Adjustment of fracture locus to improve edge crack resistance

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Abstract. Edge crack sensitivity of advanced high strength steels is posing challenges in forming the sheets with shear-cut edges. In fact, cutting process reduces formability of material by leaving residual damage at the cut edges and makes it prone to edge cracking. The difficulty of the problem mainly lies in the complex loading path that sheets undergo through shear-cutting and the subsequent forming processes. In other words, the stress state evolves from pure-shear to plane-strain during cutting process and changes to mostly uniaxial tension during the following hole-expansion test. The present study aimed to investigate the physical mechanism underlying the formation of edge cracks. The overall aim of the study is to tailor an improved microstructural configuration leading to a significantly reduced edge crack sensitivity. As a first step in this process, an artificial fracture locus is iteratively identified which promises to improve edge crack resistance. In this regard, a dual phase steel was considered as reference material and its fracture locus was calibrated based on uncoupled Bai-Wierzbicki fracture model. The artificial fracture locus representing a virtual material with improved edge crack resistance changed in a way that lower residual damage was inherited from the cutting process, which consequently improved the hole-expansion ratio.

1. Introduction
Dual phase (DP) Steel sheets are widely used in automotive industries. Their complex microstructure with soft ferrite matrix and hard martensite islands, leads them to represent good combination of strength and formability and have high potential for reducing weight components [1]. However, some challenges still remain in their forming processes. They mostly undergo several complicated forming processes to obtain their final shape. Shear-cutting is a common forming process which is used for the initial cutting, such as door bumpers or cut-out the corner of the window. This process imposes some adverse effects on the shear cut edge, which become profound during the subsequent forming processes and cause edge cracking. This type of failure, which happens in DP steels, cannot be predicted by using conventional methods like forming limit diagrams or material properties included yield strength, tensile strength and elongation. For investigating into edge crack sensitivity, the forming capacity at the manufactured edge should be considered, i.e. the residual damage at the edge and edge quality [2]. Although some methods have been proposed to prediction of edge cracking, the physical insight of this phenomenon have remained unknown yet.

The defects introduced by the pre-damage from the initial punching process and the damage accumulation during the hole expansion test (HET) determine the formation of edge crack for DP steel sheets. Wang et al. [3,4] reported that the punched edges were experienced the highest level of pre-damage which considerably influenced on the subsequent hole-expansion forming test. Habibi et al. [5] numerically investigated the effects of pre-damage and roughness of an edge from the punching process on prediction of hole expansion ratio. The results showed that the pre-damage play the most significant role in the hole expansion ratio and its prediction. Furthermore, Park et al. [6] established a dual-scale
finite element simulation to study the effect of microstructure on the punching and subsequent HET. They revealed that more homogenous microstructure led to the lower damage at the cut edge and higher hole expansion ratios.

The present work aims to a thorough study on stress state evolution during a punching and the subsequent hole expansion processes. For this purpose, the fracture strain differed at specific stress states and new fracture loci were created. This study can propose the best fracture locus configuration to design a material with higher edge crack resistance.

2. Materials and methods

Dual-phase CR590Y980T-DP steel sheets, DP1000 according to DIN EN 10346, were received with the thickness of 1.5 mm. Bai-Wierzbicki uncouple fracture model [7], was applied to describe the fracture behavior in different stress states (equation 1). It is worth mentioning that the model is defined in terms of stress-triaxiality, η, and normalized Lode angle parameter, θ, to describe stress-state of the material during the deformation.

\[
\int_0^\varepsilon^f \frac{d\varepsilon^p}{(C_1\varepsilon^p-C_2\varepsilon^p+C_3\varepsilon^p-C_4\varepsilon^p-\varepsilon^f)^\frac{1}{2} + C_4\varepsilon^p} = 1
\]  

(1)

Herein, \(\varepsilon^p\) is equivalent plastic strain, \(\varepsilon^f\) is equivalent plastic strain at fracture, and \(C_i\) is material constant. The material constants were determined by a combined experimental and numerical approach. The mechanical properties were evaluated through shear, plane-strain tension, uniaxial tension, and biaxial tension loading conditions along with ARAMIS digital image correlation (DIC) analysis. The parallel numerical simulations were performed by using finite-element software Abaqus/Explicit 2017.

In all the simulations, eight-node reduced-integration solid elements of type C3D8R were employed. In order to minimize the computational time, a mesh size of 0.1 mm was applied only on those regions of samples which were exposed higher plastic straining. The material parameters are summarized in table 1.

| \(C_1\) | \(C_2\) | \(C_3\) | \(C_4\) |
|---|---|---|---|
| 0.15 | 1.5 | 0.08 | 1.5 |

Moreover, the numerical simulations of a two-stage shear-cutting subsequent hole-expansion test were performed for a set-up with sharp cutting edges tool (edge radii of 0.05 mm) and a die clearance of 10 %. In order to reduce the computation time, only a quarter of the symmetric model was considered, 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 [3]. The contact pairs were defined as a surface-to-surface algorithm. However, the contacts between new surfaces which are created during cutting process and the tool were defined as a node-to-surface algorithm. Since the applied fracture model is a local model and influenced by the mesh size, mesh size of 0.1 mm was used in the critical regions of the sheet like the models which were used for the parameter calibration as well. In order to apply homogenous force distribution on the sheet, 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 processes. The edge crack sensitivity was assessed based on hole expansion ratio. The conventional HER is measured when a crack passed throughout the thickness of the sheet. But here HER was measured as a crack penetrated through the plane of the sheet. The crack initiation and propagation were defined by element deletion method.

3. Stress states throughout the processes

In order to design new fracture loci, the elaborate understanding of shear-cutting and hole expansion processes is required. In this regard, the stress-state during these processes were studied at different stages by tracking stress-triaxiality and Lode-angle parameter. For better illustration each steps is presented in a separate part.
Step1: Cutting process  
Step2: Subsequent hole-expansion  
Final product

Figure 1. The two-step shear-cutting_hole-expansion test.

3.1. Shear-cutting process

Figure 2 illustrates the cutting process and changes in stress-state variables, i.e. stress-triaxiality and normalized Lode angle parameter. According to the simulation results, throughout the cutting process $\bar{\theta}$ in the critical elements remained about zero, while $\eta$ increased from zero to 0.8, i.e. the stress-state changed from pure shear ($\eta=0$ and $\bar{\theta}=0$) to plane-strain tension ($\eta=0.8$ and $\bar{\theta}=0$). Therefore, the stress-state varied only on the line $\bar{\theta}=0$, the valley of the fracture locus. Note that ultimate separation was caused by meeting of two cracks in the fracture part of the edge. In fact, first a crack initiated near the punch and propagated through the thickness. Meanwhile another crack initiated from the other side of the thickness and propagated towards the first crack.

A frame before:  
Crack initiation  
Second crack initiation  
Ultimate separation

Figure 2. The evolution of stress-state at critical elements through the shear-cutting process.
3.2. Subsequent hole-expansion test

The evolution of stress-state at the hole edge during the hole-expansion test is depicted in figure 3. The results reveal that the elements at the edge experienced initially uniaxial tension state. As any crack appeared at the edge and propagated through the thickness, the ligaments between the cracks underwent pure shear deformation. Furthermore, the adjacent elements in the sheet (far from the edge) experienced relatively higher stress-triaxiality and plane-strain to biaxial tension stress-states. Therefore, when a crack is propagating through the thickness, the stress states of critical elements differs from uniaxial tension to plane strain tension, and when it is propagating in to the plane, the stress states changes from plane strain tension to biaxial tension.

![Figure 3](image_url)

Figure 3. The evolution of stress-state at edge elements through hole expansion test.

4. Fracture locus design

The effects of level and shape of fracture locus on edge crack sensitivity were studied by designing different loci. For this aim, the values of equivalent plastic strain in different stress-states were individually multiplied once by ½ and once by 2. Afterwards, the fracture locus was plotted for each condition by fitting the best surface on the fracture points of pure shear (Sh), plane-strain tension (PS), uniaxial tension (UT), and biaxial tension (BT) stress-states. Note that all new fracture loci were different from the original one. The edge crack sensitivity of each fracture locus was investigated by simulating the shear-cutting process and subsequent hole-expansion test and the results are illustrated in the following parts.

![Figure 4](image_url)

Figure 4. Example of fracture loci design, here by multiplying the equivalent plastic strain at the fracture of biaxial tension states by 1/2 (green locus) or 2 (blue locus).
4.1. Effect of fracture locus on shear-cutting process
Figures 5 and respectively compare the residual damage at the cut edge and the stroke of the cutting punch until the total separation for the original material with the imaginary fracture loci. Note that the residual damage is shown by failure indicator which varies from 0 (element with no damage) to 1 (failed element). As mentioned, the stress-state through shear-cutting process changed in the valley of the fracture locus ($\bar{\theta}=0$). In addition, the shape and level of the valley were calibrated by shear and plane-strain tension modes. In other words, by changing the value of fracture strain in uniaxial or biaxial tension, the valley still remains the same. Thus, the material showed similar behavior during the cutting process, while it depended on fracture strain of pure shear and plane-strain tension. By multiplying $\varepsilon_{S\ell}$ to half, the crack initiated earlier and propagated rapidly before any second crack can initiate. In contrast to multiplying by 2, where the first crack initiated later, which made the roll-over part bigger. Also, a second crack created, propagated further and met the first crack in upper part of the edge. This behavior induced more damage than the former condition. The influence of changing the fracture strain of plane-strain condition, damage at the edge became smaller by making $\varepsilon_{PS}$ double and higher by making it half. However, the changes are not significant regarding induced damage by the cutting process.

![Figure 5. Distribution of failure indicator at the cut edge after shear-cutting process](image)

![Figure 6. Comparison of punch displacement of ultimate separation in shear-cutting process.](image)

4.2. Effect of fracture locus on hole-expansion ratio
By differing the fracture locus, the edge behaved differently through the hole-expansion test. In some conditions, the edge was more sensitive to created multiple cracks through the thickness before a crack
passed through the specimen, such as $\frac{1}{2} \varepsilon_{SH}^f, 2 \varepsilon_{PS}^f, \frac{1}{2} \varepsilon_{UT}^f, 2 \varepsilon_{BT}^f$. Whereas in the other conditions, cracks were prone to propagate towards the specimen much earlier and led to smaller hole-expansion ratio, figure 7 and 8. It is worth mentioning, in case the fracture strain decreases at the edge (with uniaxial tensile mode), the formation of cracks at the edge becomes easier and increases. While increasing of fracture strain for elements far from the edge which were underwent plane strain and biaxial tension modes, suppresses propagation of the crack through the plane, gives the chance and encourage more cracks forming at the edge.

This behavior depended more on the stress-state through the process than the pre-damage at the edge. However, for this material and the defined materials with this small die clearance, the applied damage from the cutting process varied negligibly for all the cut edges. Also, the effect of fracture strains in high stress-triaxiality conditions was more profound and the HER became much bigger by increasing them. Moreover, by plotting the volume under the fracture locus for high stress-triaxiality versus HER, a linear relation was detected, figure 9. As mentioned, high stress-triaxialities are the reason of crack propagation into the materials.

Figure 7. Situation of edge at the frame of propagation of a crack through the specimen.
CONCLUSIONS
The level and shape of fracture surface influences on the behavior of the material through shear-cutting and the subsequent hole-expansion processes. The results show that increasing the level of fracture surface in high stress-triaxiality conditions significantly increases the resistance to edge cracking by measuring of HER as a crack penetrate through the sheet plane. Whereas, increasing the level of fracture surface in relatively low stress-triaxiality slightly degrades this resistance. As the material experiences plane strain and biaxial tension at the crack propagation into the material plane, the changes in these two stress states caused huge difference in the cracking.

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