

Predicting Failure during Sheared Edge Stretching Using a Damage-Based Model for the Shear-Affected Zone

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ABSTRACT

Hole expansion of a dual phase steel, DP600, was numerically investigated using a damage-based constitutive law to predict failure. The parameters governing void nucleation and coalescence were identified from an extensive review of the x-ray micro-tomography data available in the literature to ensure physically-sound predictions of damage evolution. A recently proposed technique to experimentally quantify work-hardening and damage in the shear-affected zone is incorporated into the damage model to enable fracture predictions of holes with sheared edges. Finite-element simulations of a hole expansion test with a conical punch were performed for both a punched and milled hole edge condition and the predicted hole expansion ratios are in very good agreement with the experiment values reported by several researchers.

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INTRODUCTION

Advanced high-strength steels (AHSS) provide the automotive industry with a promising avenue to increase fuel economy and reduce vehicle weight by producing lighter, thinner-gauge components. Unfortunately, AHSS are prone to abrupt cracking due to the initiation of local void damage during edge stretching and small-radius bending operations such as stretch flanging and hemming. In particular, dual phase steels are sensitive to sheared edge cracking at strains below the limit strain predicted by a forming limit diagram. Unlike mild steels, the microstructure of dual phase steels tends to be heterogeneous with a large strength differential between the phases. During plastic deformation, severe shear stresses develop at the interfaces between the hard and soft phases resulting in the nucleation of micro-voids [1]. It is this sensitivity to shear that sets the stage for cracking during a flanging operation since the holes are punched prior to stretching in a production environment. The hole punching procedure creates a shear-affected zone (SAZ) at the hole edge that has been severely work-hardened with nucleated voids and interface cracks that lie just below the surface.

The role of the SAZ is rarely considered in finite-element simulations of the hole expansion process since its depth is less than the sheet thickness and modeling of the jagged sheared edge requires significant computational effort. However, it is well known that sheared edge cracking originates at the surface or just below it within the SAZ so it is unrealistic to ignore its role on the fracture process [2]. In

the present work, a novel modeling strategy was developed to approximately account for the initial deformation and void nucleation within the SAZ. Finite-element simulations of a dual phase steel subjected to a hole expansion process were performed for samples with a sheared edge and also a smooth, milled edge with the SAZ removed. A damage-based constitutive model was employed to predict material softening, void nucleation and fracture during the hole expansion process.

HOLE EXPANSION TEST

Hole expansion tests are commonly used to evaluate the formability of a material in stretch flanging operations. As shown in [Figure 1](#), the test consists of expanding a 10 mm diameter punch with a conical or flat punch until the onset of cracking at the hole edge. The hole expansion ratio (HER) is the formability metric and is defined as

$$HER(\%) = 100 \left(\frac{d_f - d_o}{d_o} \right) \quad (1)$$

where d_o is the initial hole diameter and d_f is the inner diameter at fracture. Strictly speaking, a hole expansion test using a conical punch is best described as a *hole extrusion test* since the hole edge is deformed out-of-plane. A flat punch will expand the hole within the plane of the sheet and is a better description of *hole expansion*.

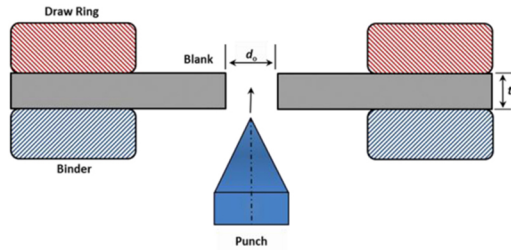


Figure 1. Schematic of the hole expansion test.

The HER of a material is related to many factors as shown in Figure 2 with the primary factors being the mechanical properties of the sheet and the edge condition of the hole. If the hole in the sheet is milled or reamed, then the HER will be a function of the mechanical properties and microstructural evolution of the material. In this condition, the influence of the microstructure can be directly related to the HER. However, if the hole is punched, as is common in an industrial setting, the hole edge becomes severely work-hardened through the creation of a shear affected zone as shown in Figure 3. The hole expansion test using a sheared edge is now a multi-stage, non-proportional forming process with significant pre-straining at the hole edge. Naturally, the HER of a sheared edge is significantly reduced compared to that of a milled hole and the sheared edge condition can obscure the role of the microstructure on fracture. Consequently, the HER with a sheared edge can appear to have no resemblance to the HER of the material with the milled hole.

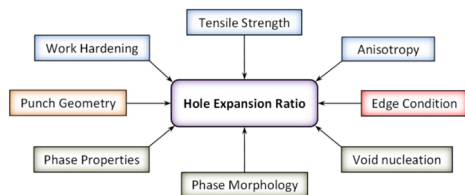


Figure 2. Factors influencing the hole expansion ratio

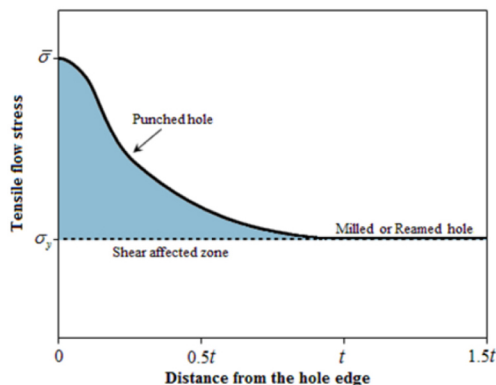


Figure 3. Schematic of the variation in work hardening at the hole edge for different hole conditions.

Strain distribution in the SAZ

Despite the well-known influence of the SAZ on fracture in sheared-edge stretching, quantifying the extent of the damage within the SAZ is rarely considered. The nucleated voids due to the punching process can be characterized using optical micrographs of the SAZ or SEM images. To characterize work hardening in the SAZ, successive hardness measurements can be correlated to the flow stress curve as done by Milosevic and Moussey [3]. Although straightforward, the resolution of the hardness measurements on the flow stress near the sheared edge is low due to hardness values saturating at high values of strain. Alternatively, the metal flow lines in the SAZ can be employed to estimate the strains in the SAZ using the recently proposed method of Wu et al. [4].

For punch-die clearances smaller than 15%, the material in the SAZ through the thickness direction can be assumed to be that of plane strain since the ratio of the thickness-to-edge radius is small. Note that in the plane of the sheet, the situation resembles plane stress. Wu et al. [4] sectioned punched holes in the radial direction of DP steels and measured the flow lines on the etched surfaces using the martensite particles as particle tracers as shown in Figure 4. The flow line tilting angles from the sheared edge were then measured and used to compute the strain in the SAZ using finite-strain theory.

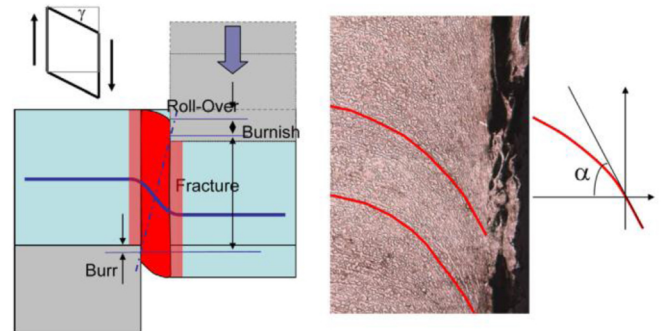


Figure 4. Schematic of Wu et al. [4] for a simple shear process and the induced tilting of the metal flow lines in a DP steel. Initially, the metal flow lines were horizontal due to the rolling process.

The deformation gradient in simple shear is written as:

$$F = \begin{pmatrix} 1 & \gamma & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \gamma = \tan \alpha \quad (2,3)$$

where α is the shear angle. The logarithmic strains can be computed as

$$\varepsilon_{ij} = \frac{1}{2} \begin{pmatrix} 0 & \ln \gamma & 0 \\ \ln \gamma & \ln(1 + \gamma^2) & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad (4)$$

and the true von Mises equivalent strain is

$$\varepsilon_{eq} = \frac{2}{3} \sqrt{\varepsilon_{22}^2 + 3\varepsilon_{12}^2} = \frac{1}{3} \sqrt{\ln(1 + \gamma^2)^2 + 3\gamma^2} \quad (5)$$

By neglecting the elastic strains, $\varepsilon^p = \varepsilon_{eq}$, the equivalent stress in the SAZ due to work hardening can be obtained from the flow rule of the material.

Assuming that the material behaviour of DP600 is isotropic, the shear angle distributions of Wu et al. [4] for the rolling and transverse directions have been combined and fit with a Weibull distribution as shown in Figure 5. The size of the SAZ can clearly be seen as approximately 27% the sheet thickness. It is important to mention that Figure 5 ignores the gradient of the shear angle through the thickness of the sheet so that the shear strain is uniform in the thickness direction. This is a reasonable first-order approximation to the shear strain in the SAZ but the shear angle may vary through the thickness depending on the martensite content and morphology. As the martensite content is increased, the size of the fracture zone at the hole edge increases and may promote an inhomogeneous distribution of the shear strain. Future work will investigate the influence of the shear angle gradient through the sheet thickness at the hole edge.

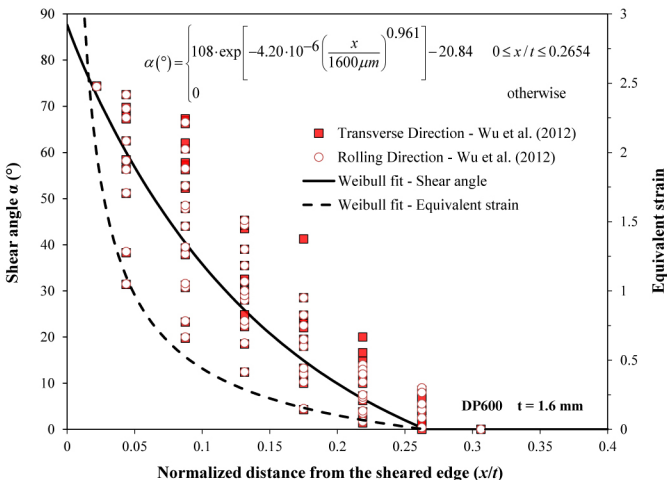


Figure 5. Variation of the shear angle and equivalent strain in the SAZ of 1.6 mm thick DP600 sheet punched with a 10% clearance. The experiment data of Wu et al. [4] for the rolling and transverse directions has been combined and fit to a Weibull distribution for the shear angle.

CONSTITUTIVE MODEL

The damage-based Gurson-Tvergaard-Needleman (GTN) [5, 6, 7] constitutive model is employed to describe the material behaviour of the DP600 sheet. The GTN model assumes that a porous ductile material can be envisaged as a periodic array of spherical unit cells, each containing a spherical void. The porosity or void volume fraction, f , will evolve during deformation due to void growth and nucleation. The GTN yield criterion is expressed as

$$\Phi = \left(\frac{\sigma_{eq}}{\sigma_M} \right)^2 + 2f q_1 \cosh \left(q_2 \frac{3}{2} \frac{\sigma_{hyd}}{\sigma_M} \right) - q_3 f^2 - 1 = 0 \quad (6)$$

where σ_M is the equivalent tensile flow stress and σ_{eq} and σ_{hyd} are the equivalent von Mises and hydrostatic stress, respectively. The parameters q_1 and q_2 are calibration coefficients introduced by Tvergaard [6] where $q_1 \approx 1 - 1.5$ and $q_2 \approx 1$.

Void growth and nucleation are considered independently and void evolution is expressed as

$$df = df_{growth} + df_{nucleation} \quad (7)$$

The growth rate of voids is proportional to the hydrostatic plastic strain increment as

$$df_{growth} = 3(1 - f) d\varepsilon_{hyd}^p \quad (8)$$

Void nucleation is assumed to be strain-controlled and obey a normal distribution [8] about a mean nucleation strain, ε_N , as

$$df_{nucleation} = \frac{f_n}{s_N \sqrt{2\pi}} \exp \left[-\frac{1}{2} \left(\frac{\varepsilon^p - \varepsilon_N}{s_N} \right)^2 \right] d\varepsilon^p \quad (9)$$

where $d\varepsilon^p$ is the von Mises plastic strain increment, f_n is the maximum porosity due to void nucleation and s_N is the standard deviation of the nucleation strain.

The void coalescence process is modeled using the critical porosity model of Tvergaard and Needleman [7]. When the porosity exceeds a critical value of the porosity, f_c , the porosity term in the GT yield criterion is replaced with an effective porosity, f^* , to mimic the load drop prior to fracture. The material has lost all load-bearing capacity when the failure porosity, f_f , is reached. The resulting criterion can be expressed as