

Experiences with Experimental Determination of the Yield Locus and its Evolution for Advanced High Strength Steels

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ABSTRACT

Accurate description of the plastic yield locus is important for accurate prediction of sheet metal formability and springback using FEM. This paper presents experimental results obtained for the initial plastic yield locus and its evolution for some selected Advanced High Strength Steels (AHSS). A review of available experimental methods was conducted to select appropriate techniques for testing. For loading in tension-shear, the Arcan test was selected, however because of lack of uniformity of the stress distribution, the test was not included in the final series of tests. Shear testing, uniaxial tensile testing, plane strain testing and stacked compression testing were used to determine the yield locus. From the test results and analysis for the selected AHSS, it seems that the onset of initial yielding and its isotropic evolution to 4% plastic strain is best described by the von Mises yield function.

INTRODUCTION

Mechanical characterization of metallic materials, especially steel products has primarily hinged on the uniaxial tensile test for purposes of specification, testing, qualification and analysis. During metalworking, the material is subjected to a generalized state of stress whereby the plastic response of the material is determined using a yield function, a flow rule and a hardening law. Several yield functions have been defined in literature to define the onset of yielding [1,2,3,4,5]. Because the prediction accuracy of springback, curl, press loads, and very often fracture is dependent on prediction of stresses, it is important to assess the applicability of these different yield functions to the plastic flow behavior of AHSS.

Experimental determination of the yield behavior of sheet materials under multi-axial loading conditions has been

studied for some time. Shear testing has been used to study kinematic hardening behavior of the yield surface [6,7,8]. Cruciform testing is popular in Europe and Japan and there have been many variations on the cruciform test geometry [9,10,11,12,13,14,15,16,17,18,19,20,21,22]. All of these geometries are shaped like a cruciform, with the central gage section being monitored for stresses and strains. It has been reported with this testing that the stress state in the central gage region may not be uniform. This often results in additional analysis or post-processing of test results to determine an effective area where biaxiality is present. In contrast, Kuwabara *et. al.* [20] developed a specimen design with slits on the pulling arms of the cruciform such that the stress state in the gage section of the specimen is uniform. The maximum achievable effective strain reported by Kuwabara is 4%, which approximately equals 2% in each direction. The advantage with this kind of direct biaxial testing is that a number of loading paths can be used ranging from uniaxial tension to balanced biaxial tension and the yielding behavior determined. The disadvantage being the high cost associated both with the initial setup in acquiring or designing such a machine and with ongoing costs incurred by machining of specimens.

Because of the issues associated with direct biaxial loading, researchers have also been working on using indirect testing method to evaluate the work hardening behavior of sheet materials under a biaxial stress state. Of these, the hydraulic bulge test and the stacked compression test have been used. The hydraulic bulge test consists of a fully restrained sample of sheet metal which is pressurized. The height of the bulge is measured using a spherometer, which gives the radius of curvature. From the measurement of pressure and the radius of curvature, the radial and hoop stresses could be determined. The stacked compression test was first used by Tozawa [23] as an alternative to direct testing. In this test,

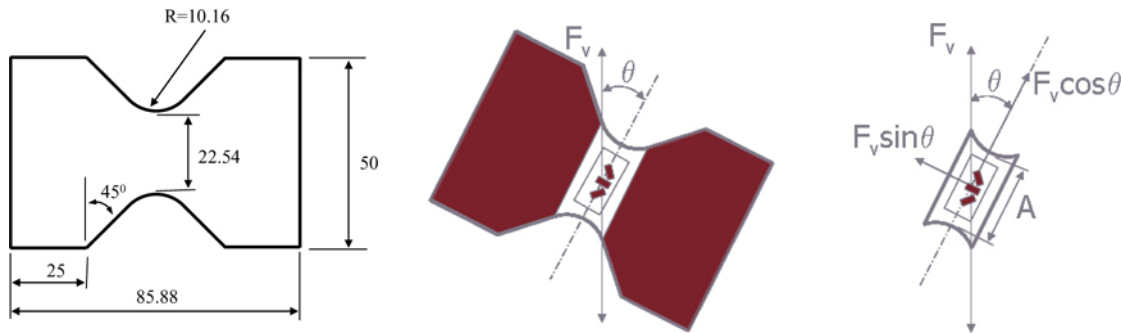


Figure 1. Geometry of the Arcan specimen showing the normal and the shear components of the applied load. All dimensions in mm unless marked otherwise

specimens are stacked and glued together and compressed using platens. There is a lubricant used between the platens to minimize friction. Using the assumption of volume constancy and independence of plastic yield on hydrostatic pressure, the stacked compression test can be used as an alternative to direct biaxial testing. There are issues with both the stacked compression test and the bulge test. The stacked compression has the issue of friction, which has a strong influence at larger strains. The assumption with the hydraulic bulge test is that of constant curvature using the spherometer, which may give inaccurate results. In reviewing the literature, it was found that comparisons between the stacked compression and bulge tests were somewhat contradictory. Kessler and Gerlach [24] compared results of bulge and stacked compression testing and report that the stacked compression test results in a higher flow stress at higher strains (greater than 10%). An and Vegter [25-26] conducted a similar comparison and concluded that the stress obtained from stacked compression tests were lower than the hydraulic bulge test. Recently, a new approach [27] of using X-Ray diffraction in conjunction with a Marciniak punch has been used to determine stresses during plane strain and biaxial loading.

This paper presents the results of research that was conducted at ArcelorMittal Global R&D Center in East Chicago to evaluate the different methods described in literature to determine the plastic yield locus of selected AHSS. Following the evaluation of existing test methods, some of these test methods were chosen to determine the plastic yield locus of 1.4mm DP590 and 1.5mm DP780 steel grades.

EVALUATION OF EXPERIMENTAL METHODS

Two materials were selected for conducting the experiments for generation of the yield surface. The standard mechanical properties for the materials are given in Table 1.

Table 1. Standard mechanical properties of materials used in the experiments

Material	Thickness (mm)	YS (MPa)	UTS (MPa)	UE (%)	TE (%)
CR DP590	1.4	379	626	15	23
CR DP780	1.5	494	796	12	19

The approach used in this work has been to investigate the feasibility of many different approaches while minimizing testing cost. Four stress states were chosen for further experimentation: (a) Tension shear (c) In-plane shear (c) Plane strain and (d) Balanced biaxial

TENSION SHEAR

The tension shear test, originally developed by M. Arcan et al. [29] as a way to determine the material behavior under complex plane stress loading conditions. In Arcan testing, the loading axis can be oriented at an angle to the specimen axes to generate different ratios of normal and shear stresses in the plane of the sheet. The stresses are determined using force measurement from a load cell and the strain field is determined by strain gages or using non-contact techniques. In this case, the strain field was determined using a 45° strain rosette. Figure 1 shows the geometry of the specimen used for Arcan testing. It was considered that a range of stress states ranging from uniaxial tension to pure shear could be obtained with this test approach.

<figure 1 here>

The normal stress σ_{xx} and shear stress τ_{xy} acting on the area A are given by the following expressions:

$$\sigma_{xx} = \frac{F_v \sin \theta}{A}; \tau_{xy} = \frac{F_v \cos \theta}{A} \quad (1)$$

The principal stresses for generalized loading can be readily derived and are given by:

$$\sigma_{1,2} = \frac{\sigma_{xx}}{2} \pm \sqrt{\frac{\sigma_{xx}^2}{4} + \tau_{xy}^2} \quad (2)$$

For uniaxial tensile loading ($\theta=90^\circ$):

$$\sigma_1 = \sigma_{xx} = \frac{F_v}{A}; \sigma_2 = 0 \quad (3)$$

For loading in pure shear ($\theta=0^\circ$):

$$\sigma_1 = \tau_{xy} = \frac{F_v}{A} = -\sigma_2 \quad (4)$$

The determination of principal strain components is illustrated pictorially in Figure 2 using the Mohr's circle for strain determination. In this figure $\epsilon^{(1)}$, $\epsilon^{(2)}$ and $\epsilon^{(3)}$ are the axial strains measured by the three individual strain gages on a 45° rosette.

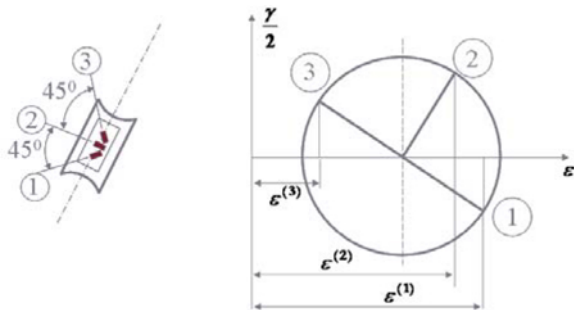


Figure 2. Gage section of the Arcan specimen showing the strain rosette and a schematic illustration of the measured axial strains on a Mohr's circle.

From geometry of the Mohr's circle, the principal strains expressed as a function of the axial measured strains can be derived to give the following expression:

$$\epsilon_{p1,p2} = \left(\frac{\epsilon^{(1)} + \epsilon^{(3)}}{2} \right) \pm \frac{1}{\sqrt{2}} \sqrt{(\epsilon^{(1)} - \epsilon^{(2)})^2 + (\epsilon^{(2)} - \epsilon^{(3)})^2} \quad (5)$$

This relationship in eq. (5) can be used to determine the principal strain fields for general loading at any arbitrary loading angle, θ where the axial strains are monitored continuously. For loading along 0° and 90° as shown in Fig. 3, the strains are determined using more straightforward relationships.

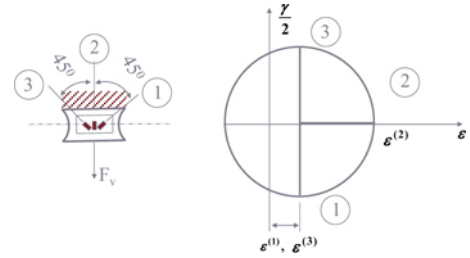


Figure 3. Orientation of the gage section and Mohr's circle representation of the strain state for normal loading ($\theta=90^\circ$)

For normal loading ($\theta=90^\circ$):

$$\epsilon_{p1} = \epsilon^{(2)}; \epsilon_{p2} = 2\epsilon^{(1)} - \epsilon^{(2)} \quad (6)$$

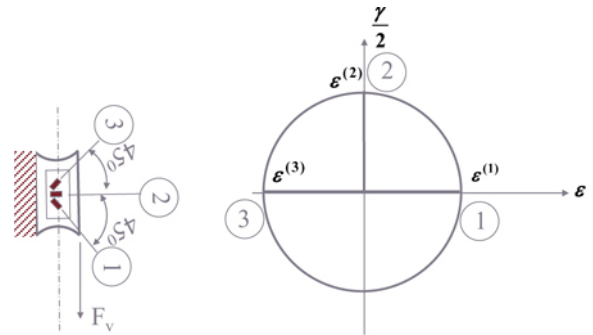


Figure 4. Orientation of the gage section and Mohr's circle representation of the strain state for shear loading ($\theta=0^\circ$)

For shear loading ($\theta=0^\circ$),

$$\frac{\gamma}{2} = \frac{\epsilon^{(1)} - \epsilon^{(3)}}{2} = \epsilon_{p1} = -\epsilon_{p2} \quad (7)$$

A fixture was designed and fabricated to conduct Arcan testing at ArcelorMittal Global R&D in E. Chicago. Figure 5 shows a photograph of the testing fixture used for conducting tension shear experiments. The circular plates in Fig. 5 have holes spaced 30° apart to facilitate loading along different angles. Gripping plates were fabricated with a knurled pattern so as to maximize friction gripping of the sample.

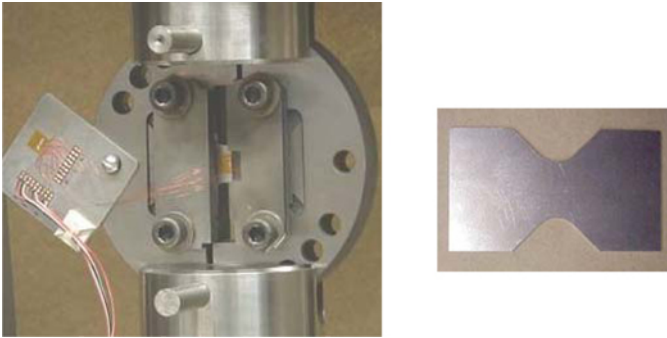


Figure 5. Test fixture for Arcan testing to test specimens in combined tension shear loading and the specimen for tension shear loading

Strain measurements were conducted using a 45° plane strain rosette. The rosette consisted of three individual strain gages. The procedure for application of the strain gages follows the recommendation given by manufacturer. For data recording, a USB-based compact DAQ system from National Instruments was acquired. This system enables the acquisition of synchronized load and strain data through the USB port on a PC using individual modules.

Several trials were conducted using this fixture. Figure 6 shows the results of a test conducted on DP590 using the Arcan fixture with a loading angle of 90°, an ASTM standard tensile test (using strain gages) and a subsized tensile test on the same material. As seen in Figure 6, the subsized tensile and the standard tensile show excellent agreement, whereas the Arcan fixture testing shows higher stresses. To understand the reason for this discrepancy FE simulations using ABAQUS Standard was conducted on the Arcan specimen. Figure 7 shows contour plots of the major and minor principal stresses in the center of the sample when loaded normally and the nodal trace of the values through the center of the specimen. As seen in Fig. 7, the major principal stress is uniform, but the minor principal stress is not uniform across the width of the sample changing from a uniaxial stress state at the edge (zero minor stress) to a stress state close to plane strain at the center of the specimen. This non-uniformity results from the deforming gauge section of the Arcan specimen. The aspect ratio (length/width) of the deforming region is 0.45 for the Arcan specimen, whereas for a standard ASTM E70 tensile specimen, the aspect ratio is 4. Because of this non-uniformity, results from normal loading of the currently designed Arcan specimen cannot be used directly in determining the yield response of the material. The determination of a nominal axial stress from a normally loaded Arcan specimen will give a value which represents some averaged behavior of the material between uniaxial tensile and plane strain testing. Similar results were obtained for a loading angle of 45° where the stress distribution was not uniform across the width of the sample.

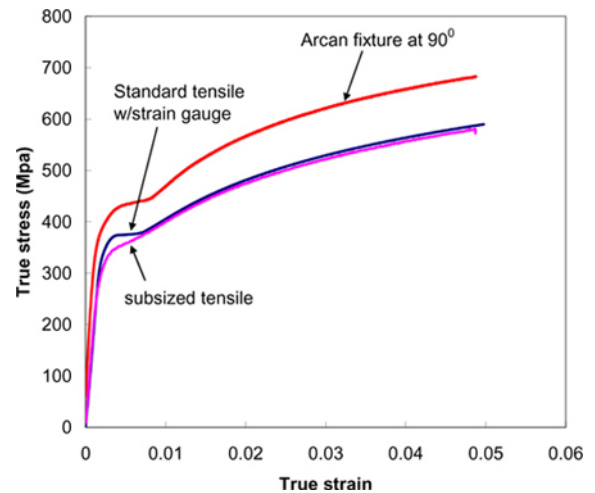


Figure 6. Comparison of Arcan testing at $\theta=90^\circ$, standard tensile with strain gauge and a subsized tensile for DP590.

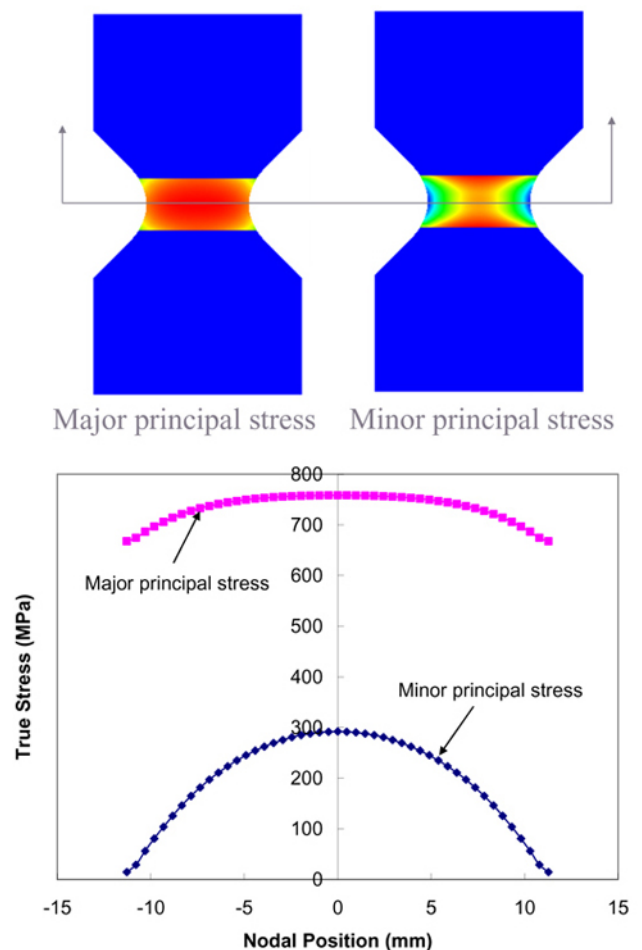


Figure 7. Contour plots of the major and minor principal stresses and the nodal trace of these values through the center of the specimen for DP590.