Considering the edge-crack sensitivity of a hot-rolled steel in forming simulation

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Abstract. The formability of sheet metal materials is locally reduced by shear cutting operations, and as a result the risk of a crack during further processing is increased at the edge. Materials particularly susceptible to this are described as sensitive to edge-cracking. A procedure for quantitatively determining edge-crack sensitivity and for applying corresponding characteristic values has not been previously established. Below, two test methods and an approach for using the results in an extended forming limit diagram are presented. The producibility of a collar drawn test component as well as a chassis component is reevaluated using this extended forming limit diagram.

1. Introduction

Because of economic goals and legal requirements, the automotive industry faces the challenge of reducing the CO₂ emissions of vehicles. A very promising approach to this challenge is lightweight steel construction. A reduction in the vehicle mass directly influences the CO₂ emissions. For every 100 kilograms of mass spared, the CO₂ emissions are reduced by 8.5 g/km [1]. The steel industry has recognized this trend and developed new products and application possibilities. Steel grades are becoming stronger and stronger, sheet metals used are becoming thinner and thinner, and component geometries are becoming more and more complex. Therefore, the requirements for the mechanical properties of the initial material increase with each new component generation. At the same time, forming technology faces appropriate challenges.

An example of such a challenge is the edge-crack sensitivity of shear-cut materials. A shear cutting process can significantly reduce the formability of the newly produced edge in comparison with the formability of the base material. In subsequent forming operations, crack formation starting from the edge can occur because of the reduced formability. Up to now it was not possible to predict this crack formation with sufficient accuracy using existing experimental and simulation methods. In the field of forming simulation, the evaluation of the formability of a sheet metal by using the forming limit curve (FLC) in the corresponding forming limit diagram (FLD) is the state of the art. However, a universally applicable approach to simulating edge-crack sensitivity that has been tested and verified on a meaningful number of practical components has not been previously established. However, approaches that add limits for the cut edge region to the forming limit diagram have been published [1a].

In cooperation with ESI GmbH, Salzgitter Mannesmann Forschung GmbH, Volkswagen Component Toolmaking, and Volkswagen Group Research, an industrially usable procedure has now been defined and
has been applied to a chassis component. The "hole expansion with Nakajima punch" and "Kobe hole
tensile test" testing methods used for this purpose are presented below.

2. Technical status
The hole expanding test as per ISO 16630 is currently the only globally standardized test for determining
dge-crack sensitivity. In this test, a hole with a diameter of 10 mm is made in the sheet metal specimen
by shear cutting (die clearance: 12%) and then expanded with a conical punch (head cone angle: 60°). The
operator stops the expansion as soon as the operator visually detects a crack extending through the entire
thickness of the sheet metal. Consequently, the results of this test greatly depend on the perception and
reaction speed of the operator. The test result is given by the hole expansion ratio, which is defined as the
ratio of the hole diameter increase to the initial hole diameter [2].

Because of the described test method, which allows, among other things, a strong influence on the
measurement results by the operator, the hole expansion ratios determined from at least three individual
specimens generally have very high scattering. This high scattering can be observed both within a test
location and across test locations [3]. Therefore, an increase in the number of specimens, among other
things, is called for in [3] with the goal of providing better statistical assurance.

In addition to the standardized hole expanding test, there are numerous other test methods that have
been developed in order to quantify edge-crack sensitivity [3a].

3. Characterisation methods, testing procedure und material description

3.1. Determination of edge forming limit
The test setup for determining a forming limit curve is used for the "hole expansion with Nakajima
punch." As in the case of the ISO 16630 hole expanding test, the test consists of two steps. First, a hole
(diameter: 20 mm) is made in a square specimen (edge length: 200 mm) by punching (die clearance:
12%); see figure 1. In the second step, the specimen prepared in such a way is expanded with a
hemispherical punch (diameter: 100 mm). On the basis of the ISO 16630 hole expanding test, the selected
punch speed must be less than or equal to 1.0 mm/s. The specimen must be placed in such a way that the
punching direction corresponds to the forming direction. The specimen must be precisely centered to
achieve reliable results. The test is immediately stopped as soon as a crack extending through the entire
thickness of the sheet metal can be detected. As in the case of the ISO 16630 hole expanding test, at least
three specimens are tested per setting. The crack initiation occurs more abruptly in the "hole expansion
with Nakajima punch" than in the ISO 16630 hole expanding test [5]. For this reason, a crack width
correction, as presented in [6], should be performed in the evaluation. The result is, again, the hole
expansion ratio described above. However, in contrast to the ISO 16630 hole expanding test, a stochastic
pattern can be applied to the surface of the sheet metal before the forming and a detailed elongation
analysis for the region of the specimen near the edge can be performed with the ARAMIS optical
measurement system from the company GOM. A comparable analysis is not possible with a standard
ARAMIS system for the hole expansion as per ISO 16630, because the specimen surface moves out of the
initial sheet metal plane to a high degree during the test. The crack initiation and the hole expansion ratio
can be automatically detected and determined by means of an evaluation macro based on Visual Basic,
which contains defined crack criteria [7].

For the "Kobe hole tensile test," a rectangular tensile specimen is used (250 x 40 mm²) as per [8], in
which a hole having a diameter of 10 mm is punched in a centered manner (die clearance: 14%); see
figure 1. Then the specimen is drawn using a tensile test machine at a speed of 10 mm/min until a crack is
initiated at the hole edge. In contrast to the procedure as per [8], the characteristic value is determined
virtually. As in the case of the "hole expansion with Nakajima punch," a stochastic pattern is used so that
the displacements and therefore the elongations in the hole region can be detected by using the ARAMIS
measurement system. The specimen is evaluated by means of a virtual measurement length. In the initial
state, this measurement length has a length of 2 mm and a distance from the edge of 1 mm and is oriented
in the direction of the longitudinal axis. The characteristic value of this test method is given by the ratio of
the extension of this measurement length at the start of cracking to the initial measurement length.
However, the gauge length value of 2 mm specified in [8] lies within the order of magnitude of the element size used in the finite element simulation. Because an optical strain measurement system (ARAMIS) is used in both the "hole expansion with Nakajima punch" and the "Kobe hole tensile test," the gauge length can be variably adapted. In this way, an elongation limit value depending on the element size can be determined in accordance with requirements.

The two testing methods, "hole expansion with Nakajima punch" and "Kobe hole tensile test," are presented below. These testing methods allow optical measurement systems to be used, which can significantly reduce the operator influence and therefore the scattering of the test results [4].

| Hole Expansion with Nakajima-Punch | Kobe Hole Tensile |
|-----------------------------------|------------------|
| Sample Size                       | Sample Size      |
| 200 mm x 200 mm                   | 40 mm x 250 mm   |
| Shear Cutting                     | Shear Cutting    |
| Ø 20 mm punch                      | Ø 10 mm punch    |
| Forming                           | Forming          |
| Ø 100 mm                          | Tensile Test     |
| Nakajima-Punch according to       | Constant Velocity: 10 mm/min |
| ISO 12004-2                       |                  |
| Turn-Off-Criterion                | Turn-Off-Criterion |
| Visual Cut through Sheet Thickness| Automatic Shutoff at 5%-Load-Drop |
| Analysis                          | Analysis         |
| • Determination of Hole Expansion Ratio | Determination of Major Strain by |
| • Strain Analysis and Automatic Determination of Crack-Moment | Measurement of Displacement from Two Virtual Points |

**Figure 1.** Test procedure of the "hole expansion with Nakajima punch" and "Kobe hole tensile test" edge-crack tests

The determined "edge forming limit" characteristic value is then integrated into an FLD as additional information. Figure 2 shows the traditional FLC (blue) and the addition of the edge forming limit (red) as a horizontal line. In the example below, an edge forming limit of about $\varphi = 0.43$ has been plotted.
3.2. Test geometry

Modularly constructed test tools are used for the shear cutting of the test blanks and the collar drawing on simple test geometries. These test tools were designed and developed at the Institute of Metal Forming and Casting at Technische Universität München. Both tools can be converted for the required parameters in a few steps (see figure 3).

Thus, different pre-holes and die clearances can be realized with the cutting tool. In the collar-drawing configuration, the expansion ratio can be varied. For the various test series, a hole with Ø 50 mm is made in each blank (200 mm x 160 mm x 3.5 mm) by shear cutting. Then this hole is expanded by a conical punch. A total of three different expansion ratios are tested (see table 1). The expansion ratio $\lambda$ (see formula 1) is set by varying the drawing punch diameter. The pre-hole was held constant at Ø 50 mm.

\[
\lambda = \frac{dz}{50 \text{ mm}} \times 100 \%
\]  

(1)
Table 1. Tool parameters and resulting expansion ratios

| Expansion ratio $\lambda$ [%] | Pre-hole diameter [mm] | Collar-drawing punch diameter [mm] |
|-------------------------------|------------------------|-----------------------------------|
| 30                            | 50                     | 65                                |
| 50                            | 50                     | 75                                |
| 70                            | 50                     | 85                                |

3.3. Test material

SZBS800 belongs to the group of complex phase steels and is distinguished by a very high yield point and tensile strength because of its largely bainitic microstructure. The most important mechanical properties are listed in table 2 below on the basis of the material data sheet of Salzgitter Flachstahl GmbH [9].

Table 2. Mechanical properties of the test material SZBS800 [9]

| Characteristic               | Value                        |
|------------------------------|------------------------------|
| Test material                | SZBS800                      |
| Yield strength               | $\geq 680$ MPa               |
| Tensile strength             | $800 - 980$ MPa              |
| Elongation at break          | $\geq 12$ %                 |

This complex phase steel is well suited particularly for forming processes. Particularly in the case of form rolling, bending, and collar drawing, SZBS800 can outperform other steel grades [9]. This is due to the low edge-crack sensitivity of SZBS800. The elongation progression along the cutting edge of the hole can be shown by using polar diagrams generated from results of the "hole expansion with Nakajima punch" (see figure 4). The elongation progressions shown indicate that the greatest elongations and contractions, which describe the anisotropy of the material, occur perpendicularly and parallel to the rolling direction. Therefore, it can be assumed that the crack nucleation likewise occurs in accordance with this orientation [6].

Figure 4. Polar diagram of the elongation distribution in the hole expansion [6]
4. Results

4.1. Results for determining the edge forming limit

The results of the "hole expansion with Nakajima punch" and "Kobe hole tensile test" testing methods are shown in figure 5. In the case of the "hole expansion with Nakajima punch," the results are from the macro evaluation. In the case of the "Kobe hole tensile test" testing method, the results were determined in accordance with the rolling direction (longitudinal, diagonal, and transverse) with five individual specimens in each case. The minimum and maximum individual results in each case were not taken into account in the calculation of the mean or the standard deviation. Therefore, each mean and standard deviation given in figure 5 represents the average from three specimens.

The characteristic values of the "hole expansion with Nakajima punch" and of the "Kobe hole tensile test" with an orientation transverse to the rolling direction are at the same level. Because the specimen of the "hole expansion with Nakajima punch," which is loaded uniformly over the contour of the punched edge, tends to crack in the rolling direction (0° or 180° direction), these two test variants have the same crack propagation direction. Also striking is that the specimen of the "Kobe hole tensile test" with an orientation transverse to the rolling direction represents the case in which the material can withstand the smallest strains. The characteristic values for the "Kobe hole tensile test" with orientations longitudinal and diagonal to the rolling direction are higher on average. At this point, it has to be mentioned, that the influences of tool contact, gauge length and strain gradients are ignored. The focus of this work is on the use of the test result in forming simulation.

![Edge crack tests](image)

**Figure 5.** Results of the "hole expansion with Nakajima punch" and "Kobe hole tensile test" edge-crack tests

The simulation results were compared with the real forming tests by using the simulation software PAM-STAMP from ESI GmbH. The comparison of the achieved results with those of the ARAMIS measurement shows that there is close qualitative and quantitative correspondence. This comparison is shown in figure 6 for the first major strain in the "hole expansion with Nakajima punch" as an example.
**Figure 6.** Comparison of the major strains in the "hole expansion with Nakajima punch" on the top side between the simulation and the laboratory specimen

Figure 7 shows the forming limit diagram extended with the edge forming limit.

**Figure 7.** Forming limit diagram with strain limits for the edge-crack sensitivity, and edge elements from the numerical simulation of the "hole expansion with Nakajima punch"
If the elongations from the simulation of the Nakajima specimen with corresponding punch travel are plotted in this diagram, a risk of cracking due to the elongation limit being exceeded is indicated. Likewise for the Kobe hole tensile test, the results from the numerical simulation with the PAM-STAMP software correspond closely to the experimental results with regard to the elongation distribution and localization. In contrast to the "hole expansion with Nakajima punch", the region of maximum strains is already predetermined because of the specimen geometry. Figure 8 shows the addition of the elongation limit arising from the edge tests to the forming limit diagram. Here again, the point of failure is correctly predicted.

Figure 8. Forming limit diagram with elongation limit for the edge-crack sensitivity, and edge element elongation from the numerical simulation of the "Kobe hole tensile test"

4.2. Application of the results to a test geometry

The "edge forming limit" characteristic value is validated using a simple test geometry in a first step. For this purpose, both simulation calculations (including of the expanded FLD) and experimental series of tests were performed and compared with each other. The simulations were performed with the simulation software AutoForm (version 6) from AutoForm Engineering GmbH and were checked with the experimental results (see test tool). The software offers the advantage that the "edge forming limit" can be stored as a parameter by using an edge-crack criterion. The failure criterion as per McEwan-Underhill-Langerack is used here [1a]. For the shear cutting, the previously determined value of
\( \phi_1 = 0.43 \) was entered for this purpose. An optimized cut edge can be achieved by two-stage shear cutting (\( \phi_2 \)) [11, 12, 14]; in this case, the possible edge forming limit is increased (\( \phi_1 \text{(Two-Stage Cutting)} > \phi_1 \)). Thus, it is possible to analyze the influence of different qualities of the cut edge in the simulation.

First, the traditional evaluation methods of thickness, formability, and forming limit diagram (without the addition of the edge forming limit characteristic value) are shown and compared with the real test in figure 9. The simulation results show that the strain in the edge region increases significantly with increasing expansion ratio. Satisfactory predictions with regard to edge-crack sensitivity are possible only for expansion ratios of \( \lambda = 30\% \) and \( 70\% \). The predictions in the limit range (\( \lambda = 50\% \)) are insufficiently accurate. If only the FLD is used as a criterion, the strain of the edge elements approaches the forming limit curve in the diagram region of uniaxial tension but does not exceed the forming limit curve. In reality, however, cracks over the thickness of the sheet metal can already be identified.

| Hole Expansion Ratio \( \lambda \) [%] | Sample Shear cutting | Thickness | Formability | Forming Limit Diagram |
|--------------------------------------|----------------------|-----------|-------------|----------------------|
| 30                                   | ![Image](image1.png)  | ![Image](image2.png) | ![Image](image3.png) | ![Image](image4.png) |
| 50                                   | ![Image](image5.png)  | ![Image](image6.png) | ![Image](image7.png) | ![Image](image8.png) |
| 70                                   | ![Image](image9.png)  | ![Image](image10.png) | ![Image](image11.png) | ![Image](image12.png) |

*Figure 9. Evaluation of the simulated collar-drawing process*

When the edge-crack criterion (including the previously determined elongation limits) is used, the edge-crack sensitivity of SZBS800 is found to be clearly predictable in the evaluation of the forming process (see figure 10). Both in the case of normal cutting and in the case of the optimized shear cutting method, the two-stage shear cutting, the simulation prediction and the experimental tests correspond very closely to each other. If the starting hole is expanded into a collar at an expansion ratio of 30\%, it is found that there is no risk of edge cracking in the case of normal cutting or two-stage cutting. The experimental series of tests for these two cases confirm this. In contrast, first cracks occur at an expansion ratio of \( \lambda = 50\% \) after normal cutting, whereas a pre-hole cut in two stages shows no tendency toward edge-crack sensitivity [11, 12]. If the expansion ratio is increased further, the risk of edge cracks also increases in the case of two-stage cutting, but edge-cracks still cannot be visually detected at \( \lambda = 70\% \) on the specimen.
### Table 1. Application of the cut-edge criterion to the test geometry

| Hole Expansion Ratio \( \lambda \) [%] | Sample Shear Cutting | Cut-Edge-Criterion Shear Cutting \( \varphi_1 = 0.43 \) | Sample Two-Stage Shear Cutting | Cut-Edge-Criterion Two-Stage Shear Cutting \( \varphi_1 \) (Two-Stage Cutting) > \( \varphi_1 \) |
|----------------------------------------|----------------------|---------------------------------|-------------------------------|--------------------------------------------|
| 30                                     | ![Image](image1.png)  | ![Image](image2.png)            | ![Image](image3.png)          | ![Image](image4.png)                      |
| 50                                     | ![Image](image5.png)  | ![Image](image6.png)            | ![Image](image7.png)          | ![Image](image8.png)                      |
| 70                                     | ![Image](image9.png)  | ![Image](image10.png)           | ![Image](image11.png)         | ![Image](image12.png)                     |

**Figure 10.** Application of the cut-edge criterion to the test geometry

### 4.3. Application of the findings to a chassis component

Below, the modular transverse matrix MQB-A track control arm for the Golf platform of the Volkswagen Group is used as an example of how the procedure, which has previously been applied only to geometries on a laboratory scale, can be put into practice. In addition, the simulation calculations were performed in this case with the PAM-STAMP software from the company ESI GmbH, again in order to establish broad acceptance of the "edge forming limit" characteristic value. On the basis of experience from the series production process, it is also assumed that the standardized simple cutting process used to produce the laboratory specimens would result in a failure of the component edges in the production of the rear track control arm.

To ensure in advance that the elongations in the forming simulation correspond to the conditions of the component, a forming analysis of the series production process is performed (see figure 11).
For this purpose, equidistant points are electrolytically applied to the flat sheet metal before forming. The sheet metal is fed to the series production process and is removed again after forming. Three-dimensional coordinates and elongation distributions are calculated from digital photos of the formed sheet metal by using the optical elongation measurement system ARGUS from the company GOM. These correspond to the surface of the sheet metal [13]. Figure 11 shows the distribution of the major strain from PAM-STAMP on the left and from ARGUS on the right. The correspondence is high enough for the further examination.

Below, various regions of the MQB-A track control arm are checked to determine whether the edge forming limit ($\phi_1 = 0.43$) determined on the laboratory scale can also be applied to a production component. The simulation examinations are performed at three points in total. The first two examples concern regions that are not significantly formed before the cutting. In contrast, the third region is an example of a component zone that is pre-elongated, cut, and further formed.

In figure 12, the element elongations of the PAM-STAMP simulation for an outer edge of the MQB-A track control arm are shown in the expanded forming limit diagram, which also contains the edge forming limit in addition to the traditional forming limit curve.
Figure 12. Evaluation of the producibility of the outer edge of the track control arm

As in the edge-crack tests, it is found that the examined region close to the edge is loaded in accordance with uniaxial tension. All elements are clearly below the FLC as well as the edge forming limit and therefore can be assessed as not at risk of edge-cracking. In addition, no influence of the sheet metal plane to be evaluated can be found. The inner, middle, and outer surfaces are only exposed to an elongation that can be withstood.

Rim holes, produced by shear cutting of a hole which is expanded by collar drawing, traditionally have proven to be particularly sensitive to edge-cracking. In collar drawing in flat sheet metal, the sheet metal segment lying over the drawing die opening is bent around the edges of the drawing die and the drawing punch. During this forming, the diameter of the pre-hole is increased while the thickness of the sheet metal is simultaneously reduced. The subject of the examinations is the collar in the center of the component (see figure 13). Because there is an elongation gradient over the thickness of the sheet metal here due to the forming, a different pattern results for each evaluation plane. Therefore, the evaluation plane having the greatest elongation must be selected for the evaluation of producibility. In the present case, this means that the rim hole is identified as not producible in the case of a standardized simple punching process. This corresponds to the empirical values. For this reason, a two-stage shear cutting process is used in practice. The two-stage shear cutting process damages the material to a lesser degree in comparison with the one-stage shear cutting process and thereby enables significantly greater formability of the edge [11].
In contrast to the previous examinations, the region examined below (see figure 14) was already formed before the cutting. In accordance with the production method, the region is formed, cut, and finally formed again. If the evaluation described above is performed here and the elongations accumulated from the two forming stages are plotted, a failure of the edge is predicted. This contradicts experience from the real production process.
This apparent misjudgment from prediction 1 could be avoided if merely the elongation path since the cutting operation were indicated in the post-processing. Figure 15 shows the corresponding illustration of the second prediction. However, this procedure is based on the assumption that the pre-strains has no influence on the formability of a shear-cut edge. This optimistic assumption appears to be just as improbable as the previous prediction. How the pre-damage (before the cutting process) affects the formability of a cut edge must be determined in the future. A test variant of the two presented edge-crack tests, with pre-strained specimens, would be conceivable. Currently, the two assumptions and predictions made are the possible limits for this.

**Figure 14.** Evaluation of the producibility of a region that is formed, cut, and formed again (prediction 1)
4.4. Deriving a work instruction

The following instructions can be derived from the above examples of how to implement the described approach for taking the reduced formability of a shear-cut sheet metal edge into account in a forming simulation.

- Because this is pure post-processing, the approach can be performed regardless of the material model used.

- The blank edge to be analyzed must have a fine mesh consisting of approximately square quadrilateral shell elements (standard value: 1.0 mm edge length).

  - If complex cutting operations are part of a multi-stage forming process, an attempt must be made to achieve the aforementioned mesh quality in the edge region by suitable software settings.

  - In PAM-STAMP, for example, this can be approximately achieved by using the function "Optimize for flanging" and the sub-function "Force orthogonal edges."

- In the post-processing, the elements which, by means of two nodes, are part of the outer edge to be analyzed are selected.
It must be ensured that not the membrane plane but rather the outer fiber having the highest major strain/tangential elongation is selected.

If material that was previously in the as-delivered condition is cut and formed, the state of uniaxial tension is predominant at the edge.

- In order to also take the anisotropy into account here, a tolerance range on each side must be provided.

- In order to still evaluate a slight pre-deformation before the cutting or a slightly nonlinear elongation path and yet detect excessive deviations, an analysis of the elongation path is recommended.
  - In the PAM-STAMP software, for example, the post-processing function "Zones by linearity" is suitable for this purpose.
  - In general, a comparison of the accumulated comparison strain with the comparison strain (based on the current major and minor strain) should enable this.

- It is recommended that characterization tests be performed with different edge qualities so that a working range can be defined.

These recommendations are intended as a basis of discussion that can be refined or corrected as experience is gathered.

5. Summary

In the production of complex chassis components, it has been found in daily practice that sheet metal edges produced by shear cutting have significantly reduced formability in comparison to the starting material, and that these regions tend to exhibit increased crack formation in subsequent forming operations. A concrete prediction of edge-crack sensitivity was previously not possible.

Therefore, the goal was to identify a testing method that can evaluate edge-crack sensitivity and at the same time provide input variables having low for the forming simulation. The "hole expansion with Nakajima punch" and the "Kobe hole tensile test" meet these requirements. Common to these two methods is that the evaluation can be performed by optical measurement and therefore a detailed strain analysis is possible for the region near the edge. Major strains shortly before the onset of cracking are determined and are added to the existing forming limit diagram as additional information.

In the experimental tests, it was found that the two methods lead to comparable and repeatable major strain values. Corresponding simulation models of the two edge-crack tests were constructed and were compared with the elongation measurements from the experiment with regard to the strain distribution. The producibility of a collar drawn component as well as track control arm was examined on the basis of the determined characteristic values and the defined procedure. In both cases the described procedure provides reliable predictions. Concerning the track control arm this procedure is limited to all component edges that were not significantly formed before the cutting process and that move in the range of uniaxial tension. However, further research is necessary if there is deviation from this described elongation path or if multi-stage forming processes lead to nonlinear elongation paths.
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