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Influence of the Hardening Models on the Grain Refinement of Ni Single Crystals During the ECAP Process

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Introduction: There are different methods which are used to convert solid metals with coarse grains into a material with fine grains. The equal channel angular pressing (ECAP) is one of such interesting methods for grain refinement and modification of the microstructure. It was invented by Segal (1974). In the ECAP process a sample with circular or square cross section is pressed through an angular die with constant cross section. At the intersection of the two parts of the channel the sample experiences a severe shear strain. This shear strain leads to significant alterations in the microstructure and the mechanical behavior of the deformed sample.

Problem Definition

The microstructure of metals influences their mechanical properties. Therefore altering the microstructure of a material during the plastic deformation will change it's mechanical properties. The ECAP is a method to alter the microstructure and grain refinement of metals. The internal variables such as hardening in this process will effect the final properties.

Objectives

The principle subject of the project is to investigate the influence of the hardening models on the grain refinement and the plastic deformation behaviour of a nickel single crystal during the ECAP process. For this purpose, some work hardening models have been implemented into the crystal plasticity material model of the ABAQUS standard finite element code.

Cooperation

1. Professor W. Skrotzki, Institute for Physics, Technical University Dresden
2. Professor T. Halle, Institute for Materials and Joining Technology, Otto-von-Guericke-University Magdeburg

Single Crystal Material Model:

- ✓ elastic law:

$$\boldsymbol{T}^{2PK} = [\boldsymbol{E}_e^G], \qquad \boldsymbol{E}_e^G = \frac{1}{2}[\boldsymbol{F}_e^T \boldsymbol{F}_e - 1]$$

- ✓ flow rule:

$$\dot{\boldsymbol{F}}_p \boldsymbol{F}_p^{-1} = \sum_{\alpha=1}^{N} \dot{\gamma}_0 \, sgn(\tau^\alpha) \left|\frac{\tau^\alpha}{\tau_c}\right|^n \boldsymbol{d}_\alpha \otimes \boldsymbol{n}^\alpha$$

- ✓ Hardening models:
  - ✓ Voce model (1955):

$$\tau_c = \tau_0 - (\tau_s - \tau_0)\left\{1 - exp\left(-\frac{h_0\gamma}{\tau_s}\right)\right\}$$

$$h = \frac{d\tau}{d\gamma} = h_0\left(1 - \frac{\tau}{\tau_s}\right)$$

  - ✓ Brown model (1989):

$$h_{\alpha\alpha} = h_0 \left|\left(1 - \frac{\tau}{\tau_s}\right)\right|^a sgn\left(1 - \frac{\tau}{\tau_s}\right)$$

  - ✓ Kocks model (1976):

$$\tau_c = \tau_0 - (\tau_s - \tau_0)\left\{1 - exp\left(-\frac{h_0\gamma}{\tau_s}\right)\right\} + h_s\gamma$$

$$\tau_c = \tau_0 + (\tau_s + h_s\gamma)\left\{1 - exp\left(-\frac{h_0\gamma}{\tau_s}\right)\right\}$$

  - ✓ Bassani & Wu model (1993):

$$h_{\alpha\alpha} = \left\{(h_0 - h_s)\, sec\,h^2\left[\frac{(h_0 - h_s)\gamma^\alpha}{\tau_s - \tau_0}\right] + h_s\right\} G(\gamma^\beta; \beta \neq \alpha)$$

$$G(\gamma^\beta; \beta \neq \alpha) = 1 + \sum_{\beta\neq\alpha} f_{\alpha\beta} \tanh\left(\gamma^\beta / \gamma_0\right)$$

Parameter Identification :

- ✓ Identification Procedure:
  The identification of the hardening parameters is based on experimental stress-strain curves. Compression tests have been carried out at Technical University Chemnitz by the research team of Professor T. Halle. A crystal plasticity model combined with the least square method have been used to determine the optimal parameters for the different hardening models. Engineering stress-strain curves in [110] and [100] directions are used for the estimation of the material parameters for the Brown model. The same method is applied for the identification of the material parameters for the other hardening models.

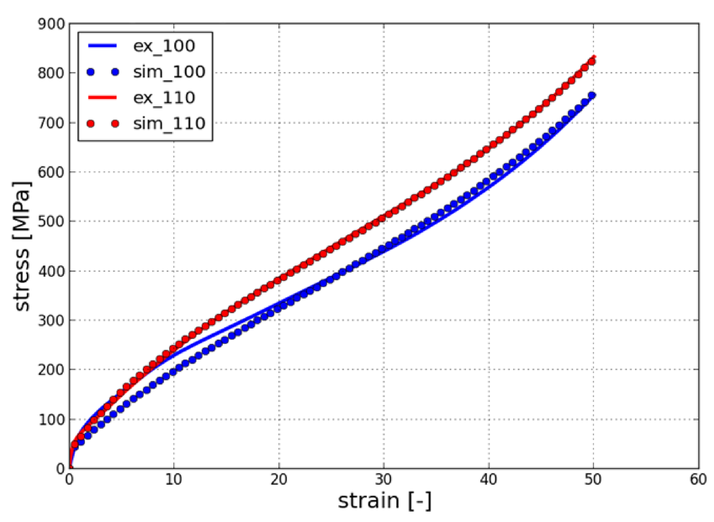

Figure 2. Experimental and predicted engineering stress-strain curves (the Brown model)

Simulation Results:

- ✓ ECAP Simulation:
  The ECAP simulation for a nickel single crystal with the crystallographic directions <010> parallel to the normal direction (ND) and <001> parallel to the transverse direction (TD) have been performed with a crystal plasticity material model using the Bassani and Wu hardening model (figure 3). After the deformation process, the Euler angles are extracted from the rotation matrix. Figure 2 shows the distribution of the Euler angles on the TD plane. The legends indicate the rotation angles in degrees around the axes.

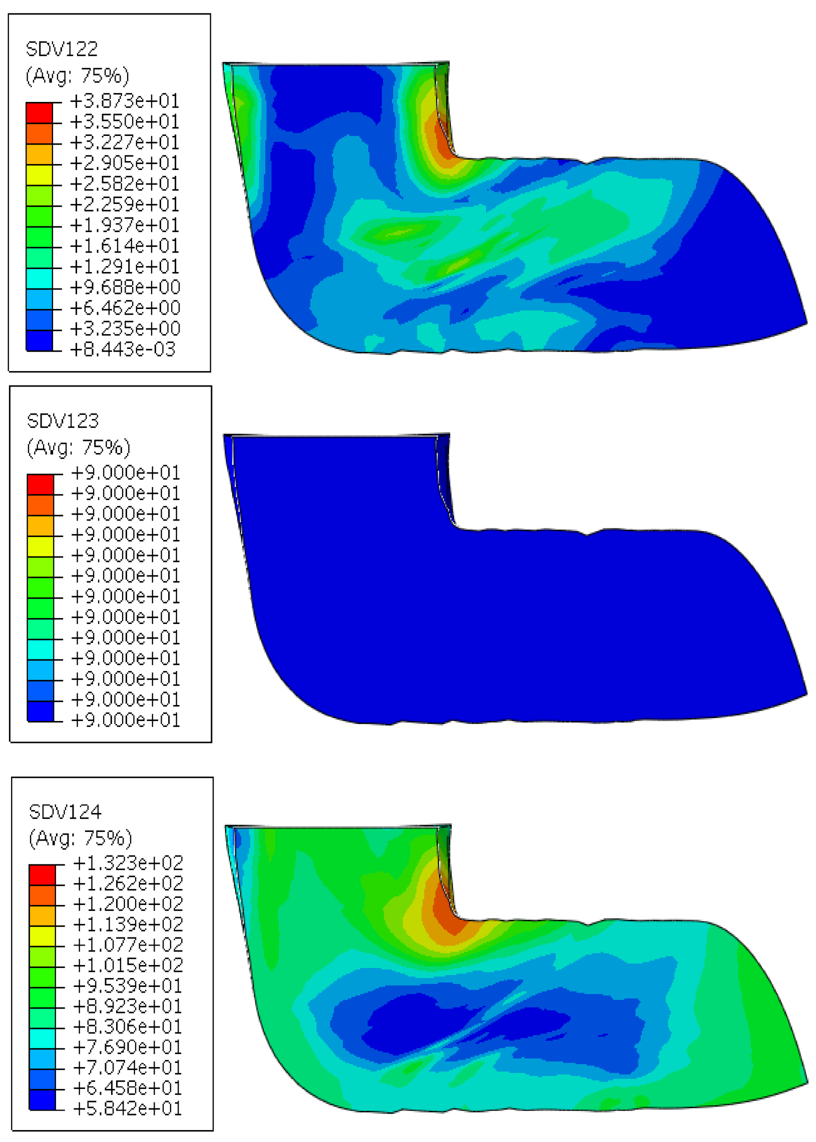

Fig. 2: Distribution of the Euler angles on the TD plane of the ECAP process

MTEX, a matlab toolbox, is used for analysis of the simulation textures. Calculated pole figures in different directions before and after the ECAP process are presented in figure 4.

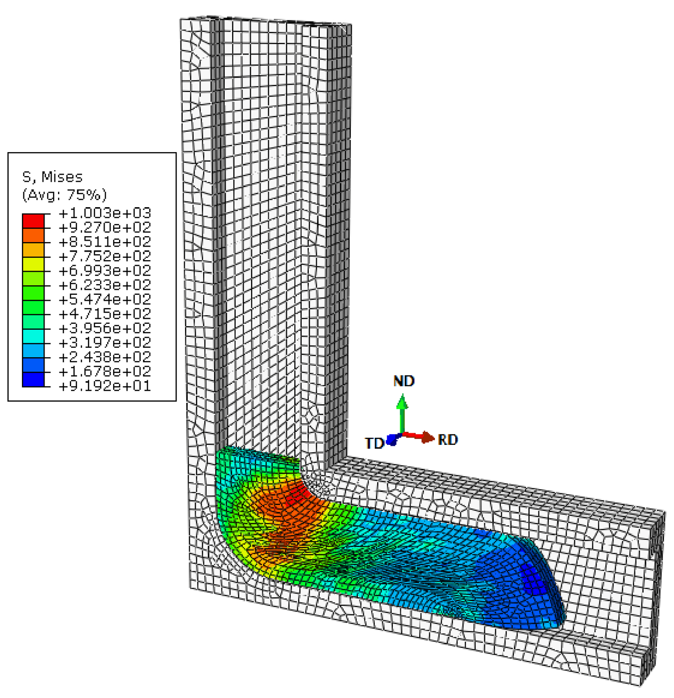

Fig. 3: Distribution of the von Mises stress on the TD plane of the ECAP process

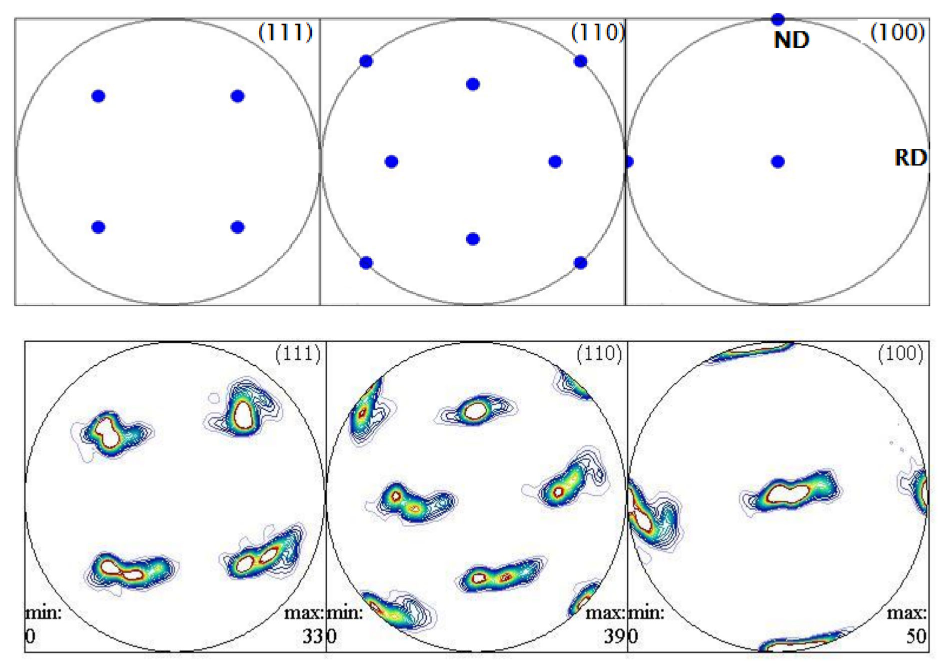

Fig. 4: Pole figure in [111], [110],[100] directions for a nickel single crystal before and after one-pass ECAP in the TD plane

Results and Discussion

The different hardening models are implemented into the finite element code, and the self-hardening parameters are estimated by comparing the experimental and simulation stress-strain curves. The results show that the hardening models used in this study can predict the three stages of strain-hardening in a nickel single crystal so that they can be used to simulate the hardening behaviour during the finite deformation due to multiple slip.
Pole figures for different directions are calculated and compared for the ECAP process. From comparing the pole figures before and after the ECAP process it can be seen that the orientations are spread around the initial orientations.

Conclusions

The results show that the hardening models used in this study can predict the three stages of strain-hardening in a nickel single crystal so that they can be used to simulate the hardening behaviour during the finite deformation due to multiple slip.
Scattering of the orientations after the deformation indicates the sub-grains formation during this process.

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