MODELLING THE EFFECT OF MICROSTRUCTURE EVOLUTION ON THE MACROSCOPIC BEHAVIOR OF SINGLE PHASE AND DUAL PHASE STEELS. APPLICATION TO SHEET FORMING PROCESS

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ABSTRACT- The aim of this work is to develop a dislocation density based model for IF and DP steels that incorporates details of the microstructure evolution at the grain-size scale. The model takes into account (i) the contribution of the chemical composition for the prediction of the initial yield stress, (ii) the description of initial texture anisotropy by incorporating grain-size dependent anisotropy coefficients in Hill'48 yield criterion, (iii) the contribution of three dislocation density "families" that are associated with forward, reverse and latent structures. It reproduces the macroscopic transient behaviors observed when strain-path changes occur. The model is implemented in FE code in order to assess its predictive capabilities in case of industrial applications.

INTRODUCTION: Several experimental studies reported that transient regimes (*i.e.* Bauschinger effect, work-hardening stagnation and softening) in the macroscopic behavior can be attributed to the evolution of the underlying microstructural details, such as dislocation structures (Gardey *et al.* [2005]). Moreover, during sheet metal forming processes local material points may experience multi-axial and multi-path loadings. Hence, many researchers focused on physically-based models that take into account the consequence of the evolution of the dislocation structures on the macroscopic behavior in order to predict the effect of strain-path changes. However, when dealing with industrial applications, some other constraints are imposed. Indeed, models (i) have to be user-friendly with limited number of material parameters with strong physical relevance; (ii) should consider "simple" measurable microstructure data such as grain size in input; and (iii) should be time-efficient (low CPU times). Hence, in the present work an innovative approach that accurately estimates steels behavior by only changing few microstructure data (*e.g.* chemical composition, grain size…) is proposed. The phenomenological hardening model developed in this work incorporates details of the microstructure evolution at the grain-size level based on Kocks-Mecking's approach in order to realistically reproduce the experimentally observed transients in the macroscopic behavior of IF and DP steels after strain-path changes.

DEVELOPPED MODEL: The predictive character of the model is achieved trough a set of physically-based parameters (k_1, k_2, λ and n_0) which is specific for metals from the same grade, where:

- k_1 stands for the dislocation storage rate which results in hardening.
- k_2 stands for the dislocation annihilation rate which results in softening.
- λ stands for the dislocation spacing.
- n_0 is the critical number of dislocations that have been stopped at the boundary on a given slip band.

This parameter set enables the work-hardening's behaviour prediction of other metals from the same grade by only modifying mean grain size D and initial yield stress Y_0.
The model consists on a combination of isotropic and kinematic hardening contributions. Based on the von Mises criterion, the yield function f is given by:

$$f = \phi(\boldsymbol{\sigma} - \mathbf{X}) - (Y_0 + R) = 0\,, \qquad (1)$$

where $\mathbf{X}$ denotes the kinematic hardening and R the isotropic hardening. Y_0 is the initial yield strength and is a function of the chemical composition and the mean grain size D. ϕ is a function of the Cauchy stress $\boldsymbol{\sigma}$ given by:

$$\phi(\boldsymbol{\sigma} - \mathbf{X}) = \sqrt{\frac{3}{2}(\boldsymbol{\sigma}' - \mathbf{X}):(\boldsymbol{\sigma}' - \mathbf{X})}\,. \qquad (2)$$

The evolution equation for the kinematic hardening is given by an Armstrong-Frederick's saturation law:

$$\overset{\circ}{\mathbf{X}} = \frac{2}{3} C_X X_{sat} \mathbf{D}^{\mathrm{p}} - C_X \mathbf{X} \dot{\lambda}\,, \qquad (3)$$

where C_X and X_{sat} are material parameters. C_X characterizes the saturation rate of $\mathbf{X}$ and X_{sat}

characterizes the saturation value of $\|\mathbf{X}\|$. $\mathbf{D}^p$ stands for the plastic strain rate and $\dot{\lambda}$ is the plastic multiplier. Hereafter, $(\circ)$ stands for the objective rate.

According to[1] and [2],

$$\begin{cases} C_X = f(\lambda, b, n_0) \\ X_{sat} = f(M, \mu, b, n_0, D) \end{cases}, \qquad \textbf{(4)}$$

where μ stands for the shear modulus, b for the magnitude of the Burgers vector and M is the Taylor factor and takes into account the texture development (M=3).

The isotropic hardening is given by:

$$R = M\alpha\mu b\sqrt{\rho}\,, \qquad (5)$$

where α is a constant and ρ is the dislocation density.

Dislocation density evolution is given by:

$$\left(\frac{d\rho}{d\overline{\varepsilon}^p}\right) = M\left(k_1\sqrt{\rho} - k_2\rho\right) \qquad \textbf{(6)}$$

According to [1] and [2], Eq. 5 is equivalent to a Voce rule in which:

$$\begin{cases} C_R = f(M, k_2) \\ R_{sat} = f(M, k_1, k_2, \alpha, \mu, b) \end{cases}, \qquad (7)$$

where C_R and R_{sat} are Voce rule's material parameters, R_{sat} being the asymptotic value of the isotropic hardening stress R at infinitely large plastic strain and C_R controls the rate of isotropic hardening.

PROCEDURES, RESULTS AND DISCUSSION: After realizing mechanical tests that enable displaying macroscopic transient behaviors under monotonic, reverse and non proportional loadings, the predictive capabilities of the developed model are validated on a set of nine IF steels with average grain sizes between 8 and 40µm, and a set of eight DP steels with different martensite volume fractions and average grain sizes between 1 and 10µm. For each category (*i.e.* single phase ferrite steels or dual phase ferrite-martensite steels), the material parameters are first identified for one "reference" steel (Fig. 1), (*i.e.* for a given microstructure data). Therefore, the macroscopic behaviors for the other steels are predicted by only changing microstructural data (chemical composition, ferrite and/or martensite grain sizes, martensite volume fraction and chemical composition). Such an approach reduces the time-consuming mechanical tests and identification procedures.

The developed microstructural phenomenological model is extended to ABAQUS/Explicit through the implementation of a VUMAT subroutine in order to assess its abilities to predict the material behavior. The cross-shape drawing is used for the thickness comparisons between simulations and experiments.

The die design and blank configuration is shown in Figure 1. A 800kN drawing hydraulic press is used with a blank holder force of 350kN. The square blank size has been chosen to be 300x300mm. The punch and die radii values are respectively 20mm and 14mm. Punch, blank holder and die are made of uncoated hardened tool steel. The blanks were lubricated with grease and Teflon. Limited possible drawing depth is around 50mm for the given blanks. Experiments have been performed at a drawing speed of 60mm/s. shows a typical drawn blank. The blanks have been marked with a 2mm dotted pattern (Figure 3) and forming analysis have been performed with the ARGUS strain measurement system with a ±1% strain accuracy (Figure 4). It measures deformations in deep-drawn parts and calculates material strain using optical measuring techniques.

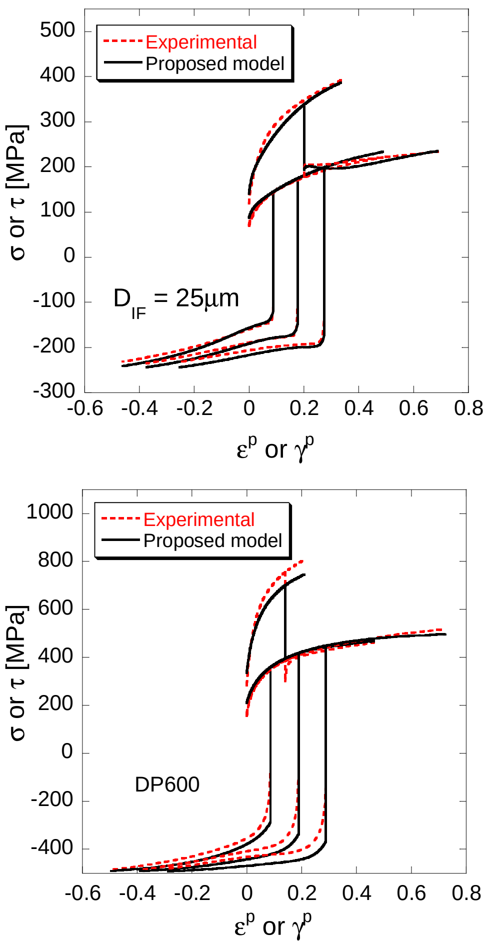

Figure 8. Results of the microstructural model identification procedure: IF steel (up) and DP steel (down).

ARGUS processes and visualizes the data gathered in order to obtain an image of the distribution of strains in the measured part. The material thinning is measured along three directions (i.e. rolling direction RD, diagonal direction DD, normal direction ND) as depicted in Figure 3 with the SOFRANEL thickness measurement system (Figure 4). This experimental setup is constituted by an ultrasonic transducer. The transducer is excited by a pulse/receiver (SOFRANEL 25 DL). Thickness is obtained in function of wave's displacement velocity in the blank. Thickness accuracy is of ±0.01mm.

The finite element simulations exhibit good predictive capabilities in terms of thickness distribution, draw-in, forming loads (Fig. 2 left). The simulations emphasize that the effect of strain-path changes on thickness distribution becomes relevant only when the amount of the equivalent plastic strain is high enough (Fig. 2 right). Also, this work allowed confirming that the role of the yield criterion is as significant as that of the hardening model.

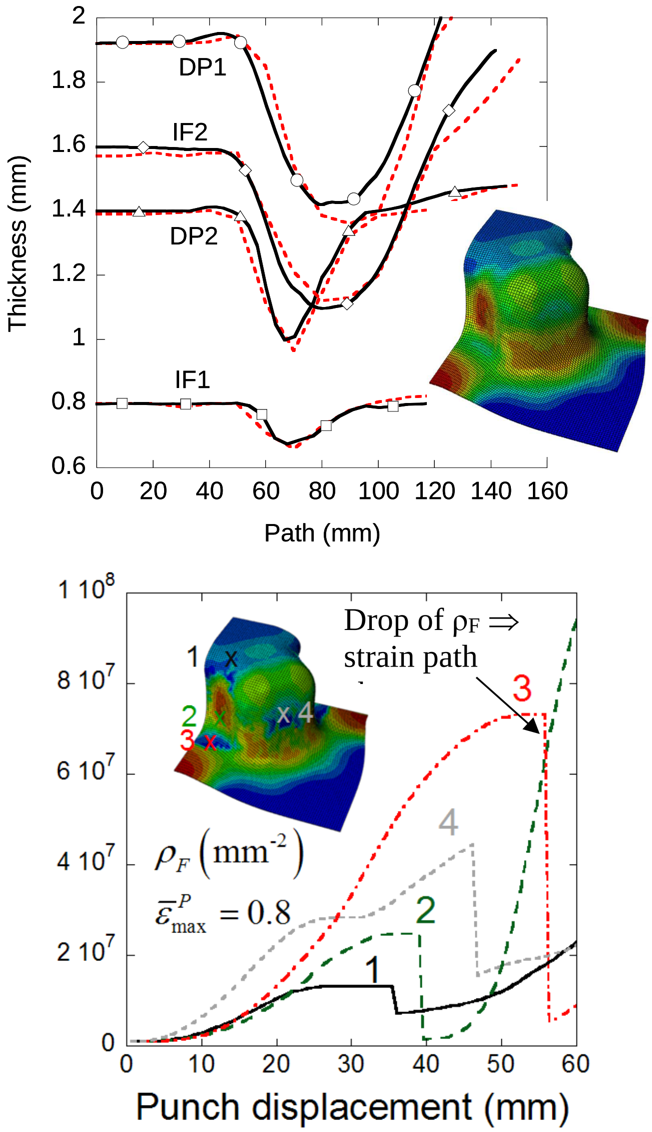

Figure 9. (Up) Thickness distribution along the rolling direction for different grades of IF single phase and dual phase steels (different initial sheet thicknesses). Dash lines: Exp, Continuous lines: Model. (Down) Forward dislocation density ρF distribution at 60mm punch displacement and evolution (right) for an IF.

Hence, on the one hand, it was noticed that a good estimation of r-values in highly anisotropic IF steels is suited for simulations accuracy. On the other hand, DP steels turned out to be less sensitive to r-values estimation. Such observations lead us to the following perspective: as anisotropy of materials evolves during deformation, an evolutionary Hill'48 physically-based yield criterion could be developed by introducing the evolution of r-values

Forming Limit Diagrams (FLDs) have been empirically constructed to describe the strain states at which a highly localized zone of thinning, or necking, becomes visible on the surface of sheet metals. FLDs can be experimentally obtained through Marciniak Stretch test, which is a modified dome test. It was designed to overcome the severe strain gradients developed by the traditional dome tests using a hemispherical punch (e.g. Nakajima test). Many automotive manufacturers use Marciniak Stretch test as a validation tool before simulating real parts.

The work described is an implementation [2] of a 3D dislocation based model in ABAQUS/Explicit together with its validation on a finite element (FE) Marciniak Stretch test. In order to assess the performance and relevance of the 3D dislocation based model in the simulation of industrial forming applications, FLDs will be plotted and compared to experimental results for different IF steels.

CONCLUSIONS: A dislocation density based model that incorporates details of the microstructure evolution at the grain-size scale is developed and aims to describe the monotonic and transient work-hardening behavior of IF and DP steels observed experimentally when strain-path changes occur. The model is implemented into ABAQUS via a user subroutine VUMAT in order to assess its predictive capabilities and time efficiency. The effect of strain-path changes modeling during complex deep-drawing is investigated.

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