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Experimental assessment of nonlinear elastic behaviour of dual-phase steels and application to springback prediction

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ABSTRACT

The aim of this paper is to identify ways to improve the description of nonlinear elastic behaviour of dual-phase steels under different loading strategies. Three mechanically-measured tests, i.e., uniaxial and biaxial loading–unloading–loading cycle tests and the proposed three-point bend test with pre-strained sheet, were introduced to determine the elastic modulus degradation with the increase of plastic strain. A significant effect of the loading strategy on the determination of the initial and the degradation of elastic modulus was observed and discussed. As a three-dimensional forming application case, the curved-flanging test for a dual-phase (DP) steel sheet sample was conducted to validate the identification of the nonlinear elastic modulus for springback prediction. To accurately capture the nonlinear elastic behaviour and anisotropic hardening of the DP steel sheet, the Yoshida chord elastic model integrated with the yield criterion Yld2000-2d and the homogeneous anisotropic hardening (HAH) model was employed. The results indicated that the uniaxial loading strategy overestimates the angular springback. The biaxial loading strategy better captures the sidewall curl than the angular springback compared to other strategies. The proposed three-point bending test with pre-strained sheets appears to be an alternative method to determine the nonlinear elastic behaviour because it leads to a good prediction of the angular springback in the curved-flanging test.

1. Introduction

The use of advanced high strength steels (AHSS) is gaining popularity for vehicle makers due to their promising higher strength without compromising ductility. However, high strength steels result in large elastic recovery (also called springback) after forming, which hinders their wider application. Therefore, many researchers have conducted experiments to characterize the material behaviour of sheet metal and developed constitutive models for the purpose of improving the accuracy of predictions.

An important phenomenon observed for various sheet metals is the degradation of the elastic unloading modulus with an increase of the plastic strain, which has a considerable effect on springback predictions [1–8]. The unloading elastic modulus was reported to decrease up to 30% for mild steel [1,9], 20% for high strength steels [9,10] and 10% for aluminium [1] at a moderate plastic strain. In particularly, for uniaxial tension, Hassan et al. [11] found that the decrease of elastic moduli for DP600 and DP1000 were 28% and 26%, respectively. More recently Mendiguren et al. [12] observed that the drop of the chord modulus for TRIP700 was about 15–20% after 12% plastic deformation. Eggertsen and Mattiasson [2] investigated the springback of the U-bend test with different hardening laws and concluded that the degradation in elastic stiffness is probably the constitutive factor that has a greater impact on the predicted springback than that of the hardening law. Kim et al. [13] studied the effects of a variable elastic modulus on springback predictions in stamping AHSS using a flexible set-up including U-bending, flanging and S-rail stamping tests. They recommended accuracy description of the nonlinear hardening and elastic modulus change as material input data for reliable simulations, particularly for springback prediction of complex part geometry. Nevertheless, so far, the nonlinear elastic behaviour has been ignored in most industrial forming applications, i.e., the elastic modulus has usually been assumed constant.

Many researchers attempted to interpret the source of elastic modulus change with the increase of plastic strain by means of microscopic observations and elasto-plastic analyses. Yang et al. [10] reported that this phenomenon is due to the mobile dislocations accompanying the pile-ups near to the grain boundaries.

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Table 1
Main chemical composition of the analysed DP steels in weight percent.

Materials	C	Mn	Si	P	S	N	Cr	Ni	Cu	Al	Nb
DP500	0.079	0.65	0.31	0.009	0.003	0.003	0.03	0.03	0.01	0.038	–
DP600	0.089	0.85	0.2	0.014	0.004	0.004	0.03	0.03	0.01	0.049	0.016
DP780	0.138	1.52	0.2	0.011	0.002	0.003	0.03	0.04	0.01	0.038	0.014

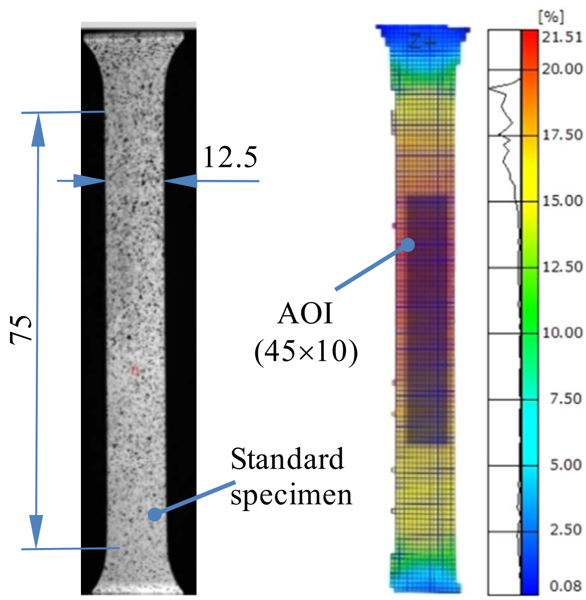

Fig. 1. DIC images of specimen and uniaxial deformation.

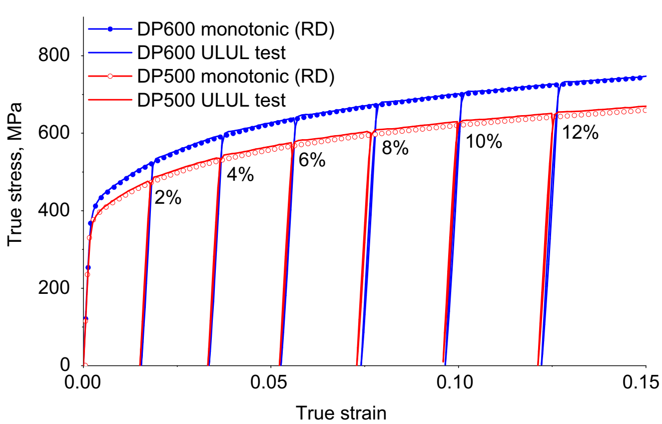

Fig. 2. The true stress–strain curves of the ULUL cycle tests for DP500 and DP600 steels.

The dislocations nucleated during pre-strain move along the slip plane and pile-up easily, while the front of dislocations can be stopped by obstacles, e.g., grain boundaries or solutes. The release of the shear stresses acting on the slip systems during unloading can induce a backward motion of the dislocation pile-ups. The density of these mobile dislocations increases with plastic strain, thereby causing an apparent decrease of the elastic modulus as the plastic pre-strain increases. Kim et al. [14] stated that the rate of increase of mobile dislocations is relatively high at small pre-strains but low after large pre-strain. Pavlina et al. [15] studied the nonlinear unloading behaviour of three different commercial DP780 steels and found that the elastic modulus degradation is greater as the strength ratio between martensite and ferrite

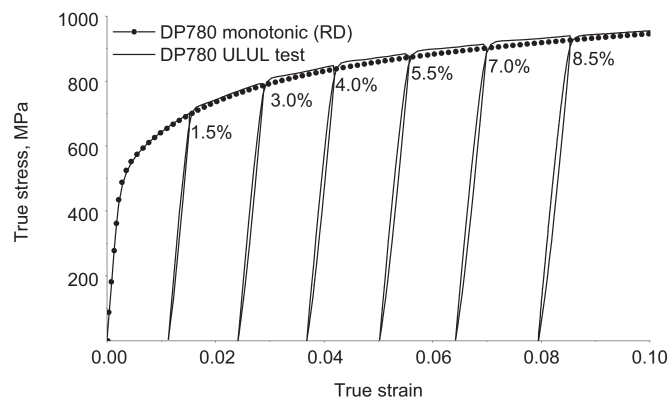

Fig. 3. The true stress–strain curves of the ULUL cycle tests for DP780 steel.

increases. They further indicated that active strain hardening mechanisms (e.g., TRIP and TWIP effects) affect the unloading behaviour of AHSS [16]. Mendiguren et al. [12] presented that the decrease of the unloading elastic modulus might be related to phase transformation but mainly to dislocation rearrangement. Vrh et al. [17] experimentally observed that a significantly greater drop in the unloading elastic modulus takes place when sheet metal is pre-strained in the perpendicular direction. This evidence indicates that in some cold-rolled sheet steels, the elastic modulus degradation is strongly strain path dependent.

In the past decade, some researchers have already taken into account the nonlinear elastic behaviour for material constitutive description of elasto-plasticity. Yoshida et al. [9] proposed an exponential representation of the change of elastic modulus. Similarly, Yu [18] introduced a polynomial expression of the elastic modulus variation with plastic pre-strain of TRIP steels. Chatti [19] developed a coupled damage-elasto-plasticity approach based on Yoshida model, which allows the prediction of the elastic modulus evolution starting from a virgin material and finishing at the fracture stage. These models are known collectively as elastic chord modulus. However, the elastic unloading curve after a prescribed pre-strain normally falls below the reloading curve to form a hysteresis loop. This complex stress–strain relationship is ignored in all chord models mentioned above. In order to describe the complex hysteresis loop, Sun and Wagoner [20] proposed the Quasi-Plastic-Elastic (QPE) model, in which a new type of strain called QPE strain was introduced. The strain is recoverable similar to elastic strain and dissipates energy similar to plastic strain. This model was later combined with a homogeneous anisotropic hardening model by Lee et al. [21] to simultaneously capture the complex unloading and plastic flow behaviours. It is more accurate model but also more complex for springback prediction. Due to its high computing cost and added difficulty in its use, the QPE model is not convenient for engineering applications. Böhlke and Bertram [22] used a phenomenological model for the evolution of the texture-dependent effective elastic properties to predict the corresponding saturation values of polycrystalline copper. The works of Vladimirov and Reese [23,24] contributed to a material constitutive framework of finite strain elasto-plasticity with evolving elastic and plastic anisotropy and combined hardening. The evolution of elastic anisotropy was