

# Maximizing the Expansion Ratio through Multi-stage Shear-cutting Process during Collar Forming

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**Abstract.** Previous investigations showed that a two-stage punching process reduced the edge crack sensitivity on high-strength multi-phase steels significantly compared to a single-stage process. This is caused by an alteration of the state of stress in the shear-affected zone during the second stage, which results in not only higher expansion ratios, but also higher collars during the collar forming test. Another preceding research project at the Chair of Metal Forming and Casting, Technical University of Munich, investigated the optimized values for cutting offset, and die clearance for both pre-cutting and re-cutting steps for a single-stage punching process.

The aim of this research project was to combine those previous findings by increasing the number of stages in a punching process with each using the optimized parameters. The behavior of milled edges served as a reference for optimum performance. The number of stages influenced material properties, such as surface characteristics, material deformation in the shear-affected zone, and roughness of the cutting surface. The quality of the cutting surface increases drastically due to various factors, such as a changed surface hardness, which affects fatigue resistance and, therefore, the component's lifetime. The validation of this punching strategy not only achieves an even higher expansion ratio in common sheet metals, but also makes highly edge-crack sensitive materials available for industrial applications.

## 1. Introduction

High-strength steels are essential in the automobile industry. The microstructure of these multi-phase steels causes high strength and good formability, which impacts lightweight construction and fuel efficiency.

Not only the material selection, but also the cutting process contribute to the risk of edge fractures. Shear cutting is one of the most common separation techniques, but it also induces work hardening and thus reduced residual formability in the shear-affected zone. [1] The degree of work hardening is influenced by the selected material, including its properties and thickness, and the selected shear cutting parameters, such as die clearance, cutting speed, and shear-cut strategy. [2] The lower formability increases the chance of edge cracks in the shear-affected zone during uniaxial load in subsequent processing steps. [3]

Utilizing appropriate testing methods allow for determining both forming potential and a material's edge crack sensitivity based on material properties and cutting parameters. These testing methods

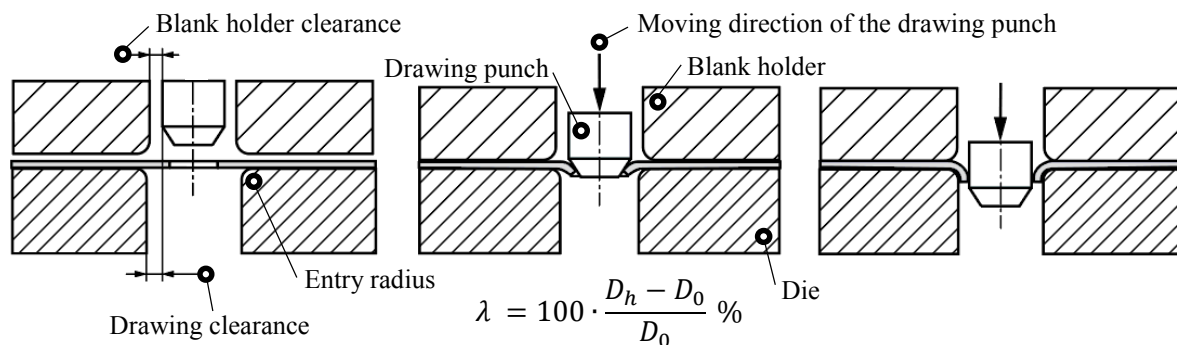


include the hole expansion test according to ISO 16630 [4], the collar-forming test [5], the open hole tensile test [6], the Diabolo-Test [7], the sheared-edge tension test [8] and the *Edge-Fracture-Tensile-Test* [9, 10].

The objective of this study was to determine the forming potential of high-strength complex-phase steels using the collar-forming test. Several shear-cutting strategies were investigated to optimize residual forming capacity of shear cut edges.

## 2. Collar-Forming Test

The collar-forming test is a more practically oriented testing method to determine edge crack sensitivity. Since the sample geometry is not defined specifically, a more application-oriented one can be chosen. Similar to the hole expansion test, the tests are performed in two steps. First, the initial hole is subsequently shear cut with a constant hole diameter of 50 mm. In order to perform multi-stage shear-cutting strategies, additional locating holes are required to ensure reproducibility and concentricity of the holes with radially constant cutting offset. The specimen is oriented in the tool analogous to the hole expansion test with the burr facing away from the drawing punch. A conical drawing punch allows the specimen to be positioned in the collar-forming tool. The collar's edge is subjected to tensile loads during the collar-forming process. Figure 1 illustrates the experimental setup of the collar-forming test according to [11].



**Figure 1.** Schematic illustration of the collar-forming test according to [11].

All final collar edges are visually analyzed for cracks or necking. Furthermore, the collar quality is assessed by the expansion ratio  $\lambda$ , using the initial diameter  $D_0$  and diameter of the punch  $D_h$ . The ratio describes the maximum expansion without complete cracks through the complete thickness of the sheet. Drawbacks of this testing procedure are not only the incremental changes of  $\lambda$ , but also the friction between the drawing punch and specimen, and the higher material consumption based on the specimen dimensions compared to hole expansion test, the Diabolo-Test and *Edge-Fracture-Tensile-Test*.

## 3. Materials

The study was performed using a CP-W 800 sheet with 4 mm thickness. Its microstructure consists of a ferrite phase with finely dispersed martensite and bainite phases. This microstructure is the reason for its high yield strength of 680 MPa – 830 MPa, minimum tensile strength of 780 MPa, and minimum elongation of 12% [12]. Table 1 lists the chemical composition of CP-W 800 [12]. The material with a thickness of 4 mm is used in automobile industry, especially for chassis parts like control arms.

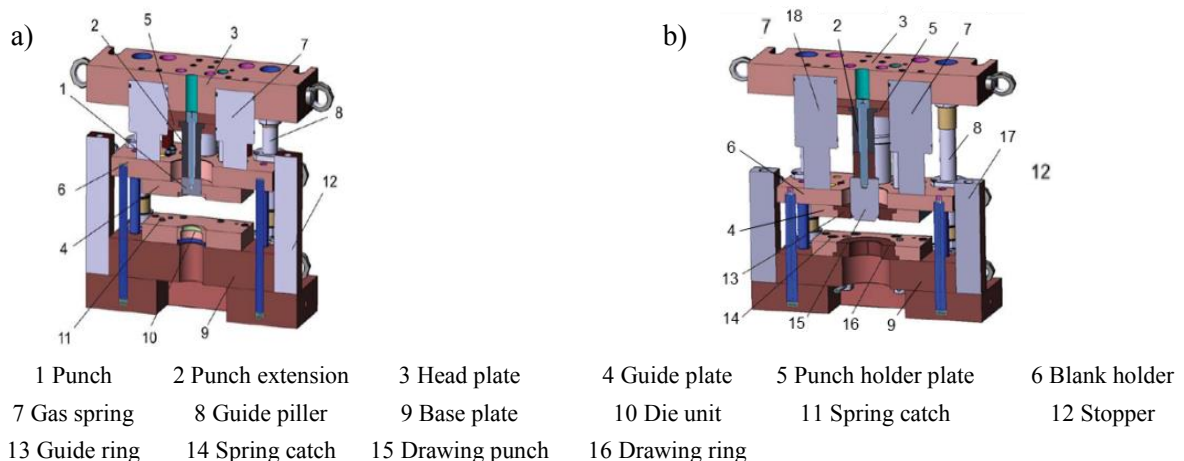
**Table 1.** Chemical composition in weight percentage of CP-W 800 sheet metal. [12]

| Chemical element  | C    | Si   | Mn   | P    | S     | Al    | Cr+Mo | Nb+Ti | V    | B     |
|-------------------|------|------|------|------|-------|-------|-------|-------|------|-------|
|                   | max. | max  | max  | max  | max   | max   | max   | max   | max  | max   |
| Weight percentage | 0.14 | 1.00 | 2.20 | 0.08 | 0.015 | 0.015 | 1.00  | 0.25  | 0.20 | 0.005 |

The tool active elements were manufactured from high chromium, high-carbon tool steel (X155CrVMo12-1). This common tool steel is usually hardened to  $58 \pm 1$  HRC and contains type M7C3 carbides with  $10 \mu\text{m}$  in size on average.

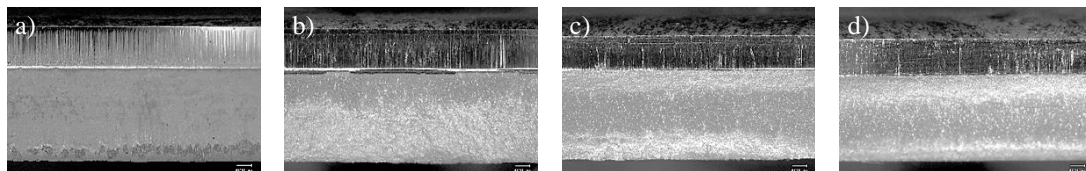
#### 4. Tools

Both tools for shear cutting (figure 2 a) and collar forming (figure 2 b) have a very high tool stiffness in order to prevent deflection or shifting of the active elements. Using the blank holder plate as a guide provided maximum guiding accuracy. In addition, alignment pins are used for the initial positioning of the blank holder plate and the die.



**Figure 2.** Schematic representation of the shear-cutting tool (a) and collar-forming tool (b). [13]

Figure 3 illustrates the high accuracy of the shear-cutting tool based on the formation of the cutting surfaces of one-step sheared holes. The images show a homogeneous trend of the rollover, clean-shear and the fracture surface.



**Figure 3.** Microscope images of cutting surfaces with variation of the die clearance, a)  $u = 10\%$ ,  $r = 50 \mu\text{m}$ , b)  $u = 15\%$ ,  $r = 250 \mu\text{m}$ , c)  $u = 20\%$ ,  $r = 250 \mu\text{m}$ , d)  $u = 25\%$ ,  $r = 250 \mu\text{m}$ .

The die clearance on the shear-cutting tool can be adjusted using different cutting punches in combination with a die with a constant diameter. The shear-cut holes are therefore smaller by twice the die clearance. Furthermore, it is possible to implement a multi-step cutting process by adding locating holes and locators in the experimental setup. This allows various cutting offsets in combination with different die clearances.

The modular design of the shear-cutting tool makes it easy to exchange the active elements. When collar forming, the die plate and the guide plate have to be changed and the drawing guide set, the drawing punch and the drawing die can be integrated. This interchangeability is necessary in order to adjust the tool for different collar-forming tests while maintaining a constant initial hole diameter. In addition, the tool is provided with communicating gas pressure springs to prevent the blank holder from tilting. Using stoppers combined with cylindrical drawing punches and a conical tip ensures a repeatable positioning of the perforated specimens.

## 5. Experimental Design

The process parameter for collar-forming test regarding edge-crack sensitivity are displayed in Table 2. The unusual cutting clearances of 5%, 30% respectively, were chosen to reproduce a tool displacement of the active elements on the shear-cutting tool. Not only the unusual die clearances of 5% and 30% were investigated, but also the incremental steps with a step size of 5% in between.

**Table 2.** Process parameter for the collar-forming test.

| Parameter                     | Value  |
|-------------------------------|--|
| Punch-cutting edge radius $r$ | <10 $\mu\text{m}$ , 50 $\mu\text{m}$   |
| Die clearance $u$             | 5%, 10%, 15%, 20%, 25%, 30%  |
| Cutting line                  | Closed   |
| Cutting offset $z_1$          | 2 mm, 3 mm, 4 mm (two-stage cutting process)<br>0.7 mm (three-stage cutting process) |
| Cutting offset $z_2$          | 1.2 mm, 1.6 mm (three-stage cutting process)   |

In addition to the single-stage shear-cutting strategy, a two- and three-stage shear-cutting strategy with different cutting offsets were tested. Each test with single- or two-stage shear-cut specimens was performed using at least ten specimens. For the three-stage collar-forming tests, only five specimens were used. All tests were carried out in accordance with chapter 2 irrespective of the number of shear-cutting operations. First, the starting blank is made by a single or multi-stage shearing operation. In the second step, the collar is formed in one stroke. The procedure is illustrated by schematic representations of the process steps in Tables 3, 4 and 5.

## 6. Results

### 6.1. Collar forming combined with single-stage shear-cutting process.

Specimens after the collar-forming test were divided into two groups according to their edge quality. While A specimens show no or only minor cracks extending over half the sheet thickness at maximum, B specimens had major cracks or were completely torn. If a testing series revealed more than five B specimens in a row, the testing was terminated. This evaluation scheme applies only to statically loaded components. If components are subjected to oscillating loads, A specimens should not show any cracks since the crack could grow due to the fatigue load. Consequently, the component could fail under use.

**Table 3.** Results for single-stage shear-cutting collar-forming test.

| $\lambda$ | Die clearance ( $r = 50 \mu\text{m}$ ) |   |            |   |            |   |            |   |            |   |            |   |
|-----------|--|---|------------|---|------------|---|------------|---|------------|---|------------|---|
|           | $u = 5\%$                              |   | $u = 10\%$ |   | $u = 15\%$ |   | $u = 20\%$ |   | $u = 25\%$ |   | $u = 30\%$ |   |
|           | A                                      | B | A          | B | A          | B | A          | B | A          | B | A          | B |
| 5%        |  | 5 | 10         |   | 10         |   | 10         |   | 10         |   | 10         |   |
| 10%       |  |   | 5          | 5 |            | 4 | 6          | 5 | 5          |   | 6          | 4 |
| 15%       |  |   |            |   |            | 4 | 6          | 5 | 5          |   |            | 5 |
| 20%       |  |   |            |   |            |   | 5          |   | 5          |   |            |   |



Table 3 shows the testing results. All die clearances but 5% failed to produce A specimens with an expansion ratio of 5%. Only the die clearances of 20% and 25% produce A and B specimens up to an expansion ratio of 15%, which supported these settings as the choice for the single-stage shear-cutting process.

As a reference, milled parts produced only A specimens to an expansion ratio up to 90%.

## 6.2. Collar-forming combined with a two-stage shear-cutting process.

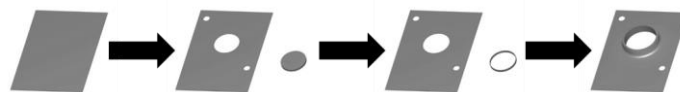
Table 4 shows the comparison between a single-stage shear-cutting collar-forming test with  $u_1 = u = 15\%$  die clearance and the two-stage shear-cutting collar-forming test with die clearance  $u_1 = 10\%$  and  $u_2 = u = 10\%$  or  $u_2 = u = 15\%$ , with different variations in cutting offset. To minimize work hardening during pre-cutting, die clearance  $u_1 = 10\%$  is selected for the first cutting process.

A maximum expansion ratio of 40% with only A specimens was achieved during the collar-forming tests of the two-stage shear-cut specimens. Consequently, changing the cutting strategy to a two-stage process resulted in an increase of good, reliable parts. The residual formability of a two-stage shear-cut edge is increased because the stress condition of the second punching process of the final hole is comparable to a shear-cutting process with an open cutting line. The reason for this effect is the reduced stiffness of the piece punched out as compared with the pre-cutting process, which also changes the properties of the final cutting surface. The shear-cutting zone does not harden as much with a suitable choice of the re-cutting parameters. If that does occur, then the piece punched out is deformed more plastically than the cutting surface to be tested. Consequently, the cutting surface has a higher residual formability.

As a reference, milled parts produced only A specimens to an expansion ratio up to 90%.

**Table 4.** Results for single-stage and two-stage shear-cutting collar-forming test.

| $\lambda$ | Cutting strategies                 |   |  |   |  |   |                      |   |                      |   |
|-----------|------------------------------------|---|--|---|--|---|----------------------|---|----------------------|---|
|           | $(u_1 = 15\%, r = 50 \mu\text{m})$ |   | $(u_1 = u_2 = 10\%, r = 50 \mu\text{m})$ |   | $(u_1 = 10\%, u_2 = 15\%, r = 50 \mu\text{m})$ |   |                      |   |                      |   |
|           | Single-stage                       |   | Two-stage                                |   | Two-stage                                      |   | Two-stage            |   | Two-stage            |   |
|           | $z_1 = 0 \text{ mm}$               |   | $z_1 = 1.2 \text{ mm}$                   |   | $z_1 = 2 \text{ mm}$                           |   | $z_1 = 3 \text{ mm}$ |   | $z_1 = 4 \text{ mm}$ |   |
|           | A                                  | B | A  | B | A  | B | A                    | B | A                    | B |
| 5%        | 10                                 |   | 10                                       |   | 10   |   | 10                   |   | 10                   |   |
| 10%       |                                    | 5 | 10                                       |   | 10   |   | 10                   |   | 10                   |   |
| 15%       |                                    |   |  |   |  |   |                      |   |                      |   |
| 20%       |                                    |   |  |   | 10   |   | 10                   |   | 10                   |   |
| 25%       |                                    |   | 10                                       |   | 10   |   |                      |   |                      |   |
| 30%       |                                    |   |  |   | 9  | 1 | 10                   |   | 10                   |   |
| 35%       |                                    |   | 10                                       |   |  |   | 10                   |   |                      |   |
| 40%       |                                    |   | 10                                       |   | 8  | 2 | 8                    | 2 | 10                   |   |
| 45%       |                                    |   | 8  | 2 |  |   |                      |   | 3                    | 7 |
| 50%       |                                    |   | 6  | 4 | 3  | 7 | 3                    | 7 | 2                    | 8 |
| 55%       |                                    |   |  |   |  |   |                      | 5 |                      | 5 |
| 60%       |                                    |   | 2  | 8 | 2  | 8 |                      |   |                      |   |
| 65%       |                                    |   |  | 5 |  | 5 |                      |   |                      |   |



### 6.3. Collar forming combined with an optimized multi-stage shear-cutting process.

Table 5 shows the results of a three-stage shear-cutting collar-forming test with die clearance  $u_1 = u_2 = u_3 = u = 10\%$  utilizing all the variations in cutting offset in comparison to a single-stage collar-forming test with the same die clearance. The cutting-edge radius of the punch is also varied.

The optimal shear-cutting process parameters are used to generate a shear-cutting surface with high residual formability based on the scientific findings of the paper “Determination of the Minimum Possible Damage Due to Shear-cutting Using a Multi-stage Shear-cutting Process,” which is also presented at the 37<sup>th</sup> INTERNATIONAL DEEP-DRAWING RESEARCH GROUP CONFERENCE 2018, Waterloo, Canada.

With respect to the cutting offset  $z_2$ , the achievable expansion ratio  $\lambda$  increases using a three-stage shear-cutting process. The punch used in the final cut had an edge radius of 50  $\mu\text{m}$ . A cutting offset  $z_2 = 1.2$  mm results in an absolute expansion ratio of 65%. If a cutting offset  $z_2 = 1.6$  mm is used, an absolute expansion ratio of 55% can be reached. The increase in the residual formability is based on the explanation given in chapter 6.2.

As a reference, milled parts were used that produced A specimens to an expansion ratio  $\lambda$  up to 90%.

**Table 5.** Results for single-stage and three-stage shear-cutting collar-forming test.

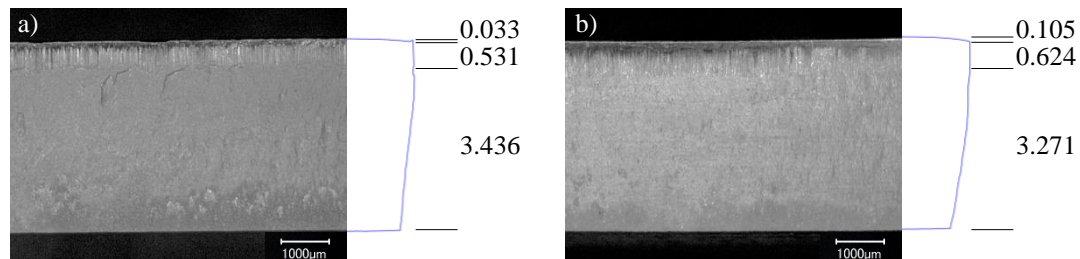
| $\lambda$ | Cutting strategies ( $u_1 = u_2 = u_3 = u = 10\%$ ) |   |                                  |   |  |   |                                  |   |
|-----------|---|---|----------------------------------|---|--|---|----------------------------------|---|
|           | Single-stage  |   | Three-stage                      |   | Three-stage  |   | Three-stage                      |   |
|           | $z = 0$ mm  |   | $z_1 = 0.7$ mm<br>$z_2 = 1.2$ mm |   | $z_1 = 0.7$ mm<br>$z_2 = 1.2$ mm                           |   | $z_1 = 0.7$ mm<br>$z_2 = 1.6$ mm |   |
|           | $r = 50$ $\mu\text{m}$                              |   | $r < 10$ $\mu\text{m}$           |   | $r_1 = r_2 < 10$ $\mu\text{m}$<br>$r_3 = 50$ $\mu\text{m}$ |   | $r < 10$ $\mu\text{m}$           |   |
|           | A   | B | A                                | A | A  | B | A                                | B |
| 5%        | 10  |   |                                  |   |  |   |                                  |   |
| 10%       | 5   |   |                                  |   |  |   |                                  |   |
| 15%       |   |   |                                  |   |  |   |                                  |   |
| 20%       |   |   |                                  |   |  |   |                                  |   |
| 25%       |   |   | 5                                |   | 5  |   | 5                                | 5 |
| 30%       |   |   |                                  |   |  |   |                                  |   |
| 35%       |   |   |                                  |   |  |   |                                  |   |
| 40%       |   |   |                                  |   |  |   |                                  |   |
| 45%       |   |   | 5                                |   | 5  |   | 5                                | 5 |
| 50%       |   |   |                                  |   |  |   | 5                                |   |
| 55%       |   |   | 5                                |   | 5  |   | 4                                | 1 |
| 60%       |   |   | 3                                | 2 |  |   | 4                                | 1 |
| 65%       |   |   | 1                                | 4 | 5  |   | 2                                | 3 |
| 70%       |   |   |                                  | 5 | 3  | 2 | 2                                | 3 |
| 75%       |   |   |                                  |   |  | 5 | 5                                | 5 |



The influence of the cutting-edge radius on the expansion ratio could be demonstrated during the investigations. The expansion ratio increases by 18% using a cutting offset of 1.2 mm and around 10% for a cutting offset of 1.6 mm. The literature shows that if the punch-edge radius becomes too large or the punch edge is worn, then the residual formability of the shear-cut edge, and hence the expansion ratio, are reduced. [14]

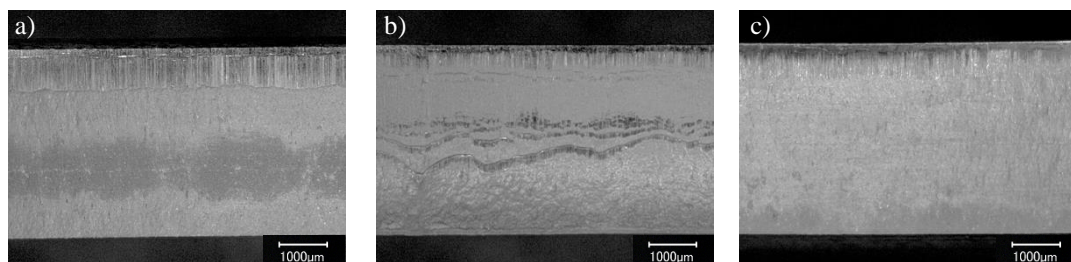


Figure 4 shows two different cutting surfaces for the three-stage shear-cutting process (cutting offset 1.2 mm) with variation of the edge radius  $r_3$ . Larger edge radii  $r_3$  lead to an increase of the rollover height and clean-shear height. Consequently, the fracture height is reduced. The angle of the fracture surface decreases from  $84.4^\circ$  to  $82.9^\circ$  using a punch with an edge radius of  $r_3 = 50 \mu\text{m}$  as compared with punch with a sharp edge. All shear-cut surfaces show burr heights less than  $5 \mu\text{m}$  because all specimens were shear cut using a die with a sharp cutting edge. The microscope images in figure 4 show that the fracture zone is more homogeneous and smooth when utilizing a punch with an edge radius of  $50 \mu\text{m}$  as compared with sharp-edge radii.



**Figure 4.** Cutting surfaces analyzed according to VDI 2906-2 [15], a) with sharp cutting edges ( $r < 10 \mu\text{m}$ ), b) rounded cutting edge on the punch ( $r_1 = r_2 < 10 \mu\text{m}$ ,  $r_3 = 50 \mu\text{m}$ ) and a sharp die edge; ( $u_1 = u_2 = u_3 = u = 10\%$ ,  $z_1 = 0.7 \text{ mm}$ ,  $z_2 = 1.2 \text{ mm}$ ).

Figure 5 visualizes the individual shear-cut surfaces on a three-stage shear-cutting process to generate an initial hole that shows the highest residual formability according to table 5.



**Figure 5.** Microscope images of the three shear-cut surfaces for an initial hole with the following shear-cutting parameters: die clearance  $u_1 = u_2 = u_3 = u = 10\%$ , cutting offset  $z_1 = 0.7 \text{ mm}$ ,  $z_2 = 1.2 \text{ mm}$ , punch edge radius  $r_1 = r_2 < 10 \mu\text{m}$ ,  $r_3 = 50 \mu\text{m}$ .

All three images in figure 5 reveal a homogeneous rollover and a constant clean-shear height across the image section. Consequently, the shear cutting tool is manufactured with sufficient accuracy and tool displacements can safely be excluded. In addition, the specimen is positioned exactly in the tool during re-cutting. The cut surface from the first stage (figure 5 a) shows a higher clean-shear height and an inhomogeneous fracture zone as compared with the final shear cut surface shown in figure 5 c). The cut surface of the first re-cutting process (figure 5 b) shows the smallest rollover height and clean-shear height when compared to the other shear cut surfaces. The upper part of the fracture zone shows a high homogeneity but in the lower half, a secondary clean-shear is formed.

## 7. Conclusion

Adapting the shear cutting process revealed the necessity of modifying both the cutting clearance and cutting strategy according to the material in order to reduce edge cracks. The residual forming capacity of shear-cut edges was increased using a multi-stage shear-cutting process instead of the single-stage process. Using an optimized multi-stage shear cutting process makes it possible to shift a bigger part of the materials deformation into the piece that is punched out during the re-cutting process. Such edges are characterized by high residual formability.

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