STRAIN HARDENING FOR STEEL UNDER NON-PROPORTIONAL LOADING

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Summary In this work, an approach is proposed for the description of the plastic behavior of materials subjected to multiple or continuous strain path changes. Although it is not formulated with a kinematic hardening rule, it provides a reasonable description of the Bauschinger effect when loading is reversed. The capability of this constitutive description is illustrated with applications on steel sheet samples subjected to two-step tension tests with varying angles between the two loading directions.

BACKGROUND

In actual forming, the deformation history experienced by any material point is not proportional but is dictated by the often complex processing route. In turn, the mechanical response of the material is strongly affected by this history. For instance, load reversal is accompanied by a Baushinger effect, which has been traditionally captured using a kinematic hardening model. In this work, an alternate method is proposed to describe the strain hardening after a strain path change.

EXPERIMENTAL

A series of two-step tension tests were conducted on extra deep drawing quality EDDQ and dual phase DP780 steel sheet samples. The first uniaxial tension step was conducted on a large specimen. Then, smaller specimens were machined at an angle ξ with respect to the previous axis and subjected to uniaxial tension again. All the tension tests were conducted on a 500 kN MTS tensile machine under a constant strain rate of 0.001/s. Fig. 1 shows the stress-strain curves for the EDDQ steel sheet measured in the transverse direction (TD) after a pre-strain of about 10% in the rolling direction (RD). This figure clearly shows that the flow stress after reloading overshoots the monotonic stress-strain curve. Then, a stage of strain hardening stagnation follows before the flow stress recovers the level of the monotonic curve. Both of these phenomena, stress overshooting and hardening stagnation, are known to result from dislocation interactions when slip systems are reversed or newly activated after a strain path change.

CONSTITUTIVE MODELING AND IDENTIFICATION

The HAH constitutive model [1] is based on a homogeneous yield function Φ of the stress deviator $\mathbf{s}$

$$\Phi(\mathbf{s}) = \left[\phi^q + f_1^q \left|\hat{\mathbf{h}}^s : \mathbf{s} - \left|\hat{\mathbf{h}}^s : \mathbf{s}\right|\right|^q + f_2^q \left|\hat{\mathbf{h}}^s : \mathbf{s} + \left|\hat{\mathbf{h}}^s : \mathbf{s}\right|\right|^q\right]^{1/q} = \bar{\sigma}$$

ϕ is a homogeneous anisotropic yield function of first degree, which expands in an isotropic manner during deformation, and q is a constant coefficient. Φ includes a tensorial state variable $\hat{\mathbf{h}}^s$, the microstructure deviator, which represents the dislocation microstructure evolution during the material loading history. The state variables f_k obey evolution laws that, after strain path change, capture the Bauschinger effect, a transient stage of high hardening rate that follows yielding and, possibly, permanent softening. Figure 2 shows schematically the yield surface shape in the π-plane after a change close to load reversal. It is worth mentioning that, for monotonic loading, the HAH approach is identical to isotropic hardening. Moreover, the coefficients describing plastic anisotropy and distortional hardening are calculated independently. In this work, a simple dislocation density based approach, which captures strain hardening stagnation after reverse loading and flow stress overshooting after cross loading [2, 3] governs the expansion of ϕ.

The curves of Fig. 1 were used for the coefficient identification of the EDDQ steel sheet sample using a simplex optimization method. The solid lines in these figures represent the calculated curves after the identification process showing that the flow stress is well captured by the HAH model. Note that, prior to identify the parameters and use the HAH model, the plane stress yield function Yld2000-2d [4] was selected to account for plastic anisotropy effects and the corresponding coefficients were calculated. A similar identification procedure was carried out on the DP780 steel sheet sample.

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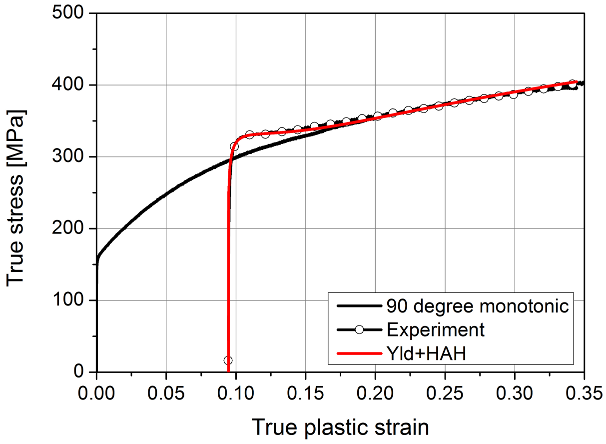

Figure 1. Two-step tension test with $\xi = 90^{\circ}$ for EDDQ steel sheet sample.

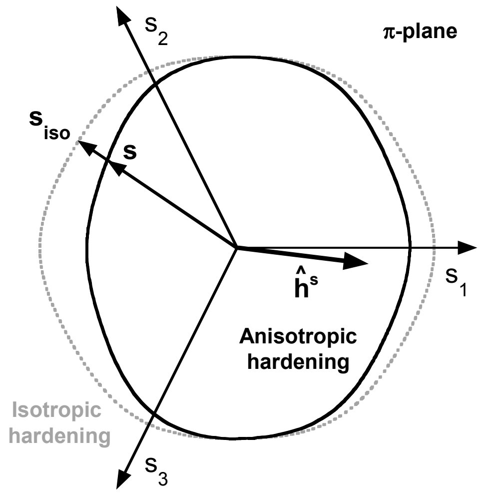

Figure 2. Schematics of yield surface distortion in π-plane after loading change

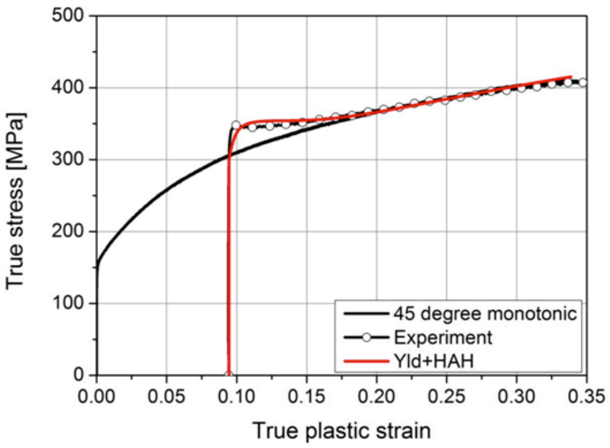

Fig. 3. Two-step tension test with $\xi = 45^{\circ}$ for EDDQ steel sheet sample.

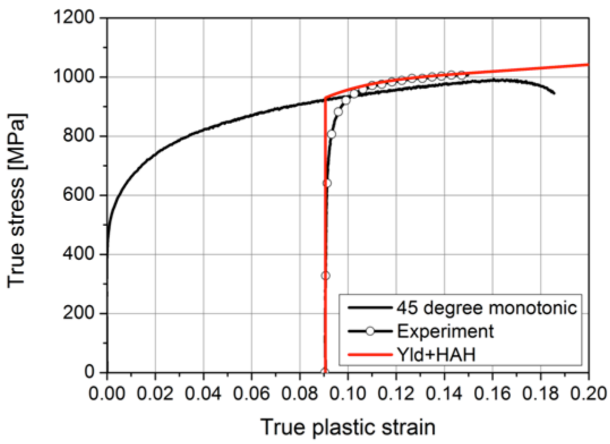

Fig. 4. Two-step tension test with $\xi = 45^{\circ}$ for DP780 steel sheet sample.

VALIDATION

Two-step tension tests similar to those of Fig. 1 were also conducted for different values of ξ. As an example, Fig. 3 shows the results for the EDDQ steel sheet with $\xi = 45^{\circ}$. All the predicted curves were in excellent agreement with the experimental data. In particular, the flow stress overshooting and strain hardening stagnation were well captured by the model. The HAH formulation indicates that the reloading flow stress should be identical to the unloading flow stress when $\xi < 55^{\circ}$ but lower when $\xi > 55^{\circ}$. This is in good agreement with the experimental results, as illustrated by Figs. 1 and 3. The HAH model was developed based on an understanding of the collective behaviour of dislocations. As a result, its application to EDDQ steel, which is a single phase material deforming by slip, was successful. In contrast, preliminary results for a dual phase (DP) steel showed that the HAH model overestimates the reloading flow stress when $\xi = 45^{\circ}$ (Fig. 4). This is likely due to the presence, in the DP steel, of a hard martensite second phase, which was not considered in the development of the HAH model. This work, however, provides a clear understanding of what is missing and what aspects to consider in order to improve the HAH formulation.

References

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