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# Evolution of mechanical properties for a dual-phase steel subjected to different loading paths

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ABSTRACT

The evolution of the mechanical properties of a dual-phase (DP590) steel sheet after being prestrained by uniaxial tension, plane strain and equal biaxial stretching was investigated. Specimens were first loaded using the three prestraining modes. Then, from the prestrained specimens, a few sub-sized samples were machined along the rolling direction and the transverse direction for further uniaxial tension testing. Six loading paths were provided. Equal biaxial stretching was performed using a cruciform specimen. The evolution of work hardening performance, elastic modulus, yield stress and tensile stress under the six loading paths were discussed in detail. The results indicate that loading paths can affect the latent work hardening performances, strain hardenability, yield stress and tensile stress evolution as well as the elastic modulus decrease during plastic deformation. The uniaxial tension–uniaxial tension path results in a cross-softening phenomenon, the largest yield stress enhancement and a mild maximum tensile stress increase. The equal biaxial stretching-uniaxial tension path leads to a cross-hardening phenomenon, the least yield stress enhancement and the largest tensile strength increase maximum tensile strength. The elastic modulus of DP590 steel not only changes with the accumulated plastic strain but also varies with the loading paths. The largest decrease of the elastic modulus equal biaxial stretching–uniaxial tension can reach 12.7% beyond 8% equivalent strain, which is 5.2% greater than that in the monotonic uniaxial tension path.

## 1. Introduction

Dual-phase (DP) steels have been shown to possess high strength, high work-hardening rates and mild formability. DP steels are increasingly used in automotive components to reduce mass and improve safety. Numerical simulation has been one of the most important methods in sheet metal forming processes and tool design. A reliable simulation requires a precise description of the mechanical properties of the target material. A few studies have reported that certain mechanical properties vary during plastic deformation instead of remaining constant [1,2]. This phenomenon creates an undesired uncertainty in the process program. Furthermore, it is unfavourable for quality control. A correct and precise description of the mechanical properties is vital for sheet metal formation.

As is well known, the plastic behaviour of metals is strongly dependent on the loading path [3–5]. During sheet metal forming, a change in loading path is extremely common [6,7]. The material should flow through the drawbeads and die corner before entering the die. The material is bent and unbent; then, it is bent again in the opposite direction. In the die, the material still experiences a slight complex deformation in adapting to the complex die configuration. Moreover, automotive panels always involve subsequent multi-stage processes, such as blanking, deep drawing and trimming. All of the above mentioned factors result in a set of complex loading paths for sheet metals. The materials properties under such complex loading conditions are crucial to modelling the target material.

A few researchers have investigated the effect of loading paths on the mechanical properties of dual-phase steels. The elastic modulus is an important parameter among these properties. Chongthairungruang et al. [8] used the uniaxial tension–uniaxial tension method to investigate the elastic modulus degradation of a DP780 steel sheet. The authors concluded that the elastic modulus of the DP780 steel sheet is sensitive to changes in the loading path. Sun and Wagoner [9] investigated the unloaded variation in the modulus of DP980 steel with prestrain and unloaded strain in uniaxial tension. The chord modulus of the DP980 steel was reported to be up to 30% less than the handbook modulus. Kim

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and Kimchi [10] determined that the elastic modulus of DP780 could decrease by up to 28% from its initial values. Furthermore, Lim et al. [11] investigated the elastic modulus degradation phenomenon of three grades of dual-phase steels after large prestrain. The elastic modulus was concluded to progressively decrease with increasing strain. However, Mendiguren et al. [12] concluded that the elastic behaviour of TRIP700 steel does not depend on the strain path.

Anisotropic hardening performances are crucial to steels subjected to strain-path changes. Tarigopula et al. [13] pointed out that the hardening behaviour of dual phase steel is dependent on the strain path. Barlat et al. [5] found that the reloading yield stress of a dual-phase steel is lower than the unloading flow stress deformed in a two-step tension test. Zang et al. [14] characterized both the anisotropy and the hardening behaviour of mild and dual phase steel sheets under uniaxial tension, simple shear and balanced biaxial tension strain paths. Ha et al. [2] studied the strain hardening responses of DP780 and EDDQ steel sheet samples deformed in tension–tension test. Their main findings for these two steels were quite different.

Several types of loading paths have been applied in recent studies. Le et al. [15] used two different prestrain path testing methods, uniaxial and plane strain, to observe the fatigue performance of a dual-phase (DP600) steel sheet under load reversals. In the study performed by Sugimoto et al. [16], DP steels were prestrained by various amounts in both uniaxial tension and plane strain modes. Then, sub-sized tensile specimens were extracted from the prestrained panels at various angles. Contrary to the results obtained for low carbon steels [17,18], the DP steel exhibits a cross-softening response rather than cross-hardening behaviour. Sugimoto et al. [16] noted that the cross-softening effect increases as prestrain increases, and the effect is more pronounced for uniaxial tension prestrain than for plane strain prestrain. Deng and Korkolis [19] proposed a cruciform specimen that is extremely accurate for constitutive identification. Korkolis et al. [20] successfully used this specimen in probing the constitutive and unloading behaviour of DP590 steel. Larsson et al. [21] studied the hardening performances of Docol 600DP steel subjected to non-linear strain path using tension and shear tests. It was concluded that neither an isotropic nor a kinematic hardening was sufficient to describe plastic hardening behaviour during non-linear strain paths. Thus, a mixed isotropic and kinematic hardening is required.

Chan and Lee [22,23]developed a crystallographic-texture-based material model to predict the plastic anisotropy response of a low-carbon steel to linear strain paths in uniaxial tension and curvilinear strain paths in biaxial tension. The authors determined that the deformation textures resulting from uniaxial tension, plane strain and balanced biaxial stretching deformation are different from the annealing texture. Gardey et al. [24] analysed the microstructural evolution of a dual-phase steel under two-stage strain-path change sequences in connection with the crystallographic grain orientation to achieve a more comprehensive explanation of the anisotropic behaviour under complex strain-path changes.

As discussed previously, dual-phase steels have gained popularity in recent years, and there are complex loading paths for sheet metals that affect the mechanical properties of metals. In this study, the evolution of the mechanical properties of DP590 steel under six different loading paths was investigated. Large specimens were first loaded in uniaxial tension, plane strain and equal biaxial stretching prestraining modes. Then, a few sub-sized samples were taken from the uniform deformation zone for further uniaxial tension testing. The evolution of work-hardening behaviour, elastic modulus, yield stress and tensile stress under the six loading paths was discussed in detail, which provides a reference for the application of dual-phase steels and related research.

## 2. Experiments

### 2.1. Materials

The material investigated in this study was a cold-rolled continuous annealed dual-phase DP590 steel sheet. The thickness of the sheet was 1.4 mm. The material's chemical composition is listed in Table 1. The volume fraction of martensite was 15.8%.

In this study, six two-stage loading paths were introduced. First, a few large-sized specimens were preloaded to 4% engineering strain in three types of deformation modes: uniaxial tension (UT), plane strain stretching (PS) and equal biaxial stretching (EB). The loading direction of the uniaxial tension and plane strain stretching modes was along the rolling direction. The specimens subject to equal biaxial stretching were loaded along the rolling and transverse directions simultaneously. Then, a few sub-sized samples were cut from the prestrained specimens along the rolling and transverse directions. These sub-sized samples were again placed in uniaxial tension to obtain the engineering stress–strain curves and several other mechanical properties.

The geometry of the specimens used in the first stage was dependent on the corresponding loading mode, which will be discussed in the following sections. It should be noted that the samples used for the second stage of loading had the same shape and the same dimensions.

According to the experimental method described above, six types of loading paths were implemented in this study: uniaxial tension (RD)–uniaxial tension (RD), uniaxial tension (RD)–uniaxial tension (TD), plane strain stretching (RD)–uniaxial tension (RD), plane strain stretching (RD)–uniaxial tension (TD), equal biaxial stretching–uniaxial tension (RD) and equal biaxial stretching–uniaxial tension (TD). Here, RD represents the rolling direction and TD represents the transverse direction.

### 2.2. Uniaxial tension

Fig. 1 provides the dimensions of the large specimens used in the prestraining stage. The large-sized specimens were connected to a grasp grip by a row of bolts. All of the sizes, including the diameter of the bolt holes, were obtained after several iterations of trial and error using finite element simulation and experimental tests. The stress concentration around the bolt holes was also considered.

The sub-sized samples used in the second stage of deformation are presented in Fig. 2. To determine the sizes of these specimens, the size of the uniform deformation zone had be considered. Another important factor that needed to be considered was the accessibility of the sub-sized samples from the prestrained specimens in all three loading modes.

From the prestrained specimens, a few sub-sized samples were machined along the rolling and transverse directions, as indicated in Fig. 1. To ensure the sub-sized samples were obtained from a domain where plastic deformation was as uniform as possible, the stress and strain fields were predicted using the finite element simulation software ABAQUS/Standard.

(a) Large-sized specimen used in first stage uniaxial tension (thickness = 1.4 mm).
(b) Large-sized specimen used in plane strain stretching (thickness = 1.4 mm).

**Table 1**
Chemical compositions of the DP590 steel (weight%).

| C | Mn | AL | N | Cr | Mo |
|---|---|---|---|---|---|
| 0.075 | 1.9 | 0.05 | 0.006 | 0.2 | 0.2 |