International Journal of Plasticity 80 (2016) 204–221

Contents lists available at ScienceDirect

International Journal of Plasticity

journal homepage: www.elsevier.com/locate/ijplas

Work hardening descriptions in simulation of sheet metal forming tailored to material type and processing

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ARTICLE INFO

Article history:
Received 29 August 2014
Received in revised form 5 November 2015
Available online 1 December 2015

Keywords:
A. Dislocations
B. Constitutive behaviour
C. Mechanical testing

ABSTRACT

In the previous decades much attention has been given on an accurate material description, especially for simulations at the design stage of new models in the automotive industry. Improvements lead to shorter design times and a better tailored use of material. It also contributes to the design and optimization of new materials.

The current description of plastic material behaviour in simulation models of sheet metal forming is covered by a hardening curve and a yield surface. In this paper the focus will be on modelling of work hardening for advanced high strength steels considering the requirements of present applications. Nowadays work hardening models need to include the effect of hard phases in a soft matrix and the effect of strain rate and temperature on work hardening.

Most material tests to characterize work hardening are only applicable to low strains whereas many practical applications require hardening data at relatively high strains. Physically based hardening descriptions are used for reliable extensions to high strain values.

1. Introduction

Improvements in the simulation of forming processes and mechanical performance of car bodies lead to shorter design times and a better tailored use of material. A better understanding of the underlying physical principles contributes to the design and optimization of new materials. Robust optimization of forming processes using numerical models can lead to higher efficiency (Wiebenga et al., 2014). These developments have one requirement in common: a reliable model to describe the behaviour of new steel grades with complicated multi-phase microstructures at various process conditions, including temperature and strain rate ranges. The classical description of plastic material behaviour in simulation models of sheet metal forming is covered by a hardening law and a yield surface. There is a tendency to move away from pure phenomenological models for this constitutive behaviour to models based on underlying physical principles (Carvalho Resende et al., 2013). Physical principles allow reliable extrapolation to large strains, in particular to stage IV work hardening, like in this paper and in Pantleon (2004). Most developments however focus on strain path changes with underlying mechanisms of latent hardening in cross-loading and dislocation annihilation in strain path reversal. Essential for these descriptions is the distinction between statistically stored and geometrically necessary dislocations. The latter ensure compatibility of deformation (Mughrabi, 2004). In Bertin et al. (2013, 2014) several aspects taken from discrete dislocation dynamics are

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http://dx.doi.org/10.1016/j.ijplas.2015.11.002
0749-6419/

incorporated in a numerical dislocation density based model to predict latent hardening. Hamelin et al. (2011) combine a mesoscopic hardening model for the critical resolved shear stress with a statistical crystal plasticity approach to simulate both hardening and anisotropic behaviour through texture development. A similar approach is used by Peeters et al. (2001) and Eyckens et al. (2015) to simulate differential hardening. One of the most promising developments in describing latent hardening and cross-loading was initiated in Rauch et al. (2011) and refined in publications by Barlat et al. (2013), Kitayama et al. (2013) and Lee et al. (2013). The homogeneous anisotropic hardening model in these publications was proposed in Barlat et al. (2011). The yield function in this model includes a tensor state variable that represents the microstructure evolution during the material loading history. Simulations show a remarkably good prediction of cross-loading behaviour for single phase material.

The current paper extends the hardening law for some practical process conditions and material types, based on underlying physical principles. With shorter production runs in the press shops the temperature range between start up and continuous production becomes more important. An accurate description of temperature and strain rate dependency of the flow stress is therefore required. For the description of the hardening behaviour of multiphase materials consisting of phases with different hardness, the additional influence of Geometrically Necessary Dislocations (GND's) due to deformation gradients between the phases must be considered. Lyu et al. (2015) takes the effect of these GND's in dual phase steels into account by making use of continuum dislocation dynamic model coupled with a viscoplastic self consistent model for the effect of the orientations of the individual grains. With this model, both the dislocation evolution inside the grain and the grain to grain interaction can be described. By introducing the influence of the GND density on the mean free path and its consequence on work hardening, an influence of the grain size can be derived. Ramazani et al. (2013) uses a full field FE-model where he is reporting on the influence of work hardening by a second type of GND's due to incompatibility of the two phases after the transformation from austenite to ferrite in dual phase steels.

Initially, a more classical approach is used here to derive the hardening law, based on the development of dislocation cell structures and its effect on work hardening. Complexity is added to the model in the following steps:

- Initial yielding followed by usual stage III hardening (Bergström, 1969)
- Work hardening at high strains indicated as stage IV hardening (Van Liempt, 1994)
- Influence of phase boundaries in multiphase steels (Vegter and Van Liempt, 2011)
- Influence of temperature and strain rate on work hardening (Bergström and Hallén, 1982)
- Thermally activated movement of dislocations over obstacles (Krabiell and Dahl, 1981; Larour, 2010)
- Effect of strain path on work hardening (Yoshida and Uemori, 2002; Rauch et al., 2011; Verma et al., 2011; Barlat et al., 2011; Van Riel and Van den Boogaard, 2007)

It is important to recognize that these phenomena can play a role in the material behaviour during forming processes. A hardening model needs to capture these phenomena that have become more important with current steel developments and increased accuracy requirements for manufacturing and performance predictability. More advanced phenomenological approaches are equally successful in the description of hardening curves (including the effect of strain rate and temperature) aimed for simulation of forming (Sung et al., 2010; Larour, 2010). In connection with new material development however, microstructure based material models can be helpful for identification of differences between materials or between batches of the same material grade, by the physical meaning of the model parameters.

The value of an advanced hardening model relies on the capability to characterize the individual contributions to the hardening behaviour. Developments in measuring techniques, in particular in optical strain measuring systems, have contributed to a more detailed knowledge of mechanical test methods. Combined with better models, the test results are interpreted more accurately. Some of the above phenomena require specific tests. It is for instance important to recognize that stage IV work hardening of steel is not captured by the conventional uni-axial tensile tests and a reliable extrapolation of hardening to high strain values depends therefore on other test results, e.g. from a stack compression test, a hydraulic bulge test or a uni-axial test with the capability to measure the geometry change in time of the necked zone. Advanced hardening models have developed from single curve fitting to more complicated material descriptions requiring input from multiple tests (Yoshida and Uemori, 2002; Kuwabara, 2007; Van Riel and Van den Boogaard, 2007; Vegter and An, 2008; Smith et al., 2014).

2. Description of work hardening including the effect of strain rate and temperature

One of the first publications on the in general additive contributions to the flow stress of metallic materials is by Kuhlmann-Wilsdorf (1962). This classical abstraction assumes that the flow stress (initial threshold level) depends on strain rate and temperature (concept of thermal activation) and the dislocation density evolves with strain (hardening). This concept is generally accepted (Bergström, 1969; Mecking and Kocks, 1981), and is usually formulated, with the hardening term according to Taylor (1934), as:

$$\tau_f = \tau_{f0} + \alpha_D \cdot G \cdot b \cdot \sqrt{\rho_i} \tag{1}$$