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Implementation of Uncoupled ductile damage model for damage assessment during edge stretching.

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Abstract. Edge cracking is a common failure when stamping dual-phase steel sheet components. The edge cracking behaviour is evaluated using a hole expansion test. The failure during hole expansion by fracture can be modeled using appropriate damage criteria. This study focuses on the analysis of a hole expansion test using an uncoupled damage model, wherein the failure is assumed to occur when the damage variable attains a critical value. A user subroutine is implemented to model the evolution of damage using a field variable. The procedure is generic and can be easily adapted to a range of materials and damage criteria. The user subroutine implemented in a commercial finite element software is validated using the test results of DP600 steel grade.

Introduction

Edge cracking during the stamping process (due to stretch flanging) is a concern in the forming of Advanced High Strength Steels (AHSS). Stretch flangeability is the ability of the material to withstand edge or flange deformation without cracking during sheet metal forming operations [1]. This tendency for edge cracking is usually determined by the Hole Expansion Test (HET). In HET, a rectangular blank of 90×90 mm^2 with a central hole of 10 mm is deformed using a rigid conical punch, and the test is continued till the appearance of a through-thickness crack [2]. A schematic of the HET is shown in Fig. 1 (a). The Hole Expansion Ratio (HER) parameter is used as a formability index for stretch flangeability. It is defined as the ratio of the change in diameter to the initial diameter (D_o) ($HER = \Delta D/D_o$). The hole expansion ratio is highly sensitive to the hole edge preparation techniques like wire electric discharge machining, punching, and laser cutting [3]. Generally, sheets with finished holes perform better than those with sheared edges. The traditionally used forming limit diagram (FLD) is not applicable to predict HER as the failure mode in FLD is by localized necking [4]. The local failure strain during HET far exceeds the tensile local necking strain observed in the material.

During a hole expansion test, the material fails at the hole edge by fracture. Therefore, the failure during the hole expansion test can be modelled using an appropriate damage criterion. A typical failure by ductile damage involves void nucleation followed by growth and coalescence and is influenced by the hydrostatic stress state of the material point. A classical approach after Gurson [5] describes the damage accumulation through the evolution of void fraction and void size during plastic deformation. The hardening rule is appropriately modified to include this effect. In this approach, the damage evolution is coupled with the plasticity relation. An alternate method is to uncouple the evolution of damage from the plasticity relation wherein the stress-strain curve obtained during an experiment does not include the damage variables. Instead, the damage evolution is modelled independently using a state variable and the failure is accounted upon attaining a critical value for this state variable. Historically, the state variable is known as the damage parameter. The uncoupled damage modelling is computationally easier to implement and has been widely adopted.

In general, a constitutive relation including damage is implemented in finite element software as a user-defined material subroutine (UMAT) [6]. Since the damage model is not coupled with the elastoplastic behaviour, the implementation of such models as UMAT is computationally expensive. It was demonstrated [7] that the elemental stress-strain history during post-processing can be used independently to identify the occurrence of damage. However, such process is laborious in extracting the element history. In the present work, an alternate simpler subroutine called 'USDFLD' is utilized to model the evolution of the damage variable in commercial software 'ABAQUS©'. This subroutine is utilized to update the user-defined field variable during each time step. The damage is modelled as a field variable and its evolution is estimated using this USDFLD subroutine. The above procedure is demonstrated by simulating the hole expansion test with damage modelled using a well-known Bao and Wierzbicki (B-W) damage model. The B-W criterion is chosen for its simplicity, for the procedure can be seamlessly adopted to other uncoupled damage models as well. The implemented USDFLD is experimentally validated using the results obtained from the experimental HET of DP600 steel grade.

Materials and method

The material used for numerical analysis is hot-rolled, pickled, and oiled DP600 steel sheet of 2.6 mm thickness. The experimental data of the uniaxial tensile test (ASTM E8 Standard of subsize specimen) and pure shear test reported by our group elsewhere [8] and tabulated in Table 1 have been utilized in the present work. These data were used to identify the parameters of the constitutive model used and to calibrate the finite element model developed for simulating HET.

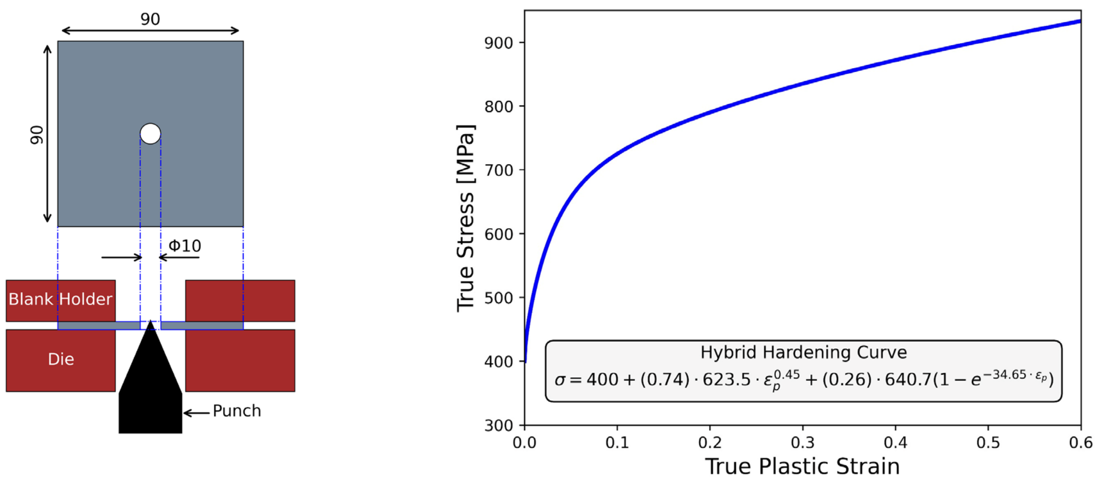
Constitutive relation. The multiaxial plastic deformation is modelled using an appropriate yield locus which is generally defined in the form, $\phi\left(\sigma_{ij}\,,\ k\right) = \sigma_{eff} - k = 0$, where σ_{ij} are the components of stress tensor, σ_{eff} is the effective stress and k is the material deformation resistance. In this work, von Mises isotropic yield criterion has been used, for which the σ_{eff} is given by Eq. 1. The scalar k (Eq. 2) indicates the size of yield locus and is governed by strain hardening. Assuming isotropic hardening, k can be modelled as a function of effective plastic strain. The widely used Ludwik hardening is inadequate for predicting the flow stress softening during damage. Therefore, a hybrid hardening combining Ludwik and Voce models with appropriate weight factors is often adopted.

The parameters of the hardening law and the weight coefficients are estimated by fitting the force-displacement data from the uniaxial tensile test.

$$\sigma_{eff} = \sqrt{\frac{1}{2}[(\sigma_{11} - \sigma_{22})^2 + (\sigma_{11} - \sigma_{22})^2 + (\sigma_{11} - \sigma_{22})^2] + 3(\sigma_{12}^2 + \sigma_{23}^2 + \sigma_{13}^2)} \quad (1)$$

$$k(\varepsilon_p) = \sigma_o + zK{\varepsilon_p}^n + (1 - z)C(1 - e^{-\alpha\varepsilon_p}) \quad (2)$$

where σ_{eff} is the von Mises stress, σ_{ij} are the stress components, σ_o is the yield stress, ε_p is the true plastic strain and C, K, n, α are the material constants and z $(0 \le z \le 1)$ is the weight factor. The stress-strain curve using the fitting parameters obtained for the chosen material is shown in Fig. (1b).



(a) (b)

Figure 1 – (a). Hole expansion test setup (all dimensions are in mm), and (b). True stress vs true plastic strain for DP600 steel.

Table 1 – Plasticity parameters for DP600 steel

σ_0 [MPa]	z	K [MPa]	n	C [MPa]	α
400	0.74	623.5	0.45	640.7	34.65
E [GPa]	μ	ρ [kg/m^3]	C_1	C_2	η_0
200	0.33	7850	1.132	0.57	0.352

Damage Model. Uncoupled damage models are used in the present work to estimate the damage evolution and predict damage in HET. In general, these models correlate the evolution of damage variable with equivalent plastic strain. Since the damage variable is uncoupled, they do not affect the constitutive relation during deformation. Historically [9], the critical equivalent fracture strain ($\bar{\varepsilon}_f$) is modelled by a continuous function of stress triaxiality. The fracture locus thus obtained is sensitive to both strain rate and temperature.

In general, the evolution of damage parameter is defined by:

$$D = \int_0^{\bar{\varepsilon}_f} \frac{d\bar{\varepsilon}_f}{d(\eta)} \quad \text{where} \quad 0 \leq D \leq 1 \tag{3}$$

where η is stress triaxiality, $\bar{\varepsilon}_f$ is equivalent plastic strain to fracture.

Bao and Wierbicki damage model. Bao-Wierzbicki (B-W) [9] damage model is one of the well-recognized uncoupled damage models, where the accumulated equivalent plastic strain at failure ($\bar{\varepsilon}_f$) is represented as a weighting function with stress triaxiality (η). The model identifies three distinct regions in terms of stress triaxiality. At large $\eta \geq 1/3$, $\bar{\varepsilon}_f$ monotonically decrease with η. At negative and low triaxialities (dominated by shear mode), the failure strain tends to infinity. The intermediate range is interploated between the limits of η.

The equivalent plastic strain to fracture in terms of stress triaxiality is given as under (Eq. 4):

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$$\bar{\varepsilon}_f = \begin{cases} \infty & (\eta \leq -1/3) \\ C_1/(1 + 3\eta) & (-1/3 \leq \eta \leq 0) \\ C_1 + (C_2 - C_1).(\eta/\eta_0)^2 & (0 \leq \eta \leq \eta_0) \\ C_2.\eta_0/\eta & (\eta_0 \leq \eta) \end{cases} \tag{4}$$

where η_0 is the mean value of stress triaxiality in uniaxial tensile test. C_1 and C_2 are $\bar{\varepsilon}_f$ (Equivalent Plastic Strain to fracture) in pure shear and uniaxial stress state respectively.

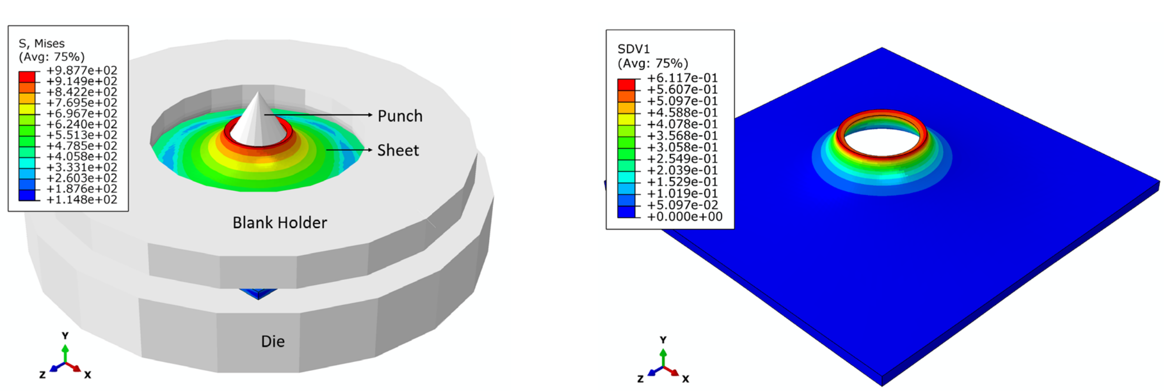
Numerical Simulation. Implicit finite element simulations were performed for the uniaxial tensile test and hole expansion test by an 8 node linear brick element with reduced integration (C3D8R element type) in ABAQUS/Standard software. The uniaxial tensile test was simulated by systematically varying the mesh size so as to replicate the experimentally determined force-displacement data. The failure strain and average triaxiality closely matched with the experiments. The damage model is implemented using the subroutine 'USDFLD'. In this subroutine, a field variable has been defined at the material point which stores the damage value at each time increment. The evolution of damage is linear where the increment in damage scales with the failure strain of corresponding triaxiality.

The BW damage model was implemented in the hole expansion test by USDFLD ABAQUS subroutine and the damage accumulation was noted by using Eq. 3 till D = 1. The final HET diameter was noted at D = 1 and HER was calculated by the equation given as under (Eq. 5):

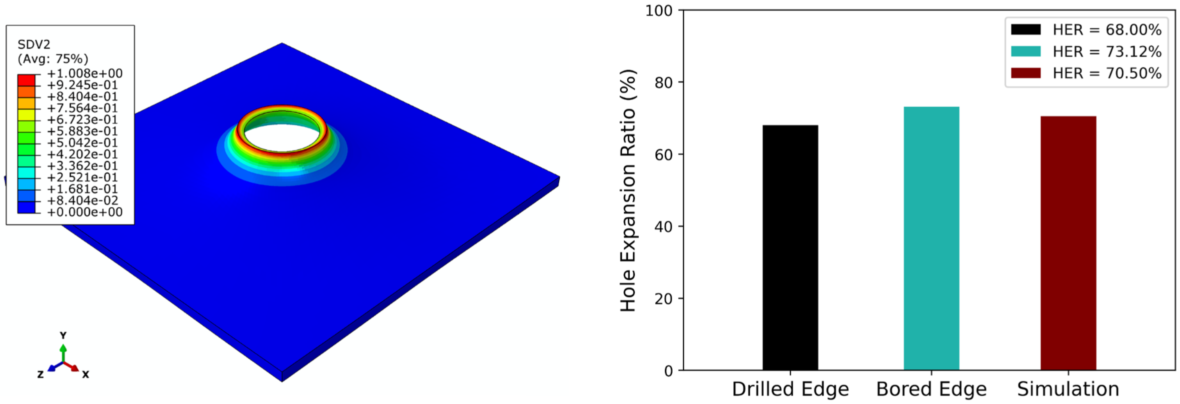
$$\text{HER} = \frac{D_f - D_0}{D_0} \times 100\ (\%) \tag{5}$$

where D_0 and D_f are the initial and final hole diameters respectively.

Finite element analysis results. The damage evolution along the hole edge was modeled up to fracture using an implicit finite element simulation. In the HET setup, the blank is held using a blank holder force of 200 KN over a die as shown in Fig. 2 (a). The punch is allowed a vertical movement of 12.45 mm until possible fracture. The damage evolution is tracked until D reached a critical value (D_c = 1). Based on a thorough mesh sensitivity study, a finer mesh of 0.5 mm was used near the hole regions with 5 elements along the blank thickness. The punch and blank interaction was modelled using a penalty friction condition with a coefficient of friction of 0.2.



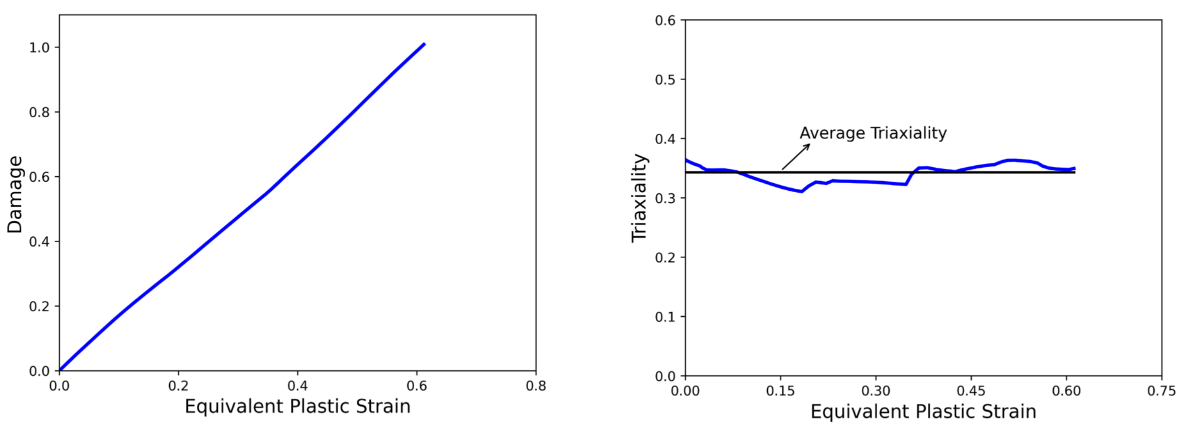
(a) (b)



(c) (d)

Figure 2 – Numerical results noted in hole expansion test (a). von-Mises stress variation at hole edge in MPa, (b). SDV1 (Solution dependent variable 1: equivalent plastic strain), (c). SDV2: damage variable according to equation 4, (d). Hole expansion ratio results compared with drilled and bored hole edge with siumlation.

The maximum equivalent plastic strain at the hole edge and the corresponding damage value at various locations at failure (D=1) have been reported in Fig. 2 (b) and (c) respectively. The FE model is validated by comparing the hole expansion ratios obtained by the damage model with the experimental HERs for different hole preparation cases, i.e. drilling and boring, as reported by Prasad et al. [8] as shown in Fig. 2 (d). The hole expansion ratio obtained using the damage model in the present work is comparable for the critical elements (fractured) when the damage reaches unity.



(a) (b)

Figure 3 – (a). Damage accumulation vs. equivalent plastic strain (b). Triaxiality vs. equivalent plastic strain

The damage (D) and stress triaxiality history for the critical elements are shown in Fig. 3. The damage accumulates linearly with the plastic strain and the average stress triaxiality remains close to the uniaxial tension condition (η_{Avg} = 0.342). It has been observed that the fracture initiates from the outer hole edge during the HET. This is indicated from the numerical simulations in the present work, where the damage reached a critical value (D_c = 1) earlier for the elements at the outer edge of the deformed region (Fig. 3).

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Conclusions

The present work focuses on introducing the USDFLD ABAQUS subroutine in the implementation of B-W damage model for DP600 material. The damage is used as a field variable to model the fracture initiation for a hole expansion test. Numerical results show that the damage initiates from the outer edge of the test specimen and proceeds towards the inner edges, which is consistent with the experimental observations. A uniaxial state of stress exists at the stretched edge of the specimen. The numerically predicted hole expansion ratios were found to be close to the experimental values for the hole expansion testing conducted for different hole preparations, i.e. for drilled and bored edge conditions.

Conflict of Interest

None declared

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