International Journal of Mechanical Sciences 138–139 (2018) 383–397

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

On the non-linear unloading behavior of a biaxially loaded dual-phase steel sheet

Nengxiu Deng[a], Toshihiko Kuwabara[b], Yannis P. Korkolis[a,*]

[a] Department of Mechanical Engineering and CAMMI – Center for Advanced Materials and Manufacturing Innovation, University of New Hampshire, 33 Academic Way, Durham, NH 03824, USA

[b] Department of Mechanical Systems Engineering, Tokyo University of Agriculture and Technology, 2-24-16 Naka-cho, Koganei-shi, Tokyo 1848588, Japan

A R T I C L E I N F O

Keywords:
Bauschinger effect
Springback
Cruciform testing
Anisotropy
Kinematic hardening
Dual-phase steel

A B S T R A C T

The response of the dual-phase steel DP 590 under continuous loading and unloading from a biaxial stress state is examined using a combination of experiments and analysis. The experiments utilize cruciform specimens of a custom geometry that develop quite uniform strain fields in the test-section and allow the development of large strains (>12%, depending on the loading path). Experiments along 9 radial stress paths in the first quadrant of the plane-stress space were performed. The first part of each unloading and reloading follows the prediction of orthotropic elasticity using the initial elastic properties. A second linear slope is observed, before the responses become fully non-linear. The non-linear strain recovery is measured to be about 1/5 of the linearly elastic strain for this material. Furthermore, the chord modulus reduces exponentially to a value of ~90% of the initial. The biaxial cruciform experiments are also used to determine contours of constant plastic work and to calibrate the Yld2000-2D anisotropic yield function. A combined isotropic/kinematic hardening model with a simple exponential-decay shrinkage of the yield surface is adopted. The non-linear unloading response is represented by a 4-term Chaboche non-linear kinematic hardening model using the Ziegler back-stress evolution rule. Plasticity during unloading is assumed to occur as soon as deviation from proportionality is detected. The 4 terms are necessary for capturing both the second linear slope after (re-) yielding and the work-hardening stagnation observed in the experiments. The agreement between experiments and predictions for the induced strain paths is very good. The predictions of the non-linear strain recovery are good overall, and are independent of the yield surface adopted. In summary, it is proposed to capture the biaxial unloading behavior using a constitutive model that includes an anisotropic yield function suitable for predicting the induced strain paths, and a non-linear kinematic hardening rule suitable for predicting the tension–compression behavior of the material at hand.

1. Introduction

The loading history during plastic forming is most of the times non-linear, including strain-path changes and unloading. The same is by definition true for multi-step forming processes, where the material is formed progressively, and then unloaded and transferred to the next forming die. After every unloading, the material experiences springback, i.e., release of the recoverable part of the total strain applied during forming (e.g., [73] and the references below). The prediction of springback both at the intermediate steps and at the end of a process chain is critical for correct design of the forming dies, especially for the modern materials used for automotive lightweighting. In particular, the advanced high-strength steels develop higher stresses during forming in comparison to mild steel, so that the recoverable strain is greater, too. Similarly, aluminum and magnesium alloys have lower moduli than mild steel, so that the recoverable strain is also greater. Furthermore, numerous manufacturing processes involve repeated loading and unloading, such as pulsed tube hydroforming [18,63] and sheet drawing in a servopress [56]. For all these reasons, the detailed exploration and the accurate modeling of the unloading behavior of materials is of interest.

The Bauschinger effect (BE) is the reduction of yield stress when the loading direction reverses (e.g., from tension to compression). The effect was first described by Bauschinger [7] on wrought iron and mild steel. More recently, Orowan [9,64] put forward the idea that the BE is caused by pinning and bowing of dislocation lines on obstacles, so that stresses imparted in the crystal in this fashion during prestraining add to or subtract from the applied stress, which appears macroscopically as permanent softening upon a loading reversal. Deak [19] performed torsion–reverse torsion experiments on polycrystalline steel, iron and copper. He highlighted the benefit of increased sensitivity in the measurement

* Corresponding author.
E-mail address: yannis.korkolis@unh.edu (Y.P. Korkolis).

https://doi.org/10.1016/j.ijmecsci.2018.02.015
Received 13 September 2017; Received in revised form 24 January 2018; Accepted 8 February 2018
Available online 9 February 2018
0020-7403/

of strain in improving the measurements of BE – which prompted us to adopt electrical-resistance strain gages in this work. Kishi and Tanabe [38] measured the BE on a variety of metals using torsion tests, and found that the decrease of the yield stress correlated very well with the prestrain using a simple powerlaw function. Miller et al. [61] and Khan and Jackson [33] examined the BE effect in copper alloys and highlighted its link to the yield criterion and the strain offset used for definition of yielding. Morestin and Boivin [62] showed that the chord modulus of various steel and aluminum alloys changes with prestrain and that springback predictions are improved when taking this into account. Cleveland and Ghosh [17] determined that the variation of the instantaneous tangent modulus during unloading can be divided into three stages. They proposed an analytical function to evaluate the change of this non-linear compliance. Yoshida et al. [76] used a laminated sheet specimen to study the BE on a mild and a dual-phase DP590 steel. They observed transient softening and work-hardening stagnation, due to the BE, as well as a decrease in Young's modulus with increasing prestrain. Boger et al. [8] proposed a tension-compression experiment suitable for thin sheets and used it to study the BE for a variety of steels, aluminum and magnesium alloys. Kuwabara et al. [47] used the in-plane tension–compression testing machine also used here, to probe the tension–compression response of a copper and an aluminum alloy. They found anisotropy in the BE of copper. Other researchers have studied the BE on QP980CR [78], TRIP 700 [58] and DP780 [57] steels and AZ31B magnesium [26,27]. Chen et al. [16] measured the elastic responses of 12 steels using tensile testing, resonant frequency damping analysis and ultrasonic pulse-echo testing and highlighted the need for accurate descriptions of the elastic response during loading and unloading.

The majority of BE experiments described so far involve uniaxial, simple shear, or torsional loading. Among multiaxial investigations of the BE, Chen et al. [15] loaded thin-walled low-carbon steel tubes under combined axial load, internal pressure and torsion. They investigated the effect of stress-ageing on the BE and the effect of the offset strain used for the definition of yielding. Pavlina et al. [65], following the work of Levy et al. [54], measured the moduli of a mild steel during plane-strain deformation using tube inflation. In a series of papers, Khan and co-workers measured the elastic properties of aluminum alloys prestrained multiaxially, using strain-gages [34,35,36]. They found that the elastic properties changed with the prestrain, and showed path-dependence. Measurements of the biaxial unloading response of a mild and a dual-phase DP590 steel were reported by Andar et al. [1] using cruciform specimens. They found that the elastic properties reduced with plastic prestrain and proposed an exponential decay model to capture the unloading stress–strain response. The work of Andar et al. [1] was limited to small strains due to limitations with the cruciform specimen used. The present paper can be viewed as an extension of that work to larger strains, more relevant to industrial forming processes.

The pure isotropic hardening assumption, where the yield surface of the material is expanding uniformly in every direction, is not appropriate to represent the BE and, as a result, to model springback. Various kinematic hardening rules were devised for this purpose [3,10,11,13,28,32,69,72,75,77,80]. In a different approach, Sun and Wagoner [70] proposed a model to predict the Quasi-Plastic–Elastic (QPE) strain, which exhibits characteristics of both elastic strain (recoverable) and plastic strain (energy dissipative). The model was subsequently expanded to multiaxial loading [52]. Furthermore, Barlat et al. [5] proposed the Homogeneous Anisotropic Hardening model as an alternative to classical kinematic hardening, and examined its behavior in capturing the BE in mild and dual-phase steels Barlat et al. [6]. Zecevic et al. [79] created a crystal plasticity model suitable for dual-phase materials, using a two-level homogenization scheme, one for the two-phase polycrystalline aggregate and the second for the polycrystalline martensitic regions. The model captured all the particular features of the cyclic deformation of the same DP 590 steel reported here with great accuracy.

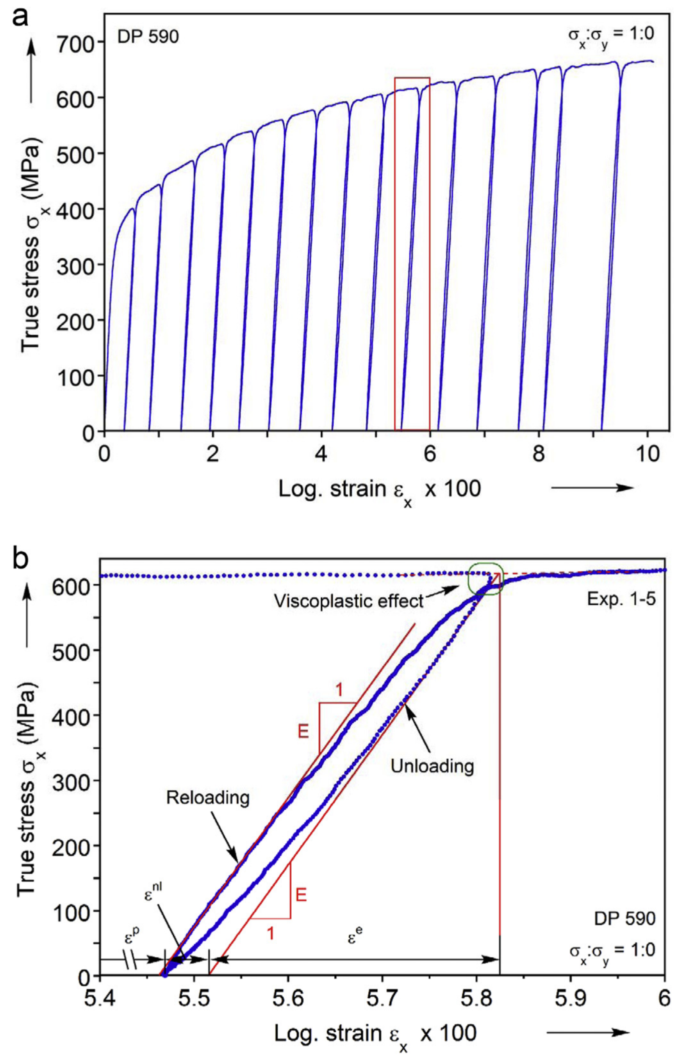

Fig. 1. (a) True stress–strain curve recorded during uniaxial loading of DP 590 sheet. (b) Zoom-in at an unloading–reloading loop, showing hysteresis, the linearly elastic, non-linear recovery and plastic strains, and elastic properties discussed in this work.

The simplest possible experiment to assess the non-linear unloading of a material is a uniaxial tension test with periodic loading and unloading (e.g., [18]). A result typical for the dual-phase steel considered in this study is shown in Fig. 1. At first, as the plastically deforming material begins to unload, a blunt corner is recorded, see Fig. 1(b). This is perhaps an indication of viscoplastic or time-dependent response, since the stress and strain are out-of-phase with respect to each other. Subsequently, the material unloads linearly, with the slope of this curve being identical to the initial elastic stiffness (i.e., the Young's modulus). This can be explained (e.g., [70]) from the fact that the elastic stiffness is a consequence of atomic bonding in the crystal lattice of the material. Since plasticity involves the movement of dislocations, the lattice bonding remains intact, which leads to the macroscopic observation of Fig. 1(b). Soon after, the material response becomes non-linear. To the authors' knowledge, the exact pinpointing of the elastic–plastic transition has not yet been accomplished. The strain recovered when the specimen is (macroscopically) stress-free will have a linearly elastic and a non-linear part (Fig. 1(b)). Upon reloading, the material exhibits the same elastic stiffness as the undeformed material, again explained by atomic bonding, as above. The response soon becomes progressively more non-linear, until it reaches the levels of stress attained before un-