

Advanced Material Characterizations and Constitutive Modeling for AHSS Springback Predictions

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Hong Zhu, S Sriram, Benda Yan and Patrick Duroux
ArcelorMittal Global R&D

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ABSTRACT

Springback prediction is one of the roadblocks for using advanced high strength steel in the automotive industry. Accurate characterization and modeling of the mechanical behavior of AHSS is recognized as one of the critical factors for successful prediction of springback. Conventional tensile test based material characterization and constitutive modeling may lead to poor springback simulation accuracy. Aiming to accurately predict springback, a series of advanced material characterizations including bi-axial material testing, large-strain loading path reversal testing, unloading tests at large strain, stress-strain behavior beyond uniform elongation, were performed for selected AHSS and associated constitutive models were developed to incorporate these characterizations. Validations through lab samples and industrial parts show that the AHSS springback prediction accuracy is significantly improved with these improved material models.

INTRODUCTION

Springback is the surface deviation of manufactured parts from design-intended shapes due to part deformation during the process of removing tooling (unloading). The amount of springback is determined by the residual stress imposed during stamping and the material's unloading behavior. Generally speaking, springback modes include a) angle opening from bending, b) side wall curl from bending-unbending, c) global twisting and d) global bowing from global unbending as schematically shown in [Figure 1](#).

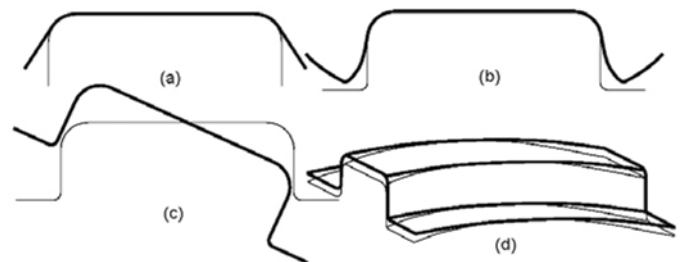


Figure 1. Schematic of the different springback modes occurring in automotive parts; (a) angle opening, (b) sidewall curl (c) twisting of sections and (d) Global bowing from unbending. The dark line is the shape of the panel after removal from tooling and the light line is the design intent.

Although many techniques have been developed to control and compensate for springback of automotive panels in the past, it is still a challenging task when using Advanced High Strength Steel (AHSS) in the automotive industry because of their higher strength and multi-phase microstructures that result in mechanical behaviors that are somewhat different from conventional steels.

Springback prediction is a vital tool for developing various compensation solutions to control springback. To ensure accurate springback predictions, three key factors are (a) accurate product/process information, (b) robustness of numerical techniques including element formulation, contact algorithm, time integration scheme; and (c) reliable test data of material behavior under various loading conditions/histories as well as appropriate constitutive models to describe these behaviors.

In most FEA predictions of stamping, conventional constitutive models are used for springback prediction. These models are based on the stress-strain curve generated from the standard tensile test, using the classical elastic-plastic theory (yield surface, flow rule, constant elastic modulus for loading and unloading) to predict stress-strain responses under complex multi-axial loading history. Standard tensile tests are used to generate the stress-strain curve to a limited strain level (uniform elongation) under uniaxial tensile condition. The classical elastic-plastic theory is based on various pre-assumed evolutionary equations and postulates (yield surface, flow theory and Drucker's postulates) to interpolate, extrapolate and predict stress-strain response. These models may lead to inaccurate stress-strain responses in the unverified domains of strain, stress-state and loading history. During stamping process, parts often go through complex bi-axial loading histories at large strains. The material behavior in these complex loading conditions is beyond the domain of standard material characterizations such as tensile test.

In recent years, ArcelorMittal has developed various advanced material characterization techniques including multi-axial loading, loading-path reversal, unloading and reloading, and generation of full-range stress-strain curve till fracture. New constitutive models to incorporate these new results have been developed for accurate description of AHSS material behavior. Validations through lab samples and industrial parts show that the AHSS springback prediction accuracy is significantly improved with the use of these improved material models. This paper presents results of these improved test methods, description of the different models, and validation of the models using laboratory samples and industrial type parts.

EXPERIMENTAL DETERMINATION OF THE YIELD LOCUS

Four types of tests were used to determine the yield locus of the materials in the experimental matrix, uniaxial tensile, plane strain, shear and biaxial loading. Standard ASTM E 8 tensile testing was used for uniaxial tension behavior. For testing in pure shear and plane strain, a special fixture was designed to be used with different specimen geometries and multi-axial loading conditions. [Figure 2](#) shows the test fixture that was used for shear and plane strain testing. The fixture was designed to eliminate slippage in the grips. The gage region was also optimized to ensure that the strain/stress was uniform in the deforming region.

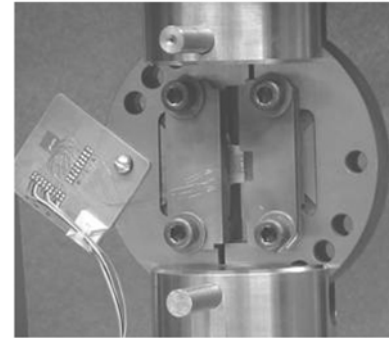
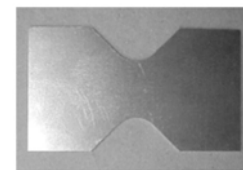
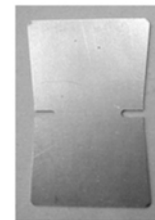


Figure 2. Test fixture for pure shear and plane strain testing



Pure Shear



Plane strain

Figure 3. Test specimens for pure shear and plane strain testing

Efforts were made to conduct biaxial testing using cruciform specimens and the hydraulic bulge test, however these tests were found to be time consuming and expensive. Instead, stacked compression testing using stacked sheet steel specimens was chosen for generating data for biaxial loading. Compression tests have been used by researchers as an alternative to balanced biaxial testing ([Tozawa, 1978](#); [Keesler et al, 2006](#); [An et al, 1998](#); [An et al, 1999](#)) for the reason of cost-effectiveness. Under the assumptions of volume constancy during plastic flow and the negligible effect of hydrostatic pressure on plastic flow it can be shown very easily that a stacked compression test is mechanically equivalent to a balanced biaxial stress test. [Figure 4](#) shows the test arrangement for the stacked compression test. Teflon sheets and oil were used between the compressing platens and the specimen stack to minimize the effect of friction.

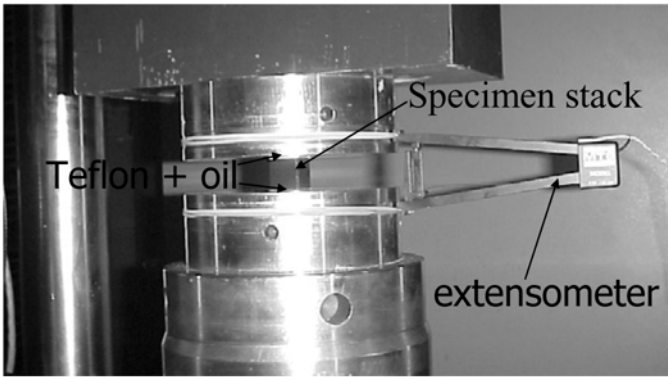


Figure 4. Stacked compression testing conducted to determine the stress strain behavior under balanced biaxial loading conditions.

The output from the different test methods are in the format of true stress vs. plastic strain specific to the test method. To enable comparison on a consistent basis, the principle of plastic work per unit volume of the material is used. The equation for determining the plastic work per unit volume is given below, where the symbols have their usual meaning:

$$dW = \sigma_{xx}d\epsilon_{xx} + \sigma_{yy}d\epsilon_{yy} + \sigma_{zz}d\epsilon_{zz} + \tau_{xy}d\gamma_{xy} + \tau_{yz}d\gamma_{yz} + \tau_{xz}d\gamma_{xz} \quad (1)$$

Using equation (1), the plastic work per unit volume can be determined for each of the tests and the flow stress can be plotted as a function of the plastic work to enable comparison on a consistent basis. Figure 5 shows the testing results of true stress vs. plastic work for DP590 using different testing methods.

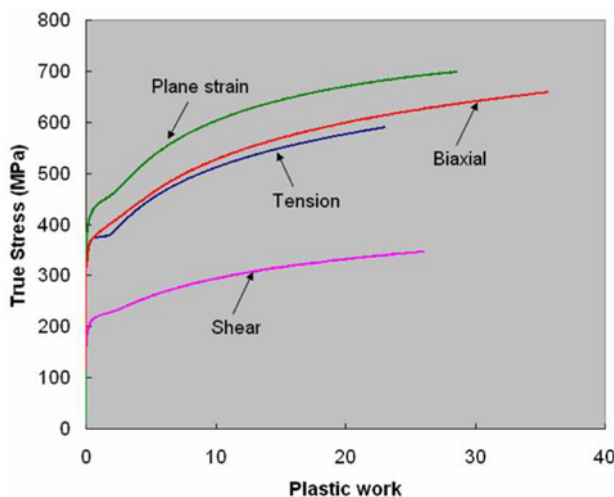


Figure 5. Comparison of the different tests using plastic work on the x-axis

The information presented in Figure 5 could be used to generate the yield surface as iso-plastic work contour maps.

However it is much more intuitive to construct the yield surface on the basis of plastic strain in uniaxial tension. To enable construction of the yield surface, regression of true plastic strain vs. plastic work for the uniaxial tension test was developed. The values of plastic work for the different tests were then converted back to corresponding values of true strain in uniaxial tension. One final consideration in the construction of the yield surface is the use of results from the plane strain test. There is no direct measurement of the minor principal stress in the plane strain test, only the major principal stress and the strains are directly measured. To circumvent this problem, the plane strain test results are plotted on a line, the slope of which is determined using isotropic elasticity, Hill's 1948 yield theory and the von Mises yield theory. For isotropic elasticity and plane stress:

$$\epsilon_2 = \frac{1}{E}[\sigma_2 - \nu\sigma_1] = 0 \quad (2)$$

$$\text{Using } \nu = 0.3, \frac{\sigma_1}{\sigma_2} = \frac{1}{0.3} = 3.33 \quad (3)$$

According to the associated flow rule, using the popular Hill's 1948 theory, the slope for plane strain is determined as follows:

$$d\epsilon_2 = d\bar{\epsilon} \frac{\partial \bar{\sigma}}{\partial \sigma_2} = \frac{d\bar{\epsilon}}{\bar{\sigma}} \left[\sigma_2 - \frac{\bar{r}}{1+\bar{r}} \sigma_1 \right] = 0 \quad (4)$$

$$\frac{\sigma_1}{\sigma_2} = \frac{1+\bar{r}}{\bar{r}} \quad (5)$$

In a previous study, (Sadagopan and Urban, 2003) the $\bar{r}$ value for DP590 and DP780 were measured to be 0.85-0.9. Using a value of 0.85, the value of the slope is 2.17.

Substituting $\bar{r}=1$ which results in the von Mises yield function, gives back a value of 2 for the slope. It is reasonable then to expect that the results of the plane strain test lie between the lines of slope 2 and 3.33 as extremes for AHSS. Figures 6 and 7 show the individual data points for the yield surface in comparison with the von Mises and the Hill's 1948 yield theory. Results are presented for two test replicates for DP590.

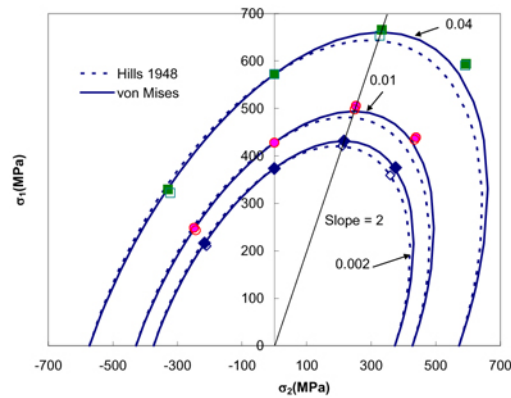


Figure 6. Comparison of points to cause yielding for DP590 determined by the different stress states to von Mises and Hill's 1948 yield theories. The plane strain results are plotted on a line with slope 2

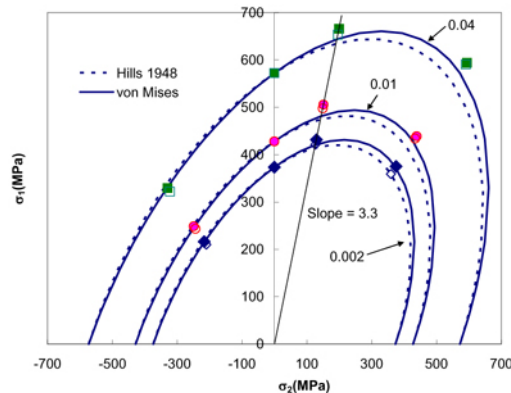


Figure 7. Comparison of points to cause yielding for DP590 determined by the different stress states to von Mises and Hill's 1948 yield theories. The plane strain results are plotted on a line with slope 3.3

From Figures 6 and 7, it can be seen that the von Mises yield function provides a very good engineering estimate of the yield behavior of DP590 under multi-axial loading conditions. The figures show that evolution of the yield surface for the strains examined in this study still follow the von Mises yield surface. Results from this study indicate that the von Mises yield surface could be used when analyzing AHSS. It can be seen that there is not much difference between the von Mises and the Hill's 1948 yield theory. This is because the r value of AHSS is much lower than mild steels. It is noteworthy that the Hill's 1948 theory does overestimate the effect of r on the shape of the yield surface (Wagoner et al, 1996), which in turn influences the stress and strain states calculated during FE analysis. In fact this was the reason for the later formulations of yield surfaces for sheet metal forming analysis, which deviate from the quadratic formulation as proposed in the Hill's 1948 yield surface. The results of this study show however that for the AHSS

examined in this study, there is no need to use a particularly complicated yield function to describe the behavior of AHSS.

LOADING PATH REVERSAL TESTS AT LARGE STRAIN AND CONSTITUTIVE MODELING

Loading-path reversal often occurs in the stamping process. For example, when sheet metal flows into the die cavity during stamping processes, the material goes through a bending-unbending cycle. Similar loading history is also seen when draw beads are used. However, it is difficult to characterize loading-path reversal at large strains using a uniaxial tensile test due to buckling of the specimen (Yoshida et al, 2002). Although some attempts have been made to use pure-shear specimens to perform these path reversal tests (i.e, Hu et al, 1992), transforming these data to the uniaxial condition needs pre-assumed yield surface. In this study, a specially designed fatigue specimen (see Figure 8) is used to perform loading path reversal test on a 22KN MTS fatigue testing machine.

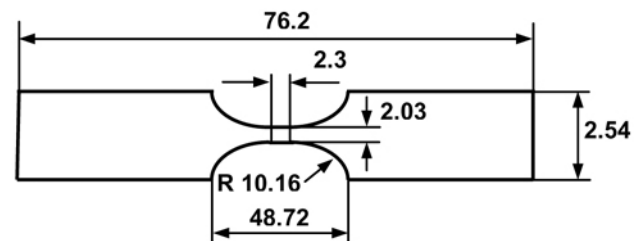


Figure 8. Special designed specimen for large strain cyclic loading and unloading tests. All dimensions in mm

The procedure for load reversal test was to pull specimens to a specified pre-strain (2%, 5%, 8%, 10%), then reverse loading until zero strain, followed by tensile reloading again. The results of reverse loading tests are shown in Figure 9 for a 1.8 mm DP780. From Figure 9, Bauschinger effect, transient effect as well as permanent softening (Yoshida, 2004) during reverse loading are observed. These phenomena are common for all steels grades but are more severe for AHSS due to their multi-phase microstructures. These phenomena originate from deformation mechanisms based on different length scales. AHSS contain phases of different strengths such as ferrite, martensite, bainite and retained austenite. Internal back stresses (residual stress) are generated between these inhomogeneous phases under tensile loading to ensure strain and stress compatibility. The evolution of this back stress contributes to the observed Bauschinger effect and transient effect after loading reversal to compression (Bate, 1986). Within each individual grain, the various dislocation substructures such as pile-ups, walls, cells and forest dislocations generated during tensile loading at large strains will go through complex transient evolution including partial annihilation and reformation once the loading