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Finite element analysis of the effect of blanked edge quality upon stretch flanging of AHSS

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ABSTRACT

Elimination of edge cracking is one of the major challenges in flanging of advanced high-strength steels (AHSS). Several studies show that edge cracking occurs at lower strains than those predicted by the forming limit curves (FLC) and it is influenced significantly by the sheared or blanked edge quality. This study focuses on FEM modeling and experiments on blanking and hole expansion of AHSS DP590. The FEM model of blanking was developed to characterize the edge quality for different punch/die clearances. Hole expansion was simulated to demonstrate the effect of sheared edge upon stretchability. Thus, it was possible to demonstrate how metal flow, strains and stresses in blanking affect the part quality and potential edge cracking in stretch flanging.

1. Introduction

Advanced high-strength steels (AHSS) have been increasingly utilized in the automotive industry worldwide due to their good formability and high strength. Stamping of AHSS can present several challenges. Two of the most well-known problems are fracture in stretch bending, and edge cracking in flanging. The hole expansion (or hole flanging) test has been commonly used to evaluate edge cracking in flanging of AHSS. Several research groups used this test and found that the edge cracking occurs at significantly lower strains than those predicted by FLC and that the edge quality of the blanked hole has a significant influence on edge cracking [1–3].

In this study, FE simulations were conducted in order to demonstrate the influence of the sheared edge quality and the stress/strain history, developed during blanking, on edge cracking during hole expansion (or flanging). The effects of punch/die clearance in blanking, burr orientation and punch geometry upon hole expansion ratio (HER) are then analyzed using the commercial FE code "DEFORM-2D^{TM}" [4]. Fig. 1 illustrates the geometric parameters of a sheared (or blanked) edge.

Simulation results were compared with the experiments conducted at two independent research laboratories, i.e. US Steel Corporation (USS) and Technische Universität München (UTG). The results show that the relation of critical damage value (CDV) between blanking and hole expansion, can be established and can be utilized to predict fracture in hole expansion tests in a variety of deformation conditions.

2. Experimental procedure

Experimental data on blanking and hole flanging was obtained from (i) the experiments conducted at USS, as presented in [1], and (ii) the experiments conducted at UTG. Both experiments were utilized to validate the procedure developed to predict edge cracking. Schematics of blanking and hole expansion are shown in Fig. 2. Process parameters used in this study are summarized in Table 1. As shown, material and testing conditions (i.e. %clearance, %expansion) used in experiments are comparable between both laboratories.

2.1. Blanking and hole flanging with conical and spherical punches at USS [1]

DP590 with the sheet thickness (t) of 1.4 mm was considered for this study. Blanking experiments were conducted with a 10 mm dia. punch (d_p) and at four different punch/die clearances (s) (i.e. 1.1–20.8% of the sheet thickness). Hole expansion experiments were conducted using two punches (i.e. conical and spherical) and two burr orientations (burr up and burr down). The notation "burr up" indicates no direct contact between punch and burr during flanging. In tests, a punch is pushed into the hole until cracking or fracture at the edge of the hole is observed. Hole expansion ratios (HER) were calculated using Eq. (1):

$$\text{HER}\ [\%] = \left(\frac{d_f - d_h}{d_h}\right) \times 100 \quad (1)$$

where d_h is initial diameter of the blanked hole (Fig. 2b) and d_f is the expanded hole diameter.

As presented in [1], experiments showed that for the conical punch, burr down results in a higher HER. But for the spherical punch, the burr orientation has only small effect on HER.

2.2. Blanking and hole flanging using a flat punch at UTG

Additional experiments were conducted at UTG, where DP600 (1.4 mm sheet thickness) was selected as test material. The small

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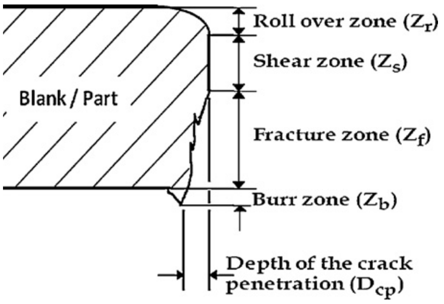

Fig. 1. Geometric parameters of the blanked edge.

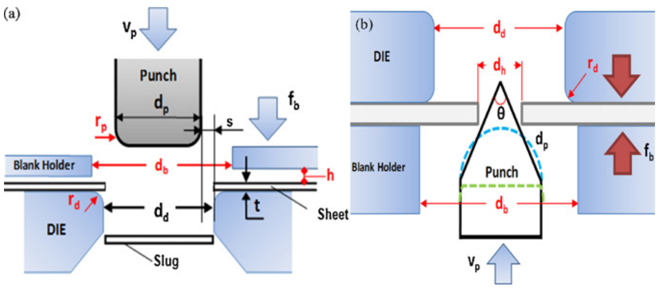

Fig. 2. Schematics of (a) blanking and (b) hole expansion (flanging).

deviation between the material properties of DP600 and DP590 is not expected to affect the comparison of the results of both materials. In these experiments, a blanked hole diameter of 50 mm and a practical range of punch/die clearances (i.e. 10.7–21.4%) were considered. A flat cylindrical punch was used in hole expansion tests. Unlike experiments conducted at USS, the punch was not stopped when the fracture occurred but it went completely through the hole to form a vertical flange. The through-flanged samples were later evaluated under microscope for existence of cracks. 5 different punch/die diameter sets were used in flanging, which result in 5 different expansion ratios (i.e. 28–52%, Table 1). Hole expansion data are presented as an evaluation matrix, in Fig. 3.

3. Finite element simulation of blanking and hole expansion

3.1. Properties of sheet materials

The material flow stress data was obtained from literature. This data was generated using the Split Hopkinson tensile tests on

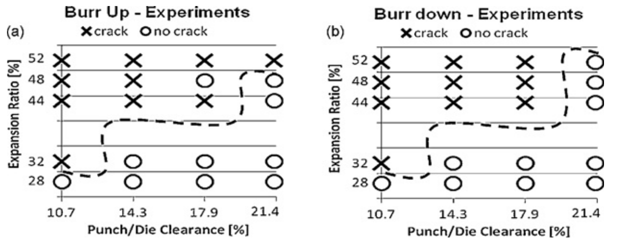

Fig. 3. Expansion ratios in form of an evaluation matrix for two cases (a) burr up and (b) burr down (from the experiments at UTG).

DP590 [5]. The flow stress data is a function of strain, strain rate and temperature, as presented in Eq. (2)

$$\bar{\sigma} = (165 + 968.6\bar{\varepsilon}^{0.206})(1 + 0.0145\ln\dot{\bar{\varepsilon}})\left(1 - \left(\frac{T-20}{T_{melt}-20}\right)^{0.868}\right) \tag{2}$$

For the testing ranges:

$0 < \bar{\varepsilon} < 0.026$ [mm/mm]
$0 < \dot{\bar{\varepsilon}} < 1500$ [s^{-1}]
$0 < T < 300$ [°C]

3.2. Finite element simulation of blanking

FE model of blanking was established to predict sheared edge geometries. Punch, die and blank holder are considered as rigid, while the sheet is considered as plastic. Simulation is modelled as non-isothermal simulation with initial temperature of 20 °C. Up to 7000 elements was used for a sheet object, where a high mesh density was assigned at the shearing zone.

To emulate material separation in the FE simulation, ductile fracture criteria and element deletion routine were utilized in commercial FE software, DEFORM-2D^{TM}. Ductile fracture criteria can be represented using the equation:

$$\int_0^{\varepsilon_F} f(\text{deformation})\,d\bar{\varepsilon} = DV \tag{3}$$

where $\bar{\varepsilon}$ is effective strain and DV is damage value.

This damage value (DV) can be obtained from the history of stress and strain data. Critical damage value (CDV) is the maximum damage value that indicates crack initiation in the simulation. Once the DVs at any mesh elements reach the CDV, those elements

Table 1
Process parameters used in blanking and hole expansion tests.

Parameter	Experiment at USS [1]	Experiment at UTG-Munich
Blanking		
Punch velocity	v_p = 0.417 mm/s	v_p = 100 mm/s
Punch diameter	d_p = 10 mm	d_{p1} = 49.7 mm (s=10.7%)d_{p2} = 49.6 mm (s=14.3%)d_{p3} = 49.5 mm (s=17.9%)d_{p4} = 49.4 mm (s=21.4%)
Die diameters	d_{d1} = 10.031 mm (s = 1.1%)d_{d2} = 10.179 mm (s = 6.4%)d_{d3} = 10.378 mm (s = 13.5%)d_{d4} = 10.582 mm (s = 20.8%)	d_d = 50 mm
Blankholder force	p_b = 1.27 MPa	F_b = 16 kN
Die corner radius	r_d = 0.05 mm (assumed)	r_d = 0.05 mm
Punch corner radius	r_p = 0.05 mm (assumed)	r_p = 0.05 mm
Blankholder dia.	d_b = 10.2 mm	d_b = 51 mm
Hole expansion		
Hole diameter	$d_h \approx$ 10 mm	$d_h \approx$ 50 mm
Punch velocity	v_p = 0.417 mm/s	v_p = 100 mm/s
Punch geometries	Conical with θ = 60°Spherical with d_p = 32 mm	Flat with corner radius of 5 mm.5 punch-die diameter sets were used for 5 expansion ratios.d_{p1} = 63.9, d_{d1} = 67.9 mm (28%)d_{p2} = 65.9, d_{d2} = 69.9 mm (32%)d_{p3} = 71.9, d_{d3} = 75.9 mm (44%)d_{p4} = 73.9, d_{d4} = 77.9 mm (48%)d_{p5} = 75.9, d_{d5} = 79.9 mm (52%)
Die diameter	d_d = 50 mm	
Blankholder dia.	d_b = 50 mm	d_b = 95 mm
Blankholder force	f_b = 6672 N	f_b = 16 kN
Die radius	r_d = 2 mm	r_d = 5 mm

will be deleted to emulate material separation. Our procedure used to determine CDV in blanking is to iterate the CDV such that the length of shear zone from the simulation matches that of experiment. 8 ductile fracture criteria were evaluated in FE simulations of blanking and previously reported in [6]. Four CDVs were obtained by matching the length of shear zone to that of experiments for 4 clearances. Theoretically, one material should exhibit one CDV. Therefore, a smaller deviation of the CDVs should reflect a better applicability of the criterion.

3.3. Finite element simulation of hole expansion

The FEM simulation of the hole expansion with a conical punch is illustrated in Fig. 4 for various conditions (a) burr up, (b) burr down, and (c) ideal edge, i.e. no burr is present. Although edge cracking is localized phenomenon and may require a 3D FE model, in this study a 2D FE model was utilized to simplify the problem and save computation time. A 3D simulation to predict local fracture initiation around the periphery of the blanked surface would require a statistical approach because it is nearly impossible to predict where the first fracture would be initiated. The present 2D approach is not "accurate" but gives information for practical use. Simulations were conducted for non-isothermal and axisymmetric conditions. To consider the stress, strain and damage history from blanking, the exact edge shape in blanking simulation was imported into the initial setup of hole expansion simulation (Fig. 4). The definition of outer and inner edge is shown in the same figure. This terminology will be used for discussing the results.

For tests at USS, 16 hole expansion simulations (4 punch/die clearances, 2 burr orientations and 2 punch geometries) were conducted. In addition, one case with a perfect edge, shown in Fig. 4c, was simulated for comparison. For tests at UTG, 40 hole expansion simulations were conducted (4 clearances, 5 expansion ratios and 2 burr orientations), using a flat punch.

4. Results and discussion

4.1. Evaluation of ductile fracture criteria

Temperature distribution during blanking, as calculated with FE simulations, indicates that due to a very high localized plastic deformation, temperature rises up to 150 °C. However, increase in temperature caused only a slight difference in the predicted load and shear edge geometries (less than 10%).

Similar to Goijaerts' work [7], fracture criteria were evaluated based on the percentage deviations over the mean CDV. Analysis of results obtained from experimental data at USS showed that Adapted Rice & Tracey's criterion (where f(deformation) = exp($\alpha\sigma_m/\sigma_{eff}$) in Eq. (3)), with α = 2.9 and CDV = 4.64, provides the smallest error in the predicted shear zone length (Fig. 1) compared with the experiments.

A similar evaluation of fracture criteria was performed using the data from blanking tests conducted at UTG. However, the lengths of shear and fracture zones from UTG tests were considerably different from those obtained at USS. As shown in Fig. 5a, the lengths of shear zone from UTG tests are about half of those from USS tests. Thus, the CDV inversely determined from UTG tests were much lower than the CDV determined from USS data. It was found that α = 1.3 and CDV = 2.5 of adapted Rice and Tracey's criterion provided the minimum amount of deviation and the best match to between the predicted shear zone length and those obtained from UTG tests.

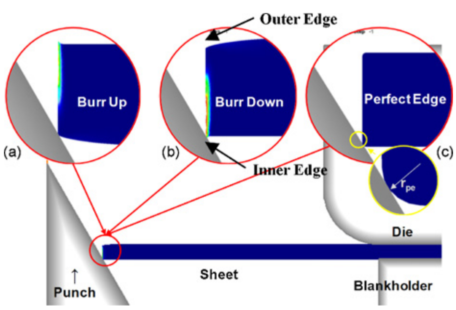

Fig. 4. Schematic of hole flanging simulation with burr orientation (a) up and (b) down and (c) perfect edge using a conical punch.

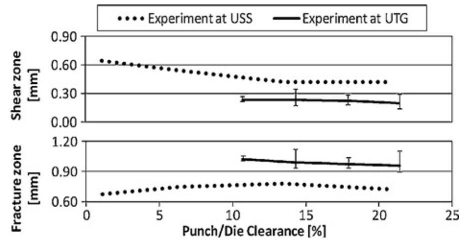

Fig. 5. Sheared edge geometries from blanking experiments at USS and UTG.

The difference in shear edge geometries, observed at USS and UTG, could be due to the difference in materials (DP590 vs. DP600) and different testing equipment used in 2 laboratories. At USS, blanking was conducted at a very slow blanking speed of 0.417 mm/s in a high-precision laboratory press. A UTG, blanking of DP600 was conducted at a conventional speed of 100 mm/s in a stamping press. Thus, the sheared edge from USS has better quality (i.e. larger shear zone and shorter fracture zone).

4.2. Hole expansion with a conical punch (USS)

Although types of material fracture are different, i.e. shearing in blanking and stretching in hole expansion, the same ductile fracture criterion was assumed. Purposes of using one criterion are to (i) simplify the procedure that is applicable to predict edge fracture in stamping, and (ii) to consider the damage history developed in sequential operations.

Fig. 6 shows the distribution of the damage value over the sheared edge (P1 is at outer edge, P100 is at inner edge) for the burr up case, when using a punch/die clearance of 1.1% at several expansion ratios until edge cracking occurs, i.e. HER is reached. DVs at the fracture zone are much higher than at any other zones (i.e. shear and rollover zones in Fig. 1). The DV increases and the sheet thickness decreases with increasing % expansion.

DV distributions can also explain why the HER is lower in burr up case (Fig. 6). At the same amount of 20% hole expansion, an increase of DV at fracture zone in burr up case is larger than that of burr down case. Therefore, the material in burr up case fails earlier. At maximum HER values, DVs at the fracture zones for both burr orientations are about the same.

Observations made from our hole expansion tests at UTG reveal that cracks initiates either at the fracture or burr zones (Fig. 1). Therefore, it is reasonable to assume that in the simulation crack initiates at this region, where very high DVs are present. Average DVs over the fracture zone can be considered as a parameter for predicting HER. Fig. 6 illustrates that average DV over the fracture zone is 3.67 before flanging and 4.67 at the point of fracture. It was found that the average DVs at fracture are about the same level for different burr orientations. Therefore, this average DV may be used as CDV in hole flanging.

Evidence indicates that CDV of flanging is related to the amount of shearing strain developed during blanking. Fig. 7 shows that the blanking strains decrease as the punch/die clearance increases and

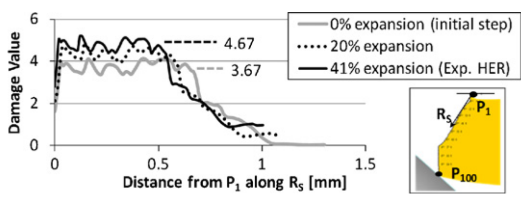

Fig. 6. Distribution of damage value over the sheared edge for burr up at different expansion ratios (punch/die clearance = 1.1%).

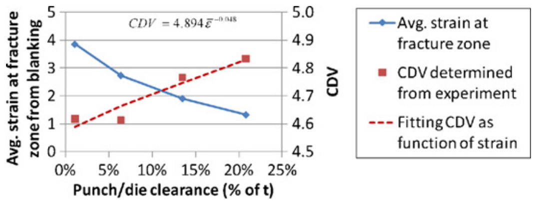

Fig. 7. Average effective strain at the fracture zone obtained from blanking simulation at different punch/die clearances, and CDV obtained from FE simulation of hole expansion for USS tests (conical punch).

that CDV in flanging increases with decreasing average strain at fracture zone in blanking.

Eq. (4) is proposed as a criterion to predict cracking in hole flanging. For simulations of hole expansion tests at USS, it was found that $K = 4.894$ and $p = -0.048$ (in Fig. 7a).

$$CDV_{\text{Flanging, Avg. over fracture zone}} = K \times \bar{\varepsilon}^{p}_{\text{Blanking, Avg. over fracture zone}} \tag{4}$$

where K and p are constants.

4.3. Hole expansion with a spherical punch (USS)

Fig. 8 shows the results from simulations obtained with a perfect edge (no burr, no strain). The figure clearly shows that DV distribution along the sheared edge is more uniform when using a spherical punch. This implies that the influence of burr orientation on HER is less significant for this punch geometry. This result agrees well with the experiments at USS.

Flanging with a conical punch causes high circumferential strain and high DV at the outer edge. The inner edge of the sheet is first pressed by contacting with the punch and later stretched when flanging. Since crack initiates at the fracture zone, the burr down case when using the conical punch yields larger HER than the burr down case when using the spherical punch.

Eq. (4), developed from hole expansion with a conical punch, is applied for predicting fracture in hole expansion with a spherical punch. The predicted HERs at fracture obtained from FE simulations are shown in Fig. 9a. These results agree well with the experiments. Compared to experiments, the errors in the predicted hole diameter at fracture are within 6%. Thus, it appears that the procedure established in this study can be used to predict edge cracking in flanging for different punch geometries.

4.4. Hole expansion with a flat punch (UTG)

The sheared edge geometries and the CDV obtained from blanking at UTG are different from those obtained from USS experiments. Therefore, a new relation between the CDV in flanging and the blanking strain needs to be established. Results of hole expansion tests with burr up were used to determine new parameters of Eq. (4) because edge cracking in burr up occurs earlier than burr down and it yields the lower CDV that represents the edge cracking limit. For tests at UTG, it was found that $K = 1.435$ and $p = -0.86$ for Eq. (4). The established equation was used to analyze the occurrence of edge cracking for UTG tests with burr down. Fig. 9b shows the analysis results, which agree well with the experimental results (in Fig. 3b).

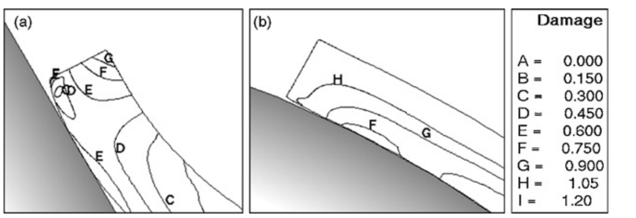

Fig. 8. Distributions of DV in hole expansion for (a) conical and (b) spherical punch, (orig. blanked hole radius = 5 mm, flanged inner hole radius = 7.5 mm).

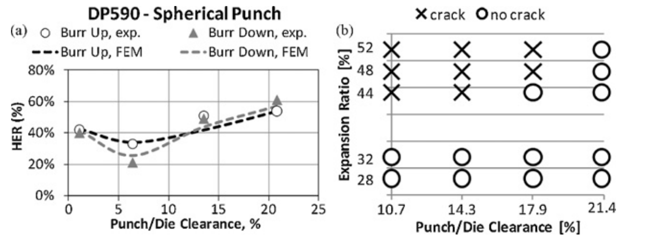

Fig. 9. (a) Comparison of HER (at fracture) for a spherical punch, from FE simulations with Eq. (4) and experiments at USS, and (b) prediction of edge cracking occurrence in hole expansion tests at UTG (burr down).

5. Conclusions

The objectives of this study are to establish a methodology to predict edge cracking in flanging by considering the sheared edge quality. The findings can be summarized as follows:

(1) It was found that adapted Rice and Tracey's criterion is the best criterion for modelling of blanking. However, parameters of this criterion determined from blanking tests at USS and UTG are different, due to difference in experimental edge geometries.

(2) A series of hole expansion simulations were conducted. It was found that
  - Simulations with a conical punch show that average DVs along the fracture zone at the step of fracture (at HER) are almost identical for different burr orientations but increase with increasing punch/die clearances used in blanking.
  - For conical punch, the outer edge always experience larger stretching. In burr up, the fracture zone is located at the outer edge and is likely to fracture earlier than the burr down.
  - Spherical punch yields more uniform distribution of DVs along the sheared edges (Fig. 8). Thus, the influence of burr orientation on HER is less significant for this punch geometry.

(3) The application of the established criterion (Eq. (4)) on hole expansion simulations with a spherical punch shows that the predicted hole radii at fracture agree well with experimental results (within 6% error).

(4) Future work may include: (i) experimental and FE analysis study of effects of blanking punch radii and tool wear, (ii) additional experiments with other selected AHSS, (iii) methodology for practical cases and in real 3D stamping.

Acknowledgements

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