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EFFECTS OF THE NUMBER OF ECAP PASSES AND ECAP ROUTE ON THE HETEROGENEITY IN MECHANICAL PROPERTIES ACROSS THE SAMPLE FROM ULTRAFINE COPPER

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Abstract. Annealed copper was processed by eight passes of equal-channel angular pressing (ECAP) using two routes, B_C and C. Pressed samples had a square section with a side length of 8 mm. Mechanical properties at tension (conventional yield strength, tensile strength, elongation and contraction) were determined at 9 points across the sample using small-size specimens, 1.5 mm in diameter, cut out along the pressing direction. Heterogeneity in the mechanical properties across the sample was determined based on the value of the variation coefficient. Heterogeneity in all the mechanical properties after eight ECAP passes was found to be higher for route B_C than for route C.

1. INTRODUCTION

Being one of severe plastic deformation methods, ECAP reduces the grain size and considerably increases strength properties. Several ECAP passes are enough to provide saturation in this process. As a rule, mechanical properties determined in standard specimens are integral values, because the cross-sectional area of such specimens is commensurable with the cross-sectional area of ECAP samples. These undoubtedly important data make it possible to assess the efficiency of ECAP, but do not make it clear how mechanical properties are distributed across the sample after ECAP.

Results of ECAP macromodeling suggest that there is considerable heterogeneity in stress and strain across the sample [1,2], which must primarily manifest itself in the heterogeneity in mechanical properties. At the same time, many studies show that the microstructure becomes more uniform at a greater number of ECAP passes [3], which implicitly leads to the conclusion that mechanical properties should also be uniformly distributed across the sample.

This study is an attempt to experimentally validate these suppositions.

2. EXPERIMENTAL PROCEDURES

Commercially pure annealed sheet-type 8 mm thick steel was chosen as a test material. ECAP samples

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had a size of 8×8×60 mm and were cut out along the rolling direction. During the first ECAP pass, the sheet's upside was faced to the outlet die channel. ECAP was performed at room temperature with a die moving at a speed of 50 mm/min. Pressing was performed using an experimental lubricant, RANOL-3, based on molybdenum disulfide and ultrafine graphite. Lead was used to extrude the samples from the horizontal channel. ECAP was performed using two routes, B_C and C. The properties were analyzed after the first, the second, the fourth and the eighth pass.

In order to look at the distribution of mechanical properties across the sample, nine small-size tension test specimens having a nominal diameter of 1.5 mm and a gage length of 7.5 mm were cut out from each post-ECAP sample in stationary sections. The axes of the small-size specimens were directed along the sample. The small-size specimens were uniformly distributed across the sample at 2.6-mm spacing. The specimens were tested at room temperature at the strain rate $\dot{\varepsilon} = 10^{-3}$ s^{-1}. The following mechanical properties were determined as a result of the tests [4]:

· tensile strength σ_B,
· conventional yield strength $\sigma_{0,2}$,
· elongation at rupture δ_5, and
· contraction ψ

3. RESULTS

Let us use the coefficient of variation (V) expressed as a ratio of standard deviation to the average value as a heterogeneity index of a value:

$$V = \frac{S}{\bar{x}}, \text{ where}$$

$$S = \sqrt{\frac{n\sum x^2 - \left(\sum x\right)^2}{n(n-1)}}, \qquad (1)$$

$$\bar{x} = \frac{1}{n}\sum x.$$

Here, (x) is the property value for each test conducted. Fig. 1 shows dependencies of the heterogeneity index of all the mechanical properties of interest upon the number of ECAP passes.

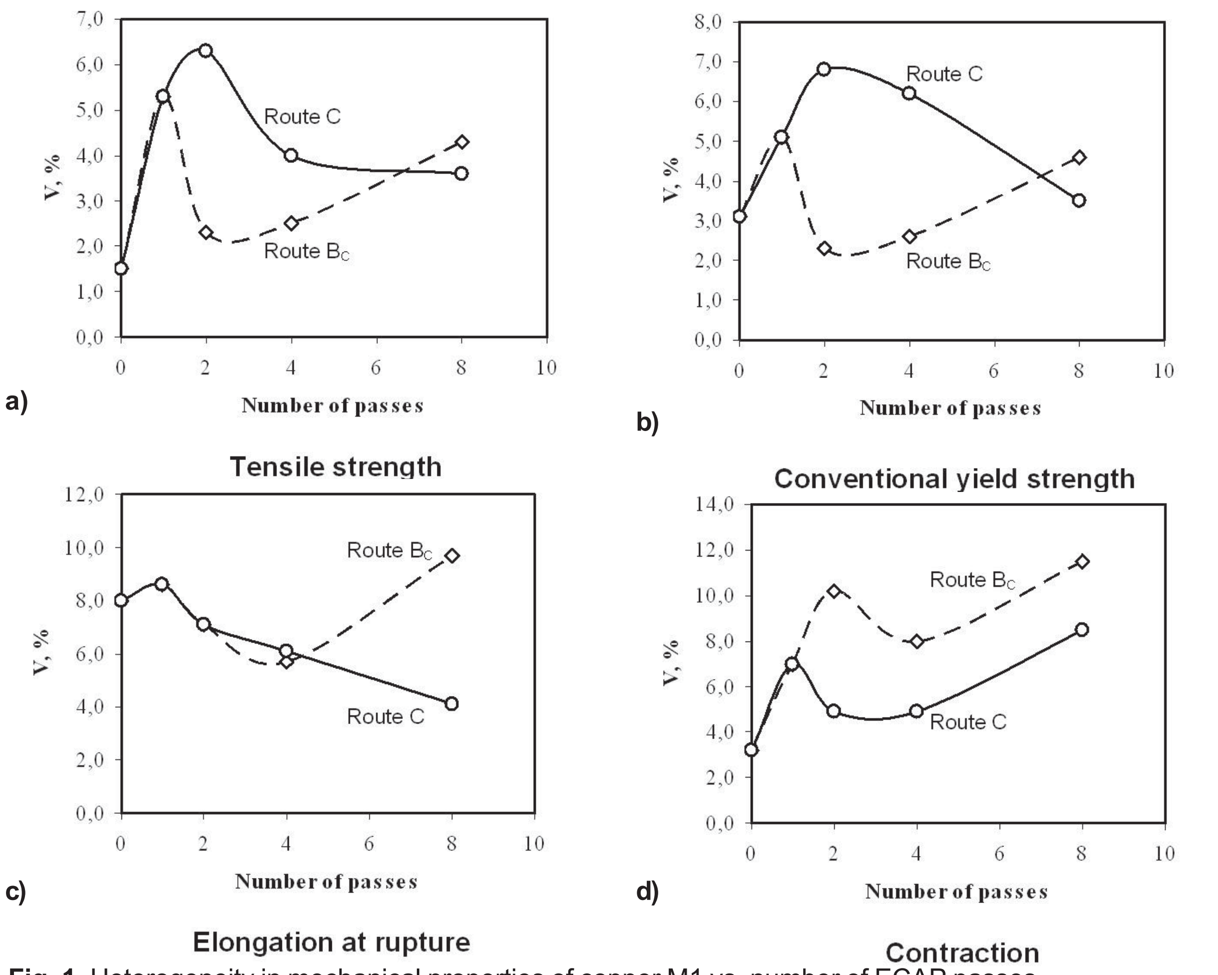

Fig. 1. Heterogeneity in mechanical properties of copper M1 vs. number of ECAP passes.

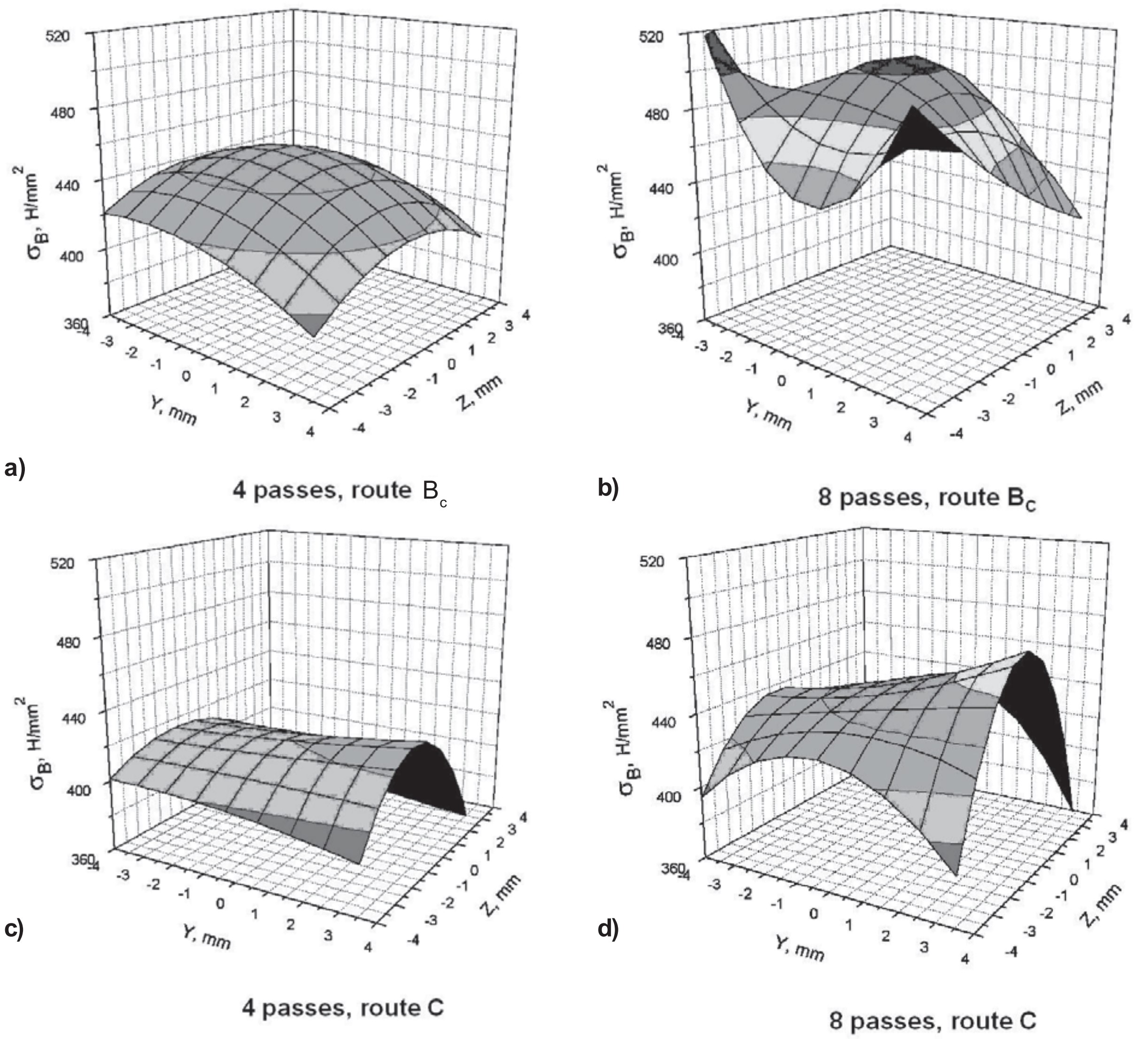

Fig. 2. Copper M1 tensile strength distribution across the ECAP sample.

The figure shows that heterogeneity across the sample increases in all the properties, although in different ways. Starting from the second pass, heterogeneity in strength properties (tensile strength and conventional yield strength) changes in directly opposite ways for the two ECAP routes. Indeed, for route B_C, heterogeneity drops almost to the level corresponding to the initial state, whereas heterogeneity for route C continues to grow. By the fourth ECAP pass, the tendency in strength heterogeneity variation for both routes reverses. Heterogeneity for route B_C begins to grow, and for route C to decrease. Whereas after the fourth ECAP pass heterogeneity in the strength properties is still higher for route C, after the eighth pass the heterogeneity becomes higher for route B_C.

The same tendencies are observed in elongation heterogeneity variation. Heterogeneity for both pressing routes remains the same after the second pass; then, after the fourth pass, heterogeneity for route C gets somewhat higher, but after the eighth pass, heterogeneity for route B_C is already twice as high as for route C.

Heterogeneity in contraction for route B_C is higher in all cases. For both routes, heterogeneity is observed to reduce after around four passes, and then it starts growing actively.

Fig.2 shows how tensile strength changes across the sample after the fourth and the eighth ECAP pass. At a rather curved response surface in each of the shown cases, one can still observe that tensile strength for route B_C is higher than for route

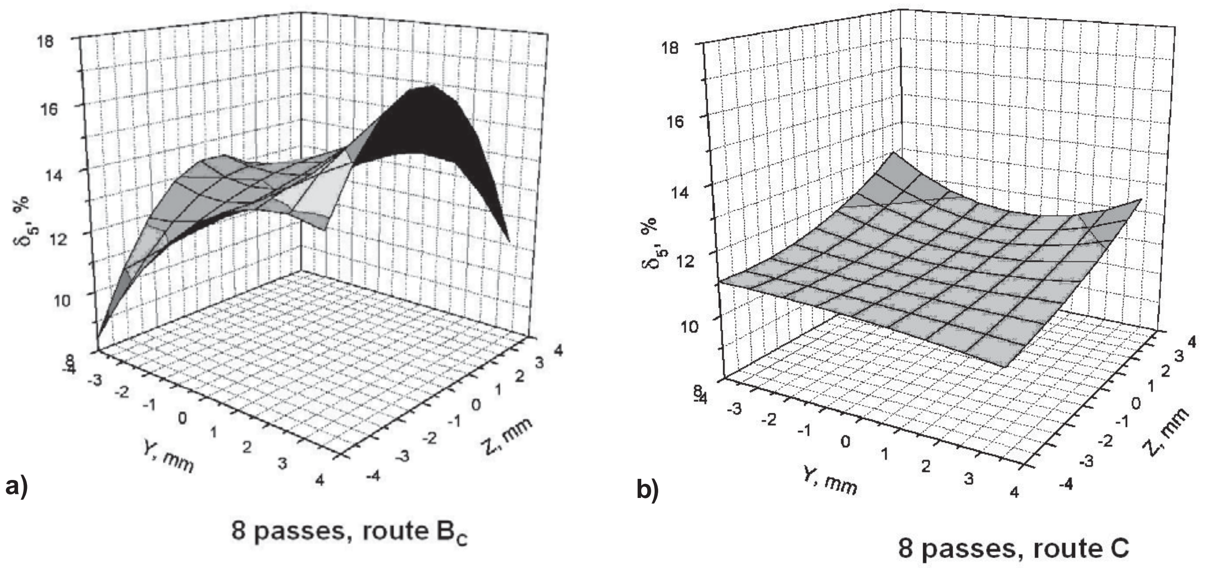

Fig. 3. Copper M1 elongation distribution across the ECAP sample.

C. One can also clearly see the increase in tensile strength with the growth of the number of ECAP passes.

The response surfaces for the two pressing routes, however, have absolutely different profiles. The response surface for route B_C has a dome-shaped profile. This means that the strength is the highest in the center of the sample, and it reduces towards the periphery. For route C, the response surface of tensile strength has a saddle-shaped profile with a symmetry axis parallel to the *Y* axis. In this case, the sample has a central region parallel to the *Y* axis, in which strength has the highest value. The farther from this region, the lower is strength. For this layout, the *Y* axis is perpendicular to the plane, in which the inlet and the outlet channels of the ECAP die lie. The profile of response surfaces for conventional yield strength is similar to that of the surfaces for tensile strength.

It is of interest to compare the distribution of elongation across the sample for different loading conditions. As can be seen in Fig. 3, elongation across the sample after eight ECAP passes by route B_C changes by a factor of almost two. At the same time, elongation for route C is practically constant at all the points across the sample.

4. CONCLUSIONS

1. The first ECAP pass results in the considerable growth of heterogeneity in all mechanical properties of copper M1 across the sample.
2. Heterogeneity in all the mechanical properties of interest after eight ECAP passes for route B_C is higher than for route C.
3. Starting from the fourth ECAP pass, one can observe a stable tendency towards higher heterogeneity in all the mechanical properties for route B_C.
4. After the fourth ECAP pass by route C, heterogeneity in strength properties and elongation at rupture is observed to tend toward reduction.

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