IOP Conf. Series: Materials Science and Engineering **418** (2018) 012070 doi:10.1088/1757-899X/418/1/012070

Determination of the minimum possible damage due to shear cutting using a multi-stage shear cutting process

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Abstract. Residual formability and edge crack sensitivity of shear cut edges depend largely on the manufacturing technique of the edges. In previous experiments, two-stage shear cutting processes have proven to reduce negative effects on the shear affected zone, which increased the forming capacity and thus also improved edge crack sensitivity significantly.

The aim of this study was to determine the optimal settings for the parameters die clearance and cutting offset in order to maximize the forming capacity of pre-milled edges in a single-stage punching process. The performance of milled reference samples without additional punching determined the optimal outcome. In general, an open cutting line achieves a better residual formability in shear cutting processes than a closed cutting line. But by choosing a closed cutting line with specific punching parameters, the resulting edge conditions can achieve the ones of a process with an open cutting line closely.

The geometry of the shear cut edge, the depth and degree of work hardening in the shear affected zone, as well as the surface roughness can be adjusted by varying the shear cutting parameters die clearance and cutting offset. The use of the collar forming test not only enabled an evaluation of the sample's edge crack sensitivity, but also resulted in the identification of the optimal combination of those shear cutting parameters. These findings allowed for an assessment of the significance of the influencing factors geometry, work hardening, and surface roughness on edge crack sensitivity and residual formability of the high-strength multi-phase steel CP-W 800. The results of this research presented a basis for another research project at the utg regarding a multi-stage shear cutting process for high-strength steels.

1. Introduction

The use of high-strength steel grades has become essential in today's automotive industry. Demands such as weight reduction and improved crash behavior are met by multi-phase steel grades, which are characterized by enhanced formability and high strength at the same time. A major challenge, accompanied by using these steel grades is the sensitivity for edge cracks, which is often observed on sheared edges [1, 2].

Parameters influencing the quality of shear cut edges and the formation of edge cracks are in particular the material properties, material thickness, die clearance, cutting edge radius, tool wear and shear cutting strategy (one-stage, two-stage). [3, 4, 5] Varying the before mentioned parameters influences the geometric shape of the shear cut edge as well as the depth of the shear affected zone and degree of work-hardening.

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A modified shear cutting strategy, such as a two-stage shear cutting process, leads to a reduction in edge crack sensitivity. It reduces the depth of the shear affected zone by adapting the shear cutting parameters die clearance and cutting offset. [6]

The aim of this study is to produce a minimally work-hardened shear affected zone using an adapted multi-stage shear cutting process by varying the influencing shear cutting parameters die clearance and cutting offset.

2. Shear cutting strategies

2.1. Shear cutting

Shear cutting is one of the most widely used methods in sheet metal working. Almost every sheet metal product undergoes one or more shear cutting operations within its manufacturing process. In most cases, the shear cutting process is carried out for preparation and post-processing or intermediate processing for forming. [7]

The material is deformed by the cutting edges until its capacity to deform is expended and the material fails. As with any forming process, high levels of plastification occur in the shear affected zone during the shear cutting process due to the very local forming. The amount of deformation and the size of the shear affected zone depend mainly on factors like material, sheet thickness and shear cutting parameters. The depth of the shear affected zone can extend up to a few tenths of a millimeter into the base material. [7, 8]

The characteristic shear cut surface, including the shear affected zone can be described according to [9] (see Figure 2).

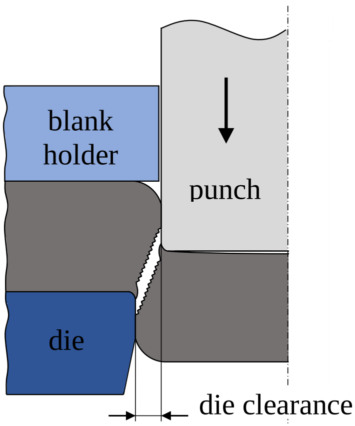

Figure 1. Schematic illustration of the shear cutting process according to [7].

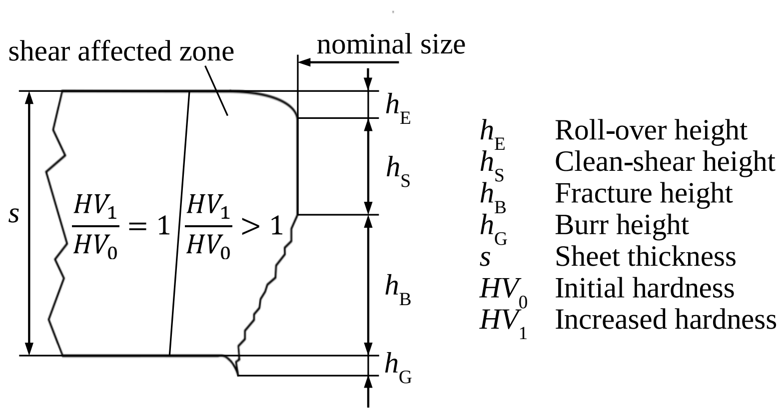

Figure 2. Characteristic shear cutting parameters and shear affected zone according to [9].

2.2. Two-stage shear cutting

Two-stage shear cutting is a special manufacturing process in the field of shear cutting and is assigned to the precision cutting processes. It is defined as the trimming of small cutting-offsets of pre-cut surfaces to produce smooth and dimensionally stable outer and inner shapes. [10]

In most cases, the two-stage shear cutting is attached to the normal shear cutting process as a post-processing step. The contour is pre-cut by conventional shear cutting, reduced by the cutting-offset, followed by the second stage of shear cutting with adapted shear cutting parameters, which are illustrated in Figure 3. The scrap, produced during the second stage, has a lower stiffness compared to conventional shear cutting, which is why it takes most of the plastification during the shear cutting process and remains less deformation in the components edge. The lack of lateral support of the cutting offset also leads to an increased bending moment, which induces higher tensile stresses at the punches edge and thus results in an early crack initiation. [11, 12]

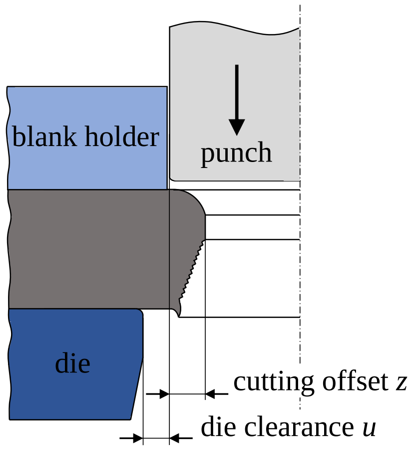

Figure 3. Schematic illustration of the two-stage shear cutting process according to [7].

Besides the die clearance, which has great influence on the resulting shear cut surface quality, the two-stage shear cutting process is influenced also by the width of the cutting-offset. Figure 3 illustrates both for the two-stage shear cutting process relevant parameters.

Another precision cutting process is shaving. This process aims to maximize the proportion of clean-shear and generate smooth square edges. For this purpose the cutting-offset is chosen very small. [13, 14] However, in case of the two-stage shear cutting process, with the aim of maximizing the residual forming capacity of the shear-cut edge, the cutting offset is chosen to be larger. It is adjusted, so that it does not maximize the clean-shear height, but the scrap absorbs most of the plastic deformation during the shear cutting process, leaving less hardening in the resulting shear affected zone of the component.

3. Collar-forming test

To determine the edge fracture sensitivity a variety of testing methods exists, for example the standardized hole expansion test (HET) [15], the collar-forming test [16] or the Edge-Fracture-Tensile-Test [17].

The collar-forming test represents the most practical testing method of the three aforementioned, because its sample geometry corresponds to components used in practice. The characteristic value for the maximum achievable deformation during collar drawing is described by the expansion ratio V_A. It is defined as the ratio of the inner collar diameter D_h to initial hole diameter D_0. The process is limited by the occurrence of radial cracks on the collars' edge, which lead to the unusability of the component [16].

4. Material

The material used for the investigations is a hot rolled 4 mm thick complex-phase steel grade CP-W 800, which consists of a fine microstructure with main phases of ferrite, bainite and martensite. It has a high yield strength of 680 MPa – 830 MPa, minimum tensile strength of 780 MPa, and minimum elongation of 12 % [18]. The mean hardness of the base material was determined to 270 HV 0.1 by microhardness measurement according to standard [19]. The chemical composition of this steel grade is listed in Table 1.

Table 1. Chemical composition in weight percentage of CP-W 800 sheet metal according to [18].

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

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5. Approach

The first aim of these investigations is to find the best possible combination of parameters consisting of die clearance and cutting offset with respect to minimum damage in the shear affected zone. For this purpose, a systematic study is carried out using die clearances between 5 and 20 %. The cutting offset is adjusted iteratively until a burr-free shear cut surface with a homogeneous fracture area can be achieved. The shear cutting process is performed on pre-milled samples with an initial hole diameter adjusted to the cutting offset, the final hole diameter is 50 mm. Table 2 summarizes the process parameters, which are used for the preparation of the sample geometry.

Table 2. Process parameters finding the maximum formability of pre-milled edges.

Parameter	Value
Punch edge radius *r*	10 µm
Die clearance *u*	5 %, 10 %, 15 %, 20 %
Cutting line	Closed
Cutting offset *z*	variable

The resulting shear cut surfaces are evaluated visually, whereby a formation of burr, secondary clean-shear or delamination in the fracture zone leads to exclusion for further analyses. The two best parameter combinations are then examined with micrographs and microhardness testing to find the least damaged edge. The maximum hardening occurs in the transition area from clean-shear to fracture zone, since the material flows the longest through the shear-cutting process and thus is most plasticized. In addition to the region of burr this transition area represents a high-risk area for the initiation of edge-cracks. [20]

The evaluation of the shear-cut edge condition with respect to edge crack sensitivity is carried out with the collar-forming test. To classify the drawn collars according to their edge quality into A- and B-specimens, all collars undergo a visual inspection, where they are examined for cracks and necking. It shows the manufacturability of the component by forming methods and is not intended to assess the fatigue strength. A-specimens have good edge qualities with only small cracks on the edge, up to half of the sheet thickness, whereas B-specimens have larger cracks which extend over half of the sheet thickness or are completely torn. Should the manufacturability of components be evaluated by edges without any cracks, then the optimum combination of parameters is the same as shown in the paper "Maximizing the expansion ratio through multi-stage cutting process during collar-forming".

After determining the combination of die clearance and cutting offset, which minimizes the hardening in the shear affected zone, a multi-stage shear cutting process is designed to manufacture the same edge quality as before. In the first step, the initial hole is shear cut, followed by a second-stage shear cutting process, which aims to eliminate the work-hardening from the first stage and at the same time achieves a nearly rectangular shear cutting surface. The surface quality of the second-stage shear cut edge has a minor role. The last step is a third-stage shear cutting process with the optimal combination of parameters found from previous investigations. Due to the hardening of the microstructure by the previous shear cutting processes, in the final step there are tested two widths of cutting offset, since the stiffness of the scrap increases as a result of the hardening. By reducing the width of the cutting offset it is possible to lower the stiffness again. Table 3 summarizes the process parameters chosen for the multi-stage shear cutting process.

Table 3. Process parameters for the multi-stage shear cutting process.

	Die clearance *u*	Cutting offset *z*	Punch edge radius *r*
First stage	10 %	-	10 µm
Second stage	10 %	0,7 mm	10 µm
Third stage	10 %	1,2 mm, 1,75 mm	10 µm

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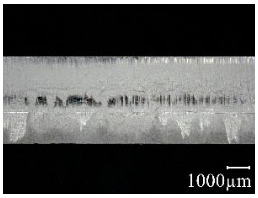
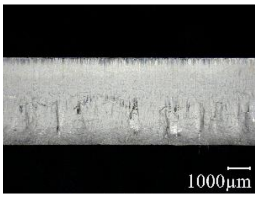
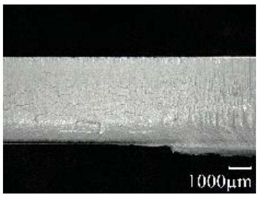
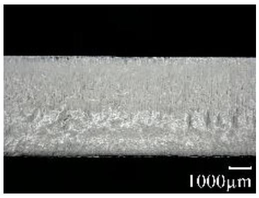
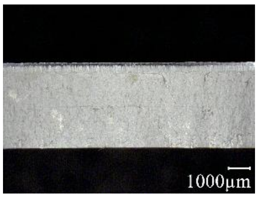
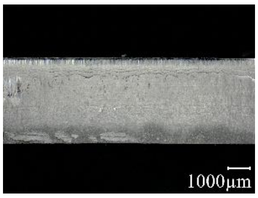
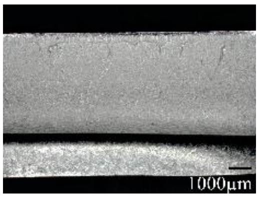
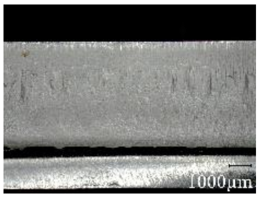
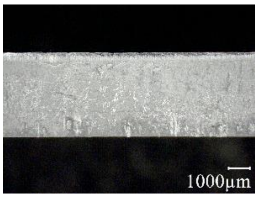
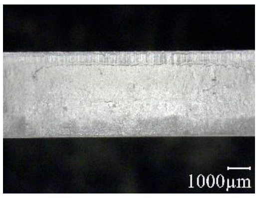
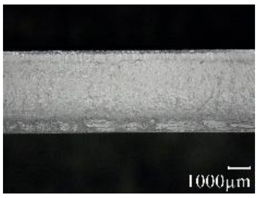
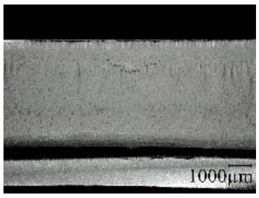
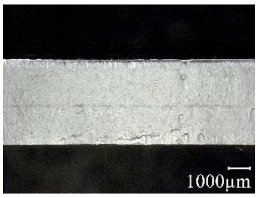
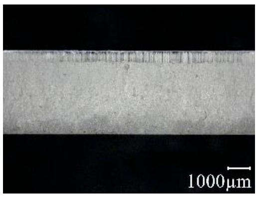
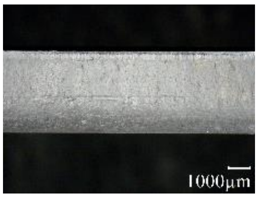
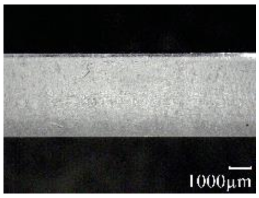
6. Results

6.1. Determination of the minimum possible damage dependent on the combination of die clearance and cutting offset

In the following, the influence of the shear cutting parameters die clearance and cutting offset on pre-milled edges is described. Table 4 shows the results of the systematic variation of die clearance and cutting offset on the optical appearance of shear cut surfaces.

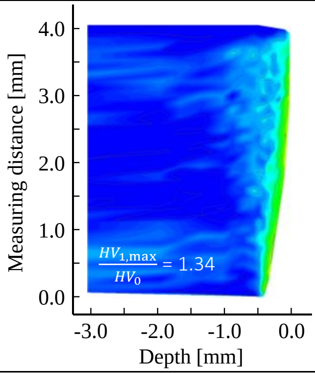
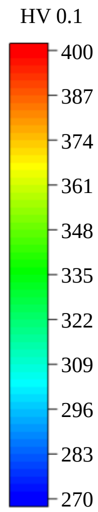
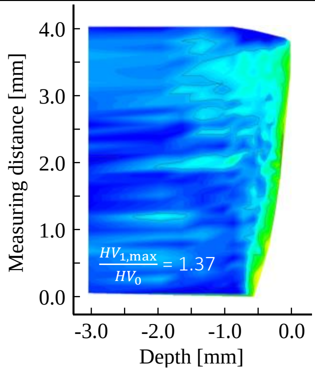
Table 4. Shear cut surfaces of pre-milled holes depending on the die clearance *u* and cutting offset *z*.

u = 5 %	u = 10 %	u = 15 %	u = 20 %
z = 1.0 mm 	z = 1.0 mm 	z = 1.0 mm 	z = 1.0 mm 
z = 1.5 mm 	z = 1.5 mm 	z = 2.0 mm 	z = 1.5 mm 
z = 1.625 mm 	z = 1.625 mm 	z = 2.25 mm 	z = 1.625 mm 
z = 1.75 mm 	z = 1.75 mm 	z = 2.5 mm 	z = 1.75 mm 

The specimens' edges, manufactured by shear cutting of pre-milled holes show different shear cut surface qualities. Edges, which are shear cut with a small die clearance of u = 5 % show for all investigated sizes of cutting offsets a secondary clean shear in the fracture area, while bigger die clearances of u = 15 % and u = 20 % combined with small cutting offsets lead to a massive formation of burr. Based on the requirement, that the best results in collar-forming can be achieved with non-burr and smooth fracture surfaces without delamination or secondary clean-shear, two parameter combinations were chosen for further investigations. The combinations of a die clearance of u = 10 % with a cutting offset of z = 1.75 mm as well as a die clearance u = 15 % with a cutting offset of z = 2.5 mm were taken to prepare microsections as well as microhardness measurements to quantify the amount of plastification and hardening in the shear affected zone (Table 5).

The microsections as well as the microhardness measurements show a smaller degree of deformation of microstructure in the shear affected zone for the combination of parameters with a die clearance of u = 10 % and cutting offset of z = 1,75 mm. The maximum hardening in the front section of the shear affected zone is 1.34 times higher than the basic hardness, the work-hardening extends to a depth of 0.7 mm. For a cutting offset of z = 2.5 mm combined with a die clearance of u = 15 % the depth of hardening is 1.75 mm and the maximum hardening 1.37 times higher than the basic hardness.

Table 5. Microsections and microhardness measurements of selected shear cutting parameters.

Shear cutting parameters	*Microsections of shear cut edge and cutting offset*	*Hardness measurement*	
pre-milled hole u = 10 % z = 1.75 mm			
pre-milled hole u = 15 % z = 2.5 mm			

The subsequently carried out collar-forming tests show, that the increase in hardening in the shear affected zone reduces the forming capacity and, as a consequence, lowers the maximum expansion ratio. A sheared edge quality produced with a parameter combination of u = 10 % and z = 1.75 mm enables a process-reliable production of A-samples including an expansion ratio of V_A = 55%. The quality of sheared edges manufactured with u = 15 % and z = 2.5 mm achieves only a maximum expansion ratio of V_A = 40% and is therefore not considered for the following investigations.

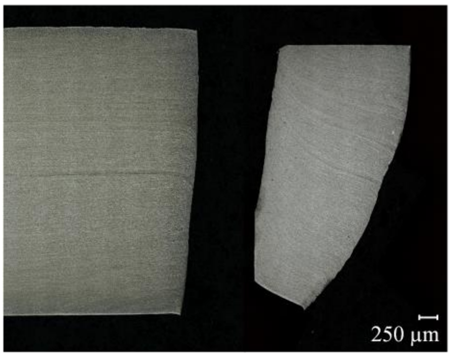
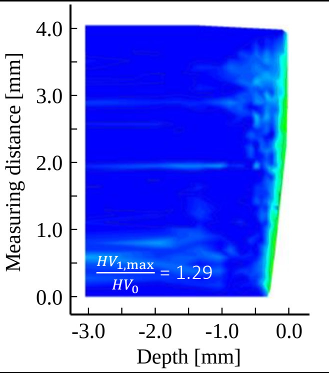
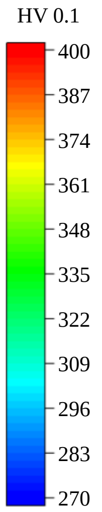
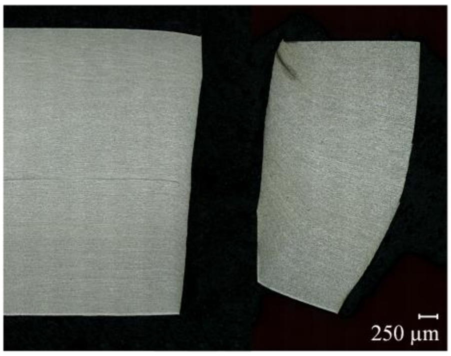
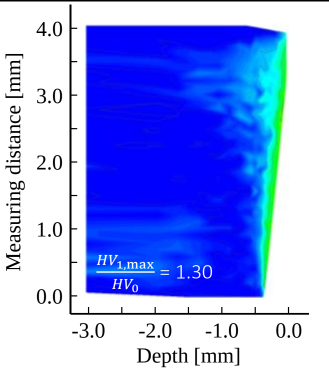
6.2. Manufacturing a minimum damaged edge by multi-stage shear cutting

The optimal shear cutting parameters for the production of minimally damaged edges, which were defined in the previous chapter, are now to be applied in a multi-stage shear cutting process. The first step is a conventional shear cutting process using a die clearance of u_1 = 10 % to keep the depth of the shear affected zone within a limit. A microhardness analysis of the plastification induced by the first shear cutting process has shown, that the shear affected zone extends up to a depth of z = 0.7 mm. Therefore the cutting offset for the second stage was chosen for z_1 = 0.7 mm to remove the work-hardened zone of the first stage. Due to the hardening, caused by the before done shear cutting processes, the optimum width of cutting offset, determined in chapter 6.1, for the third stage must be adapted. It was chosen to be 1.2 mm and 1.6 mm to gain a similar stiffness of scrap, which is dependent on the hardness and width of the scrap.

The preparation of microsections as well as microhardness measurements were performed to quantify the amount of plastification and hardening in the shear affected zone (Table6).

IOP Conf. Series: Materials Science and Engineering **418** (2018) 012070 doi:10.1088/1757-899X/418/1/012070

Table 6. Microsections and microhardness measurements of selected shear cutting parameters for the multi-stage shear cutting process.

Shear cutting parameters	*Microsections of shear cut edge and cutting offset*	*Hardness measurement*	
u_1 = 10 % u_2 = 10 % z_2 = 0.7 mm u_3 = 10 % z_3 = 1.2 mm			
u_1 = 10 % u_2 = 10 % z_2 = 0.7 mm u_3 = 10 % z_3 = 1.6 mm			

The microsections as well as the microhardness measurements of the shear affected zone show a smaller degree of deformation for the combination of multi-stage shear cutting parameters with a cutting-offset z_3 = 1.2 mm. The depth of hardening as well as the maximum hardening compared to the pre-milled samples from chapter 6.1 could be reduced even further. The depth of the hardening is now only 0.5 mm, the maximum hardening is only 1.29 times higher than the basic material.

7. Conclusion

Based on the selection of shear cut edges according to the visual evaluation combined with metallographic analysis methods the tendency to edge cracking could be correlated with the damage of the shear affected zone. Influencing factors such as macroscopic damage caused by burr, secondary clean shear and delamination were eliminated.

The study has shown, that an adapted combination of die clearance and cutting offset leads to a significant reduction in degree and depth of hardening in the shear affected zone. The majority of plastification is taken over by the scrap so that the components edge therefore has a higher residual formability. This could be proven in collar-forming tests.

Based on a multi-stage shear cutting process, the minimally damaged shear affected zone could be reproduced and the maximum hardening could even be surpassed. The results of the collar forming test with this adapted multi-stage process were investigated in paper "Maximizing the expansion ratio through multi-stage cutting process during collar-forming ". Based on the findings of the present paper, collar-forming tests with an optimized shear affected zone are performed and compared to other shear cutting strategies.

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