

AHSS Shear Fracture Predictions Based on a Recently Developed Fracture Criterion

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ABSTRACT

One of the issues in stamping of advanced high strength steels (AHSS) is the stretch bending fracture on a sharp radius (commonly referred to as shear fracture). Shear fracture typically occurs at a strain level below the conventional forming limit curve (FLC). Therefore it is difficult to predict in computer simulations using the FLC as the failure criterion. A modified Mohr-Coulomb (M-C) fracture criterion has been developed to predict shear fracture. The model parameters for several AHSS have been calibrated using various tests including the butterfly shaped shear test. In this paper, validation simulations are conducted using the modified (M-C) fracture criterion for a dual phase (DP) 780 steel to predict fracture in the stretch forming simulator (SFS) test and the bending under tension (BUT) test. Various deformation fracture modes are analyzed, and the range of usability of the criterion is identified. Good correlations have been found for failure prediction for tight radius stretch bending.

INTRODUCTION

AHSS are increasingly used in the automotive industry to meet future safety and fuel economy requirements due to their significantly higher strength than the conventional high strength steels with a relative good elongation (ductility). However, some of the manufacturing issues have limited the utilization of AHSS. One of the issues is shear fracture, which usually occurs on the die radius as the material is stretch bent over a sharp radius. Insignificant material thinning is often accompanied with this type of fracture, thus,

it cannot be predicted by the conventional FLC, even though the FLC has been used very successfully for conventional steel failure predictions. [Figure 1](#) shows an example of this kind of fracture for an automotive rail made from a DP780 steel. Fracture occurred on the radius, and it was not predicted by the simulation using the FLC. Some other examples of prediction limitations using the conventional FLC for AHSS can be found in [1].

To find an alternative criterion to predict shear fracture of AHSS, various experimental and modeling work has been conducted in recent years. Walp et al. [2] tested AHSS using a modified Duncan Shabel tester and showed that a critical radius to thickness ratio (R/T) existed in shear fracture for different materials. When the R/T ratio is lower than this critical value, material experiences shear fracture. Shih et al. [3, 4] conducted experiments using the stretch forming simulator (SFS) and the bending under tension (BUT) tests for various AHSS and developed an empirical shear fracture criterion. It was found that shear fracture depended on both the R/T ratio and the tension level in the stretch bending process. Finite element (FE) simulations were also conducted based on the conventional FLC on these two tests to identify the prediction issues in simulations [5]. Several research consortiums were also formed recently to investigate the AHSS including shear fracture. Wagoner and co-workers [6] performed draw-bend fracture tests for various AHSS. Their experiments revealed that shear fracture was related to the R/T ratio, the test velocity and the heating generated from the material deformation. Correspondingly, they simulated the tests with material models including temperature and strain rate effects obtained from experiments. The prediction

accuracy was improved with the material model incorporating those effects and shear fracture locations could be identified. Kim and Bandar [7] also simulated the same tests using a damage accumulation model considering the area fractions of micro-voids and thermal softening during deformation. They demonstrated the feasibility to simulate shear fracture with the micro-void based Gurson-Tvergaard-Needleman model and the stress ratio-strain based normalized Cockcroft-Latham damage models. Matlock and co-workers [8] also used a similar test to investigate the effect of AHSS microstructure on shear fracture. Wierzbick and co-worker modified the Mohr Coulomb (MMC) fracture criterion and generated parameters for both plasticity and fracture models for various AHSS. They also conducted FE simulations to validate and calibrate the criteria [9].

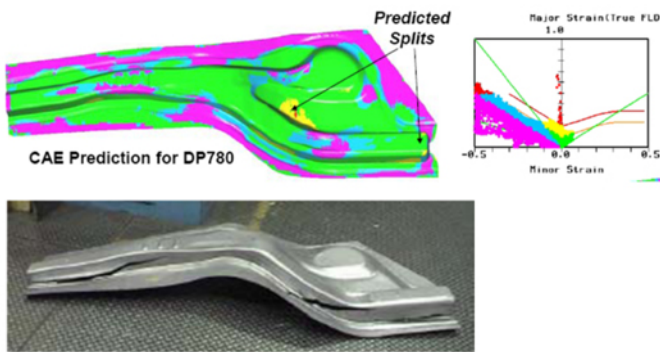


Figure 1. Shear Fracture of a Front Rail using a DP780

During stamping, fractures in conventional steel occur either in the side wall or the tangent point to the die radius, which are mainly tensile type fractures. When shear fracture occurs on the die radius for AHSS, the fracture mode can be a combination of tension, compression and shear stresses. For this failure mode, the MMC criterion is more realistic than other models that do not consider shear stress effects. In this study, the SFS and BUT tests are used to validate the MMC fracture criterion. The MMC model parameters are determined empirically for a DP780 steel using various lab experiments. FE software packages ABAQUS and LS-DYNA are used in the simulations with implemented user subroutines for the MMC fracture model. It is found that a good agreement exists between the simulations and the experiments for shear fracture in tight radius stretch bending.

MMC FRACTURE CRITERION OVERVIEW

The Mohr-Coulomb (M-C) fracture criterion assumes that the fracture occurs when a combination of normal stress and shear stress reaches a critical value and it is expressed as

$$\tau + C_1 \sigma_n = C_2 \quad (1)$$

where C_1 , and C_2 , are material constants. Bai [9] modified the M-C criteria by transforming the M-C failure criterion from stress-based form to a mixed strain-stress space of $(\bar{\epsilon}_f, \eta, \bar{\theta})$. The modified form of the MMC fracture criterion is:

$$\hat{\epsilon}_f = \left\{ \frac{A}{c_2} \left[c_3 + \frac{\sqrt{3}}{2 - \sqrt{3}} (1 - c_3) \left(\sec \left(\frac{\bar{\theta}\pi}{6} \right) - 1 \right) \right] \dots \right. \\ \left. \left[\sqrt{\frac{1 + c_1^2}{3}} \cos \left(\frac{\bar{\theta}\pi}{6} \right) + c_1 \left(\eta + \frac{1}{3} \sin \left(\frac{\bar{\theta}\pi}{6} \right) \right) \right] \right\}^{-\frac{1}{n}} \quad (2)$$

where stress triaxiality $\eta = -p/\bar{\sigma}$ is normalized hydrostatic pressure; $\bar{\theta}$ is the normalized lode angle; C_1 , C_2 and C_3 are material parameters related to fracture; and A and n are the power law hardening parameter of the material from the tension test. In the plane stress case which most sheet forming processes hold, $\bar{\theta}$ can be eliminated and the MMC criterion can be simplified to a function of variable η for a given material. Figure 2 shows a typical MMC fracture locus under plane stress condition. Various experiments can be used to calibrate the material parameters. The typical ones and the corresponding range of triaxiality values are also shown in Figure 2.

To determine the fracture limit, a “damage” parameter, which is proportional to the accumulated equivalent plastic strain, is introduced, as shown in Eq. (3).

$$D = \int_0^{\bar{\epsilon}_f} \frac{d\bar{\epsilon}_p}{\hat{\epsilon}_f(\eta, \bar{\theta})} \quad (3)$$

When a material reaches its limit of ductility, D reaches the critical value D_c , usually taken as unity and the corresponding material element fails and fracture initiates. Then, the neighboring elements experience additional stress due to the stress concentration and the damage in those elements increase as a result, which lead to fracture propagation through the part.

MATERIAL

The material used in this validation is DP780 steel. The material property from the tension test is listed in Table 1. Various tests were performed to calibrate the MMC fracture criterion and its locus in plane stress condition is shown in

Table 1. Material Properties and MMC constants

Steel Grades	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation %	n value	$\bar{R}$	C1	C2	C3
DP780	596	838	17.1	0.101	0.89	0.123	604.6	0.958

$\bar{R}$ average R values in the sheet plane.

Figure 3. The material constants for MMC are also shown in the table.

<table 1 here>

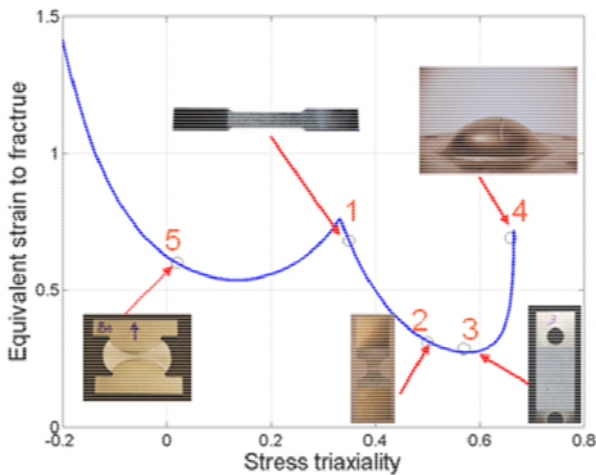


Figure 2. Typical MMC fracture locus for plane stress

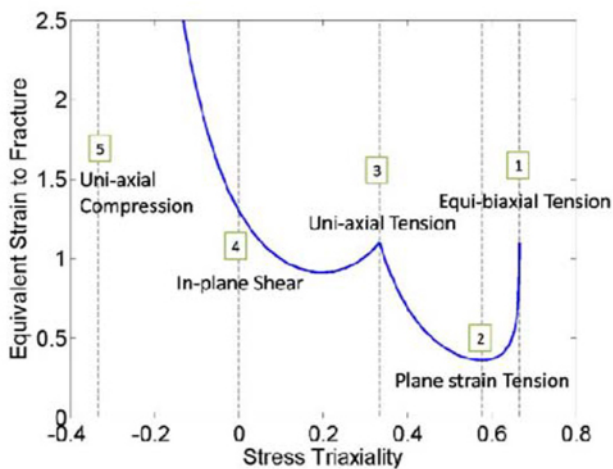


Figure 3. MMC fracture criterion locus for DP780 steel

FINITE ELEMENT SIMULATION AND VALIDATION

Two different laboratory forming tests were used to validate the MMC criterion. Both laboratory tests can simulate the

drawing of a blank over a die radius and produce shear fracture and other types of fracture. For AHSS, three types of specimen failures were observed [3, 6]: failure on the radius, failure at the boundary or tangent point between the radius and the sidewall, and failure in the sidewall (tension failure), as shown in Figure 4. Different types of fracture can be obtained in tests by changing the R/T ratio or by adjusting the back tension force in the BUT test. Details of the test are described in [3] and the test data for DP780 steel were used in the validations of Finite Element (FE) simulations.

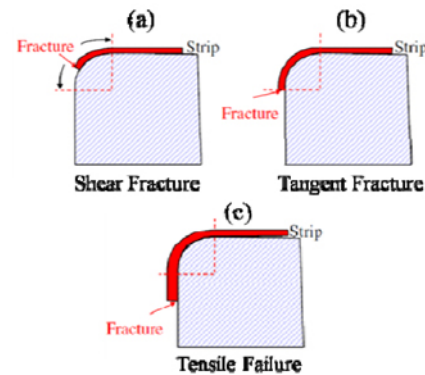


Figure 4. Three types of fractures

LAB TESTS

The two lab tests used for this validation are the stretch forming simulator (SFS) and the bending under tension (BUT). The SFS test is described in Figure 5(a) and the corresponding FE model is shown in Figure 5(b). During the forming process, the steel strip is clamped at both ends, and the upper die moves down and pulls the strip downward until the sheet strip fails. The lower die is fixed with changeable radii to provide various R/T ratios. There are two load cells in the lower die to record horizontal and vertical reaction forces.