Experimental investigation of piercing of high-strength steels within a critical range of slant angle

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Abstract. Deep drawn parts often do have complex designs and, therefore, must be trimmed or punched subsequently in a second stage. Due to the complex part geometry, most punching areas do reveal critical slant angle (angle between part surface and ram movement direction) different to perpendicular direction. Piercing within a critical range of slant angle may lead to severe damage of the cutting tool. Consequently, expensive cam units are required to transform the ram moving direction in order to perform the piercing process perpendicularly to the local part surface. For modern sheet metals, however, the described critical angle of attack has not been investigated adequately until now. Therefore, cam units are used in cases in which regular piercing with high slant angle wouldn’t be possible. Purpose of this study is to investigate influencing factors and their effect on punch damage during piercing of high strength steels with slant angles. Therefore, a modular shearing tool was designed, which allows to simply switch die parts to vary cutting clearance and cutting angle. The target size of the study is to measure the lateral deviation of the punch which is monitored by an eddy current sensor. The sensor is located in the downholder and measures the lateral punch deviation in-line during manufacturing. The deviation is mainly influenced by slant angle of workpiece surface. In relation to slant angle and sheet thickness the clearance has a small influence on the measured punch deflection.

1. Introduction

Weight of modern vehicles has steadily increased over recent years. The rising vehicle weight requires more power to move, which increases fuel consumption. In order to meet current demands for reduction of CO₂ emissions and other pollutants, automotive manufacturers are constantly working on new concepts for fuel saving. In this context, car body weight reduction provides an efficient approach to counteract the increase and thus to reduce pollutant emissions by reducing fuel consumption. The use of high-strength sheet metal materials, compared to mild steel materials, allows a reduction in the sheet thicknesses while maintaining the same properties of carbody with regard to crash performance and structural stiffness.

Thus, the use of high-strength materials offers new possibilities in the area of vehicle design which enables to achieve the target of reducing pollutant emissions. However, in the processing of high-strength steels, new problems particularly arise in production. Unexpected damage of tool materials and high wear of punching tools do show a very strong influence on the part surface quality in manufacturing. For this reason, today there is a great need to optimize trimming and punching operations of high-strength sheet materials. Previous studies on this topic supported a better understanding of the shearing process in the cutting tool and led to increase service life of such tools.
However, in literature only low experience in punching high-strength materials within a critical range of slant angle might be found. In this context, the critical range of slant angle is understood to mean a part surface which is extremely inclined to vertical tool movement. Due such extremely or inclined working conditions to slant angle, additional stresses such as bending and horizontally acting forces are applied to the punch due to extreme asymmetrical process force application. Since many deep drawn car body components today do have complex part geometry, a punching operation under such conditions often is unavoidable. In this case, a perpendicular angle of attack is not possible to perform due to the spatial geometry of the formed part. Therefore gaining detailed understanding of such punching processes is necessary for deriving design guidelines for useful and robust cutting tools. Due to the large number of influencing process parameters, it isn’t possible to derive general guidelines for the punching process within a critical range of slant angles. Therefore it is important to gain more specific understanding through new research on this topic, which is given in this paper as a first approach.

2. State of the art
The piercing of sheet metal within a critical range of slant angle designates the punching process in which forming parts are punched on to surfaces, which are not oriented perpendicularly to the punch movement. In this case, the punch hits workpiece surface similarly to figure 1, which regularly is performed after one or multiple deep drawing operations.

Intending to punch material thicknesses beyond 1.5 mm in a critical range of slant angle Hilbert [1] recommends a pre-punching operation of workpiece under plane conditions and a second punching operation under slant conditions by use of a slant heading surface of punch. Hilbert also show, how the diameter of the punch has to be selected dependent on slant angle of workpiece orientation and sheet thickness. However, the special punch geometries used for this purpose are not very suitable for industrial application since they are expensive to manufacture and to prepare for reuse.

Oehler also provides important findings in punching using slant angles in [2]. In a graph, the maximum permissible slant angle is plotted against the influence factors sheet thickness and the ratio of punch diameter to sheet thickness. In addition, a distinction is made between four levels of material strength. For the range of slant angle between 12° and 15° Oehler, also recommends manufacturing the punch heading surface parallelly to workpiece surface.

Investigations performed by Becker [3], [4] show that an extension of the process limits can be expected with a holistic approach taking into account most important influencing factors of punching processes. Using a slant heading surface of punch the acting bending moment is two times smaller, than using plane punch. Becker in his work also provides an overview of most crucial influence factors on the acted punch bending moment. Slant heading surface of punch, lateral support of the punch, sheet thickness, strength of sheet material and clearance therefore have an influence on the acting bending moment. In his investigations, Becker confines himself only to one punch length and only one punch diameter as well as a restriction of critical slant angle of 15° and 30°.

Woestmann also considers punching with slant angle in [5]. In this experimental study, the limit angle for the four sheet materials RA-K 40/70, DP-K34 / 60, MHZ340 and DX56 + Z is considered at 5°, 10° and 15°. In this case, punch failure or an excessively high burr is defined as a criterion of interruption for the long-term trials with a maximum of 100,000 strokes. In his experimental tests the
punch deflection and punch force are measured. Up to and including 10° slant angle, the punches reach the required service life for all sheet metal materials. Only at 15° a failure could be recognized by the defined maximum burr height for the materials RA-K 40/70 and DX56. Also [6] shows first numerical investigations to measure the lateral punch displacement with DEFORM 2D.

However, in the investigations of Woestmann only slant angles of up to 15° are considered and thus no critical slant angles are defined. However, since Woestmann detect the highest wear at the position of the punch which is first penetrate the sheet, optimization potentials can be recognized by use of a slant heading surface of punch, as Becker showed in his work [3].

The state of the art shows that punching with a slant angle requires further research especially for high-strength materials. This study is intended to fundamentally expand the state of the art and to support the design of large tools. Further studies on trimming with slant angle are shown in [7][8][9][10][11]. Within the framework of this paper, however, the focus will be on piercing within critical range of slant angle.

3. Experimental investigations

The process of piercing with a slant angle is often used in the field of large tool manufacturing and reflects the state of the art. However, this study considers the significant influencing factors on the process. The main influencing factors are clearance, punch length, sheet thickness, sheet material and slant angle. In order to evaluate these parameters, an experimental tool was manufactured and the various influencing factors were evaluated.

3.1. Tool technology

Within the scope of this study, a modular shear cutting tool was developed, which allows simple and fast examination of different cutting inserts, shown in figure 2a). Most important test parameters are clearance, punch length, sheet thickness and slant angle of the component. One of the most important points in tool design was modularity of the tool components since the tool needs to be quickly adapted to the numerous testing parameter variations. For determination of maximum achievable cutting limit angle, it is necessary to measure cutting force and horizontal punch deviation during cutting process. Through correlation of these two measured values and consideration of FEA, the cutting progression with a defined slant angle can be studied in detail.

The cutting force is measured by a load cell above the punch and the measurement of the lateral deviation of the punch is done by an eddy current sensor which is positioned at the downholder, shown in figure 2b). The eddy current sensor measures the distance between it and the punch up to a range of 500 µm with a measurement resolution of 0.025 µm.

![Figure 2: a) design of a modular piercing tool b) position of load cell and eddy current sensor in tool](image)

3.2. Influence of sheet thickness

The cutting force depends on tensile strength of material, shearing length and sheet thickness. It is obvious that an increase of shearing force has an effect on lateral punch deviation. Figure 3 shows the
influence of punch deflection for a sheet thickness of 1 mm and 2 mm for the material HC420LA, sheared by a round punch with a diameter of 10 mm. Used pre-drawing shows the direction of the punch deflection. A positive deflection means that the cutting punch moves away from the sensor and a negative one that the punch comes closer to the sensor. As shown in figure 3, there are vibrations in scope of 1 up to 2 µm which are caused by impact of the downholder on the die and in the further course by the punch impact on the material. At that moment the punch slides on the material and a negative lateral deviation of 5 µm for 1 mm material and 10 µm for 2 mm material is measured. The examined slant angle β was 10° for booth thicknesses examined and the clearance was held constant at 10% of sheet thickness.

Starting the shearing process, the lateral punch deviation is increasing nearly linearly up to 50 µm for 1 mm material and 105 µm for 2 mm material in the positive direction. The punch moves away from the sensor when the crack initiation begins and the deflection is declining after the maximum has been reached. In any case this investigation shows that sheet thickness has a significant influence on piercing with slant angle.

![Figure 3: Lateral punch deviation for different sheet thickness](image)

### 3.3. Influence of clearance

One of the most frequently investigated possible influencing factors in the cutting process is the clearance. The selection of the blade clearance influences both quality of the cut surface and required amount of force and work. A blade clearance that is too large may cause incipient cracks parallel to the surface mainly with the higher-strength steel grades due to unfavourable strain ratios in the blade clearance. Also while piercing with a slant angle, the clearance influences achievable part quality.

Figure 4 shows two graphs with different clearance settings cutting 2 mm thick HC420LA with a slant angle of β = 10°. The progression of the curve is similar to figure 3. The influence of an increasing clearance caused a maxima offset of 0.03 mm from 0.075 mm to 0.105 mm. However, with the addition of a smaller gap between punch and die (5% ± 0.1 mm and 10% ± 0.2 mm) the lateral punch deviation is 0.075 mm for a clearance of 5% more critical than the deviation of 0.105 mm for a clearance of 10%. Thus, the maximum limit angle is reached much earlier in case of a smaller gap.
3.4. Influence of cutting angle

As described in the previous chapter, determination of critical slang angle is very important for robust process layout. In this study three various slant angles (10°, 20° and 30°) are investigated as shown in figure 5. The progression of each graph is different. However, it is striking that the graph with the slant angle of $\beta = 10^\circ$ is positive and the course of both other slant angles is negative. As already mentioned, the maximum horizontal punch deviation is measured 0.105 mm with a slant angle of $\beta = 10^\circ$. The increase of the slant angle to $\beta = 20^\circ$ causes a maximum punch deflection of -0.050 mm. Both of these measured punch deflections don’t cause punch failure during punching. For the experiments with slant angle of $\beta = 30^\circ$, the deflection measured was -0.220 mm and thus clearly is above the clearance with 0.2 mm. In this case, the punch strikes the die and a punch failure occurs.

Figure 4: Lateral punch deviation using different clearance

![Figure 4](image)

Figure 5: Lateral punch deviation using different slant angles

![Figure 5](image)
As can be seen in figure 5 an instable system is to be expected when piercing with slant angle. The higher the slant angle the higher the negative punch deviation is measured in the process. The influence of the slant angle is significant.

4. Conclusion
This study shows different influence factors while piercing high strength steel grades with slant angle. The most important influencing factors are sheet thickness, clearance and slant angle. In order to be able to evaluate these factors, a modular tool was designed and lateral punch deviation was measured in-situ by an eddy current sensor. The results show that the highest punch deviation is caused by the slant angle. Next, the sheet thickness should be considered when piercing with slant angle. In relation to slant angle and sheet thickness the clearance has a small influence on the measured punch deflection.

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