

FINITE ELEMENT ANALYSIS ON THE EFFECT OF SHEARED EDGE QUALITY IN BLANKING UPON HOLE EXPANSION OF ADVANCED HIGH STRENGTH STEEL

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ABSTRACT

The use of advanced high-strength steel (AHSS) has been increasing in the automotive industry worldwide, due to its advantages in higher strength and better formability than conventional mild steels. However, stamping of AHSS can present several challenges, such as fracture in stretch bending, and edge cracking. The hole expansion (flanging) test is commonly used to evaluate edge cracking in flanging of sheet metals. A number of studies show that edge cracking occurs at significantly lower strains than those predicted by the forming limit curve and that the edge quality of the blanked hole has a significant influence on edge cracking.

The present study focuses on the established finite element (FE) model of blanking and subsequent hole expansion of DP 590 steel by considering the experimental data available from US Steel Corp., [1]. Ultimately, the aim of this research is to quantify how deep a flange can be formed or how much a hole can be expanded, for a given sheared edge quality.

In this preliminary FEA study, first, the FE model of blanking was developed to characterize the shear edge quality (i.e. edge geometries and stress/strain fields at the edge) for different punch/die clearances. Several ductile fracture criteria are evaluated to model the fracture in blanking. The effects of temperature-relevant material model are also discussed.

FE simulations of hole expansion were conducted in order to demonstrate the influence of sheared edge quality and stress/strain history, developed during blanking, on edge stretchability during flanging. The effects of punch/die clearance in blanking and burr orientation upon hole expansion ratio (HER) are then analyzed using the commercial FE code, DEFORM-2D™[2]. Finally, a relation between fracture behavior (determined by critical damage value) in blanking and in hole expansion test was established.

Keywords: Forming; Blanking; Hole Expansion; Hole Flanging; High Strength Steel; Finite Element; Simulation; Edge Cracking.

1. INTRODUCTION

The hole expansion (or flanging) test is commonly used to evaluate edge cracking in flanging of AHSS. A number of studies using this test show that edge cracking occurs at significantly lower strains than those predicted by the forming limit curve and that the edge quality of the blanked hole has a significant influence on edge cracking [1, 3-6].

FE simulations of hole expansion test were conducted in order to demonstrate the influence of sheared edge quality and stress/strain history, developed during blanking, on edge stretchability during flanging. The effects of punch/die clearance in blanking and burr orientation upon hole expansion ratio (HER) are then analyzed using the commercial FE code “DEFORM-2D™” [2]. Finally, a relation between fracture behavior (determined by critical damage value) in blanking and in hole expansion test was established. The results show that the relation of Critical Damage Value (CDV) between blanking and hole expansion, established from one testing condition (with one conical punch and one burr orientation), can be utilized to predict the fracture in hole expansion tests in other testing conditions (i.e. other punch geometries, blanked edge conditions and burr orientation).

2. SHEET MATERIALS AND TOOL DIMENSIONS

The sheet material used in this study is DP590. The nominal sheet thickness is 1.4 mm. The material flow stress data, valid for high strain rates, was obtained from literature. This data was generated using the Split Hopkinson tensile tests [7]. The flow stress data is a function of strain, strain rate and temperature, as presented in Equation (1).

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

$$\begin{aligned} \text{For the testing ranges:} \quad & 0 < \bar{\epsilon} < 0.026 & [\text{mm/mm}] \\ & 0 < \dot{\bar{\epsilon}} < 1500 & [\text{s}^{-1}] \\ & 0 < T < 300 & [^{\circ}\text{C}] \end{aligned}$$

Schematics of blanking and hole expansion are shown in Figure 1. Tool dimensions and process parameters used in this study are summarized in Table 1.

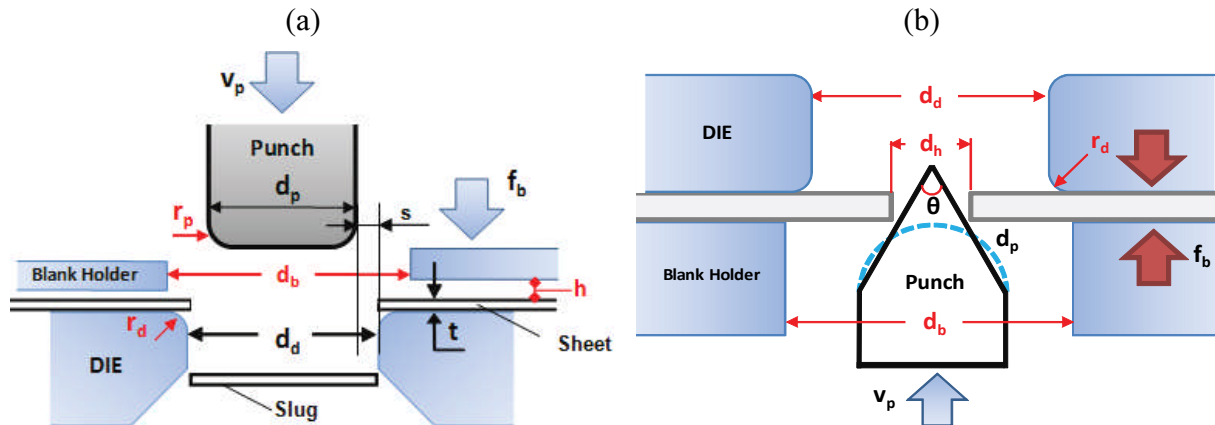


Figure 1. Schematics of (a) blanking and (b) hole expansion (flanging) operations

Table 1. Geometric and process parameters used in FE simulations of blanking and hole expansion.

Blanking	Punch velocity (assumed for conventional blanking)	$v_p = 150$ mm/s
	Punch diameter	$d_p = 10$ mm
	Die diameters (different die diameters for different punch/die clearances (s))	$d_{d1} = 10.031$ 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%)
	Blankholder force (assumed)	$f_b = 25$ kN
	Die corner radius (assumed)	$r_d = 0.05$ mm
	Punch corner radius (assumed)	$r_p = 0.05$ mm
	Diameter of the blankholder (assumed)	$d_b = 15$ mm
	Hole diameter	$d_h = 10$ mm
Hole expansion	Punch velocity (assumed)	$v_p = 1$ mm/s
	Punch geometries (assumed from [12])	Conical with $\theta = 60^\circ$ Spherical with $d_p = 38.1$ mm
	Die diameter	$d_d = 50$ mm
	Blankholder diameter (assumed from [12])	$d_b = 60$ mm
	Blankholder force (assumed from ISO/TS-16630)	$f_b = 25$ kN
	Die radius (assumed from ISO/TS-16630)	$r_d = 5$ mm

3. EXPERIMENTAL PROCEDURE

Experimental data on blanking and hole flanging was obtained from the experiments conducted at US Steel Corporation, as presented in [1]. Although in [1] several AHSSs were used, only DP590 with the sheet thickness of 1.4 mm was considered for this study. Blanking experiments were conducted with a 10 mm dia. punch and at four different punch/die clearances (i.e. 1.1%, 6.4%, 13.5% and 20.8% of the sheet thickness, adjusted by changing the die inserts), Figure 1. Hole expansion experiments were conducted using two punches (i.e. conical punch and spherical punch) and two burr orientations (burr up and burr down). In his tests, a punch is pushed into the hole until the occurrence of a through-thickness cracking at the edge of the hole. Hole expansion ratios (HER) were measured.

$$HER[\%] = (d_f - d_h) / d_h \times 100 \quad (2)$$

where d_h is initial diameter of the blanked hole and d_f is the expanded hole diameter.

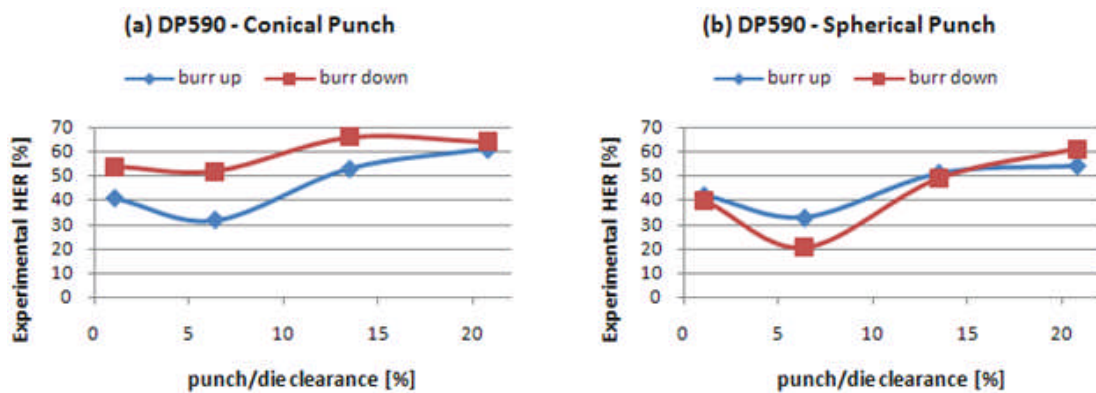


Figure 2. Illustration of variation of HER as a function of punch/die clearance, tested for two burr orientations with (a) conical and (b) spherical punch. [1]

HER at fracture of DP590 are shown in Figure 2 [1]. The notation “burr up” indicates no direct contact between punch and burr during flanging. For the conical punch, burr down results in a higher HER. But for the spherical punch, the burr orientation has no significant effect on HER. This phenomenon may be the result of different mode of deformation and will be studied in later sections.

4. FINITE ELEMENT SIMULATION OF BLANKING AND HOLE EXPANSION

4.1 Finite element simulation of blanking

To conduct the FE simulation of blanking, the input parameters follow experimental settings in [1] and the simulation procedure used in an earlier study, conducted at CPF [8]. Ductile fracture criteria and element deletion routine are employed in commercial FE software, DEFORM-2D™. Ductile fracture criteria that integrate the deformation history can be represented by the following form:

$$\int_0^{\bar{\epsilon}_F} f(\text{deformation}) d\bar{\epsilon} = C \quad (2)$$

where $\bar{\epsilon}$ is effective strain and C is damage value.

This damage value (DV) can be obtained from the history of stress and strain data in FE simulations. Critical damage value (CDV) is the maximum damage value that indicates crack initiation in the simulation. Once the CDV at certain mesh elements is reached, that element will be deleted from the workpiece object to emulate material separation. CDV can be determined inversely from blanking test, in conjunction with FE blanking simulation. The procedure used to determine CDV can be described as follows:

- (i) Conducting FE simulation of blanking, considering a fracture criterion without activating element deletion routine
- (ii) Stopping the simulation when the shear zone height (see Figure 3a) is equal to those obtained from experiment and detecting the maximum damage value
- (iii) Conducting a new simulation setting using the maximum damage value in step (ii) as a CDV and activating element deletion
- (iv) Comparing the shear zone height again, if they match, then the desired CDV is obtained. Otherwise, CDV will be adjusted and simulation will be repeated until a match is obtained.

Initial setup of FE simulation of blanking is shown in Figure 3b. Punch, die and blank holder are considered as rigid, while the sheet is considered as plastic. Simulation is modeled as non-isothermal simulation with initial temperature of 20 °C. Isothermal simulations, those previously used to model blanking in the literature [9, 10], are also conducted for comparison purpose. Results are evaluated to understand the significance of temperature in blanking. Using 7,000 elements, the mesh distribution was set such that high mesh density was located at the shearing deformation zone (i.e. along the line between the punch and the die corners, see Figure 3b).

Various ductile fracture criteria used in this study are shown in Table 2. These criteria were tried out in blanking simulations of four different punch/die clearances. Four values of CDV were obtained by matching the shear zone heights of four different punch/die clearances. Theoretically, one material should exhibit one CDV. Thus, a smaller deviation between the mean CDV and the CDV of each punch/die clearance should reflect a better applicability of the fracture criterion. Candidate criteria that gave a small deviation are utilized in FEM simulations again by using only a mean CDV for all simulations with 4 punch/die clearances. The criterion

that gives the best match with the experimental shear zone heights is considered suitable for modeling of blanking.

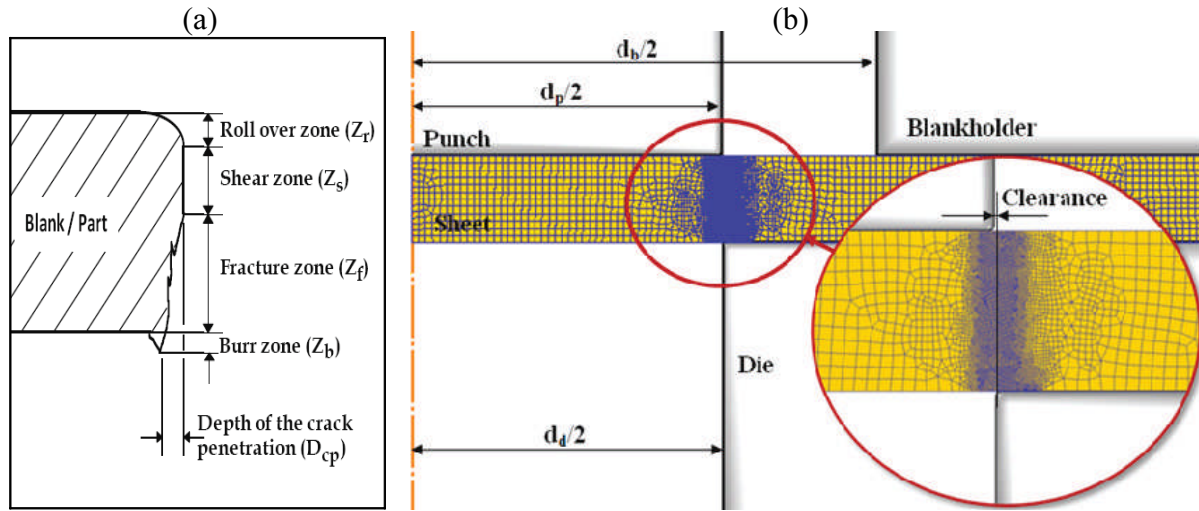


Figure 3. (a) Geometric parameters of the blanked edge [8] and (b) Initial setup for FE simulation of blanking

Table 2. Various ductile fracture criteria used in FE simulations of blanking.

Fracture criterion	Formulation	Nomenclature
Normalized Cockroft & Latham	$\int_0^{\bar{\epsilon}} \frac{\sigma^*}{\bar{\sigma}} d\bar{\epsilon} = C$	$\bar{\sigma}$: effective stress, $\bar{\epsilon}$: effective strain, C : calculated damage value, σ^* : maximum principal stress, σ_m : hydrostatic stress (mean stress), n : strain hardening coefficient, σ_a : principal stress in the direction of the greatest void deformation, σ_b : principal stress normal to σ_a , α_0 : Oyane constant, α : Rice & Tracey constant.
McClintock	$\int_0^{\bar{\epsilon}} \left(\frac{\sqrt{3}}{2(1-n)} \sinh \left(\frac{\sqrt{3}(1-n)}{2} \frac{\sigma_a + \sigma_b}{\bar{\sigma}} \right) + \frac{3}{4} \frac{\sigma_a - \sigma_b}{\bar{\sigma}} \right) d\bar{\epsilon} = C$	
Oyane et al.	$\int_0^{\bar{\epsilon}} \left(1 + \frac{\sigma_m}{\alpha_0 \bar{\sigma}} \right) d\bar{\epsilon} = C$	
Adapted Oyane [11]	$\int_0^{\bar{\epsilon}} \left(1 + \frac{\sigma_m}{3.9 \bar{\sigma}} \right) d\bar{\epsilon} = C$	
Ayada	$\int_0^{\bar{\epsilon}} \frac{\sigma_m}{\bar{\sigma}} d\bar{\epsilon} = C$	
Rice & Tracey	$\int_0^{\bar{\epsilon}} \exp \left(\frac{\alpha \sigma_m}{\bar{\sigma}} \right) d\bar{\epsilon} = C$	
Adapted Rice & Tracey [11]	$\int_0^{\bar{\epsilon}} \exp \left(2.9 \frac{\sigma_m}{\bar{\sigma}} \right) d\bar{\epsilon} = C$	
Goijsaerts [11]	$\int_0^{\bar{\epsilon}} \left(1 + 3.9 \frac{\sigma_m}{\bar{\sigma}} \right) \epsilon^{0.63} d\bar{\epsilon} = C$	

4.2 Finite element simulation of hole expansion test

For the FEM simulation of the hole expansion, an initial simulation setup of blankholder, punch and die is based on experiments of [1] and [12]. Simulation considers non-isothermal and axisymmetric assumptions.

Due to their unavailability, few process parameters (e.g. punch corner radius, blankholder diameter, punch speed) are assumed according to ISO standard, see Table 1. These assumed parameters may affect the accuracy of simulation results. Nevertheless, these simulations should

be able to provide qualitative results that explain the effect of sheared edge quality and burr orientation upon HER in flanging. To consider the stress, strain and damage history from blanking, the exact edge shape and information of all mesh elements in blanking simulation were imported into the initial setup of hole expansion simulation (Figure 4).

Eight hole expansion simulations, with the four different punch/die clearances and two burr orientations were conducted. In addition, one flanging case with a perfect edge, shown in Figure 4c, was simulated for comparison. To avoid a numerical error due to the single-point contact between punch and sheet, a small radius of 0.05 mm was assumed for the “perfect” edge.

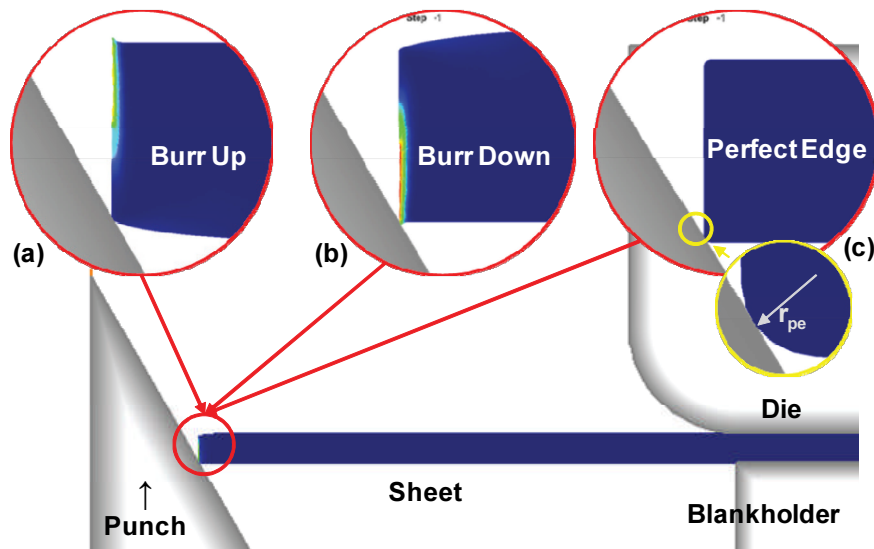


Figure 4. Schematic of hole flanging simulation with burr orientation (a) up and (b) down and (c) perfect edge using a conical punch (original undeformed hole diameter = 10 mm)

5. RESULTS AND DISCUSSIONS

5.1 Significance of temperature in modeling of blanking and evaluation of ductile fracture criteria

Temperature distribution developed during blanking has been calculated using FEA. Due to a very high localized deformation in the shearing zone, temperature rises up to 150 °C. Comparison of load-stroke curves between non-isothermal and isothermal simulation showed that, as expected, the material at higher temperatures has the lower flow stress and thus requires smaller blanking forces. However, only slight difference of the forces, about 10%, was observed. The influence of temperature could be significant if blanking at higher punch speed and/or with different materials. Our early blanking simulation study in [8] showed that the temperature could go up to 550 °C when blanking AISI 1050 sheet at a very high speed of 180 m/min.

Different ductile fracture criteria (Table 2) were tried out in blanking simulations. Four values of CDV were obtained for four different punch/die clearances. Similar to Goijaerts' work [6], the application of CDV was established by the hypothesis that one material should have only one CDV that describes fracture in one particular process. Thus, for each criterion, percentage deviations of the CDVs were calculated. Results are shown in Figure 5a. From this study, three criteria (i.e. adapted Rice & Tracy, normalized Cockroft & Latham, and adapted Oyane) provided smallest deviations and were used for rerunning the blanking simulations with only one

mean CDV. Comparisons of the length of the shear zone obtained from simulations using three candidate criteria and from experiments are shown in Figure 5b. Adapted Rice & Tracey's criterion with the CDV of 4.64 provides the smallest error of the shear zone length (~5%) when compared with the experiments. Thus, it is considered to be the best criterion for FE modeling of blanking in this study.

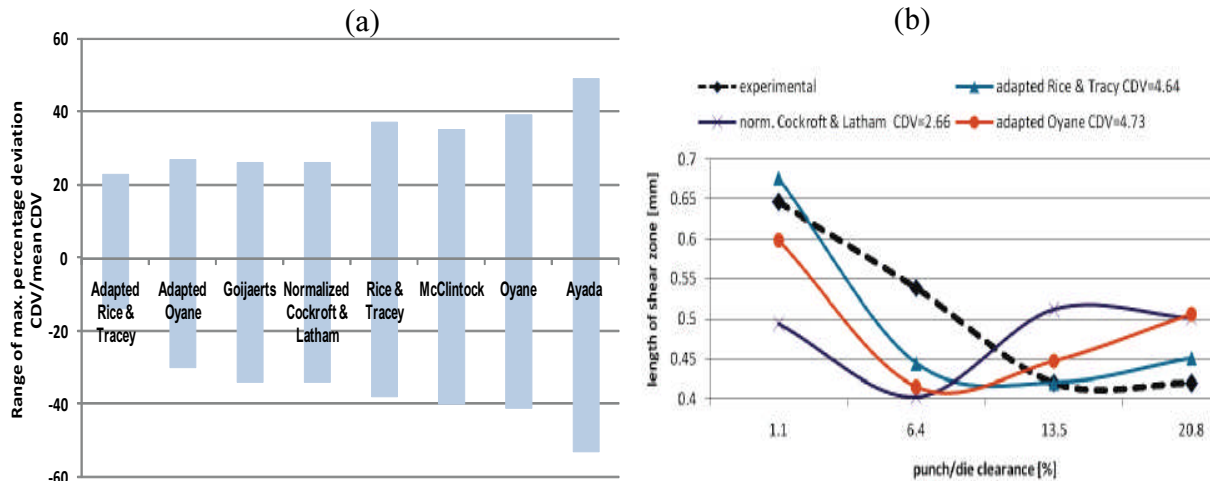


Figure 5. (a) Range of maximum percentage deviation (CDV/mean-CDV) of different fracture criteria used in blanking simulation, and (b) comparison of the simulated length of shear zone using candidate fracture criteria and the experiments

5.2 Hole expansion with a conical punch

Hole flanging with a perfect edge was simulated in order to compare the predictions with the other eight simulations that consider the sheared edge quality. Distribution of circumferential strains and effective strains are shown in Figure 6. The definition of outer and inner edge as well as the coordinates R_s and Z_s are shown in the same figure. These terminology and parameters will be used for representing the results in this section and thereafter.

Simulations show that circumferential strain is distributed in corresponding to maximum principle strain and is the highest strain component during flanging. Maximum circumferential strain is at the outer edge due to its largest amount of stretching. This fact is in good agreement with experimental and simulation observations from [13]. The highest effective strain was found at the inner edge where the punch pressed on the inner edge of the sheet and remains nearly constant along R_s direction. The distributions of damage values (DV) are similar to those of circumferential strains, where the location of the maximum DV is at the outer edge (Figure 10a).

Hole expansion simulations considering a sheared edge from blanking were also conducted. The damage distributions along the sheared edge are plotted and compared. To measure the distributions of DV, the software function “State variable between two points” in DEFORM-2D was used by defining 100 points along the surface of the sheared edge from the outer to the inner edge (R_s direction), see Figure 7. P_1 is at the outer edge while P_{100} is at the inner edge.

Figure 7 also shows the damage value distribution over the sheared edge for the (a) burr up and (b) burr down cases, when using a punch/die clearance of 1.1% at increasing punch displacements until edge cracking (at experimental HER). This trend for the DV is representative of all other punch/die clearances. As shown in Figure 7, from the beginning step of flanging,

DVs at the fracture zone are much higher than at any other zones (i.e. shear and rollover zones in Figure 3a). The DVs increase and the sheet thickness decreases with increasing punch displacement.

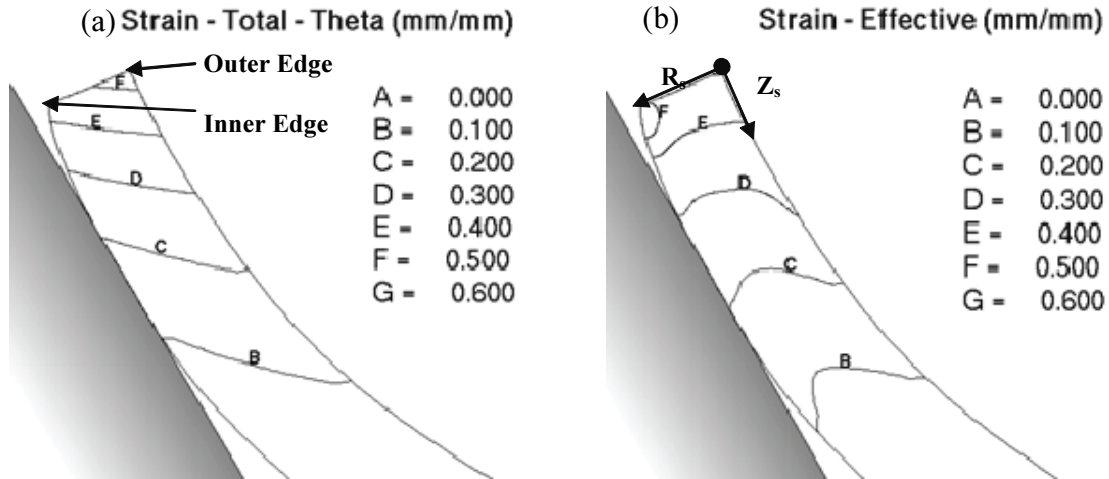


Figure 6. Simulation of hole expansion with a conical punch using a “perfect” edge: Distributions of (a) circumferential strains and (b) effective strains (at the expanded hole radius of 7.75mm, the original hole radius = 5 mm)

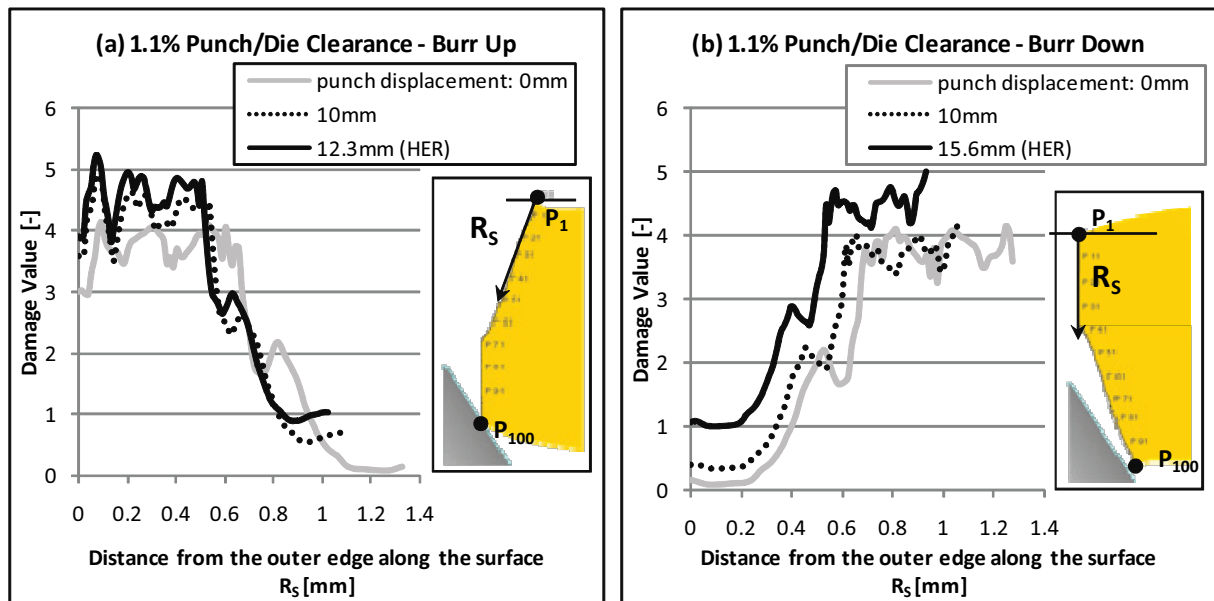


Figure 7. Distribution of damage value over the sheared edge: (a) Burr up and (b) burr down at different punch displacements (punch/die clearance = 1.1%, initial blanked hole dia. = 10 mm)

Concerning the influence of burr orientation, DV distributions from the simulations can well explain why the HER is lower in burr up case. With burr up, the fracture zone of the edge is located near the outer edge where it is subject to larger circumferential strain and larger increase of the DV during flanging. From Figures 7a and 7b, at the same punch displacement of 10 mm, an increase of DV at fracture zone is larger for burr up case. Therefore, the material fails earlier

than in burr down case in which the fracture zone is located at the inner edge. At maximum punch displacement (where HER is recorded), DVs at the fracture zones for both burr orientations are about the same.

Observations from the experimental study by [14] show that all crack initiates at the burr and fracture zones for hole flanging with burr up. Our ongoing experiments at UTG-Munich confirm this observation and further proved that this observation is also valid for burr down case. Therefore, it is reasonable to assume that the crack initiates at this region, where very high DVs are present, rather than at the outer edge.

Average DVs over the fracture zone are considered as a criterion to predict HER. Figure 8 illustrates average DV taken from the simulation of 13.5% punch/die clearance with burr down. For 13.5% clearance, average DVs over the fracture zone are 3.72 before flanging and 4.41 at the point of fracture. It was found that the average DVs at fracture are about the same level for different punch/die clearances and burr orientations, see table on the right side of Figure 8. Therefore, this average DV may be used as a fracture criterion in hole flanging.

The average damage value over the fracture zone at cracking is about 4.61 and almost identical to the CDV of 4.64 from blanking. Therefore, it may be assumed that the Equation (3) is valid to predict cracking in hole flanging of DP 590. This criterion is later used to predict cracking in hole flanging with a spherical punch

$$CDV_{Flanging, \text{ Avg. over fracture zone}} = CDV_{Blanking} \quad (3)$$

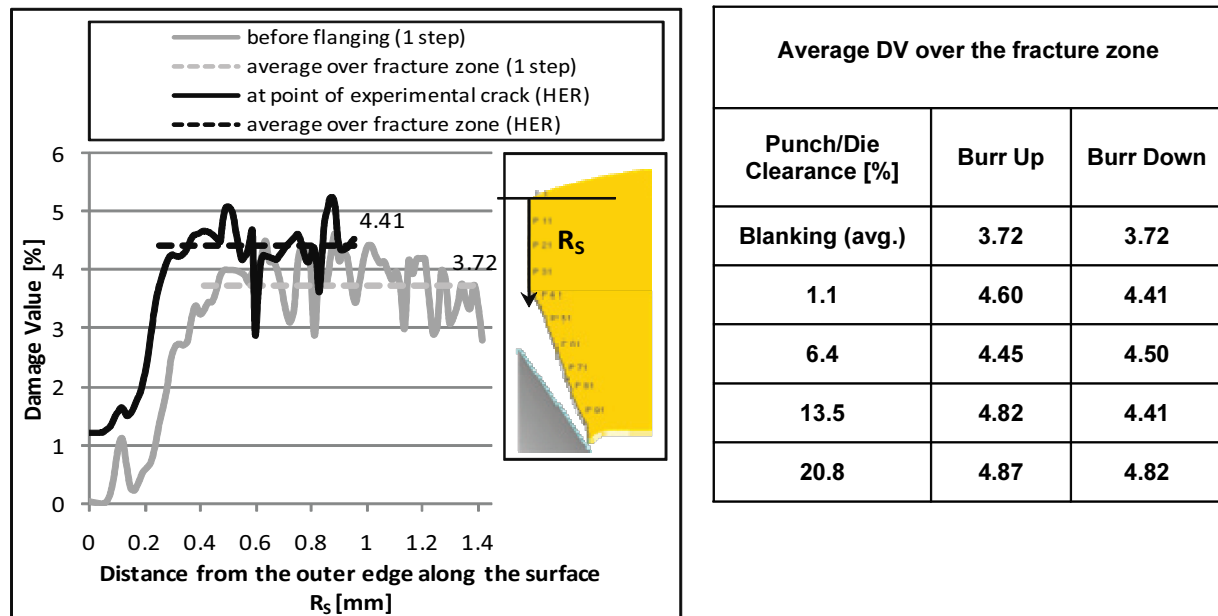


Figure 8. DV distribution and average DV over the fracture zone (for punch/die clearance 13.5%, burr down) and table of all average DVs for different punch/die clearances and burr orientations.

5.3 Hole expansion with a spherical punch

The flanging with a conical or spherical punch results in different modes of edge deformation and different final orientation of the sheared edge. To form to the same hole diameter, a higher punch displacement is required for a conical punch because the sheet is curled upward. Flanging with a conical punch also causes higher circumferential strain at the outer edge, see Figure 9 for

the results from simulations with a perfect edge. In addition, the figure clearly shows that damage 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 Konieczny's experiments [1] (in Figure 2).

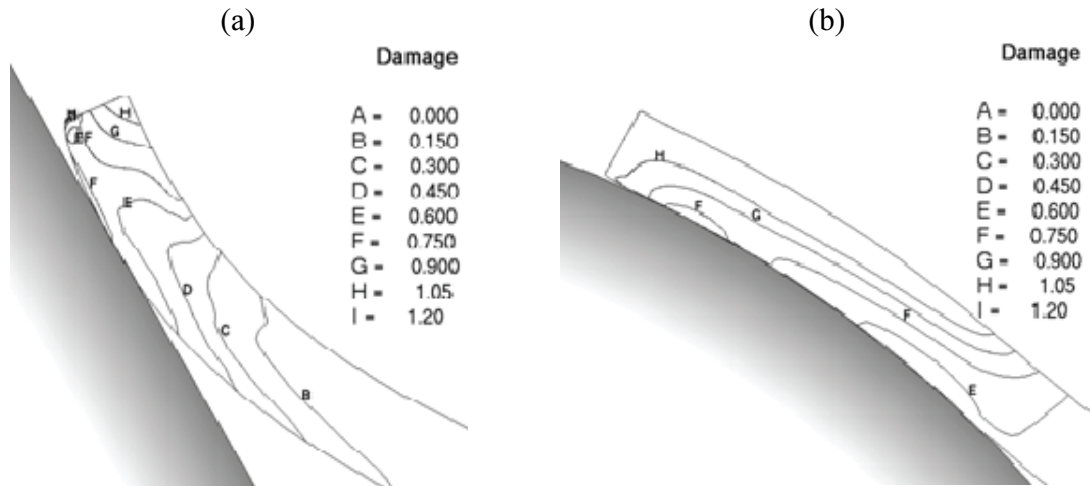


Figure 9. Distributions of damage values in hole expansion simulations with a perfect edge, for (a) conical and (b) spherical punch, after flanging to get the inner hole radius of 7.5 mm (original blanked radius = 5 mm)

The strain path was obtained with FEA during flanging at the outer and inner edge for the (a) conical and (b) spherical punch. The major strain ϵ_1 is along the circumferential direction and the minor strain ϵ_2 is assumed to be along the radial direction. For the spherical punch (b) the deformation around both edges can be regarded as uniaxial tension because the strain path follows nearly exact the uniaxial tension state ($\epsilon_1 = -2 \cdot \epsilon_2$). For the conical punch, the strain path of the inner edge first follows the uniaxial compression state ($\epsilon_1 = -\frac{1}{2} \cdot \epsilon_2$) and then parallel to uniaxial tension state. This is due to the fact that inner edge of the sheet is first compressed and later stretched when flanging with a conical punch.

Different strain paths of the inner edges explain the difference in HERs obtained from the experiments for the burr down case (see Figure 2). HER of the conical punch is influenced by compression in addition to circumferential strain at the inner edge. With a hypothesis that a crack initiates at the fracture zone, the burr down case when using the conical punch is more crack resistant than the burr down case when using the spherical punch. This also explains the results shown in Figure 9, where a higher concentration of DV is at the outer edge rather than at the inner edge for the conical punch.

Equation (3), a criterion developed from hole expansion with a conical punch, is applied for predicting fracture in hole expansion with a spherical punch. The final hole radii at fracture obtained from simulations and the criterion given by Equation (3) are shown in Table 3. These results are compared with the experiments. The errors are within a range of 15.0% (0.91 mm). Thus, it appears that the procedure established in this study can be used to predict edge cracking in flanging with different punch geometries.

Table 3. Final hole radii obtained in simulations (estimated by applying the criterion of Equation (3)) and experimental radii at HER from hole expansion with a spherical punch [1]

Punch/Die Clearance [%]			1.1	Error	6.4	Error	13.5	Error	20.8	Error
Expanded hole radius [mm]	Burr Up	FEM	7.10	0.0%	6.90	3.8%	6.83	9.5%	6.92	10.1%
		exp.	7.10		6.65		7.55		7.70	
	Burr Down	FEM	7.19	2.7%	6.96	15.0%	7.03	5.6%	7.43	7.7%
		exp.	7.00		6.05		7.52		8.05	

6. CONCLUSIONS

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

1) Different ductile fracture criteria were evaluated by considering that one critical damage value (CDV) is valid for four selected punch/die clearances. It was found that adapted Rice & Tracey's criterion seems to be the best criterion for modeling of blanking and thus assumed to be applicable for modeling of hole expansion.

2) Total of 16 hole expansion simulations were conducted, considering 4 sheared edges (obtained from 4 different punch/die clearances in blanking), 2 burr orientations (up and down) and 2 punch geometries (conical and spherical). It was found that

- Damage values are very high at the fracture zone of the blanked edge. These DVs increase with increasing punch displacements during flanging.
- All 8 simulations with a conical punch show that average DVs along the fracture zone at the step of fracture (at HER) are almost identical and within $\pm 5\%$ variations, regardless of different final punch displacements (see Figure 8).
- The effect of burr orientation can be explained by the location of fracture zone of the blanked edge (edge region with high DVs) and the strain paths. For conical punch, the outer edge always experience larger stretching. In burr up case, the fracture zone is located at the outer edge and is likely to fracture earlier than the burr down case.
- The effect of punch geometry can be explained by DV distributions at the sheared edge. Comparisons show that the spherical punch yields more uniform distribution of DVs along the sheared edges (see Figure 9). Thus, the influence of burr orientation on HER is less significant for this punch geometry.

3) An approach to predict edge cracking in hole flanging simulations was established, using a criterion, " $CDV_{Flanging, Avg. over fracture zone} = CDV_{Blanking}$ " in (Eq. 3). The application of this criterion on hole expansion simulations with a spherical punch shows that the predicted hole radii at fracture agree reasonable well with experimental results (0 to 15% error, see Table 3).

4) This study indicated that, it is possible to estimate how process variables and blanking conditions affect fracture in hole flanging. However, it is not possible to predict how scratches or irregularities on blanked edges may quantitatively determine fracture in hole flanging.

5) Future work may include

- FE analysis of additional experiments of blanking and hole expansion with a flat punch, conducted at Technische Universität München (utg).
- Experimental and FE analysis study of effects of blanking punch radii and tool wear.
- Additional experiments and simulations with other selected AHSSs in order to validate the established procedure.
- Work to reach the ultimate goal which is to be able to apply the developed

methodology for practical cases and real products, as presented in [6]. Application to the actual flanged part may require 3-dimensional analysis and a more complex model to predict edge cracking.

7. ACKNOWLEDGEMENTS

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