Edge cracking sensitivity – advanced experimental and numerical methods of valuation

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Summary

The edge cracking sensitivity of a bainitic steel was investigated using the test method hole expanding test according to ISO 16630 (in the following called "ISO-test"). In order to study the influence of different edge qualities on the edge cracking sensitivity the edges were cut both in an one-step cutting process changing the clearance and in a two-step cutting process using a constant clearance but varying trimming additions. Cut edges that were manufactured by means of a two-step cutting process led to a twice as high hole expansion ratio compared to a standard one-step cutting process. Reasons for these results could be identified by determining the characteristics of the cut edge as well as by investigating residual stresses and hardness increase close to the cut edge for both cutting processes. The numerical simulation shows comparable results and is used to increase the understanding of cutting process.

1. Keywords

hole expanding test, hole expansion ratio, cut edge, formability, residual stress, hardness, cutting simulation

2. Introduction and Motivation

Reducing the weight of automotive components in order to minimize the CO_2 emission is one of the main challenges the automotive industry is currently faced with. As a result the requirements for and demands on mechanical properties and thus on the material used for manufacturing increase with each new component generation. Due to complex part geometries as well as the process windows that get smaller and smaller the material is stressed close to its limit during the forming process. These facts require an accurate analysis and description of the material properties and application limits taking into account the previous production processes. The forming limit curve (FLC) determined according to ISO 12004-2 [1] is commonly used for evaluating the formability of the material. This description is, however, limited exclusively to the base material. The formability of an edge produced by shearing cannot be predicted satisfactorily using FLC. This is due to the pre-damage of the edge caused by the cutting process. There are a number of different types of test methods available that evaluate the tendency of the material to fail from the cut edge. Among all these test methods the "ISO-test" is currently the only ISO standardized [2].

In several series of experiments it was shown that the edge quality is one of the most influencing factors concerning the level of edge cracking sensitivity [3,4]. The edge quality, that means the pre-damage of the edge, is influenced among other things by the clearance. Moreover, sheared edges with improved quality can be achieved by applying multi-stage cutting processes as described in [5,6,7]. For this reason, in the following investigation a variation of the clearance and a two-step cutting process are compared in order to find the best settings concerning minimal pre-damage. The amount of pre-damage and the formability of the edge respectively are evaluated using the tools of the edge cracking method "ISO-test". By comparing the geometrical conditions of the cut edges, the characteristics of the residual stresses close to the cut edge as well as the hardness gradient, reasons for the different results concerning edge cracking sensitivity, are investigated. The numerical forming simulation with the finite element method is used to generate a deeper understanding about the process of cutting.

3. Experimental Procedure

3.1. Material

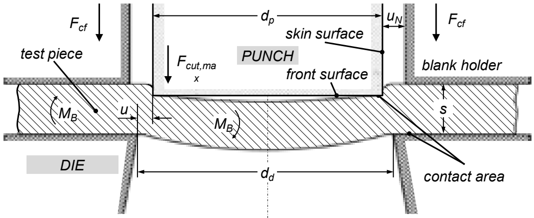
The bainitic steel grade SZBS800 with a thickness of 2.0 mm is used for these investigations. SZBS800 is a thermo-mechanically hot rolled, microalloyed bainitic steel grade with a tensile strength of higher than 800 MPa. The mechanical properties (see table 1) are sufficient for forming applications such as mobile crane constructions and also complex parts like suspension components [8].

Table 1: Mechanical properties of SZBS800

nominal size e	yield strength R_{eH}	tensile strength R_m	total elongation A_{80}
2 ≤ e < 3 mm	≥ 680 MPa	800 – 980 MPa	≥ 10 %

3.2. Shear Cutting

In accordance to DIN 8580 shear cutting belongs within the third main group "separation" to the sub-group "dissecting" [9]. The material is cut between two cutting edges which pass each other with a defined clearance (see Figure 1). The clearance u is defined by equation (1) [2].

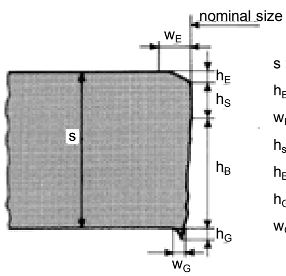


F_{cf}: clamping force
$F_{cut,max}$: cutting force
M_B: bending moment
u: cutting clearance
u_N: blank holder clearance
s: sheet thickness
d_p: punch diameter
d_d: die diameter

Figure 1: Standard cutting process based on [10]

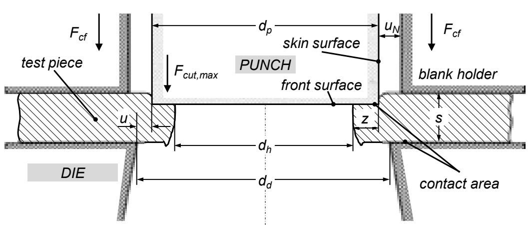
$$u\,[\%] = \frac{d_d - d_p}{2 * s} * 100\,\% \qquad (1)$$

The characteristics of a sheared edge for the manufacturing method shear cutting are shown in Figure 2. In order to obtain sheared edges with a higher edge quality in terms of accuracy in size, smoothness and cracks, multi-stage cutting processes are employed. The second cutting process that is called trimming means cutting of small rims from preprocessed sheet pieces (see Figure 3). The trimming addition z is defined by equation (2) [6,11]:



s : sheet thickness
h_E : rollover height
w_E : rollover width
h_s : clear cut surface height
h_B : shearing zone height
h_G : burr height
w_G : burr width

Figure 2: Characteristics of a sheared edge for the manufacturing method shear cutting based on [11]



F_{cf}: clamping force
$F_{cut,max}$: cutting force
u: cutting clearance
u_N: blank holder clearance
s: sheet thickness
z: trimming addition
d_p: punch diameter
d_h: hole diameter
d_d: die diameter

Figure 3: Trimming process based on [10]

$$z\,[\%] = \frac{d_{p2} - d_h}{2 * s} * 100\,\% \qquad (2)$$

3.3. Cutting Simulation

There are techniques like hardness and residual stress measurement that deliver information about the condition at a cut edge. In order to acquire a better understanding of the cutting process a punch stroke dependent analysis using this kind of measuring techniques would cause an enormous effort. A way to reduce this effort is to perform a finite element simulation of the process. This was done with a 2D axissymmetric solid model using LS-Dyna. Whether this approach is only qualitative or even quantitative depends significantly on the used failure model and its parameters. In this case *MAT_TABULATED_JOHNSON_COOK (*mat224) was employed. Here the failure strain can be defined as a function of triaxiality to take out the overloaded elements [12]. All relevant tool radii were modeled with a radius of 30 µm. The elements close to the cutting zone have an edge length of about 7 µm. The boundary conditions and the contact pairs are shown in Figure 4. Temperature and strain rate effects were not taken into account.

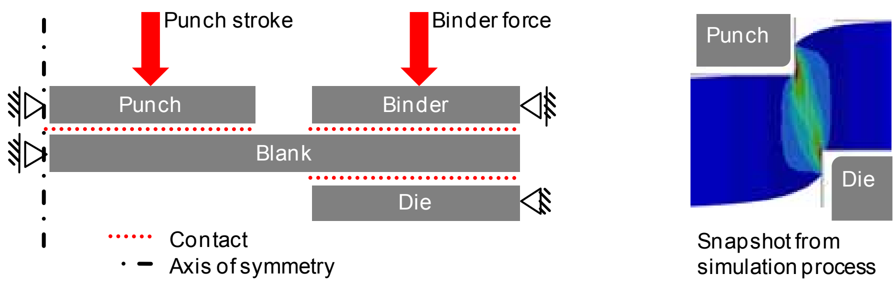
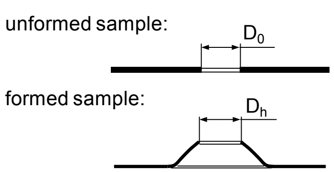


Figure 4: Model for cutting simulation

3.4. ISO 16630 Hole Expanding Test

The “ISO-test” is currently the most widespread edge cracking test method in the industrial environment. This test is conducted in two steps. First of all a hole with a diameter of 10 mm is punched with a clearance of 12 % into the test piece that has to have a size of at least 90 mm x 90 mm. In a second step this hole is expanded using a conical punch with a tip angle of 60° ± 1° until a crack appears through the full thickness of the test piece. The detection of the crack is carried out visually by the press operator. That means that the test result is influenced by the operator´s perception and reaction rate. The test result is given by the ratio of the increase in the hole diameter to the original hole size according to equation 3 (see Figure 5) [2]. At least three samples per setting have to be stamped, expanded and subsequently evaluated.



$$\lambda\,[\%] = \frac{D_h - D_0}{D_0} * 100\,\% \qquad (3)$$

λ : limiting hole expansion ratio
D_h : average hole diameter after rupture
D_0 : original hole diameter

Figure 5: Determination of the “ISO-test”

4. Results and Discussion

4.1. Cut Edge Geometry

In order to determine the geometry of the cut edges three cross-sections are extracted from each cut edge sample, that means parallel, transverse and 45° to the direction of rolling. Hence the results illustrated in Figure 6 represent the mean value of three single specimens for each cut edge. The characteristics are named in accordance to Figure 2.

Comparing the geometrical measurements it is obvious that the trimming process variation samples show a significantly smaller rollover height than the clearance variation samples. Moreover, a burr height is only detectable in the case of the cut edge with a clearance of 25 %.

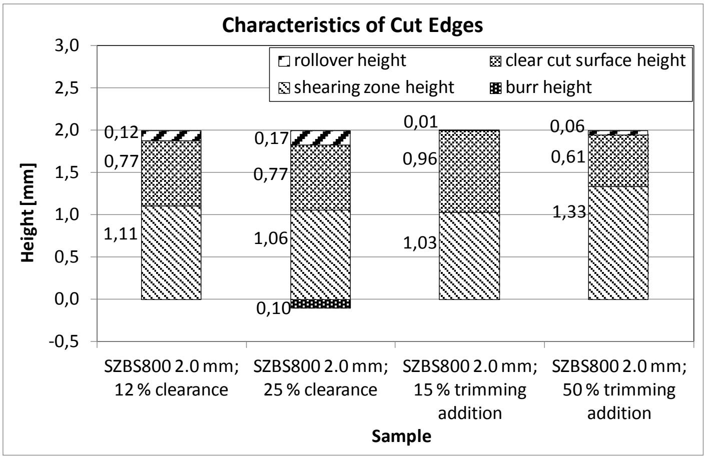


Figure 6: Results of the characteristics of cut edges

4.2. Hardness

As before the results presented in Figure 7 are the mean values of the corresponding three single metallographic specimens. It has to be noted that the hardness measurement is not conducted according to any standard due to the small distance of the hardness indentation to the edge of the specimen. Nevertheless a qualitative comparison between the differently cut samples is possible. By comparing these measurements it can clearly be seen that the hardness increase is much higher in the case of the clearance variation samples. The samples manufactured using a two-step cutting process show only a very small increase in hardness. In accordance to the formula of [13] high hardness values are corresponding with high plastic strains.

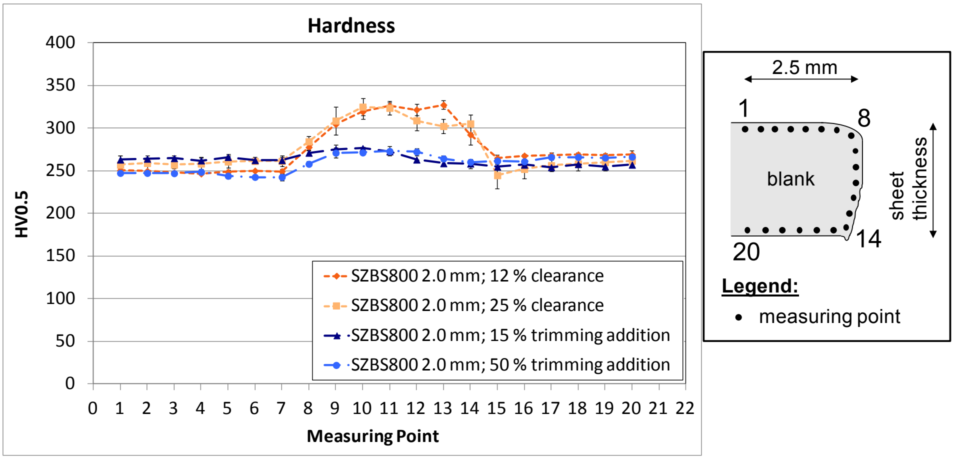


Figure 7: Results of the hardness investigation

4.3. Residual Stress

The residual stresses are determined on the rollover side of each sample using a X-ray diffractometer. The distance of the first point to the cut edge as well as the distance of the following points to each other is approximately 1.0 mm. The results shown in Figure 8 are the mean values of the corresponding measurements in each direction tangential to the cut edge. It can be seen that the affected zone is pretty close to the cut edge. Only the first two measuring points show a significant difference compared to the residual stresses of the base material. The algebraic sign of the stress data shows that there are only tension stresses on the rollover side of the specimen. By comparison the cut edge that is produced in a one-step cutting process using a clearance of 25 % shows the highest residual tension stresses.

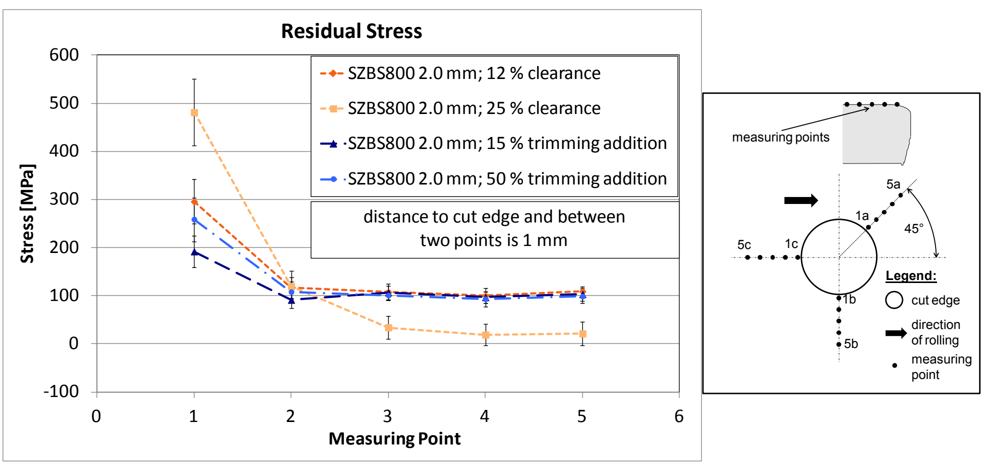


Figure 8: Results of the residual stress investigation tangential to cut edge

4.4. Cutting Simulation

The parameter set for failure model *mat224 are determined by comparing the contours of the cut edge from experiment and simulation. To ensure a universal validity this adjustment has to be done for different cutting conditions. For example a narrow and a wide cutting clearance have to be taken into account to cover a wide range of triaxiality states. Figure 9 shows exemplary the contours from experiment and simulation for one-step cutting with a clearance of 12 %.

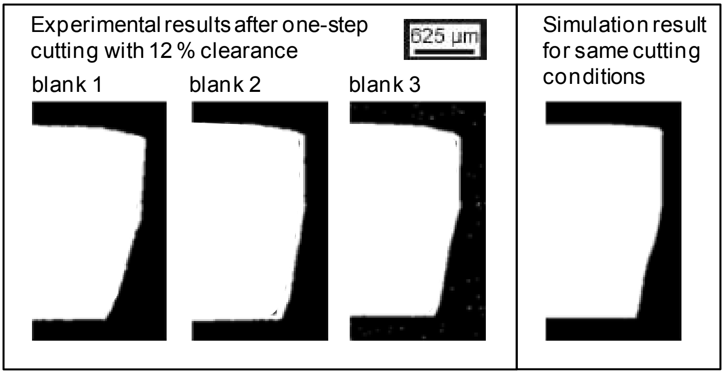


Figure 9: Comparison of cut edge contour from experiment and simulation

With the determined parameter set cutting simulation are conducted in accordance to the experimental procedure. Exemplary results are shown in Figure 10. A two-step cutting operation leads in the experiment and also in the simulation to a more even and rectangular contour. Here the contour for a trimming addition of 15 % is shown.

The one-step cutting leads to a higher rollover and also to higher strains in this zone. The two-step cutting has only a narrow stripe that is affected by the cutting process.

Paying some attention to the stresses in the tangential direction of the cut edge (normal to model plane; same direction as residual stress analysis) the influence of the process is obvious. The two-step cutting reduces the tension stresses in the middle of the sheet and also on the rollover side of the specimen.

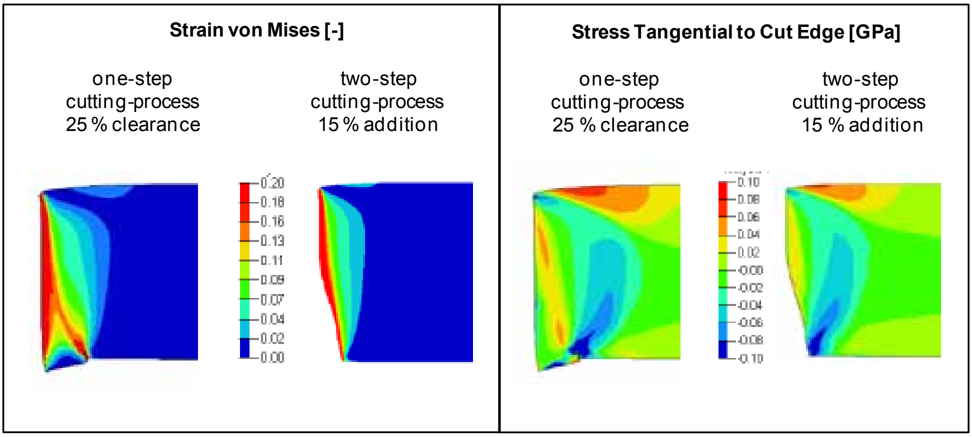


Figure 10: Exemplary results of cutting simulation

4.5. Hole Expanding Test

In Figure 11 the results of the clearance variation and of the trimming process variation are shown using the expanding tool in accordance to “ISO-test”. The results represent the mean value as well as the standard deviation of eight samples. The minimum and maximum hole expanding ratios are eliminated prior to averaging.

The clearance varies between 5 % and 25 %. It can be noted that the measurements tend to result in higher hole expansion ratios increasing the clearance. The trimming addition varies between 15 % and 75 % whereas the clearance is constantly set to 12 % for the first and second cutting step. It can clearly be seen that the hole expansion ratios reach approximately twice as high values compared to the one-step cutting process. The maximum hole expansion ratio is obtained using a trimming addition of 50 %. The results scatter in the same order of magnitude as in the case of clearance variation. Both in the case of clearance variation and trimming addition variation two samples are chosen for further metallographic investigations.

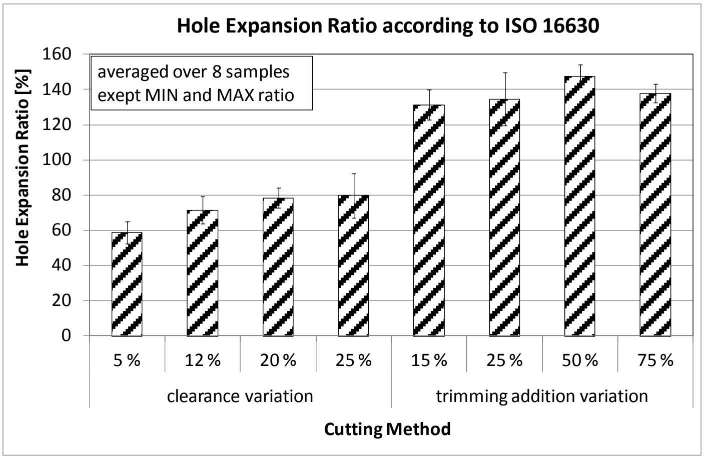


Figure 11: Results of the clearance variation and trimming addition variation for SZBS800 with a sheet thickness of 2.0 mm

5. Conclusion

The measured rollover heights correspond with the residual stresses on the rollover side. High rollover heights led to high residual stresses and vice versa. In general tension stresses in the area around the cut edge affects the forming capacity negatively [14]. But in this investigation both in case of the clearance variation and trimming addition variation the samples with higher rollover height showed higher hole expansion ratios. One reason for this effect might be the geometry of the expanding punch and the expanding procedure of the ISO 16630 test itself. The tension stresses originated from the rollover seem to be compensated by pressure resulting from the contact with the expanding punch in a way that the hole expansion ratio is not influenced negatively. Based on the results of the hardness measurement it can be noted that less hardness increase has a positive influence on the hole expansion ratio.

The simulation of the cutting process leads to comparable results on the cut edge in terms of cut edge geometry, strains and stresses. In addition to that the understanding of the changing strain and stress states in the process affected zone could be increased.

The edge cracking sensitivity of sheared edges can be reduced significantly using a two-step cutting process. In comparison to an one-step cutting process twice as high hole expansion ratios according to the “ISO-test” could be obtained. A variation of the clearance in one-step cutting process around the standard of 12 % resulted in only slightly higher ratios.

Hence, if there is a need for an even higher forming capacity of the cut edge a more complex two-step cutting process can be a workaround.

6. References

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