Modelling and Simulation of Dynamic Recrystallization (DRX) in OFHC Copper at Very High Strain Rates

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Abstract. At high strain rates, deformation processes are essentially adiabatic and if the plastic work is large enough dynamic recrystallization can occur. In this work, an examination on microstructure evolution of OFHC copper in Dynamic Tensile Extrusion (DTE) test, performed at 400 m/s, was carried out. EBSD investigations, along the center line of the fragment remaining in the extrusion die, showed a progressive elongation of the grains, and an accompanying development of a strong <001> + <111>dual fiber texture. Discontinuous dynamic recrystallization (DRX) occurred at larger strains, and it was showed that nucleation occurred during straining. A criterion for DRX to occur, based on the evolution of Zener-Hollomon parameter during the dynamic deformation process, is proposed. Finally, DTE test was simulated using the modified Rusinek-Klepaczko constitutive model incorporating a model for the prediction of DRX initiation.

INTRODUCTION

During deformation at high temperature, restoration processes as recovery or recrystallization may occur. Dynamic recovery processes mainly occur during thermomechanical processes such as hot rolling, extrusion and forging [1]. When restoration processes take place, the flow stress of the material is reduced promoting plastic deformation. They also have an effect on texture and grain size. The occurrence of restoration process in materials has been investigated mainly at low strain rate. At high strain rate the deformation process is essentially adiabatic, and if plastic work is large enough, the combination of accumulated strain, strain rate and temperature can determine the conditions for DRX to occur [2]. In 1992, Chen and Kocks [3] theorized an effect of the strain rate on the activation of DRX. In 1994 Andrade *et al.* [2] found evidence of DRX in top-hat copper specimen deformed at large strain (>3-4) at high strain rate (10^4 s^{-1}). Murr *et al.* [4], recently, reported complete DRX in copper and iron Explosively Formed Projectiles. Recently, the Dynamic Tensile Extrusion (DTE) test has been introduced by Gray III *et al.* [5] to probe the material at large strain and high strain rate. In this type of test, the material is launched in a conical die and dynamically extruded experiencing plastic deformation that can be larger than 5.0 with a strain rate that is of the order of 10^4-10^5 s^{-1}. Hörnqvist *et al.* [6] found evidence of DRX in OFHC copper close to the tip of the fragment that remains in the extrusion die. In this work, in order to predict the occurrence of DRX for complex deformation path involving temperature and strain rate variation, a simple criterion based on the evolution of the Zener-Hollomon parameter is proposed. The model has been implemented in commercial finite element code and used in the simulation of DTE test of copper at 400 m/s impact velocity. The location at which DRX is predicted to occur has been compared with EBSD findings given in Hörnqvist *et al.* [6].

MATERIAL AND TESTING

The material under investigation is OFHC copper received in the half-hard condition. DTE samples were machined and successively annealed for 1/2 h at 400 °C in an oven using inert atmosphere. The final grain size was 47 μm using

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the intercept method neglecting the twin boundaries, 14 μm otherwise. The DTE test configuration is the same as given in Gray III *et al.* [5]. The projectile used in this study has the same mass as in Gray III *et al.* [5] but different shape. A bullet shape was selected for practical purposes and because it allows to verify post-mortem the alignment of the projectile at the impact [7]. Tests at different impact velocities, ranging from 330 up to 450 m/s have been performed. Hereafter, the 400 m/s impact test, for which EBSD analysis was available, was selected as reference case. Tests were performed using a single stage light gas gun with 7.62 mm bore in a vacuum chamber and extruded fragments were soft-recovered in a ballistic gel block.

A MODEL FOR DRX INITIATION UNDER VARIABLE STRAIN RATE

Criteria providing the conditions for the occurrence of DRX are mainly empirical in nature. These relationships indicate the critical plastic strain at which DRX starts for given temperature. They are usually obtained by interpolating data obtained from uniaxial compression tests at constant (low) strain rates. Andrade *et al.* [2] suggested that DRX in dynamic deformation of copper would occur when the plastic shear strain exceeds 2.0 and the strain rate is larger than $10^4\ \mathrm{s}^{-1}$. In a dynamic deformation process such as that occurring in the DTE test, the strain rate and temperature are not constant. Therefore, the aforementioned criteria becomes inapplicable. Alternatively, the Zener-Hollomon (Z-H) parameter can be used to characterize the deformation process. The Z-H parameter is defined as follows

$$Z = \dot{\varepsilon} exp\left(\frac{Q}{RT}\right) \tag{1}$$

here, $\dot{\varepsilon}$ is the strain rate, R is the universal gas constant, T is the temperature in K and Q is the apparent activation energy given in kJ/mol. For a constant strain rate and temperature, the critical plastic deformation at which DRX occurs can be given as a function of Z as in Eqn. (2)

$$\varepsilon_{cr} = K_{\varepsilon} Z^m \tag{2}$$

where K_ε and m are material parameters. For pure metals, K_ε depends on the initial grain size and the metal purity while m is usually assumed a material constant. In addition, pressure, which develops in dynamic impact condition, has the effect of delaying the occurrence of DRX. Based on experimental data available in the literature for copper, the following expression of K_ε as a function of the initial grain size is proposed

$$K_\varepsilon(d_0) = \bar{K}_\varepsilon \left[1 - exp\left(-\frac{d_0}{d_0^*}\right)\right] \tag{3}$$

where $\bar{K}_\varepsilon$ and d_0^* are material constants. This expression can eventually be used to account for grain size reduction during the extrusion process. DRX is predicted to occur for a given deformation process when the current plastic deformation is exceeding the critical strain predicted by Eqn. (2) calculated for the current Z. In other words, the condition for DRX is predicted to occur at the intersection of the two curves given by Eqn. (1) and Eqn. (2).

NUMERICAL SIMULATION OF DTE TEST AND RESULTS

The DTE test of OFHC copper at 400 m/s was simulated with FEM. Because of symmetry, the model was simulated using four node isoparametric elements in axisymmetric formulation. Both the projectile and extrusion die were modelled as deformable bodies in contact considering friction effects. Because of the large deformation occurring in the projectile, global adaptive remeshing capability was used. The modified Rusinek-Klepaczko model was used to simulate copper behavior at large strain and high strain rates. Details on the model formulation and equation derivation can be found elsewhere, [8]. Numerical simulation results were validated by comparing the size and the number of fragments at different impact velocities. After validation, the DTE test at 400 m/s was simulated implementing the DRX criterion given above to calculate the extent of the region that is predicted to undergo DRX. In Figure 1, the material undergoing DRX is indicated in yellow. Here, it can be seen that for the 400 m/s impact, the proposed model predicts the DRX can occur potentially in all fragments. For the fragment which remains in the extrusion die, DRX is predicted to start at location 3 (see Fig. 2 (a) for the locations definition). Hörnqvist *et al.* [6], performed EBSD investigation of the fragment trapped in the extrusion die for the OFHC copper DTE sample tested at 400 m/s impact. They reported the evolution of the microstructure for five locations along the fragment symmetry axis, Fig. 2 (a).

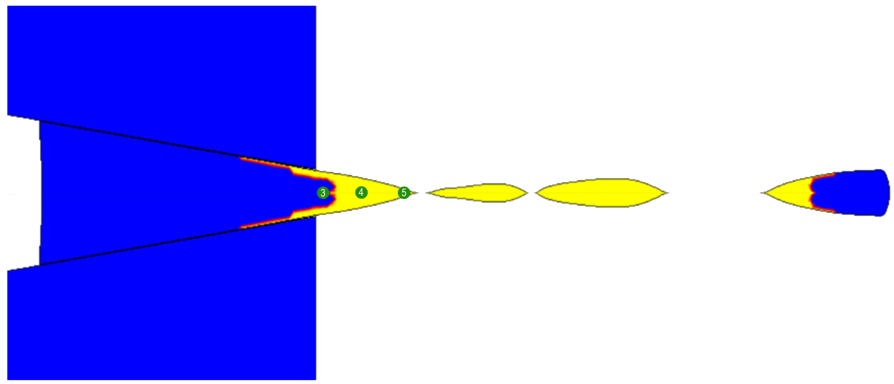
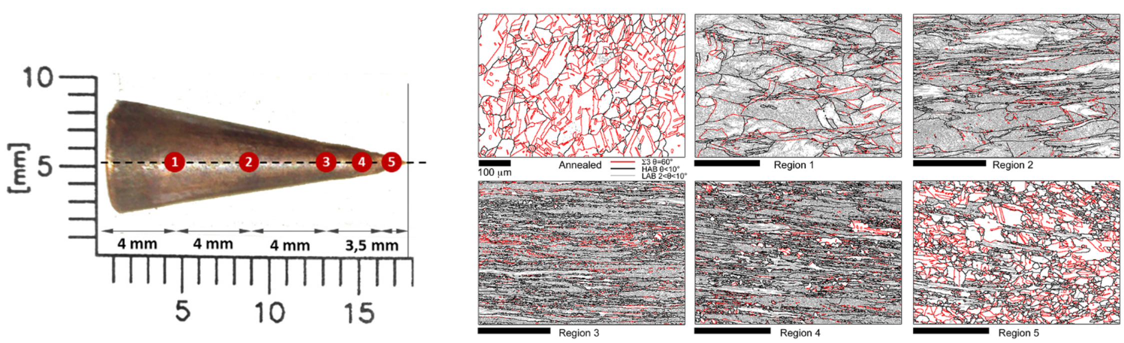


FIGURE 1. Calculated DRX region in extruded fragments of DTE test in OFHC copper at 400 m/s .

Plotting the evolution of the Zener-Hollomon parameter as a function of the plastic strain, Fig. 3, they showed that these points undergo the same deformation path although reaching different plastic strain level. In Figure 2 (b) it can be seen that grains becomes more and more elongated with the increasing the plastic strain level. Grain fragmentation starts to occur at location 3 where the calculated plastic strain is 2.2 approximately. Increasing deformation, region 4 DRX nuclei start to become visible, while in region 5 (plastic strain 5.3) DRX has occurred for 70 % of the area fraction with some grain growth occurred after deformation during the cool down of the sample in the die. It can be noted, that the calculated location for DRX initiation was found to be in a good agreement with EBSD analysis results. Further validation could eventually come from EBSD analysis of other fragments that are predicted to undergo DRX completely.



(a) (b)

FIGURE 2. (a) EBSD locations, (b) grain evolution at the selected locations (red lines indicate twins).

CONCLUSIONS

The DTE test offers a unique opportunity to investigate microstructure and texture evolution at large plastic strain and high strain rate. For non-constant strain rate and temperature deformation paths, a simple criterion for DRX initiation was proposed and implemented in a finite element code. The numerical simulation results for OFHC DTE test at 400 m/s predict the occurrence of DRX in all fragments although with different extent. EBSD analysis results performed on the fragment trapped in the die, provide evidence of DRX. The location of the initiation of DRX for this fragment are predicted fairly well by the proposed criterion.

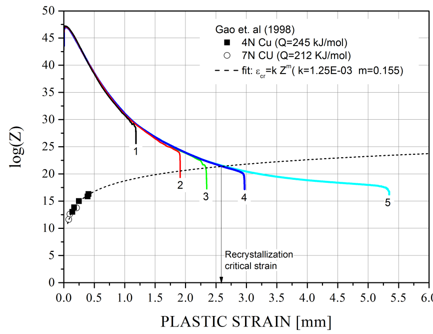


FIGURE 3. Evolution of the Zener–Hollomon parameter with plastic strain for the five locations selected for EBSD analysis on DTE test in OFHC copper at 400 m/s .

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