The effects of shear affected zone on edge crack sensitivity in dual-phase steels

N. Habibi 1*, T. Beier 2, H. Richter 2, M. Könemann 1 and S. Münstermann 1

1 Steel Institute (IEHK), RWTH Aachen University, Aachen, Germany
2 Thyssenkrupp Steel Europe AG, Kaiser-Wilhelm-Str. 100, 47166 Duisburg

Niloufar.habibi@iehk.rwth-aachen.de

Abstract. Dual phase steels offer good combination of mechanical properties which is attractive for automotive industry. However, some challenges still remain and suppress using them widely. One of these challenges is the formation of premature cracks at shear-cut edges during the subsequent forming processes, which cannot be predicted by the conventional finite element methods. Therefore, the present study aims to propose a numerical tool to predict edge cracks in DP steel components. In this regard, the hole expansion method was applied as an edge crack detection technique on DP1000 steel sheets. To elaborate the study, parallel finite element simulations were performed as well. The simulation method considered the whole hole piercing process and the following hole expansion test as a one-stroke two-step strategy. The hole piercing process was applied in the first step on the sheet and a hole was cut. The results reveal that this process forms some surface irregularities and applies a special amount of damage at the cut edge, which both could have effects on the edge crack sensitivity. To study these effects, the subsequent hole expansion test was simulated on the manufactured hole. Thus, the effects of both surface irregularities and residual damage from hole piercing process were investigated in different case studies with all possible combinations of these effects. This strategy provides possibilities to numerically separate effects of surface quality and residual damage. The contribution shows on the one hand the experimental investigations and on the other hand deals with the numerical influence analyses.

1. Introduction
By developing new generations of advanced high strength steel (AHSS) sheets, they become more qualified for the use in car body panels. Through their manufacturing application, shear-cutting processes, including blanking, trimming, and piercing, are often used as initial manufacturing steps to prepare the sheets for subsequent forming processes to obtain the final product. These processes result in reduced forming potential and surface irregularities at vicinity area of the shear-cut edge, which is called shear affected zone (SAZ), and consequently reduces the ductility of the material. This reduction is significant in some AHSS like dual-phase (DP) steels and causes premature edge cracks through the subsequent forming processes [1]. These cracks pose a big challenge in component design and manufacturing process, since they cannot be predicted by using conventional numerical and computer aided methods, like forming limit diagram. Despite several experimental works have been carried out to assess edge crack sensitivity and stretchability at cut edges, few numerical attempts have thus far been made in this regard [2-7].
Sartkulvanich et al. [2] studied on occurrence of edge cracking in DP590 steels. The edge qualities of blanked holes were modeled by a commercial finite element code, Deform-2D, for different cutting punch/die clearances. The edge crack initiation was assumed to be happening at the region with higher damage value and HER which is related to edge crack sensitivity could be also predicted by considering the value and distribution of damage at the blanked edge. In addition, the hole expansion ratios for spherical and conical punches were predicted from simulations obtained with a perfect edge (no burr, no strain). Butcher et al. [3] predicted hole expansion ratio (HER) of DP600 sheet by employing GTN (Gurson–Tvergaard–Needleman) damage model on the base material and SAZ, separately. In this purpose, the model was calibrated by using x-ray micro-tomography, which is a complicated and expensive method. Wang et al. [4] modeled SAZ of a punched DP780 blank by applying pre-damage mapping model. In this regard, an uncoupled phenomenological fracture criterion was used to calculate the amount of accumulated damage from the punching process. Hu et al. [5] predicted HER for an aluminum alloy by simulating 3D hole expansion test based on the data of a pierced blank which was taken from 2D axis-symmetric punching model. Also, Mu et al. [6] studied the effect of different ductile fracture models on predicting punching and subsequent hole expansion test. The results showed that the criterion, which was able to calculate a wide range of stress-states more precisely, could predict HER accurately as well, since the material experienced non-proportional strain paths during these forming processes. Furthermore, in a recent study [7], the effects of die clearance on the edge quality were simulated by using Rice and Tracey (1969) [8] fracture model. The damage distributions and edge shapes were in good agreement with the experimental results.

The objective of the present study was to investigate the physical mechanism underlying the formation of edge crack and to introduce a promising computation model which is able to predict edge crack formation precisely. For this purpose, the effects of pre-damage and surface irregularities, as the characteristics of SAZ, on the hole expansion ratio were studied for a DP steel blank with a pierced hole.

2. Methods

2.1. Plasticity and Damage model
In order to describe the mechanical behavior of the material in the simulations, Hollomon strain hardening (equation (1)) and Modified-Bai-Wierzbicki damage [9] models were employed. In this plasticity-damage model, the damage parameter appears in the flow potential (Φ) to degrade the stress level as damage initiates (equation (2)).

\[
\sigma_e = k \cdot (\bar{\varepsilon}^p)^m
\]

Herein, \(\sigma_e\) is the equivalent stress, \(\sigma_{yld}\) is the yield stress, and \(D\) is the ductile damage variable. According to the damage model, equation (3), the initial material is assumed to be defect-free and only strain-hardening contributes to the deformation. The damage initiates when the equivalent plastic strain, \(\bar{\varepsilon}^p\), reaches a critical value, \(\bar{\varepsilon}^i\) as defined in equation (4). Afterwards, the damage propagates linearly in proportion to the flow stress at damage initiation, \(\sigma_{yld}\), and an energy-dissipation coefficient, \(G_f\). The damage evolves until the fracture occurs at equivalent plastic strain of \(\bar{\varepsilon}^f\), where \(F\), the failure indicator in equation (4), reaches one. It is worth mentioning that the damage model is defined in terms of stress-triaxiality, \(\eta\), and normalized Lode angle parameter, \(\bar{\theta}\), to describe stress-state effects on damage initiation and accumulation Note that all \(C_i\) and \(D\) parameters are materials’ constants, which have to be calibrated by quasi-static tensile tests, table 1.

\[
\Phi = \sigma_e - (1 - D)\sigma_{yld} \leq 0
\]

\[
D = \begin{cases} 
0, & \bar{\varepsilon}^p \leq \bar{\varepsilon}^i \\
\sigma_{yld} \int_{\bar{\varepsilon}^i}^{\bar{\varepsilon}^p} d\bar{\varepsilon}^p & \bar{\varepsilon}^i < \bar{\varepsilon}^p \leq \bar{\varepsilon}^f \\
\frac{\sigma_{yld}}{G_f} \int_{\bar{\varepsilon}^i}^{\bar{\varepsilon}^f} \bar{\varepsilon}^p d\bar{\varepsilon} & \bar{\varepsilon}^f < \bar{\varepsilon}^p
\end{cases}
\]

2
\[
\vec{\varepsilon} = \left( C_1 e^{-\varepsilon_{\text{f}}} - C_3 e^{-\varepsilon_{\text{c}}} \right) \vec{\varepsilon}_{\text{f}}^2 + C_4 e^{-\varepsilon_{\text{c}}}
\]

\[
F = \int \left( D_1 e^{-\varepsilon_{\text{f}}} - D_3 e^{-\varepsilon_{\text{c}}} \right) \vec{\varepsilon}_{\text{f}}^2 + D_4 e^{-\varepsilon_{\text{c}}}
\]

Table 1. Mechanical properties of the investigated material [10].

| Parameter | Value | Value | Value | Value |
|-----------|-------|-------|-------|-------|
| \(E\) (GPa) | \(v\) | \(R_{0.2}\) (MPa) | \(k\) (MPa) | \(n_i\) |
| 210 | 0.3 | 693 | 1476 | 0.10 |
| Parameter | \(C_1\) | \(C_2\) | \(C_3\) | \(C_4\) | \(G_1\) | \(D_1\) | \(D_2\) | \(D_3\) | \(D_4\) |
| Value | 0.4 | 1 | 0.1 | 1.5 | 6500 | 0.15 | 1.5 | 0.08 | 1.5 |

2.2. Simulation methodology

In order to study the effects of shear affected zone on the edge cracking sensitivity, hole expansion test was applied at holes with different edge characteristics. The simulations were applied on a DP1000 steel sheet with thickness of 1.5 mm. Its chemical composition and mechanical properties have been discussed in details in ref. [10].

For this purpose, a one-stroke hole piercing-hole expansion test was modeled. For the piercing process, a 30-mm die with the clearance of 10% was used and a conical punch (angle=25°) was applied to expand the hole. In this case, the effects of both surface irregularities and pre-damage from hole piercing process on the HER were considered. This condition named here as wSwD. All the cutting tool edges were considered as sharp edges. In order to reduce the computation time and by considering the symmetric axes, only a quarter of the set-up was modeled, figure 1. In both steps the tools were considered as discrete rigid parts, and the sheet was modeled as a deformable homogenous solid. Friction between the tools and the sheet was considered as the Coulomb model with a coefficient of 0.1 [4]. Since new surfaces are created during the blanking process, the contact pairs were defined by a node-to-surface algorithm. As the applied damage model is a local one which is influenced by the size of element, the mesh size of critical regions in the sheet was considered 0.1 mm, similar to the size that was used for the calibration of damage parameters. In order to employ homogenous force on the sheet during the deformation, finer elements were defined in the contact regions of the tool. An optimal clamping force was chosen such that the blank was neither drew in nor torn improperly during the forming processes. The hole expansion ratios were measured as a quantitative parameter of edge cracking sensitivity. According to the standard ISO 16630:2017 [11], HER should be calculated as a through-thickness edge crack occurs.

Furthermore, other edge conditions created by manipulating the data or processes in the simulations. By assigning the state variables similar to the initial material after the first step, the piercing process, effect of damage was eliminated. Therefore, the edge only inherited the shape of pierced edge not the damage. This condition called here wSwD. In order to eliminate the effect of surface shape, also a one-step hole expansion test was modeled on a blank with simple sketched hole. In this case, the hole expansion test performed once without assigning any initial conditions and once with applying corresponding average material state variables from piercing simulation at four critical partitions, figure 2. These conditions named woSwD and woSwD, respectively.

3. Results and discussion

The influence of shear affected zone on edge cracking was investigated. In this regard, damage evolution and surface characteristics at the hole edge, which were supposed to play the main roles in the failure process, were detected throughout the whole process. Also, the stress triaxiality and Lode angle parameter, as the variables of stress state, were detected throughout the processes. In order to elaborate discussion, results are presented into two parts: hole edge conditions and hole expansion tests.
3.1. Hole edge conditions

By applying different strategies, described in section 2.2, edges with different characteristics were created, figure 2. The surface shape and residual damage vary for the different edges that were studied. Thus, in wSwD condition, both residual damage and surface irregularities were inherited from shear-cutting process. In wSwoD, only the surface shape was considered. In woSwD, only average damage was effected on the edge. In woSwoD condition, neither surface irregularities nor damage were influenced on the hole edge. Since the data of surface irregularities and damage were obtained from the shear-cutting simulation, the reliability of the hole expansion simulation is dependent on the simulation of this condition. Therefore in the following, the simulation results of piercing process is explaining in details.

| Characteristics of hole edges | (a) wSwD | (b) wSwoD | (c) woSwD | (d) woSwoD |
|------------------------------|----------|----------|----------|-----------|
| Surface irregularities | ✓ | ✓ | ✗ | ✓ |
| Damage | ✓ | ✗ | ✓ | ✗ |

![Figure 2](image)

**Figure 2.** The initial condition of hole edges in hole expansion tests.

The simulation results of hole piercing are compared with the experiments in figures 3 and 4. The force-displacement curves are illustrated in figure 3, coincide well for almost the entire process. Figure 4 depicts the surface characteristics of pierced hole. The sizes of rollover, burnished, fracture, and burr parts are comparable. For the study material and tool condition, two cracks initiated during the shear-cutting process. First one initiated from adjacent to the punch and propagated towards the cutting direction, while the second one initiated from the opposite surface and propagated upwards. Initiation of the second crack could affect on the size of the burr part and made it negligible. By tracking
stresstriaxiality and Lode angle parameter, the evolution of the stress state through the piercing process was revealed, which was pure shear at the beginning and gradually changed to plain strain tension. This evolution was also reported previously [10] for the same material but die clearance of 15%.

![Figure 3. Comparison of force-displacement curves between simulation and experimental results for the piercing operation.](image)

**Figure 3.** Comparison of force-displacement curves between simulation and experimental results for the piercing operation.

![Figure 4. Characteristics of SAZ and fracture surface of pierced hole. The parameters h_E, h_S, h_B, and h_G represent height of the rollover, burnished, fracture, and burr parts, respectively [12].](image)

**Figure 4.** Characteristics of SAZ and fracture surface of pierced hole. The parameters $h_E$, $h_S$, $h_B$, and $h_G$ represent height of the rollover, burnished, fracture, and burr parts, respectively [12].

### 3.2. Hole expansion tests

The hole expansion tests were simulated on the blanks with the different hole edges properties introduced in figure 2. The force-displacement curves are compared to experimental values in figure 5. It is worth mentioning that the edge characteristics of experimental pierced hole was supposed to be represented by the wSwD condition, i.e. both surface irregularities and residual damage existed. On the other hand the edge of wire-cut hole was supposed to be same as woSwoD or wSwoD conditions. Moreover, the hole expansion ratio of different conditions are compared in figure 6. The results reveal how the edge quality affects the edge crack sensitivity. Based on the experimental tests, HER for wire-cut hole was six times bigger than the pierced one. Furthermore, according to the simulation results, it can be concluded that pre-damage plays the main role in provoking the shear-cut edges into edge cracking.
Figure 5. Effect of surface irregularities and residual damage at the hole edge on the material response throughout the hole expansion test. The dashed lines represent the experimental data and the solid lines show the simulation results.

Figure 6. Hole expansion ratio for different edge conditions.

Moreover, throughout the hole expansion test several cracks initiated from elements with the higher damage value and propagated through the thickness by 45° to the normal direction, figure 7. Note that all the minor cracks cannot travel through the whole thickness.

4. Conclusion
The present work focused on the influence of shear affected zone on prediction of edge cracking and hole expansion ratio. The important findings of this study are summarized below:

- Intrinsic and extrinsic factors can influence on the edge cracking sensitivity. The material’s mechanical and damage behaviors are considered as intrinsic factors, while the manufacturing methods of holes are counted as extrinsic factors.

- Cutting processes can have essential influence on the material’s properties at the edge like pre-damage and surface quality. Depending on how severe they could be, the edge crack sensitivity will vary. For example, the introduced damage is much higher and the surface structure much more complex in shear-cutting process than in wire-cutting process, consequently its HER is significantly lower in the former case.

- For simulating a forming process of parts with a shear-cut edge, the accumulated damage, as the key factor, should be taken into the consideration. In contrast, the surface contour turned out to have only a minor effect on the edge cracking. However, it could be important to simulate manufactured holes which underwent very smooth processes, like wire-cutting.
Figure 7. The view of cracks after propagation in the experiment and simulation.

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