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Modelling the surface roughness influence on the hole expansion ratio of multiphase steel

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Abstract. There exist both extrinsic manufacturing process-related and intrinsic material-immanent effects on the edge crack sensitivity of dualphase steels. Extrinsic influences can be further divided into effects of residual damage as well as roughness-induced effects. A new simulation framework is applied to quantitatively assess the surface roughness-induced influences on the edge crack sensitivity of cold rolled dualphase steel of grade DP1000. Hole expansion ratios are numerically predicted for four different edge manufacturing processes, including drilling, milling, waterjet cutting, and wire cutting. The simulation framework applies the idea to make use of a ductile damage mechanics model. It employs realistic material parameters for all elements situated in the bulk, whereas those elements situated at the edge to be expanded during the test apply artificial model parameters. These are identified with the help of sub-models with geometrical surface representation. For the sub-model construction, roughness profiles are experimentally characterized by white light confocal microscopy. With the new simulation framework, numerical predictions of hole expansion ratios can be significantly improved, even though a remarkable overestimation still remains. Among others, this general overestimation can be attributed to local strain hardening, residual stresses, and microstructural modifications.

1. Introduction
Especially for dualphase steels, the edge crack sensitivity belongs to the limiting factors for the material’s applicability in the automotive sector [1]. Most probably, the pronounced edge crack sensitivity of dualphase steels is based on their microstructural features with dispersed hard martensitic islands, which are embedded into a rather soft ferritic matrix. This configuration will result in inhomogeneous local strain distributions favorable for ductile damage initiation and accumulation [2-4]. To conclude, the microstructural impact on the underlying mechanisms of damage initiation and accumulation can be understood as a major material-intrinsic influencing factor on the edge crack sensitivity of dualphase steels. Nevertheless, also external influences can be named which promote ductile damage evolution. These external influencing factors can mainly be categorized into two different groups: residual damage from previous edge manufacturing processes [5] as well surface roughness effects [6]. Residual damage is mainly activated when the edge manufacturing process is accompanied by a certain amount of plastic strain below the newly created edge, since this plastic strain will already trigger ductile damage mechanisms. This consequently reduces the remaining edge
formability. A typical example for such kind of edge manufacturing process is shear cutting. In addition, it has to be accepted that any edge manufacturing process will create a surface roughness profile on the cut edge. These tiny scratches and imperfections act as local stress raisers and alter the local state of stress, so that the initiation of ductile damage is promoted significantly. Typical examples for such kind of manufacturing process are milling, drilling or water jet cutting.

Despite a number of well-known disadvantages [7], the hole expansion test is regularly applied to assess the edge crack sensitivity of cold formable steel sheets. However, it has been regularly reported that the results of hole expansion tests not only rely on material intrinsic factors, but also on the abovementioned extrinsic parameters resulting from the manufacturing of specimens [8,9]. Especially the surface roughness of the edge which is to be expanded during the test exhibits an enormous impact on the hole expansion ratio, so that this characteristic value can only be evaluated in a meaningful manner when also the sample manufacturing process is taken into consideration. This, however, leads to problems in interpretation of experimental data, especially when forming processes have to be designed to avoid edge crack formation.

In the following, a simulation framework is presented that is capable of predicting surface roughness effects on the hole expansion ratio. The approach combines macroscopic simulations with a phenomenological ductile damage mechanics model with sub-model simulations in which roughness profiles are geometrically considered. The macroscopic simulations will be performed with the modified Bai Wierzbicki (MBW) model, which applies strain based and state-of-stress dependent criteria for ductile damage initiation and ductile fracture. The surface layer, however, will make use of damage initiation criteria that are systematically lowered to compensate for the roughness effects. The amount of lowering is derived by sub-model simulations with geometrical surface roughness representation. The concept of roughness consideration in sub-model simulations picks up results presented in [10,11].

2. MBW model

The MBW model is a macroscopic ductile damage mechanics model. It can be categorized into the group of coupled approaches because it considers damage-induced softening by coupling a \((1 - D)\) term into both the yield potential and the definition of elastic constants [12,13]. Herein, \(D\) is a damage variable, which is calculated according to an evolution law. The yield potential of the MBW model describes isotropic hardening and reads:

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

(1)

Herein, \(\sigma_e\) is the von Mises equivalent stress, \(D\) is the damage variable and \(\sigma_{yld}\) is the material’s flow stress. With the initial elastic modulus denoted by \(E_0\), the effective elastic modulus \(E_{eff}\) is defined as:

\[
E_{eff} = (1 - D) \cdot E_0
\]  

(2)

The damage evolution law of the MBW model applies individual criteria for damage initiation and ductile fracture. The damage initiation locus (DIL) provides the equivalent plastic strain to ductile damage initiation \(\epsilon^{ddi}\) as a function of stress triaxiality \(\eta\) and Lode angle parameter \(\overline{\theta}\). These two parameters characterize the local state of stress by relying on the invariants of the stress tensor and the deviatoric stress tensor, respectively. With the principal stresses denoted by \(\sigma_1, \sigma_2\) and \(\sigma_3\), the three invariants of the stress tensor are defined respectively by

\[
p = -\sigma_m = -\frac{1}{3} (\sigma_1 + \sigma_2 + \sigma_3)
\]  

(3)

\[
q = \sigma_e = \sqrt{\frac{1}{2} \cdot [ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 ]}
\]  

(4)
Using these invariants, stress triaxiality and Lode angle can be calculated according to:

\[ \eta = -\frac{p}{q} \]
\[ \theta = \frac{1}{3} \arccos \left( \left(\frac{r}{q}\right)^3 \right) \]

It has been known for decades that stress triaxiality provides a rather pronounced influence on damage evolution [14-16], because voids and cavities will grow mainly due to hydrostatic stress components. In contrast, the pronounced influence of the Lode angle has only been discussed for the last ten years [17-19]. It is to be noted that the Lode angle is defined for \( 0 \leq \theta \leq \pi/3 \). After normalizing this parameter, the Lode angle parameter or normalized Lode angle \( \bar{\theta} \) is defined by:

\[ \bar{\theta} = 1 - \frac{6\theta}{\pi} \]

The dependence of the equivalent plastic strain to ductile damage initiation on the local state of stress is expressed by

\[ \varepsilon_{\text{ddi}} = \left( c_1 \cdot \exp(-c_2 \cdot \eta) - c_3 \cdot \exp(-c_4 \cdot \eta) \right) \bar{\theta}^2 + c_5 \cdot \exp(-c_6 \cdot \eta) \]

The MBW model assumes that a material point will fail according to the ductile fracture mechanism as soon as a strain-based, stress state dependent failure criterion is fulfilled. The ductile failure locus (DFL) defines the equivalent plastic strain to ductile failure \( \varepsilon_{\text{df}} \) as a function of stress triaxiality and normalized Lode angle according to the following function:

\[ \varepsilon_{\text{df}} = \left( c_1 \cdot \exp(-c_2 \cdot \eta) - c_3 \cdot \exp(-c_4 \cdot \eta) \right) \bar{\theta}^2 + c_5 \cdot \exp(-c_6 \cdot \eta) \]

With these criteria at hand, a damage evolution law can be designed. It assumes \( D = 0 \) for any equivalent plastic strain below the DIL. Once the damage initiation criterion has been fulfilled, a linear relationship between \( D \) and equivalent plastic strain is assumed for the special case of proportional loading. Its characteristic slope is defined by the characteristic energy dissipation \( G_f \) between damage initiation and ductile fracture of a material point. Finally, the damage variable will be set to 1 as soon as the equivalent plastic strain reaches the ductile fracture locus. Consequently, the damage evolution law for the special case of proportional loading reads:

\[
D = \begin{cases} 
0, & \varepsilon^p \leq \varepsilon_{\text{ddi}} \\
\frac{\sigma_{y,i}(\varepsilon^p - \bar{\varepsilon}^l)}{G_f}, & \varepsilon_{\text{ddi}} < \varepsilon^p < \varepsilon_{\text{df}} \\
1, & \varepsilon_{\text{df}} \leq \varepsilon^p
\end{cases}
\]

Herein, \( \varepsilon^p \) denotes the equivalent plastic strain, \( \sigma_{y,i} \) is the von Mises equivalent stress at the instant of fulfilling the damage initiation criterion, and \( \bar{\varepsilon}^l \) defines the value of the DIL for the actual combination of stress triaxiality and Lode angle parameter. It has to be noted that the MBW model in its current release [20] is able to consider the effect of non-proportional loading by relying on indicators for ductile damage initiation and ductile fracture, respectively. These indicators still rely on DIL and
DFL, but they additionally evaluate the loading path in the 3D space of stress triaxiality, Lode angle parameter, and equivalent plastic strain. Consequently, also a more complicated ductile damage evolution law has to be established which relies on the abovementioned indicators. However, for the presented study, it turned out that this differentiation is not necessary due to the damage initiation and accumulation mechanisms in the selected steel of grade DP1000.

3. Material and material parameter calibration

The investigated material is a dualphase steel of grade DP1000. It was delivered as cold rolled material in a thickness of 1.5 mm. The material has already been characterized for previous scientific investigations [10,11], so that only a short summary of its properties is given here. Light optical metallographic investigations on HNO$_3$-etched samples revealed a multiphase microstructure with ferrite and martensite as major constituents. The fractions of these phases are 62 % (ferrite) and 38 % (martensite). Compared to other dualphase steel grades of lower strength, the selected steel DP1000 not only shows a relatively high martensite strength to achieve the desired strength, but also the fine grain structure of the ferritic phase is remarkable. It can be concluded that this grain refinement was applied on the ferritic phase in order to contribute to the relatively high strength without increasing the risk of undesired embrittlement. Tensile tests were performed to characterize the material’s strength properties and to identify the flow curve for macroscopic simulations with the MBW model. The material’s yield stress is 770 MPa while the ultimate tensile stress is 983 MPa. The uniform elongation and $A_{80}$ fracture strain are 5.2 % and 11.0 %, respectively. The flow curve used for numerical simulations reads:

$$
\sigma_{\text{yld}} = 0.5 \cdot 1300 (2.3 e^{-14} + \bar{\varepsilon}^P)^{0.075} + 0.5 \cdot [266.2 + 507.1 (1 - e^{-73.94 \bar{\varepsilon}^P})]
$$

(12)

Systematic studies on the damage initiation mechanisms reveal that in steel DP1000, voids are created as a result of martensite breakage, whereas decohesion at phase or grain boundaries is only rarely observed. This behaviour can be attributed on the one hand to the high possible level of tensile stress in the martensitic phase and on the other hand to the relatively small mismatch between strength of ferrite and martensite compared to other DP steel grades of lower strength. Likewise, strain gradients are less pronounced in steel DP1000, so that localization of plastic strain can be avoided until stress-controlled fracture of martensite is triggered. In addition to this study on the dominant damage initiation mechanisms, also the damage accumulation phase has been systematically characterized. These studies revealed that fracture follows ductile damage initiation almost immediately, so that the damage evolution in steel DP1000 has to be explained by late damage initiation and an extremely short accumulation phase. With respect to macroscopic damage modelling, this allows to neglect the role of damage accumulation by simply merging the DIL and the DFL. Then, the material’s response is described by an uncoupled model enriched with a strain-based, stress-state dependent failure criterion. This criterion has been identified in previous studies in a conventional curve-fitting approach. The MBW parameters used in this study are summarized in table 1 [11].

| $c_1^i$ | $c_2^i$ | $c_3^i$ | $c_4^i$ | $G_f$ |
|--------|--------|--------|--------|------|
| 1.24   | 3.0    | 0.29   | 0.78   | 2500 |

4. Methods and approaches

The effect of surface roughness on strain localization and ductile damage in steel DP1000 has been systematically studied in [10], where a systematic approach to translate statistical descriptions of roughness profiles into geometrical sub-models was discussed. With the help of this approach, it could be explained why samples of one material show different critical bending angles in VDA238-100
bending tests as soon as different surface roughness profiles are established by means of polishing or grinding. However, these preliminary studies suffered from the shortcoming that no coupling back from the microscale to the macroscale could be achieved, so that the effect of roughness-induced damage on the macroscopic force-deflection curve could not be quantified by the simulation framework. This shortcoming has been solved with the further development that has recently been described in [11]. The latest developments are based on the idea to perform macroscopic simulations of the bending tests with a different set of MBW material parameters for those elements that are situated at the surface. Thus, the idea is to “hide” the roughness influence in the model parameters. Consequently, the question has to be answered how these artificial parameter sets can be identified based on a quantitative assessment of the roughness of the investigated sample. Having this question answered with an approach described in the following chapter, also the force-deflection curves from bending tests on samples made of steel DP1000 in two different surface configurations (fine grinded and polished / 80-grit sand paper grinded) could be reproduced on a high level of accuracy. This study therefore focuses on the application of the simulation framework to predict hole expansion ratios for samples of steel DP1000 that have undergone four different manufacturing processes: i. drilling, ii. milling, iii. waterjet cutting, iv. wire cutting.

5. Results
Rectangular sheets of 110 mm x 110 mm were manufactured from steel DP1000 by shear cutting. Afterwards, these samples were prepared for hole expansion tests by creating circular holes with a diameter of 10 mm in the centre position of these sheets. These circular holes were created by the abovementioned manufacturing processes drilling (D), milling (M), waterjet cutting (WJ), or wire cutting (WC). For each of these processes, 10 samples were produced, because a relatively high scatter of experimentally determined hole expansion ratios (HERs) was expected based on previous experience. The samples were used for hole expansion tests according to the testing procedure ISO 16630:2017. Fig. 1 shows the test result in terms of punch force-displacement curves. A macroscopic simulation with the fully calibrated MBW model was also performed. Since no roughness profiles were considered in these first simulations, their results can be interpreted as expectable behavior for samples with perfectly smooth surface conditions.

Figure 1. Punch force-displacement curves from hole expansion tests performed on samples manufacturing by drilling (D), milling (M), waterjet cutting (WJ), or wire cutting (WC) in comparison to a macroscopic damage mechanics simulation (sim) with the fully calibrated MBW model (no roughness consideration).

Obviously, there exists a pronounced effect of surface condition on the sample’s behavior in hole expansion tests, since all experimental results fall behind the values predicted by the numerical simulation. Furthermore, the impact of wire cutting is less severe than the ones of drilling, milling or waterjet cutting. Finally, it turns out that the effects of drilling, milling and waterjet cutting on the sample’s behavior is approximately the same. Before the experiments were conducted, the edges at the circular holes were investigated by white light confocal microscopy. With this technique, surface
profiles can be quantitatively measured, and by stitching of individual images, a representative area of several mm² can be evaluated. In addition, by filtering the surface profiles with respect to the measured wavelength, it is possible to distinguish between waviness and roughness. Fig. 2 gives a comparison for the typical roughness profiles as created by the four investigated edge manufacturing methods.

![Figure 2](image)

**Figure 2.** Roughness profiles of the edges of the circular holes produced by drilling, milling, waterjet cutting, or wire cutting.

The identified roughness profiles were afterwards statistically described. A self-written python script was then used to create sub-models with surfaces that reproduce these statistical data, so that individual sub-models could be created for each of the four selected manufacturing processes. These different sub-models are depicted in fig. 3, highlighting obvious differences especially between the wire cut samples and all the other ones.

![Figure 3](image)

**Figure 3.** Statistically representative surface models.

Each of these sub-models was afterwards subject to an FE simulation with the fully calibrated MBW model. These simulations were performed on geometrical models with an edge length of 0.2 mm with an enmeshment by C3D8 elements which is characterized by an element edge length of 0.003 mm at non-critical regions, 0.002 mm at transition regions, and 0.001 mm at the critical regions. Displacement boundary conditions for these simulations were taken from the previous macroscopic simulation of the hole expansion test for the critical position of first edge crack appearance.

Fig. 4 compares the individual strain paths observed during the sub-model simulations by plotting the evolution of equivalent plastic strain over stress triaxiality (left diagram) and normalized Lode angle (right diagram). Firstly, it turns out that the load path is rather proportional and close to the uniaxial tensile condition. Secondly, the fracture event (indicated by the end of the respective curve) is postponed with decreasing roughness. Obviously, these failure strains for the uniaxial condition could be used for the following macroscopic simulations, where roughness effects should be considered indirectly by finding artificial damage criteria for surface elements. More details on the strategy to determine artificial criteria including roughness effects can be found in [11]

With the artificial set of MBW model parameters for the row of surface elements, macroscopic simulations of the hole expansion tests could be repeated. Fig. 5 gives a comparison between experimentally determined hole expansion ratios and the corresponding results of numerical simulations.
with the new simulation framework. It reveals that a significant improvement of the numerical prediction can be achieved by incorporating the effect of roughness into the simulation framework. However, even with this obvious and rather significant improvement provided by the newly developed simulation scheme, the relative overestimation of experimental HER values remain on an unacceptable level.

![Fig 4] Proportional strain paths observed during the calibration of virtual damage parameters based on sub-model simulations.

![Fig 5] Comparison between experimentally determined hole expansion ratios for samples produced by manufacturing processes and corresponding simulation results generated with the new simulation framework.

6. Conclusions

- Consideration of roughness significantly improves the numerical prediction of HER values. Nevertheless, an unacceptable overestimation of experimental values remains. This is attributed to the fact that the simulations still neglect effects of local strain hardening, residual stresses, and possible microstructure modifications during edge manufacturing.
- The agreement between numerical prediction and validation experiment can be improved by an improved roughness description considering full-field or 3D roughness profiles especially for waterjet and wire cutting. In addition, taking the previous manufacturing history into account will also improve the numerical prediction, in particular for drilling and milling.
- The presented study focuses on the four processes of drilling, milling, waterjet cutting, and wire cutting. Shear cutting has not been investigated, even though this manufacturing process is widely applied in industry. The selection was made because it is well-known that shear cutting is a process that leaves a remarkable amount of residual damage below the cut edge, which is most probably the most dominant extrinsic effect on the edge crack sensitivity.
- In the presented simulations, a simplification on the MBW model was used, because in the selected steel of grade DP1000, damage initiation and ductile fracture almost coincide due to an extremely short damage accumulation phase. However, the general simulation framework to
consider roughness influences can also be applied in combination with other ductile damage mechanics models and for materials with a more complicated damage evolution behavior.

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