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Hardening behavior and texture evolution of TWIP steel during strain path change

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Abstract. Polycrystal materials exhibit large changes in the flow stress and hardening behavior during the strain path change. Such changes are related with the crystallographic texture anisotropy and the rearrangement of dislocation structure during the pre-loading. These effects have been captured by a dislocation hardening model embedded in the visco-plastic self-consistent (VPSC) model. In this work, the texture evolution and mechanical behavior of TWIP steel during the strain path change are investigated. The experimental studies are carried out on rolled TWIP steel sheet. The mechanical responses are obtained under tensile tests along rolling direction, followed by tension along the directions with 0° and 90° from the pre-loading direction. The simulated results of strain-stress curves and the texture evolution are in good agreement with the experimental data.

1. Introduction

Twinning-induced plasticity (TWIP) steel is characterized by an excellent formability despite having an extremely high tensile strength values up to 1500MPa. The TWIP steels are typically austenitic steels, i.e. face-centered cubic (FCC) alloys, with a high manganese content in the range of 15-30 mass%. In low stacking fault energy (SFE) austenitic steel, it is well known that twinning deformation results in increasing of the strain-hardening by the creation of the twin boundaries that act as strong barriers for the dislocation glide [1,2].

A lot of studies have been carried out to explain the work hardening behavior of metals and alloys subjected to strain path change. During last years, many authors have developed the constitutive models to account the Baushinger effect, strain hardening stagnation and permanent softening after reverse loading. Recently, Beyerlein and Tomé [3] have proposed a hardening model based on the classic Voce law. This model accounts for the direction and magnitude of shear for each slip plane in each grain. This approach is able to predict the transient mechanic response due to the strain path change.

The purpose of this study is to adopt the model developed by Beyerlein and Tomé [3] to predict mechanical behavior and microstucture evolution of TWIP steel during the strain path change. A new formulation is added to account for the effect dislocation recombination. It is shown that this model captures well the mechanical response.

2. Experimental procedure

Large dog-bone samples are cut from a 1.8 mm thick sheet of FeMnAlC austenitic TWIP steel, with gauge length of 300 mm and width of 60 mm, and then subjected to uniaxial tensile test for a pre-strain of ε_p =9%. The pre-straining was carried out along the rolling direction (RD). Reloading was performed by uniaxial tensile tests done on tensile specimens cut from the pre-deformed material at 0° (RD) and 90° (TD) from the RD using as a guidance the striations left by rolling on the rolling plane. Pole figure measurements have been carried out on X-ray texture goniometer. From the processed data of the initial texture, a discrete set of 1000 grains have been weighted, extracted and used for the input of the VPSC model [3].

3. Modeling

During reloading of metals and alloys, the significant changes in the reloading yield stress and hardening evolution depending on the direction of reloading are observed [4]. Such a behavior can be explained by the texture anisotropy and the dislocaiton-based microstructure evolution in single crystals. In the present work, these mechanisms are taken into consideration and the critical resolved shear stress (CRSS) can be expressed as:

$$\tau_c^\alpha = \tau_h^\alpha + \Delta\tau_B^\alpha + \Delta\tau_{rec}^\alpha \qquad (1)$$

where τ_h^α represents the strength due to the generation and patterning of dislocations. This term is calculated by the Voce law [5]. $\Delta\tau_{rec}^\alpha$ is related to the dislocation recombination. $\Delta\tau_B^\alpha$ represents the contribution of Bauschinger effect.

The dislocation structures generated during forward loading induce internal stresses, this stresses resists to the applied load and leads to immobilization of the dislocations during forward loading. During the strain path change a fraction of the dislocations (reversible dislocations) generated during pre-loading is reversed with a lower slip resistance. The reversibility of the dislocation under the applied loading leads to the yield stress drop after reloading, which is usually known as Bauschinger effect [6]. Beyerlein and Tome [3] propose the following expression for the evolution of $\Delta\tau_B^\alpha$ term with strain:

$$\Delta\tau_B^\alpha = \Delta\tau_{B,0}^\alpha \exp\left(-\frac{\upsilon_{new}^\alpha}{\upsilon_B}\right) \qquad (2)$$

$\Delta\tau_{B,0}^\alpha$ represents the degree of the reversibility and the reversible dislocations created during pre-strain. We should note that the value of $\Delta\tau_{B,0}^\alpha$ is negative when the shear on the slip system is reversed. The parameter υ_B is related to how fast the backstress is nullified with the accumulated strain on slip plane α since revese (υ_{new}^α).

After reloading, the reversible dislocations generated during pre-loading will be recombined gradually. It leads to a decrease of the total dislocation density and thus a decrese of the CRSS. Notice that the dislocation recombination is also dependent on the reversibility and the previous accumulated reversible dislocations. Therefore, the $\Delta\tau_{B,0}^\alpha$ is considered in the expression of $\Delta\tau_{rec}^\alpha$:

$$\Delta\tau_{rec}^\alpha = \Delta\tau_{B,0}^\alpha \left(1 - \exp\left(-\frac{\upsilon_{new}^\alpha}{\upsilon_{rec}}\right)\right) \qquad (3)$$

where υ_{rec} is the “rate” of the dislocation recombination.

4. Results and discussion

The measured true strain-true stress curves are presented in Fig. 1a. The experimental monotonic true stress-true strain curve loaded until 40% along RD is also shown. The yield stress during reloading decreases as the angle with respect to the preload direction increases. Fig. 1b shows the measured initial texture which is a typical brass-type texture for rolled sheet of low stacking fault energy metal. The measured final texture of the monotonic tensile test is presented in Fig. 1c.

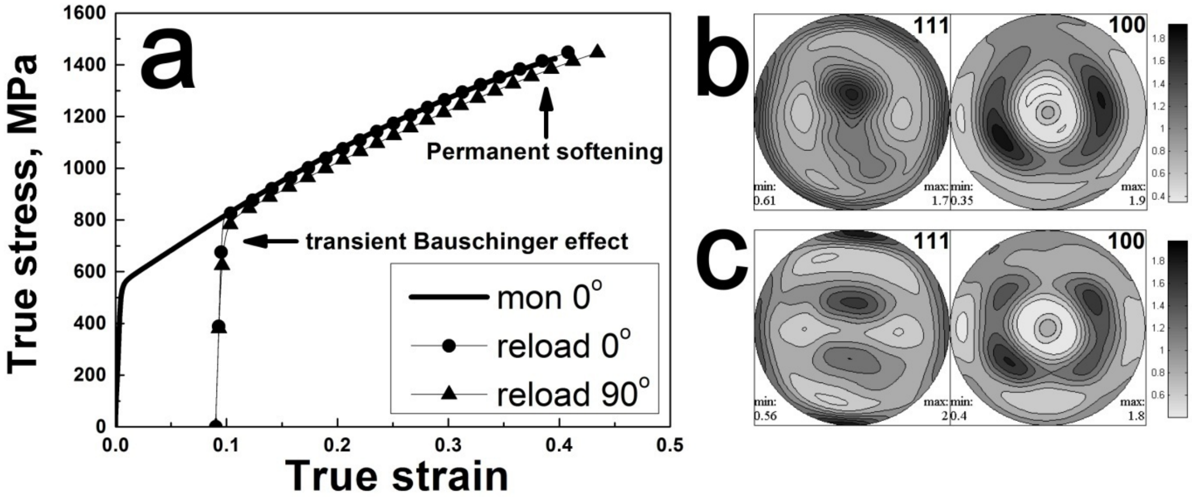

Fig.1 The experimental results (a) the measured true strain-true stress curves (b) measured initial texture (c) measured final texture after monotonic loading until 40%

Table 1. Hardening parameters

Slip				Twinning						
τ_0	τ_1	Θ_0	Θ_1	τ_0	τ_1	Θ_0	Θ_1	S^t	A^{th1}	A^{th2}
200	250	410	148	260	570	470	15	0.707	0.08	0.5

The simulation is carried out under the full strain-imposed boundary condition. The twinning reorientation is calculated by the Predominant Twin Reorientation (PTR) scheme [7]. The best results are obtained using the affine interaction. The VPSC model is not able to capture the elasto-plastic transition. In order to correctly evaluate the predicted curves, the elastic part of the experimental curves is removed. The VPSC framework associated with the new hardening law predicted successfully the deformation behavior. The values of the Voce hardening parameters (listed in Tab.1) are adjusted according to the experimental responses under the monotonic tensile test along the RD. Other hardening parameters are listed in Tab.2. The predicted true strain-true stress curves are shown in Fig. 2a and 2b. The predicted and experimental curves are in good agreement. This model captures well the effect of back-stress after reloading. The texture effect on strain path change is not evident in this work. The lower flow stress response for 90° reloading from RD is mainly contributed by the effect of dislocation recombination. The predicted texture evolution at different stages of deformation is presented in Fig. 3.

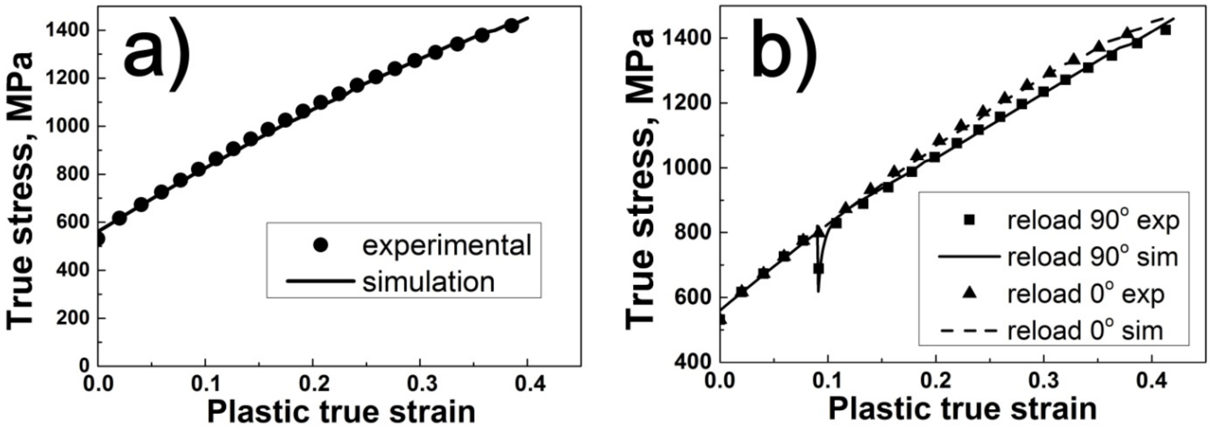

Fig.2. The simulation results for: true strain-true stress curve for monotonic tension (a) and for tension reloading at 0° and 90° from RD (b).

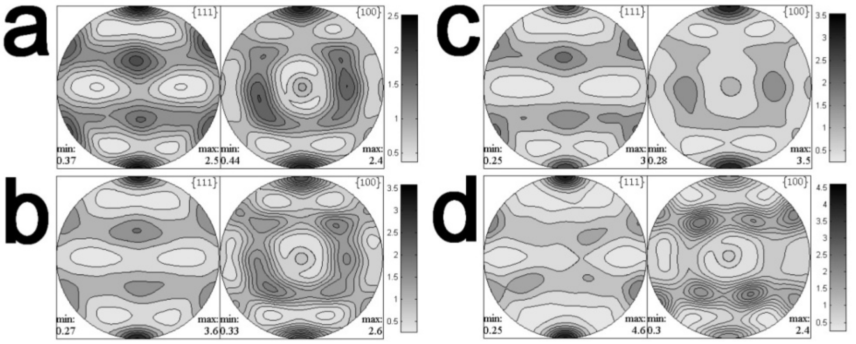

Fig.3. Predicted {111} and {100} pole figures for the texture after 9% pre-deformation (a), after monotonic loading (b), after tensile test reloading at 0° from RD (c), after tensile test reloading at 90° from RD (d).

Table 2. List of the material-dependent parameters for TWIP steel

	Value
μ (shear modulus)	60GPa
θ_B (rate of saturation for reverse shear)	15
$\upsilon_{B,sat}$ (maximum shear available for Bauschinger effect)	0.01
υ_B (related to how fast the backstress is nullified)	0.01
υ_{REC} (rate of the dislocation recombination)	0.5

5. Conclusions

In the present study, the hardening model, considering the various reversal mechanisms, is successfully applied to predict the mechanical response and texture evolution of TWIP steel subjected to two-step tension tests. The experimental results present a decrease of yielding stress during strain path change. This phenomena is well captured by presented model and contribution of the dislocation reverse-related mechanisms in the decreasing of yield stress is analyzed.

Acknowledgments

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