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Influence of shear cutting parameters on the fatigue behavior of a dual-phase steel

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Abstract. The influence of the edge condition of car body and chassis components made of steel sheet on fatigue behavior under dynamic loading presents a major challenge for automotive manufacturers and suppliers. The calculated lifetime is based on material data determined by the fatigue testing of specimens with polished edges. Prototype components are often manufactured by milling or laser cutting, whereby in practice, the series components are produced by shear cutting due to its cost-efficiency. Since the fatigue crack in such components usually starts from a shear cut edge, the calculated and experimental determined lifetime will vary due to the different conditions at the shear cut edges. Therefore, the material data determined with polished edges can result in a non-conservative component design. The aim of this study is to understand the relationship between the shear cutting process and the fatigue behavior of a dual-phase steel sheet. The geometry of the shear cut edge as well as the depth and degree of work hardening in the shear affected zone can be adjusted by using specific shear cutting parameters, such as die clearance and cutting edge radius. Stress-controlled fatigue tests of unnotched specimens were carried out to compare the fatigue behavior of different edge conditions. By evaluating the results of the fatigue experiments, influential shear cutting parameters on fatigue behavior were identified. It was possible to assess investigated shear cutting strategies regarding the fatigue behavior of a high-strength steel DP800.

1. Introduction

Modern car body construction is driven by demands for improved crash behavior and lightweight design. Therefore, high performance materials such as high-strength steels, are increasingly used in order to comply with these requirements. For crash-relevant components, a weight reduction can be achieved by reducing the material-thickness of high-strength steels. [1]

The fatigue crack growth in components made of steel sheet usually starts from a cut edge, whereby the condition at the cut edge, which depends on the manufacturing process, has a great influence on the fatigue performance of the component. The influence of the cutting process on the fatigue behavior of different steel sheet grades is shown in many investigations [2-6]. In [3] the effect of shear cutting on the fatigue behavior of four different steel sheet grades is investigated. It is shown that the loss of fatigue strength through shear cutting, compared to the polished edge, increases with the surface roughness of the cut edge and the ultimate tensile strength of the steel sheet. This corresponds to the results in [1] and [2].

The shear cutting process is one of the most economical separation processes, since it combines high production rates with low costs. The quality of the shear cut edge depends in particular on the material properties, material thickness, die clearance, cutting edge radius, tool wear and shear cutting strategy.
(one-stage, two-stage) [7]. Each edge, manufactured by shear cutting, has a characteristic shear cut surface, which can be described according to [8] (see Figure 1).

![Figure 1](characteristic-shear-cut-surface-quality.png)

**Figure 1.** Characteristic shear cut surface quality according to VDI 2906-2 [8].

The variation of the aforementioned influence factors can affect the shear cut surface quality significantly. In addition to the four surface characteristics roll-over, clean-shear, fracture and burr, the cutting process causes a shear affected zone, which extends from the shear cut edge into the adjacent material. The shear affected zone represents the volume of material, which is subjected to plastic deformation during the shear cutting process and therefore experiences a strong work-hardening. Since the fatigue crack growth in shear cut components normally starts from a cut edge, the shear cut surface as well as the shear affected zone both have a significant impact on the fatigue behavior of the component.

In practice, fatigue life predictions of components made of steel sheet are based on material data, determined by specimens with polished edges, whereas in the series production process of car body components, shear cutting represents the dominant manufacturing process [9]. As a result, there is the risk of a non-conservative component design, or of applying high safety factors of an inefficient material utilization.

To determine a shear cutting strategy with a minimal influence on the fatigue properties of component edges, five shear cutting strategies were applied to manufacture fatigue specimen of DP800. The results of the fatigue tests for the shear cut specimen then are compared to a polished edge condition.

2. Material

The material used for the investigations is a cold-rolled 1.5 mm thick steel grade DP800, produced by Voestalpine Steel GmbH, Linz, Austria. In its initial state, the material consists of a fine microstructure with main phases of ferrite and martensite. This dual phase steel represents an advanced high strength steel and is typically used for car body components such as the A- and B-pillar. The mechanical properties, determined with the quasi-static tensile test [10] at the Laboratory for Material and Joining Technology of the University of Applied Sciences, are listed in Table 1, the chemical composition of this steel grade according to [11] is listed in table Table 2.

| Table 1. Mechanical properties DP800. |
|--------------------------------------|
| Yield Strength [MPa] | Tensile Strength [MPa] | Uniform Elongation [%] | Total Elongation [%] |
|----------------------|------------------------|------------------------|----------------------|
| 508                  | 813                    | 11.4                   | 16.4                 |
Table 2. Chemical composition in weight percentage of sheet steel DP800 [11].

| Chemical element | C max | Si max | Mn max | P max | S max | Al total | Cr + Mo max | Ti + Nb max | V max | B max |
|-----------------|-------|--------|--------|-------|-------|----------|------------|------------|-------|-------|
| Weight percentage | 0.18  | 0.80   | 2.50   | 0.08  | 0.015 | 0.015-2.0 | 1.40       | 0.15       | 0.20  | 0.005 |

3. Experimental Methods

3.1. Manufacturing of specimens

To perform the shear cutting process, a Bruderer BSTA 1250 high performance punching press of Bruderer AG, Frasnacht, Switzerland, has been used. The machine has a nominal force of 1250 kN and a maximum speed of 850 strokes per minute. To manufacture the fatigue specimen a shear cutting tool of high stiffness was used to avoid displacements of the active elements during the shear cutting process. The initial blank has guiding holes, which allow to position the blank in the tool precisely. The geometry of the unnotched specimen ($K_t = 1$), produced by shear cutting, for the fatigue tests according to [12] is shown in Figure 2. The sampling was done transverse to the rolling direction (RD).

![Figure 2. Geometry of the unnotched specimen for fatigue testing.](image)

The specimen were produced with different combinations of shear cutting parameters. Adjusting the die clearance (first-stage, second-stage), the punch edge radius and the cutting offset for the manufacturing of the unnotched specimen led to five different parameter settings (Tables 3 and 4).

Table 3. Shear cutting parameter settings one-stage shear cutting process.

| Name of the strategy | Edge radius [µm] | Die clearance [%] |
|----------------------|------------------|-------------------|
| Reference            | 10               | 15                |
| Wear                 | 300              | 15                |

Table 4. Shear cutting parameter settings two-stage shear cutting process.

| Name of the strategy | Edge radius [µm] | Die clearance (first-stage) [%] | Cutting offset [mm] | Die clearance (second-stage) [%] |
|----------------------|------------------|---------------------------------|---------------------|---------------------------------|
| Two-stage 1          | 10               | 5                               | 0.4                 | 2                               |
| Two-stage 2          | 10               | 5                               | 0.2                 | 2                               |
| Two-stage 3          | 10               | 5                               | 0.4                 | 10                              |
3.2. Characterisation of shear cut-edges

Describing the shear-cut surface, a photographic documentation as well as a contour and roughness measurement was carried out. The photographic documentation was done with a digital microscope from Keyence Co., Ltd., Osaka, Japan. With a contour and roughness measurement system MarSurf XCR 20 from Mahr GmbH, Göttingen, Germany the standardized shear cut surface characteristics according to [8] were determined. By using a probe arm with two needles, the measuring system can record the profile of the shear cut edge with an accuracy of 0.5 µm. The measurement was carried out at five measuring points on each side of the sample. To evaluate the roughness characteristics $R_a$, $R_z$ and $R_{max}$ according to [13] in the fracture area, a limit wavelength of 0.8 mm was chosen. Per parameter setting ten specimen were measured.

Microsections and microhardness testing were used to characterize the shear affected zone. In order to visualize the deformation of the microstructure, the specimen were polished and etched with 3 % Nital. The microhardness measurement was carried out on a microhardness testing machine AMH-43 of LECO Instrumente GmbH, Mönchengladbach, Germany. According to [14] the microhardness testing was performed by applying a load of 50 g for 10 s on a measuring grid to obtain a map of hardness of the affected zone. The distance of the hardness indentation and the edge of the material is uniformly 0.0725 mm, while the distance between the hardness indentions is a minimum of 0.09 mm. In order to achieve a higher measuring point density, the measuring lines are aligned offset to one another. In total 12 measuring lines were evaluated over the depth of the shear affected zone. The last measuring line is located at a depth which corresponds to the sheet thickness. The measuring grid is visualized schematically in Figure 3.

![Distance to shear cut surface](image)

**Figure 3.** Measuring grid for microhardness testing.

3.3. Experimental setup and methods used for fatigue testing

The stress controlled fatigue tests were performed with a resonance test system from Sincotec Test Systems GmbH, Clausthal-Zellerfeld, Germany with a maximal force of 100 kN. The fatigue tests were carried out by testing under constant amplitude and using a load ratio $R = \frac{\sigma_{min}}{\sigma_{max}}$ equal to -1 at a frequency of about 50 Hz. While fatigue testing, a buckling support was attached to the specimen to prevent buckling of the flat specimen under pressure loading. The investigations focused on the high cycle fatigue region, therefore each S-N-curve in the high cycle fatigue region was determined by a linear regression of at least 13 to 18 individual fatigue tests. An individual test in the high cycle fatigue region ended with the failure of the specimen. The endurance limits of the S-N-curves, presented in this paper were estimated with the maximum-likelihood-method with 1 to 3 runouts. A test is defined as a runout when no failure of the specimen occurred at 5 000 000 cycles.
4. Results
The focus of the experimental work is the influence of the shear cut surface quality on the fatigue behavior of the specimens made of DP800 steel. Therefore the macroscopic condition as well as the microstructural properties of the shear affected zone are investigated. The evaluation of the fatigue behavior of selected cutting strategies is based on the S-N-curves, which result from fatigue testing.

4.1. Characterization of shear cut surface
The shear cut surfaces of the different shear cutting strategies which were investigated are shown in Figure 4. Below the photographic documentation of the shear cut edge, the two-dimensional profile of the shear cut edge is illustrated with the corresponding shear cutting parameters. Each shear cutting strategy generates an edge, which has individual surface properties. Figure 5 shows the portions of shear cutting surface characteristics for each of the investigated shear cutting strategies.

Figure 4. Photographic documentation and profiles of investigated shear cutting strategies.

Figure 5. Shear cutting surface characteristics of investigated shear cutting strategies.

The “Reference” shear cut specimen were shear cut with experience-based parameters such as a die clearance of 15 % and a punch edge radius of 10 µm, which means that the punch was sharp-edged. To investigate the influence of wear on the active elements, the punch edge was rounded up to 300 µm, the die clearance stayed constant. Because of the high edge radius it comes to a bigger die clearance in the beginning of the shear cutting process, resulting in a larger roll-over. Continuing the shear cutting process, the die clearance gets smaller and in combination with the rounded cutting edge radius, compressive stress leads to an increase of the clean-shear height. The photographic documentation of the “Two-stage 1” shear cutting process compared to the “Reference” strategy shows a slight difference, but the two-dimensional profile visualizes a nearly rectangular shear cut edge with a very small portion
of roll-over. This small roll-over as well as the bigger clean-shear height result from the small cutting offset of 0.4 mm. The stiffness of the scrap is lower than for a one-stage shear cutting strategy and therefore leads to a smaller proportion of roll-over and a higher proportion of clean-shear. With the “Two-stage 2” shear cutting strategy the influence of the cutting offsets’ width was investigated. The surface of the shear cut edge is nearly rectangular with a comparable portion of roll-over. The portion of clean-shear increases up to nearly 70 %. The “Two-stage 3” shear cutting strategy investigated the influence of the second-stage die clearance. The portion of clean-shear is about 40 %, but the surface has a smaller fracture angle and is no more rectangular.

Table 5. Roughness characteristics on fracture area of investigated shear cutting strategies.

| Name of the strategy | $R_a$ [$\mu m$] | $R_z$ [$\mu m$] | $R_{\text{max}}$ [$\mu m$] |
|----------------------|-----------------|-----------------|-----------------|
| Reference            | 1.90            | 11.04           | 14.09           |
| Wear                 | 2.73            | 15.47           | 19.70           |
| Two-stage 1          | 1.86            | 10.66           | 13.59           |
| Two-stage 2          | 2.16            | 11.90           | 15.70           |
| Two-stage 3          | 2.21            | 12.61           | 16.01           |

Table 5 lists the roughness characteristics for each of the investigated shear cutting strategies which were measured in the area of fracture. The results show no tendency that depends on the shear cutting strategy.

4.2. Characterization of shear affected zone

The microsections as well as the corresponding results from the microhardness measurement of the different shear cutting strategies which were investigated are shown in Figures 6 and 7. The magnification of the zone near the shear cut edge illustrates the degree of deformation of the microstructure. By using microhardness testing, the depth and degree of work hardening in the shear affected zone were analyzed. The hardness of the material in the initial state is 235 HV 0.05.

![Figure 6. Microsections and microhardness plots of one-stage shear cutting strategies.](image-url)
The microsection of the “Reference” strategy shows that the biggest grade of deformation as well as the maximum hardening is located in the area of fracture. The increase of hardness on the shear cut edge is 1.53 times higher than the initial material. The depth of the shear affected zone is approximately 0.6 mm, which corresponds to more than one third of the sheet metal thickness.

For the “Wear” strategy the maximum hardness is 1.62 times higher than the hardness of the initial material, especially in the area of clean-shear. The area of maximum plastification is also located there, which can be seen in the enlarged microsection. Besides the higher maximum hardening, the depth of the shear affected zone is also higher than for the “Reference” strategy. Figure 7 illustrates the microsections and microhardness plots for the three different two-stage shear cutting strategies.

**Figure 7.** Microsections and microhardness plots of two-stage shear cutting strategies.
The “Two-stage 1” strategies’ shear cut surface shows a decrease of maximum hardness in the front section of the shear cut edge and achieves a homogeneously distributed hardening over the whole surface. The depth of the shear affected zone decreased as well and is only about a tenth of the sheet metal thickness. This is due to the small cutting offset, which takes most of the plastification during the shear cutting process. This can be seen in the microsection of the cutting offset as well.

The “Two-stage 2” shear cutting strategy with the smaller cutting offset has an even lower maximum hardness being only 1.26 times higher than the initial material. As for the “Two-stage 1” strategy earlier, the depth of hardening here is also very small.

The last strategy “Two-stage 3” with the larger second-stage die clearance has a higher maximum hardness at the crossing of clean shear and fracture, but the depth of hardening here is also as low as it was for the other two-stage shear cutting strategies.

4.3. Fatigue behavior

Figure 8 visualizes the S-N-curves for a survival probability of $P_S = 50\%$, determined by fatigue testing the specimen, which were manufactured with varying shear cutting strategies.

![Figure 8. S-N-curves of unnotched specimen out of DP800 steel sheet produced with varying shear cutting strategies, $P_S = 50\%$, $R = -1$.](image)

The S-N-curves show that shear cutting of DP800 material causes a loss of fatigue strength compared to the specimen with polished edges. Since the fatigue crack always starts from the shear cut edge, the loss in fatigue strength depends on the condition of the shear cut edge. The shear cutting strategy which causes the highest drop of fatigue strength is the “Wear” strategy. Based on $10^5$ cycles in the high cycle fatigue region, the specimen lost 14% of fatigue strength compared to the polished specimen. According to the results in previous chapters 4.1 and 4.2, the shear cut edges of the specimen produced with the “Wear” strategy show the highest hardening in the shear affected zone and a very uneven shear cut surface. The shear cutting strategy which causes the highest fatigue strength produced by shear cutting is the “Two-stage 2” strategy that applies the smallest cutting offset of the two-stage shear cutting strategies used in these investigations. The loss of fatigue strength compared to the specimen with polished cut edges is 3% at $10^5$ cycles. The specimen produced with this strategy show the lowest hardening in the shear affected zone and a nearly rectangular shear cut surface.
5. Discussion
To evaluate which property of the shear cut edge is mainly responsible for the loss of fatigue strength, the measured values characterizing the shear cut edge have been investigated for a correlation with the fatigue strength of the specimen. Since the fatigue strength is generally influenced by the surface roughness, it could be expected that the fatigue strength in this investigation depends on the surface roughness at the fracture zone, from where the fatigue crack mostly started. However, no correlation occurs between the surface roughness at the fracture zone and the loss of fatigue strength. Neither does a correlation occur between the size of the four surface characteristics roll-over, clean-shear, fracture and burr and the fatigue strength. The only value which correlates with the loss of fatigue strength is the maximum hardness in the shear affected zone. Therefore, in Figure 9 the relative fatigue strength of the specimen, manufactured with varying shear cutting strategies at $10^5$ cycles, is plotted versus the maximum hardness measured in the shear affected zone of the specimen.

![Figure 9. Relative fatigue strength against maximum hardness of the investigated shear cutting strategies at $10^5$ cycles.](image)

It can be seen that the loss of fatigue strength, compared to the specimen with polished edges, is increasing with the maximum hardness in the shear affected zone. This means that the hardening effects caused by the shear cutting process have to be minimized in order to improve the fatigue behavior of specimen or components, produced by shear cutting.

6. Conclusion
Based on extensive characterization methods, the influence of shear cut component edges on the fatigue resistance could be investigated. The study has shown that fatigue resistance is strongly dependent on the shear cutting strategy employed. By varying the shear cutting parameters, the formation and hardening of the shear affected zone, as well as the geometry of the shear cut surface, can be influenced significantly. For unnotched specimens ($K_i = 1$) a two-stage shear cutting strategy with a small cutting offset and a small die clearance improves fatigue resistance behavior compared to a reference strategy. A high proportion of clean-shear with homogeneously distributed hardening and low depth of hardening into the specimen’s interior has a positive effect on the fatigue resistance. The shear cut specimens with the best fatigue behavior lose only 3% of stress amplitude based on $10^5$ cycles to failure compared to polished specimens.
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