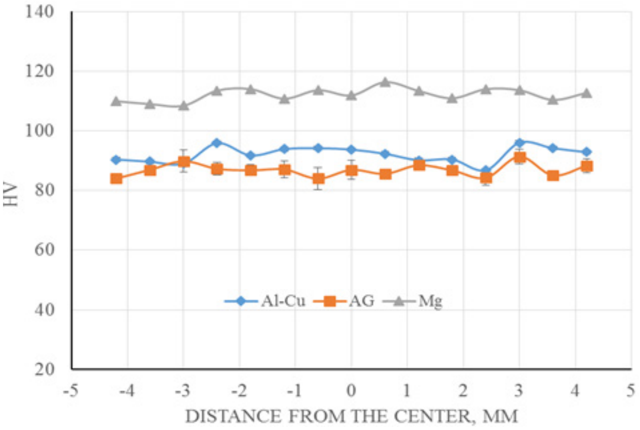

**Figure 2.** Microhardness data for Al-2Cu alloys. Values of standard error are added for alloy with 0.5 Ag addition

**Thermal Stability.** The effect of aging temperature on microhardness values in alloy 3 is shown in Fig.3. The results showed slight increase in hardness values at 200℃, followed by continuous decrease up 300℃ and afterwards hardness tends to be stabilized around 65 HV. Similar figures are plotted for the base alloy and alloy 2. The average hardness is calculated at each temperature and plotted as function of temperature for the tested alloys after ECAP processing for one and two passes. Fig. 4 shows the variation of microhardness with aging temperature for one-pass specimens. Standard error for average value is also included. The microhardness is almost constant up to 200℃ and decreases gradually with increasing aging temperature. Alloy 3 exhibited higher values as compared to other alloys. Base alloy and alloy 2 have similar values of hardness at temperatures above 250℃. Fig. 5 demonstrates the change in microhardness for samples processed for two passes using route A as a function of aging temperature. The hardness decreases gradually with temperature up to 300℃ when it started to increase again to higher values in all specimens. This behavior could be related to a precipitate of a new hard phase. To unequivocally resolve this issue detailed investigation is required. The level of hardness in alloy 3 is higher than that for other alloys. Both base alloy and alloy 2 have similar hardness values after two passes.

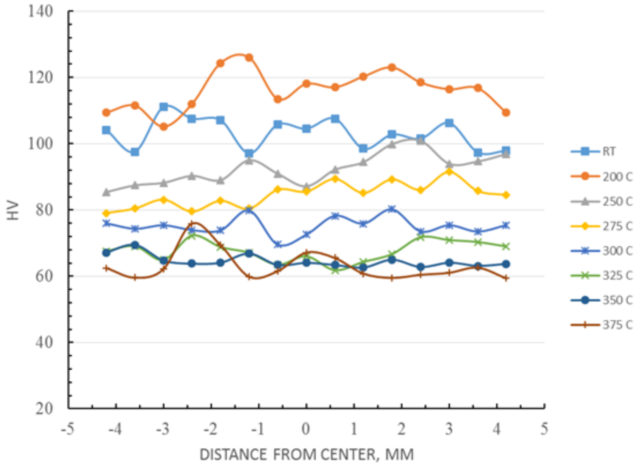

**Figure 3**. Variations of microhardness in alloy 3 ECAPed for one pass with heating temperature at various positions.

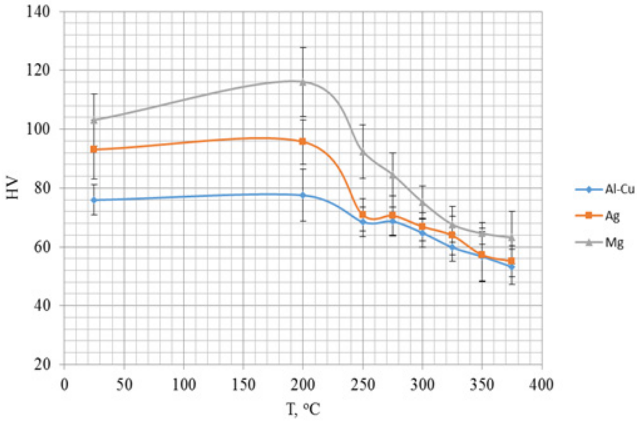

**Figure 4**. Variation of microhardness of one-pass ECAP processed specimens with aging temperature.

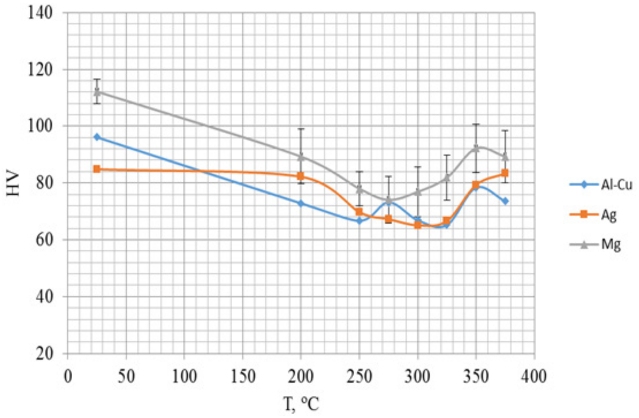

**Figure 5.** Variation of microhardness of two-pass ECAP processed specimens with aging temperature.

**Stress – Strain Response.** Fig. 6 and Fig. 7 represent the true stress – strain response under tension for processed samples of alloys 2 and alloys 3, respectively after overaging and ECAP deformation. The overaged sample showed elastic region followed by normal strain hardening reaching ultimate strength and then failure. For one-pass sample, first part of the curve shows high strain hardening rate over a short period of strain reaching a maximum value of stress and necking is developed and failure occurs after noticeably large amount of post-necking strain. For two-pass specimen, after yielding the specimen strain harden until reaching a tensile strength of 275 MPa. Afterwards necking is developed and ductility is similar to that of one-pass specimen (11%). Fig. 7 is true stress-strain response in alloy 3 after various processing. The behavior of alloys looks similar under similar experimental conditions. However, strength values in alloy 3 are much higher than that of alloy 2. For one pass, alloy 2 has ultimate strength of 200 MPa as compared to 275 MPa in alloy 3. For two-pass processing, ultimate strength is 275 MPa as compared to 340 MPa in alloy 3. The elongation percent is similar in ECAP processed specimens.

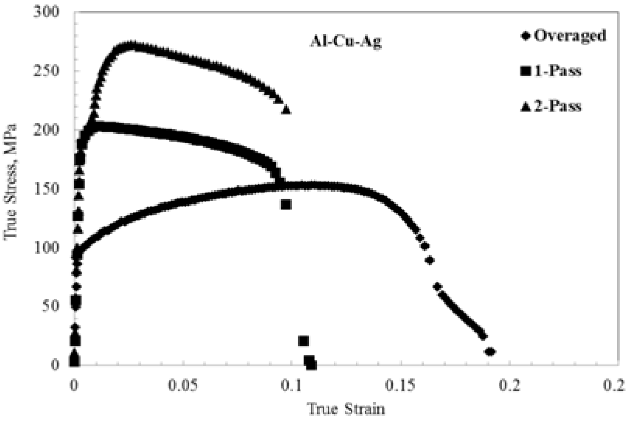

**Figure 6.** True stress-true strain response for alloy 2 after various processing.

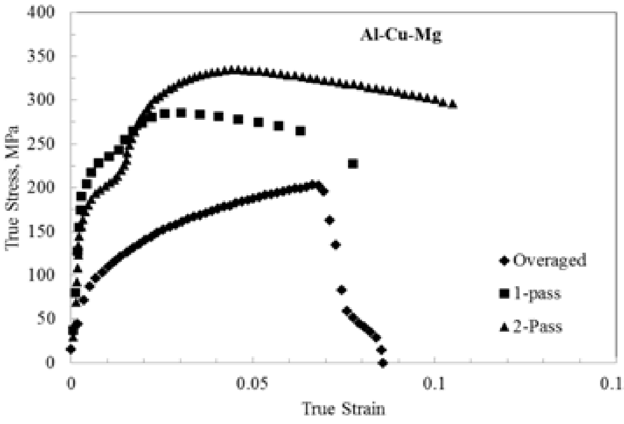

**Figure 7.** True stress-true strain response for alloy 3 after various processing.

The stress-strain response in commercial purity Al [13] after two passes using route A is similar to that reported for alloy 2 after one pass. It was noticed that increasing the number of passes in pure Al above two had resulted only in a slight change in mechanical properties. Generally, most of the hardening occurred in the first two passes [13].

The second region of strain hardening exits in the present alloys was not reported in pure Al [4,13]. This second region of strain hardening is clear in both alloys after two pass processing. The presence of solute atoms and formation of precipitate play a major role in the hardening of alloys. This is reflected in second region of strain hardening that leads to high ultimate tensile strength in both alloys. The effect of Mg in hardening is more pronounced as compared to Ag effect.

## 4. Conclusions

1. Microhardness values of ECAP proceeded and annealed samples did not show preferred inhomogeneity, rather these values scatter around mean value with ±5 HV as standard error.
2. Microhardness values of one-pass ECAP processed specimens showed slight increase in hardness after annealing at 200℃ and afterwards hardness gradually decreased with increasing temperature.
3. Microhardness values of two-pass ECAP processed specimens showed an increase in hardness values after annealing temperatures above 300℃.
4. ECAP processed specimens showed high yield and tensile strength as compared to overaged specimens.
5. Two-pass ECAP processed specimens exhibited high strain hardening rate after yielding reaching tensile strength of ~ 350 MPa in alloy 3.

## Acknowledgements

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