

Experimental Study of the Plasticity Responses of TRIP780 Steel Subjected to Strain-Path Changes

HaiYan Yu, ZeZhen He, and JiaYi Shen
Tongji University

ABSTRACT

The work-hardening response of TRIP780 steel subjected to strain-path changes was investigated using two-stage tension experiments. Large specimens were prestrained and then sub-sized samples were subjected to tension along various directions. The influence of strain-path changes on flow stress and work hardening performance was discussed in detail. The specific plastic work was calculated to compare the kinematic hardening behaviour after strain-path changes. The results showed that transient hardening was observed for TRIP780 sheets subjected to orthogonal strain-path change. The strain-hardening exponent (n -value) was influenced by prestraining levels and the strain path. The n -value exhibited a greater decrease under an orthogonal strain-path change. Prestraining can delay the onset of high work hardenability of TRIP steels. It is meaningful for the safety design of vehicles.

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INTRODUCTION

The production of panels in the automotive industry often involves a series of forming processes that may result in large strains and complex strain-path changes. Some investigations have shown that strain-path changes can lead to macroscopic kinematic hardening behaviour on the stress-strain curve[1].

There have been many studies of the kinematic hardening behaviour of metals subject to strain-path changes, such as steels[2, 3, 4], copper alloys[5, 6, 7, 8, 9] and aluminium alloys[10, 11, 12, 13, 14]. Kinematic hardening is characterized by a number of phenomena under cyclic loading, such as the Bauschinger effect, cross effects, permanent softening and work-hardening stagnation[13]. Tarigopula et al[15, 16], concluded that isotropic hardening was insufficient to model the hardening behaviour of dual-phase steel subjected to strain-path changes. Barlat et al[10,17], proposed a constitutive model to describe the plastic behaviour of materials subjected to multiple strain-path changes. Achani[18] concluded that non-linear isotropic hardening was sufficient to describe the hardening behaviour of prestrained aluminium alloys subject to strain-path changes. Kim et al.[19] performed a three-stage deformation in which sheets were prestrained in the rolling direction. Prestraining was then performed at several angles to the rolling direction, and tensile specimens were cut out and tested in various directions. Butuc et al[20], validated the hardening model of DC06 steel under linear and complex strain paths. Nagai et al[21], performed 2% prestraining on ferric steels. When the strain path was changed orthogonally, the re-yield stress was lowered and the work-hardening rate at low-plastic strain increased. Cetlin et al[22], found that the work-hardening characteristics of AISI 420 and 304 stainless steels were dependent on strain path. Sakharov et al[23], performed pure tension,

rolling and rolling-tension strain-path sequences on brass sheets. The results indicated that strain-path change promotes the onset of premature twinning of brass. Boer et al[24], designed a new testing device for investigating the complex behaviour of sheet metals under non-proportional loading. Larsson et al[25], studied the kinematic hardening behaviour of two high-strength steels, Docol600DP and Docol1200M, through a series of tensile and shear tests. Zang et al[26], 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[27], studied the strain-hardening responses of DP780 and EDDQ steel sheets using a tension-tension test. A significant Bauschinger effect accompanied by a transient hardening behaviour after reverse loading was found for the DP780 steel. In contrast, EDDQ exhibited stress overshooting followed by strain-hardening stagnation.

It is well known that transformation-induced plasticity (TRIP) steels are different from other high-strength steels because of the TRIP effect. Therefore, much research has concentrated on the effect of the strain path on the forming limit diagram[28, 29, 30] and finite-element simulation[31, 32, 33, 34, 35]. Kulawinski[36] investigated the stress-strain curves of cruciform specimens of metastable austenitic cast stainless steel under biaxial planar loading. Spencer et al[37], investigated the influence of strain history on the mechanical properties of austenitic stainless steel that exhibits the TRIP effect. Carbonnière et al.[38] compared the kinematic hardening behaviour of aluminium alloy and TRIP steel using bending-unbending and simple shear. Mendiguren et al.[39] concluded that the elastic behaviour of TRIP steel does not depend on strain-path changes. This conclusion seems to be different from other published results.

In this study, the work-hardening response of a cold-rolled TRIP780 steel sheet subjected to strain-path changes was investigated with two-stage uniaxial tension tests. Large specimens were prestrained to six engineering strain levels. Sub-sized dog-bone samples were machined from the gauge section along various directions. The influence of prestrain and strain-path changes on the flow stress as well as the hardening response was studied in detail. The specific plastic work was also used to determine the kinematic hardening behaviour after the strain-path changes.

2. EXPERIMENTAL PROCEDURES

2.1. Materials

The material used in this work was an uncoated cold-rolled TRIP780 steel sheet of thickness 1.4 mm and chemical composition as shown in Table 1. The austenite content was about 6%.

Table 1. Chemical composition of the TRIP780 steel in wt-%

C	Si	Mn	Mo	Al
1.70	0.59	2.50	0.08	0.47

2.2. Example Two-Stage Uniaxial Tension

Two-stage uniaxial tension was applied to the TRIP780 steel sheet. First, large specimens were uniaxially tensioned to different strain levels along the rolling direction. Then, from the uniform-deformation domain of the prestrained large specimens, sub-sized samples were cut along the rolling direction (0°), the transverse direction (90°) and at 45° to the rolling direction, as shown in Fig. 1. The sub-sized specimens were then uniaxially tensioned until fracture occurred.

The large specimens used in this study were 537 mm long and 190 mm wide, as shown in Fig. 1. The specimen gauge section was 320 mm long and 120 mm wide. These specimens were prestrained to six engineering strain levels: 4.16%, 5.83%, 6.94%, 8.3%, 10.0% and 14.6%. The dimensions of the sub-sized samples are shown in Fig. 2. A precise Epsilon extensometer was used to measure the strain. The uniaxial tension for the large specimens was applied at a constant speed of 3 mm min^{-1} in an electric loading machine with a 200 kN load cell, while the uniaxial tension for the sub-sized specimens was applied in a Zwick electric loading machine with a 100 kN load cell.

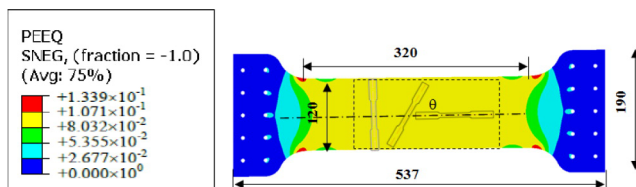


Fig. 1. Dimensions and equivalent plastic strain of a large specimen

To ensure that the sub-sized samples were cut from a domain where the strain distribution was as homogeneous as possible, the stress and strain fields of the large specimens were simulated with ABAQUS/Standard software. The specimen was meshed into more than 20000 shell elements. Enforced displacement was applied at the end of the specimen. The equivalent plastic strain distribution is shown in Fig. 1, from which it can be seen that the majority of the gauge domain

was subjected to homogeneously distributed strain. Therefore, the subsequent sub-sized samples that were cut from there were believed to have the same prestrain. The thickness was measured using an ultrasonic thickness gauge PX-7 and the thickness variation was found to be negligible in that region.

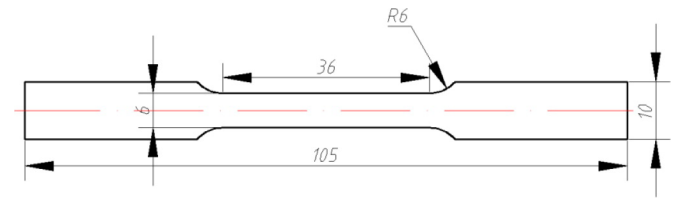
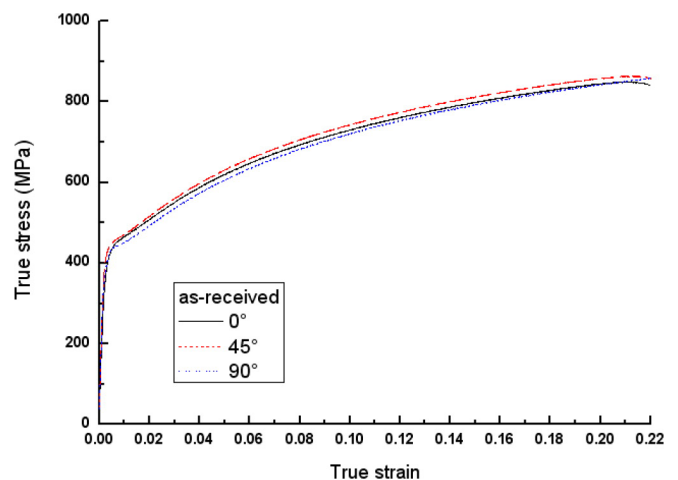


Fig. 2. Dimensions of a sub-sized specimen

3. RESULTS AND DISCUSSION

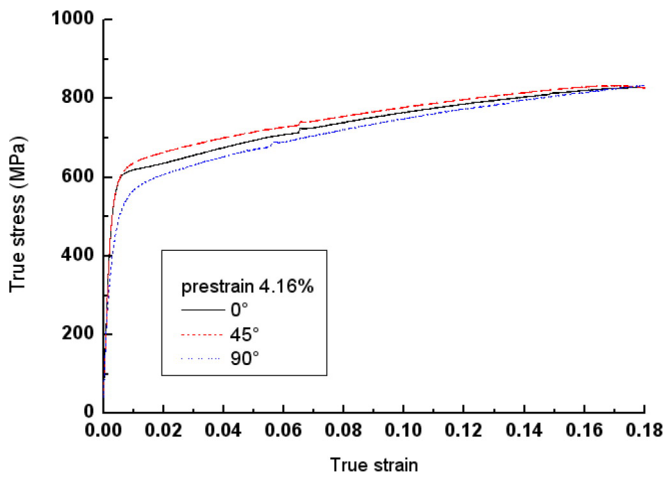
3.1. Influence of Prestraining on Flow Stress

True stress-strain curves of the as-received and prestrained TRIP780 specimens are shown in Figs. 3a-3g, in which 0° , 45° and 90° indicate the angle between the length direction of the sub-sized samples and the rolling direction of the sheets. In Fig. 3a, the differences among the flow stresses of the three directions in the elastic-to-plastic transition region is very small. Since there is no typical yielding platform, the stress at 0.2% offset strain is regarded as the yield stress. However, in Figs. 3b-3g, there is a prominent difference among the flow stresses in the different directions, especially in the 90° curves. They have rounder corners than the other curves, which indicate the appearance of transient hardening behaviour in the early stage. The length of the transition region increases with the prestrain. This is ascribed to the effect of strain-path change on the dislocation [40]. After the rounder corner, the difference in flow stress tends to diminish as the plastic deformation advances, regardless of the direction, as shown in Figs. 3b-3f. This demonstrates that the flow stress curves tend to converge. Tarigopula *et al.* [15-16] obtained similar results for dual-phase steels, and they attributed the specific differential hardening behaviour to deformation-induced residual stresses imparted to the ferrite and martensite during prestraining.

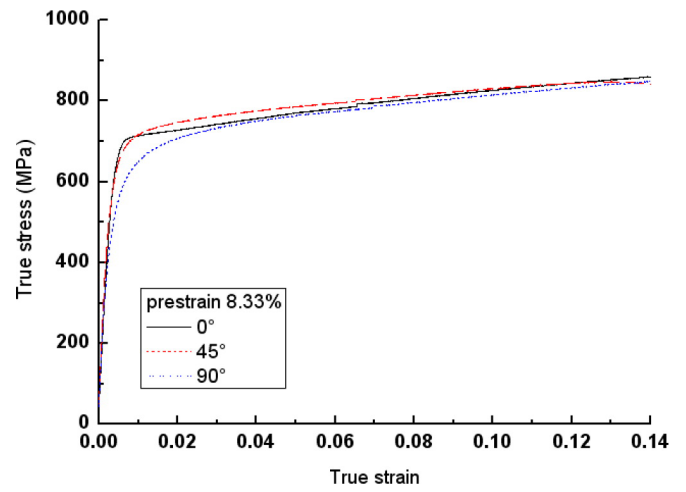


a.

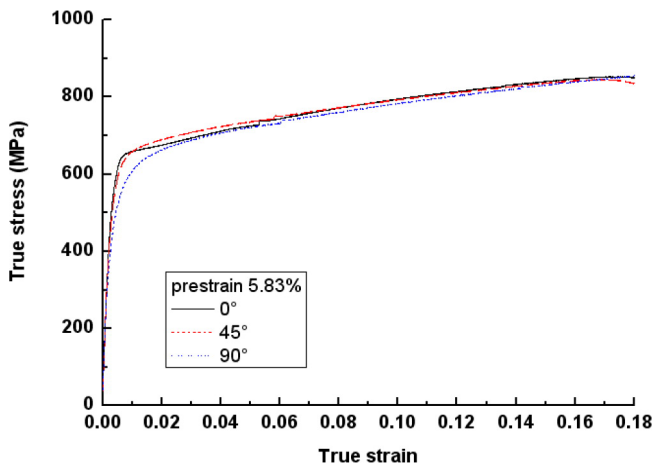
Fig. 3. True stress-strain curves of sub-sized samples subject to different prestrains: (a) $\epsilon_p = 0$; (b) 4.16%; (c) 5.83%; (d) 6.94%; (e) 8.3%; (f) 10.0%; (g) 14.6%



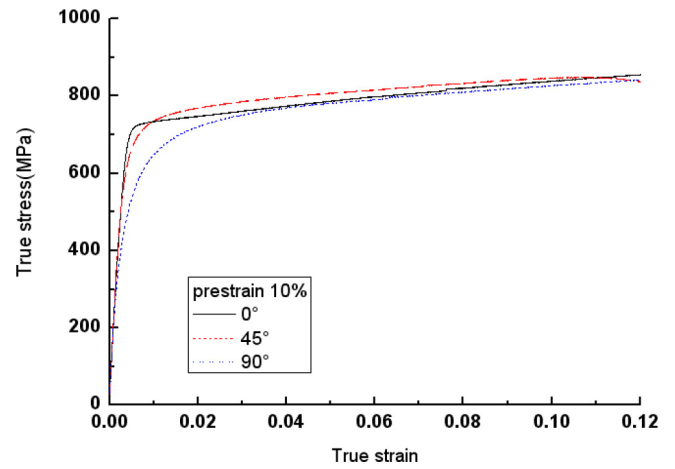
b.



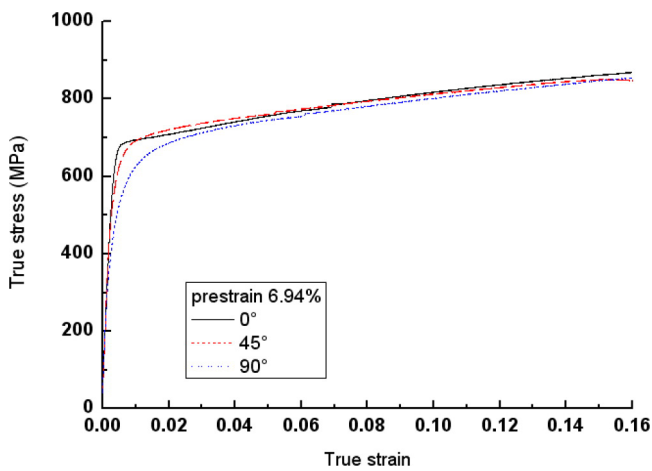
e.



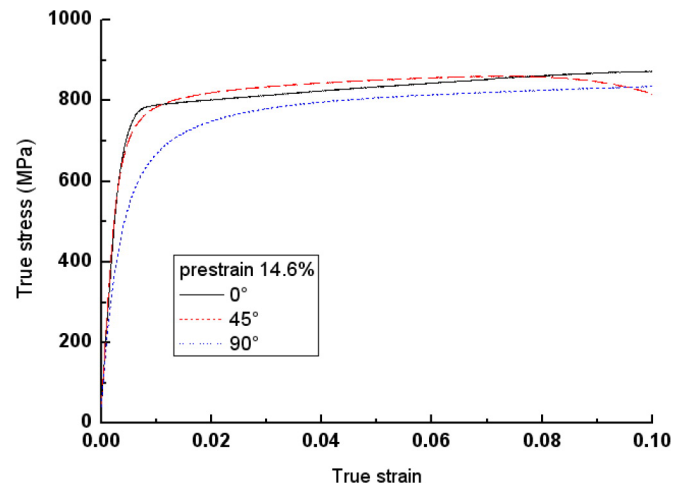
c.



f.



d.



g.

Fig.3 (cont). True stress-strain curves of sub-sized samples subject to different prestrains: (a) $\varepsilon_p = 0$; (b) 4.16%; (c) 5.83%; (d) 6.94%; (e) 8.33%; (f) 10.0%; (g) 14.6%