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Mechanical, microstructural behaviour and modelling of dual phase steels under complex deformation paths

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ABSTRACT

This paper aims to identify the mechanisms associated to the transient hardening behaviour of dual phase steels under strain path changes, and to capture the observed material behaviours with appropriate constitutive models. First, three DP steel sheets with different amounts of martensite were tested under monotonic and various strain path changes. Second, microstructural analysis of the materials before and after strain path change were performed by means of SEM, TEM, and EBSD. The contribution of texture evolution on the mechanical behaviour was also assessed using the visco-plastic self-consistent (VPSC) polycrystal plasticity model. Transient hardening behaviour and permanent softening were observed in the tension–tension tests for all the studied DP steels. These behaviours were explained by the development of strain gradients during the first load resulting from strain accommodation incompatibilities between the ferrite and martensite phases. For the purpose of describing the macroscopic material behaviours, the enhanced homogeneous anisotropic hardening (HAH) model (Barlat et al., 2014) integrated with the Yld2000-2d anisotropic yield function were adopted for constitutive modelling. The simulation results were discussed in view of the microstructure evolution.

1. Introduction

Dual phase (DP) steels are of high commercial importance as engineering material due to their unique properties of strength and ductility (Khan et al., 2012; Matsuno et al., 2015). They have been extensively used in the production of automotive components with reduced weight but improved crash performance (Bouaziz et al., 2013). Their mechanical behaviours can be interpreted from their microstructure, which is predominantly composed of soft ferritic matrix with hard martensitic particles. The hard martensite provides substantial strength while soft ferrite phase is associated with good ductility.

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In many cases, metallic components can be economically produced by sheet metal forming operations. These operations always involve large strains and complex loading paths that can significantly change the sheet metal formability and promote plastic instabilities with negative consequences on the quality of the final products. The optimization of these operations can be attained numerically with finite element (FE) simulations. However, the success of this approach relies on the accuracy of the constitutive equations that describe the mechanical behaviours of the metals under the processing conditions. Thus, they should be based as much as possible on the physical mechanisms of plastic deformation under monotonic and complex loading conditions.

Flow stress, strain hardening and plastic anisotropy are crucial parameters that have to be considered in the constitutive equation formulations. In the un-deformed state, plastic anisotropy is usually controlled by the crystallographic orientation of the grains while strength and strain hardening are strongly affected by other microstructural features such as solutes and second phases. After a certain amount of plastic deformation, anisotropy and strain hardening are also affected by the dislocation structure (Akbarpour and Ekrami, 2008; Gracio et al., 2004; Lopes et al., 2003; Rauch et al., 2007). These microscopic features tend to interact with each other and their evolution leads to a complex anisotropic mechanical behaviour.

The dislocation microstructure developed in the plastic deformation depends on the distribution of slip on the active systems, which change with the loading conditions, and material characteristics such as crystal structure, grain orientations, stacking fault energy, second phases and solutes, etc. (Rauch, 2000). In polycrystalline materials, the dislocation microstructure also depends on the local stresses associated with the compatibility of plastic deformation between neighbour grains or second phases (Abid et al., 2015).

Due to prior thermo-mechanical processing, the grains of polycrystalline materials usually exhibit preferred crystallographic orientations that evolve during plastic deformation. The effect of crystallographic texture on the flow stress can be estimated using the average value of the macroscopic stress to the critical resolved shear stress ratios (<M>). Lower or higher values of <M> correspond to, respectively, more or less favourable grain orientations for slip due to the applied stress.

Premature plastic flow localization can also occur due to a change of strain path, which affects the dislocation substructure evolution. In turn, the stress–strain curve depends on this evolution and, in particular, on the amplitude of the strain path change, which can be characterized by the parameter α proposed by Schmitt et al. (1994).

$$\alpha = \frac{\varepsilon_p \cdot \varepsilon}{\left\|\varepsilon_p\right\| \left\|\varepsilon\right\|} \tag{1}$$

In the above relationship, ε_p and ε correspond to the strain tensors of the pre-strain and subsequent loading, respectively. The highest and lowest values of α, i.e., 1 and -1, represent monotonic and reverse loading tests, for which the slip system is reactivated in the same and opposite directions, respectively. A value of α equal to zero corresponds to a cross-loading condition for which the prior activated slip systems become latent during reloading (Rauch et al., 2011).

In the past decades, most of the studies involving complex strain paths were performed on single phase metals (Haddadi et al., 2006; Haddag et al., 2007; Holmedal et al., 2008; Khadyko et al., 2016; Kitayama et al., 2013; Manik et al., 2015; Rauch et al., 2007; Resende et al., 2013; Rousselier et al., 2010; Wen et al., 2015). For these materials, the dislocation structures formed in the pre-strain become unstable during reloading and, by mechanisms involving multiplication and mutual annihilation of dislocations, a new structure, characteristic of the new strain path, develops (Nesterova et al., 2001a,b; Rauch et al., 2002). Depending on the pre-strain amount and amplitude of strain path change (α), this evolution may lead to transient strain hardening at the earlier reloading stage (Gardey et al., 2005; Vincze et al., 2005) and to premature strain localization (Da Rocha et al., 2009).

In recent years, many work have been dedicated to the mechanical behaviours of DP steels (Franz et al., 2009; Gardey et al., 2005, 2006; Ha et al., 2013; Larsson et al., 2011; Marcadet and Mohr, 2015; Resende et al., 2013; Sun and Wagoner, 2013; Tarigopula et al., 2008, 2009; Weiss et al., 2015; Yoshida et al., 2011; Yu and Shen, 2014). Their results revealed that the mechanical behaviours of DP steels present some distinctions compared with single phase steel, due to the existence of dispersed hard martensitic particles in the softer matrix. However, the influences of the local stain incompatibilities between the two phases on the macroscopic behaviour of these important advanced high strength steels (AHSS) during strain path change are not completely understood and need to be further investigated.

To capture the anisotropic work-hardening behaviours of materials under complex strain paths with the final aim to be used in the metal forming simulations, various types of constitutive models have been developed. For instance, the widely used kinematic hardening-based models (Chun et al., 2002a,b; Chung et al., 2005; Geng and Wagoner, 2002; Taherizadeh et al., 2015; Yoshida and Uemori, 2002; Yoshida et al., 2015) and multi-surface representations (Lee et al., 2007) were introduced to reproduce the complex hardening behaviours of materials observed under reverse loading conditions, such as transient hardening at high rate, flow stress stagnation and permanent softening. A detailed review of these models was addressed by Chaboche (2008) and further by Yoshida et al. (2015). Recently, considerable attention has been focused on the constitutive description of the anisotropic hardening behaviours of DP steels. The developed models can be divided into two categories: physical approaches and phenomenological approaches. Concerning the physical approaches, some micromechanical models (Franz et al., 2009; Kim et al., 2012; Lai et al., 2015; Resende et al., 2013; Wei et al., 2015; Yoshida et al., 2011) have been proposed by incorporating a number of microstructural parameters, which were used to describe the mutual interactions between phases, dislocation–grain-boundary interactions and other microstructural features. The

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