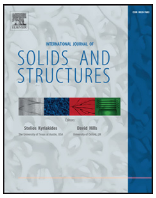
International Journal of Solids and Structures 000 (2017) 1–7

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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



On the nonlinear anelastic behavior of AHSS

A. Torkabadi*, E.S. Perdahcıoğlu, V.T. Meinders, A.H. van den Boogaard

Nonlinear Solid Mechanics, Faculty of Engineering Technology, University of Twente, Enschede, The Netherlands

ARTICLE INFO

Article history:
Received 30 November 2016
Revised 3 March 2017
Available online xxx

Keywords:
Springback
Anelasticity
Dislocations
Nonlinear unloading
AHSS

ABSTRACT

It has been widely observed that the loading/unloading behavior of metals which have previously undergone plastic deformation is nonlinear. Furthermore it shows a hysteresis behavior upon further unloading/reloading cycles. The origin of this nonlinearity is attributed to additional dislocation based micromechanics which contribute to the total reversible strain, referred to as anelastic strain. Compared to a FE model prediction using only elastic contribution to reversible strain the actual springback will be larger. In this work the unloading behavior of DP800 AHSS is analyzed in detail and a mixed physical-phenomenological model is proposed to describe the observed nonlinearity for different levels of pre-strain. This one dimensional uniaxial model is generalized to a 3D constitutive model incorporating elastic, anelastic and plastic strains. The performance of the model is evaluated by comparing the predicted cyclic unloading/reloading stress-strain curves with the experimental ones. It is shown that by incorporating anelastic behavior in the model the prediction of the cyclic behavior of the material is significantly improved.

1. Introduction

There has been an increasing interest by the automotive industry towards employing Advanced High Strength Steels (AHSS) in the past years. However, due to springback, the dimensional accuracy of the components made of AHSS remains an industrial issue (Wagoner et al., 2013). Therefore, an accurate prediction and compensation of the springback are important for utilization of AHSS. Finite element simulations are typically used during the die design stage to estimate the springback in the part. The simulation results are used to adapt the die geometry to compensate for the springback (Burchitz, 2008). The accuracy of such simulations are highly dependent on the constitutive models employed in the simulations that can describe the material behavior during the forming process (Li et al., 2002a).

In the past years most of the research was focused on the development of novel plasticity models to give an accurate stress prediction. On the other hand, little has been done in modeling the material behavior during unloading upon release of the constraining force. The material behavior upon unloading is of importance for the springback prediction considering that the experimental evidence shows that assuming a Hookean behavior to describe the unloading is not realistic. It has been observed experimentally that the material shows a nonlinear unloading/reloading behavior after being plastically deformed (Cleveland and Ghosh, 2002; Eggertsen et al., 2011; Sun and Wagoner, 2011; Eggertsen and Mattiasson, 2010; Govik et al., 2014; Kim et al., 2013; Mendiguren et al., 2013, 2015; Pavlina et al., 2015a, 2015b; Chen et al., 2016b, 2016a). This is caused by an extra reversible strain recovered during unloading along with the pure elastic strain (Cleveland and Ghosh, 2002; Torkabadi et al., 2015; van Liempt and Sietsma, 2016; Arechabaleta et al., 2016). The root cause of this phenomenon has been proposed to be the short-range reversible movement of the dislocations known as anelasticity (Zener, 1948; Ghosh, 1980; Pérez et al., 2005; van Liempt and Sietsma, 2016; Arechabaleta et al., 2016; Chen et al., 2016a). The dislocation structures, which are impeded by the pinning points or piled up before the grain boundaries, can move to a new equilibrium upon the relaxation of the lattice stress and contribute to some extra microscopic strain. From an engineering perspective, considering that the total recovered strain during unloading governs the springback magnitude, it is essential to take into account the anelastic strain in the material models for the FEM springback simulations. In that respect, various researchers have adopted an approach attributed to E-modulus degradation (Morestin and Boivin, 1996; Li et al., 2002b; Yoshida et al., 2002; Yang et al., 2004; Fei and Hodgson, 2006; Yu, 2009; Chongthairungruang et al., 2012). In this approach the E-modulus of the material is made a function of the equivalent plastic strain in the simulations. Hence, the E-modulus represents the chord modulus which is measured from the cyclic experiments. In such experiments, the material is repeatedly plastically deformed to a certain pre-strain and unloaded to zero stress. The chord modulus repre-

---

* Corresponding author.
E-mail address: a.torkabadi@utwente.nl (A. Torkabadi).

http://dx.doi.org/10.1016/j.ijsolstr.2017.03.009
0020-7683/

sents the slope of the straight line connecting the stress point at the start of unloading to the point at zero stress. The drawback with the E-modulus degradation approach is that it is assumed that all the points in the material are unloaded to zero stress. This is not a realistic assumption in industrial forming processes, where residual stresses are commonly present after unloading, leading to significant errors in springback prediction (Wagoner et al., 2013).

In order to address the above mentioned issue, few attempts have been made in order to model the nonlinear unloading behavior. Eggertsen et al. (2011) and Sun and Wagoner (2011) have taken similar approaches based on the two-yield-surface plasticity theory (Lee et al., 2007) and proposed two-surface constitutive models in which the inner surface defines the transition between the linear and nonlinear elasticity and the outer surface gives the yield criteria. In that way, as long as the stress state is within the inner surface, the stress-strain relation remains linear. This was found in contradiction with the experimental observations (Chen et al., 2016a). On top of that, such models are built based on mathematical convenience rather than capturing the underlying physics of the phenomenon. The model developed by Sun and Wagoner, known as QPE model, has been incorporated with the homogeneous anisotropic hardening (HAH) model by Lee et al. (2013) and a combined isotropic-nonlinear kinematic hardening model by Ghaei et al. (2015) for springback simulations. They found an improvement in the springback prediction capability of the simulations using the QPE model in comparison with the E-modulus degradation approach.

It is therefore the aim of this study to develop a model for the nonlinear unloading behavior of the material for a better springback prediction. This is achieved by first quantifying the anelastic strain by uniaxial tensile tests using sensitive force and displacement measurements. After that a model is developed using the theoretical background of anelasticity in a uniaxial setting which is then generalized into a full 3D constitutive model following conventional continuum plasticity approach. Finally the results are validated by experiments.

2. Experimental procedure

For the experimental part of this study a commercially available DP800 steel grade is used which belongs to the AHSS family. The samples were cut according to ASTM E8 standard from a steel sheet with a thickness of 1 mm in the rolling direction. The tensile tests were conducted using a Zwick/Roell electromechanical universal testing machine and the strain was measured using a custom-made double-sided clip-on extensometer. The double-sided extensometer measures the strain on both sides of the specimen and outputs the average. At low strain levels, misalignment and bending of the sample can have a significant contribution on scatter and uncertainty in the strain measurement which is minimized by averaging the strain measured on both sides of the sample. All the experiments were performed at room temperature.

For the cyclic loading/unloading/reloading experiments (LUR), the controller was programmed to load the specimen to 6000 N and then unload it to zero force. Immediately after the first loading/unloading cycle, the specimen was reloaded to 6500 N of force and unloaded again. This procedure was repeated with increments of 500 N loading until 10 kN of force was reached. The cyclic tests were carried out at a constant crosshead speed of 2, 5 and 10 mm/min which results in strain rates of 0.0002, 0.0005 and 0.001 s^{-1} respectively. The schematic illustration of the experimental procedure is shown in Fig. 1. For every strain rate the experiment was performed on three specimens.

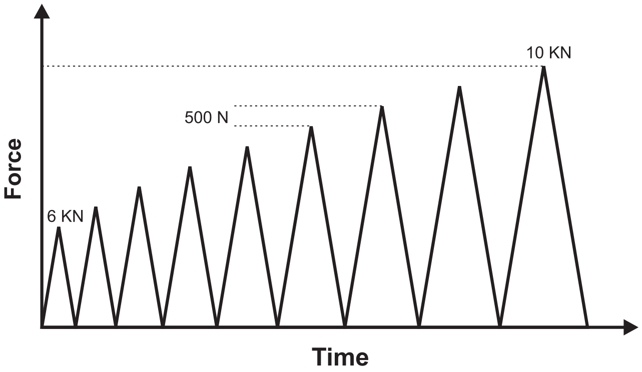


Fig. 1. Schematic illustration of the LUR experimental procedure.

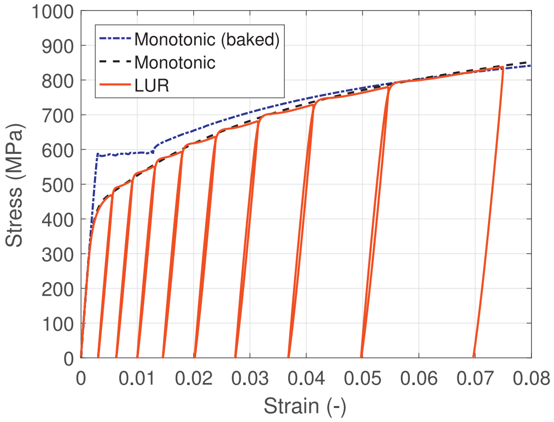


Fig. 2. Experimental stress-strain curves.

The hardening parameters of the material were determined from the monotonic tensile experiment. The specimen was strained up to 15% engineering strain at a constant crosshead speed of 5 mm/min resulting in a strain rate of 0.0005 s^{-1}.

In order to determine the pure E-modulus, the specimen was first baked at 220 °C for 20 min which theoretically should eliminate the anelastic behavior due to pinning of dislocations. Next, the specimen was strained up to 15% and the E-modulus of the specimen was determined according to ASTM E111 standard. The same pre-strained specimen was baked at the same condition once again and the E-modulus was reevaluated according to the same procedure. After every baking treatment, the specimen was first naturally cooled down to room temperature before the tensile test. The experiment was repeated with three specimens.

3. Experimental results

The stress-strain curves obtained from the monotonic (for the baked and as-received specimens) and cyclic (LUR) tensile experiments are shown in Fig. 2.

Comparing the tensile experiment results of the as-received and the baked specimens it is clear that the upper yield point and the yield point elongation phenomena are restored in the baked specimen. Such phenomena are associated with the lack of mobile dislocations in the material. At high temperatures interstitial solute atoms such as carbon can diffuse to the dislocation lines and pin them (Cottrell and Bilby, 1949). In this way when the material is loaded, the dislocations movement is confined and therefore the anelastic strain vanishes. Hence, the slope of the stress strain curve represents the pure elastic modulus. In this context this value is referred to as the E-modulus. To check whether the E-modulus of the baked specimen is affected by pre-straining, the same specimen (after 15% pre-strain) was baked at the same condition (at 220 °C for 20 min) and the E-modulus was re-evaluated. The stress-strain plots of the baked specimen before straining and the baked spec-

Please cite this article as: A. Torkabadi et al., On the nonlinear anelastic behavior of AHSS, International Journal of Solids and Structures (2017), http://dx.doi.org/10.1016/j.ijsolstr.2017.03.009