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Effect of the deformation temperature on the deformation behavior of a Cu-Cr-Zr alloy

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Abstract. The mechanical properties and deformation behavior of a Cu-Cr-Zr alloy after solution treatment (ST) or aging (ST+AT) and equal channel angular pressing (ECAP) at elevated temperature were investigated. ECAP at elevated temperature led to strengthening and degradation of plasticity compared with the initial state. The deformation behavior of the alloy after 1 and 2 ECAP passes at 200 °C was almost the same. An increase in ECAP temperature promoted uniform strain and plasticity. An increase in the number of ECAP led to a gradual increase in strength. YS and UTS in ST+AT condition were higher than in ST samples regardless of the ECAP temperature and the number of passes. The maximum values of YS and UTS were obtained after 4 ECAP passes at 400 °C and achieved 525 MPa and 600 MPa in ST and 570 MPa and 650 MPa in ST+AT condition, respectively. The effect of deformation strain and ECAP temperature on work hardening rate and recovery were discussed in terms of the Voce equitation.

1. Introduction

Cu-Cr-Zr alloys have been advanced materials for electrical applications due to their high electrical conductivity and strength [1-2]. Fine precipitations formed during heat treatment or warm deformation provide the required combination of these properties [3-4]. Severe plastic deformation, as a promising working technique, may change the microstructure and deformation behavior of Cu-Cr-Zr alloys [5-6]. Strain-induced low- and high-angle boundaries particle precipitation, high dislocation density promote work hardening and recovery [7]. However, the microstructure-property relationship in Cu-Cr-Zr alloys has not been sufficiently investigated. The aim of this work is to study the mechanical behavior of the Cu-Cr-Zr alloy after severe plastic deformation at elevated temperatures and to quantitatively estimate the effect of the deformation temperature on work hardening and recovery of the material.

2. Experiment

The Cu-0.3%Cr-0.5%Zr alloy after solution treatment (ST) or aging (ST+AT) followed by ECAP at elevated temperature was chosen as the object of the present study. Solution treatment was carried out at 920 °C during 0.5 h with subsequent water quenching. A part of the samples was subjected to aging at 450 °C for 1 h. Then, 1, 2 and 4 ECAP passes was performed at temperatures of 200 °C, 300 °C or 400 °C via route B_C. The channel intersection angle of the ECAP die was 90°. The mechanical properties were studied using an Instron 5882 machine using the specimens with a gauge length of 6 mm. The initial strain rate was about 6×10^{-3} s^{-1}.

3. Results and discussion

True stress – true strain curves

Deformation behaviour after ST or ST+AT was characterized by a rather high uniform elongation and significant plasticity (Figure 1). The strength in the ST condition was lower and the plasticity was higher than after the ST+AT. ECAP at elevated temperature led to strengthening and degradation of plasticity. The difference between the yield strength (YS) and the ultimate tensile strength (UTS) was about 10 MPa after ECAP at 200 °C; and the uniform strain was about 0.01. An increase in the ECAP temperature was beneficial for uniform strain and plasticity. The mechanical behaviour of Cu-Cr-Zr alloys after 1 and 2 ECAP passes at 200 °C was almost the same. YS and UTS after 1 pass of ECAP at 300 °C were lower by about 50 MPa than that for the samples ECAPed at 200 °C. 2 and 4 ECAP passes at 300 and 400 °C were characterized by a gradual increase in strength. In the ST+AT condition plasticity achieved its maximum value after 2 ECAP passes at all the ECAP temperatures. YS and UTS in ST+AT samples were higher than that in the ST condition at a different ECAP temperature and number of passes. The maximum YS and UTS have been measured to be 525 MPa and 600 MPa after 4 ECAP passes at 400 °C for ST samples and 570 MPa and 650 MPa for ST+AT samples, respectively.

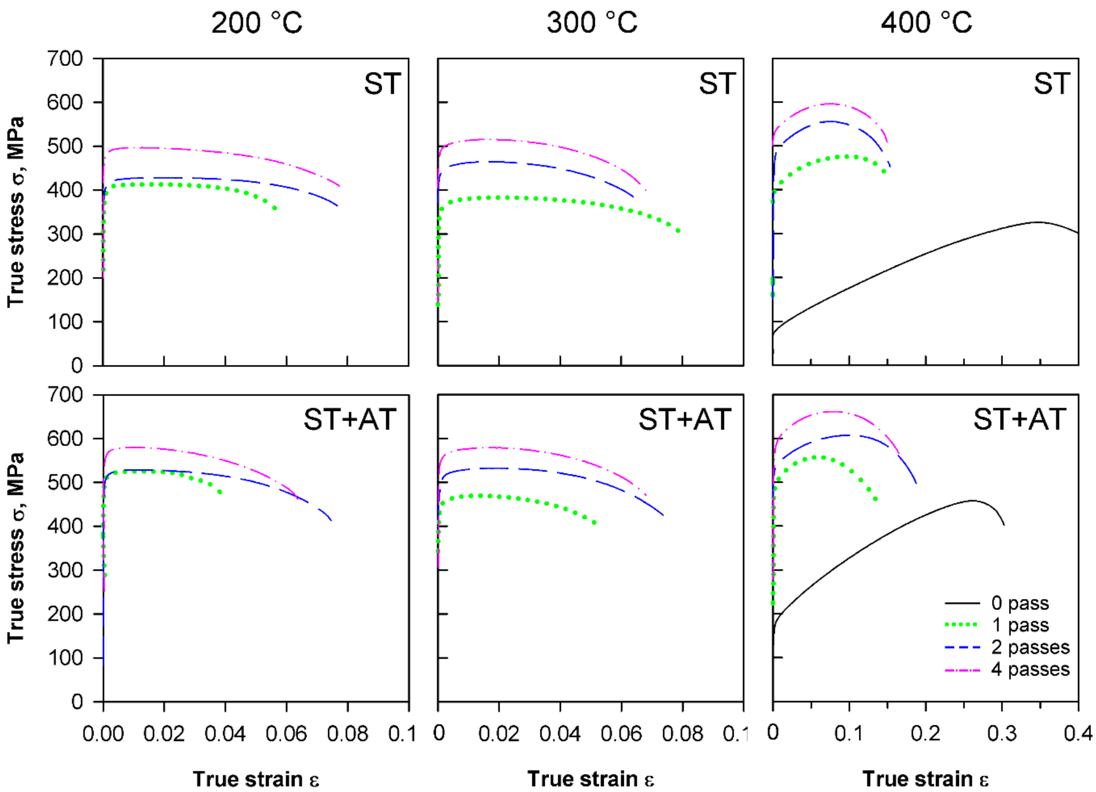

Figure 1. True stress – true strain curves of the Cu-Cr-Zr alloy in the solution treated (ST) and aged (ST+AT) condition after 0 (black line), 1 (green line), 2 (blue line) and 4 (pink line) ECAP passes at temperatures of 200 °C, 300 °C, or 400 °C.

Voce analysis

Analysis of the mechanical behavior can be carried out with the Voce approach. The Voce equation describes the mechanical behavior during uniform deformation as follows [8-9]:

$$\sigma = \sigma_v + (\sigma_0 - \sigma_v)\exp\left(-\frac{\varepsilon}{\varepsilon_v}\right) \quad (1)$$

where σ is the flow stress, σ_v is the saturation stress, ε_v is a characteristic strain corresponding to σ_v, σ_0 is the back-extrapolated stress to ε=0, ε is a true strain. Then the strain hardening can be expressed by the linear function as:

$$\frac{d\sigma}{d\varepsilon} = \frac{\sigma_v}{\varepsilon_v} - \frac{1}{\varepsilon_v}\sigma \quad (2)$$

The Δσ/Δε - σ curves are shown in Figure 2. The lines in Figure 2 can be approximated by linear function in accordance with equitation (2).

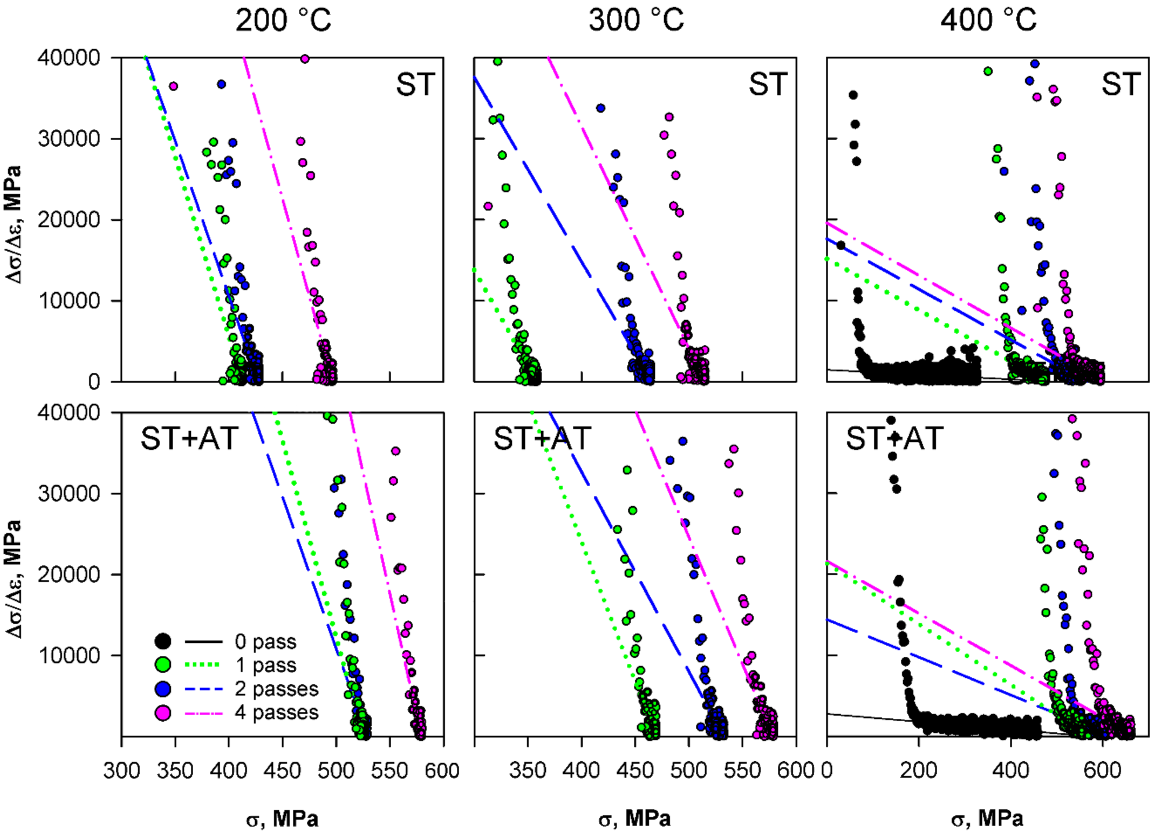

Figure 2. Work hardening rate (Δσ/Δε) vs. true stress (σ) curves of the Cu-Cr-Zr alloy in the solution treated (ST) and aged (ST+AT) condition after 0 (black), 1 (green), 2 (blue) and 4 (pink) ECAP passes at temperatures of 200 °C, 300 °C, 400 °. Lines correspond to the Voce equitation (2).

The slope of Voce line $1/\varepsilon_v$ was higher in ST+AT samples regardless of the ECAP temperature and strain. An increase in the number of ECAP passes was accompanied by an increase in Voce line slop $1/\varepsilon_v$ and σ_v/ε_v constant in the all ECAP temperature range in the ST condition (Figure 3). Voce line slop in ST+AT samples had a minimum after 2 ECAP passes at 200-400 °C. An increase in the ECAP temperature led to a decrease in Voce line slop and σ_v/ε_v constant in both conditions.

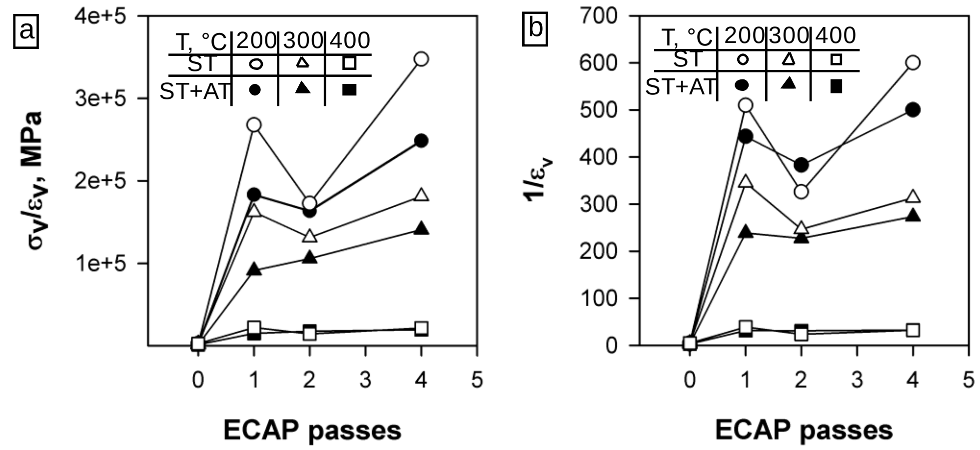

Figure 3. Effect of ECAP temperature and strain on constant, σ_v/ε_v, (a) and a slope of Voce line, $1/\varepsilon_v$, (b) in the Cu-Cr-Zr alloy in the solution treated (ST, black symbols) and aged (ST+AT, white symbols) condition.

The coefficient, σ_v/ε_v, corresponds to the work hardening rate and strongly depends on ε_v. An increase in the ECAP temperature led to a decrease in the work hardening rate due to a significant change of ε_v from 0.001-0.005 for ECAP at 200 °C to 0.01-0.05 for ECAP at 400 °C. The Voce line slop of $1/\varepsilon_v$ is reciprocal of characteristic strain that defines the velocity of σ_v attaining. An increase in ε_v corresponds to an increase in uniform deformation and prolongation of dislocation accommodation and their rearrangement that is associated with recovery of the material.

So, ECAP at elevated temperature led to strengthening and degradation of plasticity. An increase in the ECAP temperature promoted uniform strain and plasticity. An increase in ECAP numbers led to a gradual increase in strength. YS and UTS in ST+AT condition were higher than in ST samples regardless of ECAP temperature and number of passes. An increase in the ECAP temperature led to a decrease in the work hardening rate and promoted recovery significantly.

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