

Fracture Modeling of AHSS in Component Crush Tests

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ABSTRACT

Advanced High Strength Steels (AHSS) have been implemented in the automotive industry to balance the requirements for vehicle crash safety, emissions, and fuel economy. With lower ductility compared to conventional steels, the fracture behavior of AHSS components has to be considered in vehicle crash simulations to achieve a reliable crashworthiness prediction. Without considering the fracture behavior, component fracture cannot be predicted and subsequently the crash energy absorbed by the fractured component can be over-estimated. In full vehicle simulations, failure to predict component fracture sometimes leads to less predicted intrusion. In this paper, the feasibility of using computer simulations in predicting fracture during crash deformation is studied. Three material fracture models, MAT_24, MAT_123, and MMC fracture model, available in LS-Dyna® finite element analysis code are adopted to simulate the fracture behavior of two dual phase (DP) grades, i.e., DP590 and DP780 steels. To provide test data for the model validations, components made of DP590 and DP780 were fabricated and tested with axial crush and three-point bending loading conditions. During the simulation, forming simulation results such as plastic strains, thinning and damage parameters were mapped to the crash models as initial conditions in crash simulations so that the sensitivity of the forming effect on fracture modeling could be studied. The predicted crush force and crush mode were then compared to those from the component crush tests. The capability of the three material fracture models for fracture prediction was assessed and the results are discussed.

INTRODUCTION

AHSS, including Dual Phase (DP) and Transformation Induced Plasticity (TRIP) steels, have improved crash energy absorption capability when compared to conventional mild steels. In recent years, AHSS have been widely accepted as the material of choice to balance vehicle weight, vehicle crash, durability and NVH performance. According to a study on North American light vehicle metallic material trends by Ducker Worldwide [1], AHSS will grow 10% annually and reach over 204 kg per vehicle by 2020. It is expected that AHSS will be used approximately 3 times more frequently than current levels by 2020 in North American light vehicle body structures.

While the increased usage of AHSS resulted in weight savings, one performance parameter to be studied is fracture during a vehicle crash event. Fracture that was rarely observed in crash tests a decade ago occurs more frequently in AHSS parts due to the relatively lower ductility compared to conventional mild steels. To appropriately apply AHSS and maximize weight reduction potential, it is important to develop the capability to predict the fracture behavior correctly in crash simulations and to accurately assess designs in the vehicle development process.

Although crash simulations have been successfully used during vehicle development to assess the energy absorption capability of the vehicle, continuous improvements in many areas are still required to further improve the quality of the crash simulations. One of those areas is the prediction of the fracture behavior of structural components under different crash loadings. Crash simulations that do not take into account the fracture behavior may overstate the load-carrying

capacity and the absorbed energy of a structural component. The application of AHSS makes fracture prediction more important since those materials can be relatively prone to fracture during crash deformation.

Many original equipment manufacturers (OEMs) have been using the material failure model CrachFEM linked to various explicit dynamic finite element method (FEM) programs to predict ductile and shear fracture [2, 3]. In this study, material fracture models available in the widely used explicit FEM code LS-Dyna® are adopted to simulate the fracture behavior of two of the most widely used AHSS grades, i.e., DP590 and DP780 steels in crush loadings. Three material models, i.e., *MAT_PIECEWISE_LINEAR_PLASTICITY (MAT_24) with a maximum equivalent plastic strain as the failure criterion, *MAT_MODIFIED_PIECEWISE_LINEAR_PLASTICITY (MAT_123) with a major in-plane strain or the major principal strain as the failure criterion, and the newly modified Mohr-Coulomb (MMC) fracture model [4] with stress triaxiality dependent equivalent plastic strains as the failure criterion, are investigated. The predicted crush force, crush and fracture modes are then compared to those from the component axial crush tests and three-point bending crush tests. The capability of the three material fracture models for the fracture prediction is assessed and the results are discussed in the paper.

MATERIAL MODELS

Some commonly used failure and damage criteria in LS-Dyna® are reviewed in [5]. The three material fracture models investigated in this study are summarized in Table 1. *MAT_PIECEWISE_LINEAR_PLASTICITY (MAT_24) is the most commonly used material model in vehicle crash simulations. It uses the von-Mises yield function with an isotropic hardening rule. The strain-rate sensitivity effect can be easily incorporated by defining a table of stress-strain curves at different strain rates. The fracture criterion in MAT_24 is the equivalent plastic strain limit at failure ϵ_{pf} . When the equivalent plastic strain in an element reaches this value, the element is deleted from the simulation. One problem with this criterion is that fracture will occur as long as the equivalent plastic strain reaches this limit no matter what the stress state is. It would be treated as failure even when the stress state is in compression. As illustrated in Figure 1, all five points (x and o) outside of the ellipse, which has the same equivalent plastic strains ϵ_{pf} , would be predicted as failure using this criterion.

*MAT_MODIFIED_PIECEWISE_LINEAR_PLASTICITY (MAT_123) is similar to MAT_24, but with enhanced failure criteria. Failure is based on the effective plastic strain limits ϵ_{pf} , thinning limit ϵ_{3f} , or the major principal in-plane strain limit ϵ_{1f} . In this study, the major principal in-plane strain

criterion is used. When the major strain in an element reaches the prescribed failure limit, the element is deleted from the calculation. As illustrated in Figure 1, only two points (o) located above the line $\epsilon_1=\epsilon_{1f}$ would be predicted as failure by this criterion. One successful application of this fracture criterion to predict the failure of ultra high strength steel in three-point bending tests was reported in [6]. The above two fracture criteria are simple and easy to implement, but they share the same drawback that failure is not dependent on the stress state.

Table 1. Comparison of three material models

	Failure Criterion	Dependency of		
		Load path	Strain rate	Stress state
MAT_24	$\epsilon_p \leq \epsilon_{pf}$	yes	no	no
MAT_123	$\epsilon_p \leq \epsilon_{pf}$ $\epsilon_1 \leq \epsilon_{1f}$ $\epsilon_3 \leq \epsilon_{3f}$	yes	no	no
MMC Model	$\int_0^{\bar{\epsilon}_p} \frac{d\bar{\epsilon}_p}{\bar{\epsilon}_f(\eta, \bar{\theta})} \leq 1$	yes	no	yes

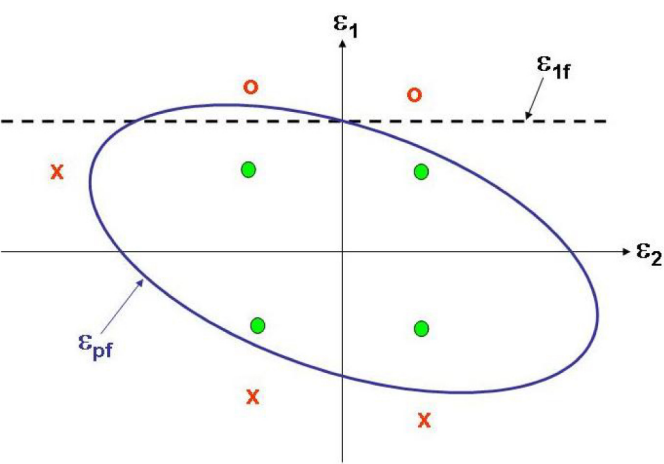


Figure 1. Fracture criteria for MAT_24 and MAT_123

Recently, Bai and Wierzbicki [4] revisited the Mohr-Coulomb criterion with an objective to capture shear fracture in addition to ductile fracture of crack-free solids. In the Mohr-Coulomb failure criterion, fracture occurs when a combination of shear stress and normal stress reaches a critical value:

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

where C_1 and C_2 are material constants. Bai and Wierzbicki [4] modified Equation (1) by transforming it from the stress-based form to a mixed strain-stress space of $(\bar{\epsilon}_f, \bar{\eta}, \bar{\theta})$. The modified Mohr-Coulomb fracture criterion is described as:

$$\bar{\epsilon}_f = \left\{ \frac{A}{c_2} \left[c_3 + \frac{\sqrt{3}}{2 - \sqrt{3}} (1 - c_3) \left(\sec\left(\frac{\bar{\theta}\pi}{6}\right) - 1 \right) \right]^* \right\}^{-\frac{1}{n}} \quad (2)$$

$$\left[\sqrt{\frac{1 + c_1^2}{3}} \cos\left(\frac{\bar{\theta}\pi}{6}\right) + c_1 \left(\bar{\eta} + \frac{1}{3} \sin\left(\frac{\bar{\theta}\pi}{6}\right) \right) \right]$$

where $\bar{\epsilon}_f$ is the equivalent plastic strain at fracture, $\bar{\eta}$ is stress triaxiality defined by the ratio of the mean stress to the von Mises equivalent stress, $\bar{\eta} = \frac{\sigma_m}{\bar{\sigma}}$, and $\bar{\theta}$ is the normalized Lode angle parameter. c_1 , c_2 and c_3 are fracture-related material parameters. A and n are material constants described in the modified Swift law in the uniaxial tension test:

$$s = A(\epsilon_0 + \bar{\epsilon}_p)^n \quad (3)$$

For sheet metals deformed in the plane stress state, $\bar{\theta}$ can be eliminated, and the 3-D MMC criterion described in Equation (2) can be simplified to a 2-D fracture criterion defined in the space of $\bar{\epsilon}_f$ and $\bar{\eta}$. Figure 2 shows a typical MMC fracture locus under the plane stress condition and the corresponding material characterization tests used to calibrate the material parameters [7]. Since the model has three parameters, a minimum of three tests are needed to calibrate the parameters. It is recommended [7] that the equi-biaxial punch fracture test, the transverse plane strain fracture test and the shear fracture test be used for parameter calibrations. These tests maintain a constant stress triaxiality evolution until the point of fracture and allow for the direct measurement of the strain at fracture.

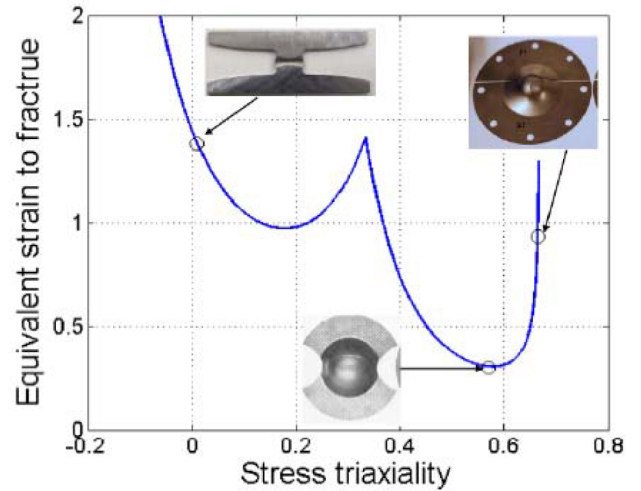


Figure 2. A typical MMC fracture locus and the material characterization tests

In addition to the fracture locus, a damage parameter D is defined to specify the damage evolution rule when the material is deformed under non-proportional loadings. It is assumed that the damage parameter D is accumulated as a linear function of the increment of the equivalent plastic strain normalized with respect to the current value of the fracture locus $\bar{\epsilon}_f(\bar{\eta}, \bar{\theta})$ under proportional loading:

$$D = \int_0^{\bar{\epsilon}_p} \frac{d\bar{\epsilon}_p}{\bar{\epsilon}_f(\bar{\eta}, \bar{\theta})} \quad (4)$$

Fracture initiates when D reaches the critical value D_c , usually taken as unity, and the corresponding element is deleted. The MMC model is currently implemented in LS-Dyna® with a user subroutine using material model card *MAT_USER_DEFINED_MATERIAL_MODELS. The MMC fracture model has been successfully applied to the shear fracture prediction that occurs on the bending radius when AHSS material is drawn and bent over the radius during forming [8, 9].

The same parameters of the MMC model used in [9] were adopted for the DP780 material. For DP590 material, various tests were performed at United States Steel Corporation's Automotive Center and calibrated parameters were also obtained. The fracture locus in the plane stress condition is shown in Figure 3 for both DP590 and DP780. The characterized material constants for the MMC model and tensile properties are shown in the Table 2.