

# Characterization of Advanced High Strength Steel Sheets in View of the Numerical Prediction of Sidewall Curl

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## ABSTRACT

In this study, a procedure for characterizing advanced high strength steel sheets is presented in view of determining the material parameters for constitutive models that can be used for accurate prediction of springback and sidewall curl.

The mechanical properties of DP980 and TRIP780 sheets were obtained experimentally, and their cyclic tension-compression behaviour was modeled with the Chaboche nonlinear kinematic hardening model and the Yoshida-Uemori two-surface plasticity model that are implemented in LS-DYNA. The unloading moduli were determined from monotonic tension tests at various prestrain levels. An inverse approach based on linear and quadratic response surfaces created by Sequential Strategy with Domain Reduction (SRSM) methodology using LS-OPT software was used and investigated to identify specific material parameters in each constitutive model.

It was found that the quadratic meta-model with a quadratic approximation of history variables was able to accurately reproduce the cyclic stress-strain data when multiple tension-compression cycles are considered.

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## INTRODUCTION

Advanced high strength steels (AHSS) are multiphase steel grades with a tensile strength that can range from 500 to 1500 MPa. The microstructure of AHSS contains mixtures of ferrite and martensite. Bainite and/or retained austenite can also be present. These steels with a mixture of phases have more advantageous mechanical properties compared to single-phase ferritic high-strength steels.

The two common grades of AHSS used for automotive applications are dual phase (DP) steels and transformation induced plasticity (TRIP) steels. As shown in Fig. 1, the microstructure of DP steels consists of ferrite and martensite, while TRIP steels include martensite and/or bainite and more than 5% retained austenite. DP steels have good formability due to their high volume fraction of softer ferrite and also have good spot weldability due to the smaller amounts of

alloying elements. TRIP steels have extremely high elongation and work hardening ability relative to DP grades [1]. TRIP steels provide opportunities for designing automotive body parts with complex geometries at strength levels that are not possible with the equivalent DP strength, but TRIP steels present greater challenges for welding due to higher content of alloying elements compared to the DP grades [2].

The increased utilization of AHSS sheet materials has however created additional manufacturing challenges such as more severe springback problems, shear fractures, and edge cracking. Huang and Brouwer [3] as well as Shih [4] reported that springback and sidewall curl are much greater for AHSS than for traditional HSS. However, it could be stated more accurately that the springback of AHSS is different from springback of high strength steels (HSS) and an in-depth

understanding of the mechanical behaviour of AHSS is required.

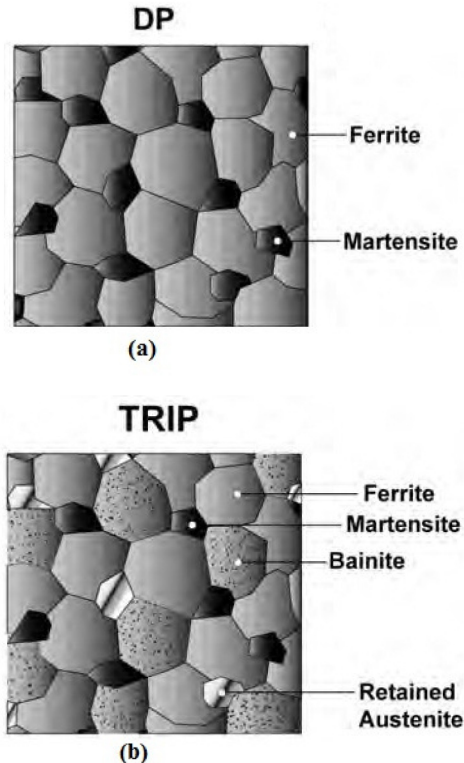


**Figure 1. a) Schematic shows islands of martensite in a matrix of ferrite in DP steels, b) Bainite and retained austenite are additional phases in TRIP steels [1]**

The most challenging form of springback is sidewall curl. When a channel-shaped part is stamped the sheet material is drawn over a die entry radius (or through a drawbead) and the drawn sidewall tends to curl instead of remaining straight. As the sheet is successively bent and unbent over the die radius, the material on the intrados of the bend first experiences compression followed by tension, whereas the material on the extrados of the bend undergoes tension followed by compression. And since the behaviour of AHSS in reverse loading is generally quite different from that during the initial loading the drawn sidewall inevitably exhibits different levels of residual stress on the intrados and extrados of the bend. The resulting sidewall curl makes it difficult to mate parts with this non-flat surface during assembly, and vehicle manufacturers strive to eliminate, or at least to minimize sidewall curl.

Geng and Wagoner [5] observed that the finite element (FE) predictions of sidewall curl are not sufficiently accurate and the shape distortions estimated for some industrial applications have been notably erroneous. Firat et al. [6] performed an investigation of such predictions in representative cases and indicated that the discrepancies cannot be explained on the basis of variability of the input parameters or numerical factors alone and the plasticity

models employed in the FE analyses significantly influence the predicted deformation.

Several advanced constitutive models have been developed and implemented in FE codes that are able to accurately describe the cyclic work hardening behavior of AHSS sheets, and in particular the early re-yielding, or Bauschinger effect and its transient behaviour during reverse loading. However, the first issue is to identify the material parameters for such constitutive models from the experimental cyclic stress-strain data obtained from either tension-compression tests, bending-unbending or reverse shear tests.

Researchers have used a number of non-linear optimization techniques to calibrate material models with experimental data. Yoshida et al. [7] used an iterative multipoint approximation concept which minimized the differences between the experimental cyclic bending moment versus curvature data and simulated results of the same test. Material parameters were identified for a combined isotropic-nonlinear kinematic hardening model. The same method was also used by Yoshida and Uemori [8] for determining parameters in the two-surface Yoshida-Uemori (YU) plasticity model from cyclic tension-compression tests of mild and high strength steels. It was also expanded for identification of Chaboche model parameters for an aluminum clad stainless steel sheet by Yoshida et al. [9].

Cao et al.[10] used tensile specimens of DP600, BH180 and AA6111-T4 and determined material parameters using curve fitting methods for a combined isotropic-kinematic hardening law based on the Chaboche model as well as a modified two-surface model based on the Dafalias-Popov and Krieg models. Recently, Eggertsen and Mattiasson [11] used an inverse approach to determine different hardening parameters, using simulations of three-point cyclic bending tests that were carried out with the explicit FE-code LS-DYNA [12]. The identification of the hardening parameters was performed by means of the optimization code LS-OPT [13] and the response surface methodology (RSM) in which the corresponding mean square error (MSE) between experimental and simulated results was minimized.

In addition to the material hardening parameters, the variation of the unloading modulus with plastic deformation has been shown to have a significant effect on springback behaviour. Benito et al.[14] showed that the apparent unloading modulus decreased with a nonlinear behaviour as the plastic strain increased, and this phenomenon seemed to be related to the microstructure of the DP material. By introducing the variation of elastic response during unloading, significant improvements were observed in the simulation of a bending process for four different grades of DP steel.

In this paper, results from a full-cycle tension and compression test and a multiple-cycle tension and compression test for DP980 and TRIP780 were used to identify the material parameters for two different hardening models. The cyclic tests were simulated with the finite

element code LS-DYNA. An inverse methodology based on a sequential strategy with domain reduction (SRSM) implemented in LS-OPT was used to determine the hardening parameters. In the optimization procedure, a curve mapping metric was calculated and minimized to obtain values for the corresponding set of parameters. The parameter values in Hills 1948 yield criterion were identified from uniaxial tension tests carried out at various orientations with respect to the sheet rolling direction. Evolution of the unloading modulus was also investigated for both materials from a series of uniaxial tension tests at various levels of prestrain.

## MATERIALS

The chemical compositions of DP980 and TRIP780 steels used in this study are presented in Table 1. Tensile specimens were prepared parallel to the rolling, transverse and diagonal directions according to ASTM E8 and machined by wire EDM. Fig. 2 a. and b. show that the stress-strain curves are almost identical for all three orientations and that the anisotropic nature of the yield stress is not significant. Young's modulus was determined by a linear fit to the beginning portions of the test data and the average value of the elastic modulus was found to be 207 GPa. Poisson's ratio was taken to be 0.3 throughout the study for both materials. The plastic anisotropy coefficients (r-values) were determined from the tensile stress-strain data based on ASTM E517 and the strain hardening exponents (n-values) were determined according to ASTM E646. The mechanical properties of the study materials are summarized in Table 2 as measured from the tensile tests.

**Table 1. Chemical composition of the study materials (%)**

| Material | DP980 | TRIP780 |
|----------|-------|---------|
| C        | 0.14  | 0.22    |
| Mn       | 0.14  | 0.22    |
| P        | 0.01  | 0.01    |
| S        | 0.005 | <0.005  |
| Si       | 0.31  | 0.07    |
| Cr       | 0.02  | 0.21    |
| Ni       | <0.01 | <0.01   |
| Mo       | <0.01 | <0.01   |
| Al       | -     | 1.35    |

## UNLOADING MODULUS

Previous experimental studies of Van Tyne et al. [15] have shown a significant decrease in the apparent unloading modulus compared to the initial elastic modulus for high strength sheet materials. Eggertsen and Mattiasson [16] observed a difference between the unloading and reloading curves which deviated from linearity around an imaginary “mean” line representing the secant to the curve as shown in Fig. 3. The slope of the secant decreased with increasing plastic strain and was strongly material-dependent

Since the decrease of the unloading modulus has a significant effect on the prediction of springback, Yoshida et al. [9] proposed an empirical equation that has been implemented in various constitutive models to account for the degradation of unloading modulus:

$$E_u = E_0 - (E_0 - E_{sat})(1 - e^{-\zeta \bar{\epsilon}^p}) \quad (1)$$

where  $E_u$  is the unloading elastic modulus,  $E_0$  is the initial Young's modulus,  $E_{sat}$  is the unloading modulus for an infinite prestrain, and  $\zeta$  is a material constant which determines the rate of decrease of the effective unloading modulus with respect to plastic strain,  $p$ .

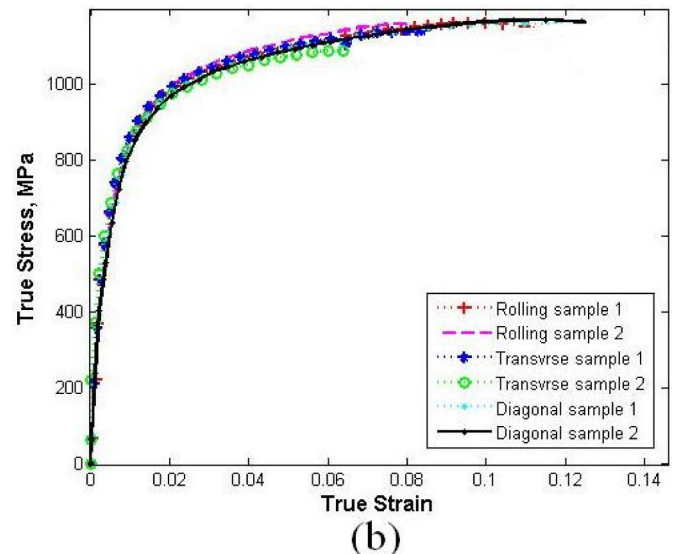
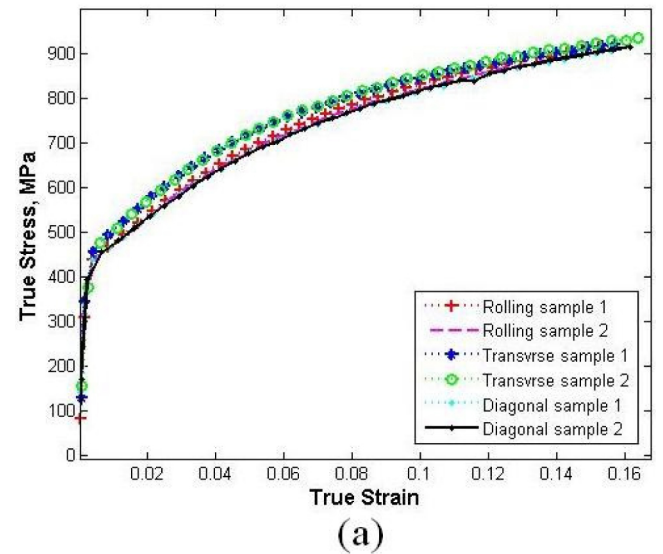


**Figure 2. True stress-strain data obtained in uniaxial tension for: a) TRIP780, b) DP980 [2]**

Eggersten and Mattiasson [16] proposed that the nonlinearity of the unloading behaviour could be modeled by an additional surface inside the yield surface. However, it has