International Journal of Mechanical Sciences 53 (2011) 338–347

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Prediction of anisotropy and hardening for metallic sheets in tension, simple shear and biaxial tension

S.L. Zang [a,b,1], S. Thuillier [a,b,*], A. Le Port [a,b], P.Y. Manach [a,b]

[a] LIMATB, Université de Bretagne-Sud, Rue de Saint Maudé, BP 92116, F-56321 Lorient, France
[b] Université européenne de Bretagne, France

ARTICLE INFO

Article history:
Received 15 May 2010
Received in revised form
4 November 2010
Accepted 9 February 2011
Available online 21 February 2011

Keywords:
Anisotropic yield
Constitutive behavior
Metallic material
Mechanical testing

ABSTRACT

The mechanical behavior of mild and dual phase steel sheets is investigated at room temperature in quasi-static conditions under different strain paths: uniaxial tension, simple shear and balanced biaxial tension. The aim is to characterize both the anisotropy and the hardening, in order to identify material parameters of constitutive equations able to reproduce the mechanical behavior. In particular, a good description of flow stress levels in tension and shear as well as plastic anisotropy coefficients is expected. Moreover, the Bauschinger effect is investigated with loading–reloading in the reverse direction shear tests and the balanced biaxial tension test gives insight of the mechanical behavior up to very high equivalent plastic strains. Yoshida–Uemori hardening model associated with Bron–Besson orthotropic yield criterion is used to represent the in-plane mechanical behavior of the two steels. The identification procedure is based on minimization of a cost function defined over the whole database. The presented results show a very good agreement between model predictions and experiments: flow stress during loading and reverse loading as well as plastic anisotropy coefficients are well reproduced; it is shown that the work-hardening stagnation after strain path reversal is well estimated in length but Yoshida–Uemori model underestimates the rate of work-hardening.

1. Introduction

Nowadays, phenomenological models are widely used in finite element analysis of sheet metal forming process, since they present a good compromise between simulation accuracy and computation time. Such models of the elasto-viscoplastic behavior of sheet metals are based on the definition of a yield surface, to describe the initial anisotropy related to the crystallographic texture, and its evolution with plastic strain. Initial orthotropy is a good representation for rolled sheets and is assumed to be kept during strain, by considering a corotation of the anisotropy frame with material rotation. Strain-induced anisotropy, such as Bauschinger effect, is described by the evolution of internal variables with plastic strain. Several experimental tests, like tension-compression [1,2] and simple shear [3], have been performed to characterize the hardening behavior of sheet metals under strain reversal, which refers to the fact that the subsequent loading direction is opposite to that of former loading, and is quite common in sheet metal forming processes; for example, bending–unbending on the die radius and reverse bending–unbending at the punch nose. This behavior under strain reversal, called the Bauschinger effect, is characterized by a lower yield stress under strain reversal, further transient behavior that corresponds to the smooth elastic-plastic transition with a rapid change of strain-hardening rate, and a hardening stagnation, the magnitude of which depends on the prestrain and permanent softening characterized by stress offset.

The prediction of the anisotropy and hardening of metallic sheets depends not only on the constitutive model but also on the accurate material parameter identification which refers both to the type of the experimental tests being used and the identification methods. Tension, simple shear and balanced biaxial tension tests provide relevant information on the shape of the yield surface and its evolution with plastic strain. However, current researches seldom consider all of them to identify the material parameters. The general identification strategy is that the first step is the identification of the initial yield surface, using either the yield stresses or the anisotropy coefficients, or both, and the second step is the hardening behavior, e.g. [4].

In the present study, an alternative procedure is used and the material parameters of both the yield function and the hardening model are identified from the stress–strain curves and both longitudinal and transverse strain in tension at the same time. The constitutive equations are derived from Bron–Besson yield

* Corresponding author at: LIMATB, Université de Bretagne-Sud, Rue de Saint Maudé, BP 92116, F-56321 Lorient, France. Tel.: +33 297874570; fax: +33 297874572.
E-mail address: sandrine.thuillier@univ-ubs.fr (S. Thuillier).
[1] Present address: School of Mechanical Engineering, Xi'an Jiaotong University, No. 28, Xianning Road, Xi'an, Shaanxi, China.

0020-7403/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijmecsci.2011.02.003

function [5] and Yoshida–Uemori hardening model [6] and identification of material parameters in tension, monotonic and Bauschinger simple shear and balanced biaxial tension tests are presented for DP500 and DC04 steels: balanced biaxial tension allows to reach high equivalent plastic strain, whereas simple shear involves large material rotations. Considering these three tests leads to a complementary experimental database well suited for phenomenological approach, though it is rather constraining for parameter identification. The ability of Yoshida–Uemori model to predict the work-hardening stagnation after strain path reversal in simple shear is particularly studied. This test allows an equivalent plastic prestrain up to 0.2 to be investigated and to reach after straining an equivalent plastic strain of 0.5.

2. Experiments

Two thin sheet materials are considered in this study: a mild steel DC04, with a thickness $e=0.67$ mm and a dual phase steel with a thickness of 0.6 mm and a tensile strength of 500 MPa (DP500). For this last material, SEM micrographs have evidenced a volume fraction of martensite around 6% and a grain size of 5 μm. The mechanical behavior of these two steels is investigated under three different stress and strain states, i.e. uniaxial tension, simple shear (both of these tests are performed at several orientations to the rolling direction or RD) and balanced biaxial tension. The experimental procedure is described in the following paragraphs.

2.1. Tension

Tensile tests were carried out on rectangular samples of dimension 20 $\times$ 180 $\times$ e mm^3. The free edges were machined in order to eliminate the hardened areas induced by the cutting and thus to increase the range of homogeneous deformation. Components of the strain tensor in the sheet plane are calculated by image correlation. Monotonous tensile tests were carried out at 0°, 45° and 90° to the RD for DP500 and in addition at 22° and 77° for DC04, in order to study the material anisotropy. For these tests, a cross-head speed of 10 mm/min is imposed which leads to $\dot{\varepsilon} \simeq 2.4 \times 10^{-3}$ s^{-1}. The logarithmic strain as well as the Cauchy stress are calculated from the raw data (Fig. 1). The plastic anisotropy coefficients $r_\alpha = d\varepsilon^p_{YY}/d\varepsilon^p_{ZZ}$, where $\vec{e}_X$ denotes the tensile, $\vec{e}_Y$ the transverse and $\vec{e}_Z$ the normal directions, respectively, and α the angle between the RD and the tensile direction, are calculated from the transverse strain ε_{YY} and the assumption of volume conservation in the plastic area; they are given in Table 1.

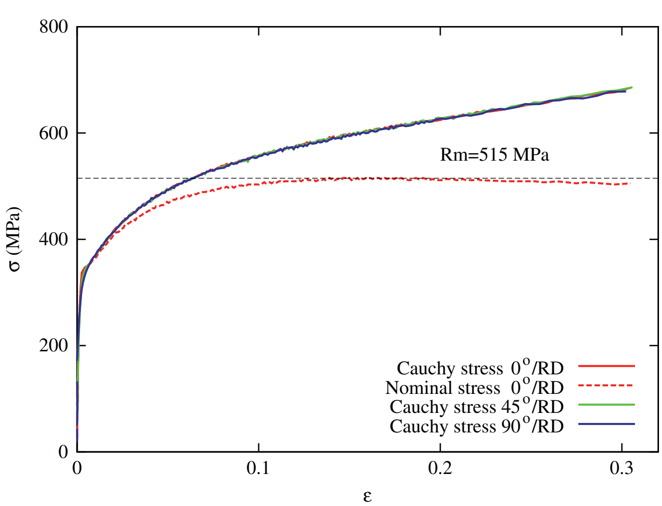

Fig. 1. Cauchy stress versus logarithmic longitudinal strain evolution for DP500 in tension. The strain range is investigated a little further necking, evidenced on the nominal stress–strain curve, and by neglecting any triaxiality effects in this area. This assumption has been validated by finite element simulation.

The deformation gradient $\boldsymbol{F}$ [7] in the central zone of the sample is given by $\boldsymbol{F} = F_{XX}\vec{e}_X \otimes \vec{e}_X + F_{YY}\vec{e}_Y \otimes \vec{e}_Y + F_{ZZ}\vec{e}_Z \otimes \vec{e}_Z$ where $\vec{e}_i, i=X,Y,Z$ are the basis vectors of the global reference frame. The test is controlled by the evolution of F_{XX} with time and by constraining $\sigma_{YY} = \sigma_{ZZ} = 0$. The signals calculated from the recorded raw data are the components F_{YY} and σ_{XX} = load/(actual section). The strain range is limited to its maximum value before necking, which corresponds to 0.18 for DP500 and 0.25 for DCO4, whatever the orientation to RD.

2.2. Simple shear

The simple shear device is presented in detail in [8]. The specimens have a rectangular shape, a gauge area of length L = 50 mm and width h of 4 mm; the shear direction is along the length of the specimen (Fig. 2). The samples are kept under the grips by six screws tightened by a dynamometric key which torque is calibrated depending on the tested material. The optimal value is obtained with the lowest torque that minimizes the sliding between the sample and the grips. Monotonous shear tests were performed on samples at the same orientations to the RD than for the tensile test, at a cross-head speed of 0.5 mm/min, which corresponds to $\dot{\gamma} = 2.1 \times 10^{-3}$ s^{-1}. Moreover, cyclic tests are performed in order to highlight the Bauschinger effect and to measure kinematic hardening parameters. These tests are composed of a loading up to several values of γ followed by a load in the opposite direction until $\gamma = -0.4$. Each kind of test is performed three times to check the reproducibility and a representative test is chosen for the database. Shear strain γ, which corresponds to the non-diagonal component of the planar transformation gradient in the case of an ideal simple shear kinematics [8], is measured from a digital correlation system and is then defined as an average over a rectangular zone on the sample surface. Fig. 2 shows a rather constant value of γ except near the free ends of the specimen, over a distance of approximately 5 mm.

The kinematics of the simple shear test can be described by $\boldsymbol{F} = \boldsymbol{I} + F_{XY}\vec{e}_X \otimes \vec{e}_Y$ with $\boldsymbol{I}$ the second order identity tensor. The test is controlled by the evolution of F_{XY} with time, where $\vec{e}_X$ is parallel to the shear direction and $\vec{e}_Y$ perpendicular to $\vec{e}_X$ in the sheet plane, and by constraining $\sigma_{iZ} = 0 (i=X,Y,Z)$. This assumption of a planar stress state comes from the small sheet thickness.

2.3. Balanced biaxial tension

A hydraulic bulge test, developed in the Université de Bretagne-Sud (A. Penin, V. Grolleau, unpublished results, 2001),

Table 1
Plastic anisotropy coefficients of the two steels. The average anisotropy coefficient $\overline{r} = (r_0 + r_{90} + 2r_{45})/4$, which characterizes the normal anisotropy and the planar anisotropy, measured by the coefficient $\Delta r = (r_0 + r_{90} - 2r_{45})/2$ are also given.

Material	r_0	r_{22}	r_{45}	r_{77}	r_{90}	$\overline{r}$	Δr
DC04	1.680 $\pm$0.025	1.680 $\pm$0.0316	1.890 $\pm$0.051	2.206 $\pm$0.035	2.253 $\pm$0.062	1.928	0.08
DP500	0.866 $\pm$0.005	–	1.040 $\pm$0.01	–	1.033 $\pm$0.005	0.995	0.09