Non-linear strain path experiment and modeling for very high strength material

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Abstract. The goal of this work is to develop experimental methods and modeling of very high strength steel sheets subjected to non-linear strain paths. A 1.6 mm thick TRIP steel sheet with a tensile strength of 1180 MPa was investigated. A suitable test for the uniaxial tension pre-strain was developed. A constraint was to achieve an as uniform as possible strain field over the entire gauge area. The pre-strain was conducted on a 500kN MTS tensile testing machine. The geometry of a new specimen was optimized through finite element simulations and experiments on the TRIP1180 material. Then, different types of subsequent specimens were extracted from the pre-strained material by electro-discharge machining (EDM) for the second deformation step leading to a strain path change. The subsequent plastic behavior was measured and modeled using the HAH distortional plasticity model. Comparisons between the experimental and predicted behavior are discussed.

1. Introduction
When a strain-path change occurs, a material exhibits a different hardening behavior compared with monotonic loading such as a Bauschinger effect after load reversal which, in turn, can affect the success of forming operation. Therefore, it is very important to research the influence of non-linear strain path experimentally and to develop advanced hardening model allowing the prediction of final shapes as accurately as possible.

The literature on this topic has been extensive over the last five or six decades and many test combinations have been used to investigate the issue. Recently, Ha et al. [2] investigated the strain hardening response under two-step tension experiments conducted on advanced high strength steel (AHSS) sheets. The experimental stress-strain curves were predicted using the so-called HAH distortional plasticity model [3]. The limitation of this study was that both the pre-strain and the subsequent deformation were uniaxial tension segments. Bin Zaman (2018) developed a large-scale tensile specimen from which, cruciform specimens were extracted after the pre-strain to measure the yield surface evolution experimentally after tension for two steel samples [4]. To measure the subsequent yield surface after the first loading step, biaxial tension tests with different load ratio were conducted [5] and the results were also predicted with the HAH model.

Recently, the automotive industry has started to produce parts with AHSS of over 1 GPa tensile strength but the above-mentioned methods were not designed for such very high strength steels. Therefore, a new experimental method for very high strength steels is needed, which is the objective of this work. A new tensile specimen was designed for the pre-strain stage of the non-linear strain path
experiment. After the first loading step, different types of subsequent specimens were extracted from the pre-strained material. The stress-strain curve after the first loading step was measured and predicted with the HAH model.

2. Experiment

2.1. Material properties
A 1.6 mm thick TRIP1180 steel sheet sample was investigated in this work. Uniaxial tension tests were conducted on a 500 kN MTS tensile machine according to ASTM E8 standard in different directions with respect to the rolling direction (RD) to characterize the material properties. The result of the uniaxial tension test is shown in Figure 1. For the Lankford coefficient, the so-called r-value, two mechanical extensometers were used. The different material properties are listed in Table 1. The TRIP1180 (transformation-induced plasticity) steel experiences phase transformation from austenite to martensite during plastic deformation. This causes a change of the hardening rate in the early stage of plastic deformation in uniaxial tension as shown in Figure 1.

![Figure 1. Monotonic stress-strain curves of TRIP1180 in uniaxial tension tests conducted in different directions with respect to RD](image)

| Direction  | Young’s modulus (GPa) | Yield stress (MPa) | Uniform elongation (%) | UTS (MPa)  | R-value |
|------------|-----------------------|--------------------|------------------------|------------|---------|
| 0 degree   | 197.36                | 1040               | 8.98                   | 1316.3     | 0.983   |
| 45 degree  | 200.50                | 1050.4             | 9.79                   | 1342.39    | 0.990   |
| 90 degree  | 203.17                | 1060.8             | 9.04                   | 1345.80    | 0.953   |

2.2. Development of medium-scale specimen
For a detailed investigation about non-linear strain paths, many experiments should be done with different strain-path changes. Figure 2 is a schematic illustration of strain-path histories with each experiment represented on the π-plane when the material is first pre-strained in uniaxial tension along the transverse direction (TD). All the angles indicated in the figure correspond to that obtained by a specific load with respect to tension in the RD. To represent shear stress state on the π-plane, the concept of cosϕ which is a value from the double dot product of two stress tensor was adopted [3]. This value corresponds to cosθ, which θ means angle difference between two stress states on the π-plane. Strain-
path histories for shear stress state were drawn to correspond same $\cos \chi$ as like Figure 2. From those experiments, the material behavior over the various types of strain-path change were measured.

![Figure 2](image)

**Figure 2.** Strain-path history with different experiment after pre-strain in $\pi$-plane.

For the subsequent strain path, specimens should be extracted from a uniformly deformed area of the pre-strained specimen. For this, a large-scale specimen was designed as shown in Figure 3a from which, cruciform specimens were extracted and deformed in biaxial tension with various load ratio after tension [4]. This specimen has the advantage of accommodating various kinds of strain path changes. However, for very high strength material with a tensile strength of over 1000 MPa, a large force is needed for pre-strain. In addition, because the strain uniformity in the specimen is not perfect, many specimens are needed for just one non-linear strain path experiment. Therefore, a smaller specimen with better strain field uniformity over the entire gauge area, called medium-scale specimen, should be developed for various non-linear strain path experiments.

![Figure 3](image)

**Figure 3.** (a) Large-scale specimen (left) (b) Medium-scale specimen (right)

The tensile force is significantly affected by the cross-section of the specimen gauge area. Thus, the gauge width of the specimen should be reduced for high strength material. As a result, for biaxial tension as a second loading step, the cruciform specimen also should be redesigned to reduce the gauge width.
of the specimen. The gauge length and fillet radius of the medium-scale specimen were optimized through experiments to achieve a strain field as uniform as possible over the entire gauge area. Figure 3b shows the final size of the medium-scale specimen. When deformed up to a given point, the average logarithmic plastic strain along loading direction and standard deviation in the uniform area was about 5.2 % and 0.41 % respectively, as shown in Figure 4. The experimental result will be discussed in Section 4 with model predictions.

The cruciform specimen was reduced proportionally while constraints for the specimen were satisfied [6]. Figure 5 shows the detail size of the original and reduced cruciform specimen. There is no significant difference in terms of stress-strain curves from biaxial tension with 1:1 load ratio using TRIP1180 as shown in Figure 6. This indicates that the reduced cruciform specimen can be used instead of the original.

**Figure 4.** Strain distribution in the medium-scale specimen during tension and extraction area of 2nd loading specimen

**Figure 5.** Size of original and reduced cruciform specimens

**Figure 6.** Stress-strain curves in biaxial tension with 1:1 load ratio
3. Constitutive models and parameters identification

In the constitutive model, the Hockett-Sherby [7] stress-strain equation was chosen for monotonic loading, as well as Yld2000-2d [8] for the yield condition and HAH distortional plasticity model [3] for anisotropic hardening.

The Hockett-Sherby equation, which was used to describe the isotropic hardening behavior, was fitted to the stress-strain curve in uniaxial tension along the rolling direction. The coefficients were identified and the resulting calculated curve looked reasonable except for the early deformation stage as shown in Figure 7, which is likely due to phase transformation.

![Figure 7. Fitting result for Hockett-Sherby equation](image)

In order to determine the Yld2000-2d parameters, yield stress and r-value from uniaxial tension test conducted at 0, 45 and 90º along the RD and biaxial tension were needed. However biaxial tension test using cruciform specimen cannot get large strain deformation as shown in Figure 6. Thus bulge test, which can get about 40% strain as shown in Figure 8, was carried out to get yield stress in biaxial stress state while r-value in biaxial stress state was calculated from biaxial tension test using cruciform specimen. Yield stresses for each condition were determined at 90 MPa of plastic work. The eight Yld2000-2d anisotropy coefficients were calculated based on these experimental values.

![Figure 8. True stress-true strain curve of TRIP1180 in bulge tests](image)

The HAH distortional plasticity model was selected for the simulation because this model is widely used to predict material behavior under non-linear strain path. For parameter identification of the HAH model, an experiment which contains strain path changes like tension-compression or cyclic shear test is necessary. In this study, a tension-compression test was conducted. Using an optimization algorithm,
Nelder-Mead simplex algorithm, the HAH coefficients were optimized based on the experimental stress-strain curve. All the constitutive model coefficients of TRIP1180 are listed in Table 2.

Table 2. Constitutive model parameters of TRIP1180

| Hockett-Sherby | Yld2000-2d (a = 6) | HAH |
|-----------------|-------------------|-----|
| \(\sigma_s\)     | \(\sigma_y\)   | \(p\) | \(N\) | \(\alpha_1\) | \(\alpha_2\) | \(\alpha_3\) | \(\alpha_4\) | \(\alpha_5\) | \(\alpha_6\) | \(\alpha_7\) | \(\alpha_8\) |
| 7284.31         | 1040.22          | 0.436 | 0.0097 | \(\sigma = \sigma_y - (\sigma_s - \sigma_y) \times \exp(-N\epsilon_p^p)\) | 1.0329       | 0.9469       | 1.0296       | 0.9963    | 0.9982    | 1.0055    | 0.9918    | 0.9725   |
|                 |                  |      |       | \(k\) | 30             | 167.58       | 71.90       | 0.168     | 0.933     | 8.53      |

4. Results and Discussion

Experimental results and HAH predictions are represented in Figures 9 and 10 for uniaxial tension and balanced biaxial tension as subsequent loadings. In figure 9 and 10, the solid and dashed lines correspond to HAH predictions for monotonic loading and subsequent loading after TD tension respectively. In addition, black and red circles mean that the true stress - effective plastic strain curve from the experiment for monotonic and subsequent loadings with uniaxial tension in the TD as a pre-strain. Because strain path change occurs after the 1st loading, like uniaxial tension in RD after uniaxial tension in TD, true strain which is logarithmic strain along loading direction is not proper to express the amount of pre-strain. To represent the amount of pre-strain, all graphs were plotted about equivalent plastic strain (effective plastic strain) in x-axis while y-axis means true stress in each stress state.

Figure 9 shows the true stress - equivalent plastic strain curves for subsequent uniaxial tension at 0 and 45º from the RD. The material exhibits lower yield stress and strain overshooting after the strain path change. The lower yield stress can be associated with the Bauschinger effect and cross-loading contraction.

Figure 9. True stress-equivalent plastic strain curve in uniaxial tension with different directions after tension along the TD

The true stress - equivalent plastic strain behavior after biaxial tension with a 1:1 load ratio as a subsequent loading is represented in Figure 10. It was impossible to achieve large strains with this experiment due to early fracture. This explains the small number of experimental points in this figure. Nevertheless, lower yield stress is observed just after strain path change.
Strain path changes can be divided into two groups depending on whether the angle difference between the first and second loading on the π-plane is over or under 90º. Under the 90º strain path angle, the material experience cross-loading effect only as a non-linear strain path effect. In the other case, over 90º strain path angle, cross-loading and reverse-loading effects occur simultaneously when strain path change occurs. 45º uniaxial tension and biaxial tension after strain path change are under 90º strain path angle while 0º uniaxial tension after pre-strain is over 90º strain path angle difference in this study.

The Hockett-Sherby equation and Yld2000-2d were used to predict material behavior under monotonic loading. As shown in Figure 7, The Hockett-Sherby equation leads to a difference with the experimental result in the early deformation stage. Inaccurate prediction in initial monotonic loading in Figure 8 and 9 may come from the difference.

As written in Table 2, HAH model consists of 5 coefficients which account the Bauschinger effect after reverse-loading and permanent softening. In other words, the HAH model doesn’t have any consideration about material behavior on cross-loading or strain overshooting. As a result, HAH model cannot predict lower yield stress at all in 45º tension and biaxial tension following the pre-strain and strain overshooting after strain path change like dashed lines in Figure 9 and 10. For better prediction under the non-linear strain path, cross-loading and latent hardening coefficients should be used and HAH model will be modified as future work.

5. Conclusion
The new experimental method was proposed to conduct a non-linear strain path experiment with very high strength material. Through the proposed method, three different non-linear strain path experiment, 0 and 45-degree uniaxial tension along RD and balanced biaxial tension with pre-strain which is TD uniaxial tension, were conducted by using TRIP1180. Strain path effects, lower yield stress and strain overshooting, were captured experimentally.

Prediction level of HAH model under various strain path changes was checked by comparing experimental result. HAH model can describe the Bauschinger effect but not the cross-loading effect because it doesn’t any consideration for cross-loading cases in the model. As a future work, coefficients to describe cross-loading behavior will be put in the model for better prediction.

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