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Numerical investigation of piercing of DP600 within a critical range of slant angle

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Abstract. Deep drawn parts often have complex designs and must therefore be trimmed or punched in a subsequent stage. Due to the complex part geometry, most punching areas have a critical slant angle (angle between part surface and ram movement direction) which differs from the vertical direction. Such piercing within the critical range of the slant angle may lead to severe damage of the cutting tool due to bending effects on the cutting punch. Consequently, expensive cam units are required to transform the ram movement direction in order to perform the piercing process perpendicularly to the local part surface. However, the critical angle of attack described above has not yet been sufficiently investigated for modern sheet metal materials. The purpose of this study is to investigate the influencing factors and their effect on lateral punch deflection during piercing of high strength steel DP600 with slant angles using the FEM Software DEFORM 3D and to create a simulation model that enables a previously sophisticated simulation of the shearing process at different cutting angles. The aim of the study was to measure the lateral deviation of the punch when cutting with a slant angle. The calculated results show that the horizontal deviation is mainly influenced by the slant angle of the workpiece surface, the cutting line and the length of the punch.

1. Introduction

Weight of modern vehicles has steadily increased over recent years. This requires more power to move and higher fuel consumption. In order to meet current demands for the reduction of CO2 emissions and other pollutants, automotive manufacturers are constantly working on new concepts for fuel saving. In this context, the weight reduction of car bodies provides an efficient approach. Here, for example, 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 car body 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 surface quality of the produced parts. For this reason, today there is a great need to optimize trimming and punching operations of such high-strength sheet materials. Previous studies on this topic supported a deeper understanding of the shearing process in the cutting tool and led to an increase in service life of such tools. In literature, however, only little experience in punching high-strength materials within a critical range of slant angle is found. In this context, the critical range of slant angle is a part surface, which is extremely inclined to vertical tool movement. Due to the extreme working conditions caused by the slant angle, additional stresses such as bending and horizontally acting forces are applied to the punch because of an asymmetrical process force application. Since many deep drawn car body components today do have complex part geometries, a punching operation under such conditions is often unavoidable. Therefore, gaining detailed understanding of punching processes within a critical range of slant angles is necessary for deriving design guidelines for useful and robust cutting tools. Hence, this paper deals with initial investigations on this topic.

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 its surfaces being oriented not perpendicular to the punch movement. Such a punching operation is regularly performed after one or multiple deep drawing operations and is schematically shown in Figure 1.

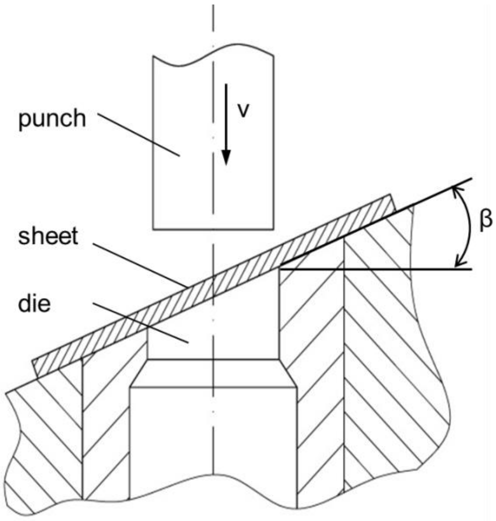

Figure 1. General sketch of piercing with a slant angle β

Intending to punch sheet material thicknesses beyond 1.5 mm in a critical range of slant angle, Hilbert [1] recommends a pre-punching operation of the workpiece under plane conditions and a second punching operation under slant conditions by use of a slant heading surface of the punch. Hilbert also shows how the diameter of the punch has to be selected dependent on the slant angle of the 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 versus the factors “sheet thickness” and “ratio of punch diameter to sheet thickness”. In addition, a distinction is made between four levels of material strength. For the range of a slant angle between 12 ° and 15 ° Oehler also recommends manufacturing the punch heading surface parallel to the workpiece surface.

Investigations performed by Becker [3], [4] show, that an extension of the process limits can be expected when taking a holistic approach 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 by using plane punch. In his work, Becker also provides an overview of most crucial influence factors on the initiated punch bending moment. Slant heading surface of the punch, ateral support of the punch, sheet thickness, strength of sheet metal material and clearance therefore have an influence on the acting bending moment. In this investigation, Becker confines himself only to one punch length and only one punch diameter as well as a restriction of a critical slant angle of 15 and 30 °.

Woestmann also considers punching in case of a 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 extended burr height is defined as a criterion for terminating long-term trials with a maximum of 100,000 strokes. In his experimental tests, the punch deflection and punch force are measured continuously. Up to 10° slant angle, the punches reach the required service life for all sheet metal materials investigated. At 15° slant angle failure was recognized by previously defined maximum burr height of the materials RA-K 40/70 and DX56. Also [6] shows first numerical investigations with regard to the measuring of the lateral punch displacement by use of DEFORM 2D. However, in the investigations of Woestmann slant angles of up to 15° were considered and thus no critical slant angles were defined by him. Nevertheless, since Woestmann detected the highest wear at the area of the punch, which penetrates first into the sheet, optimization potentials can be recognized by the use of a slant heading surface of punch, as Becker already showed [3]. Further studies on trimming with slant angle are shown in [7] [8] [9] [10] [11] [12].

The state of the art shows that punching with a slant angle requires further research especially for high-strength materials. Considering the study presented in this paper, present state with this is fundamentally expanded and so validated design rules for application can be provided in industry. For that very reason in the following the focus will be put on numerical investigation of piercing within a critical range of slant angle.

3. Numerical investigation

For some time now, forming operations such as deep drawing or bending have been modelled and calculated by modern FEM simulation software for three-dimensional visualization. Nonetheless, the simulation of 3D shearing processes remains a challenge due to models for damage modelling and element separation/ deletion as well as missing material properties in this field. For this reason, spatial problems often are reduced to 2D numerical approaches for fundamental research. Since shear cutting processes mainly focus on operations performed in sheet thickness direction, a numerical 2D calculation looks acceptable as a first approach. This evidently leads to shorter computing times and economic advantages [13]. The software DEFORM 2D/3D provided by SFTC today is used in a large number of scientific papers for the numerical investigation of shear cutting processes, cf. [14], [15], [16], [17], [18], [19]. The advantage of this software is the sophisticating representation of elastic-plastic material properties by considering local and global springback effects. The software's FE code also implements an automatic remeshing function that allows reproducing large plastic deformations during the cutting process without an excessive deformation of the FE mesh [13], [20].

3.1. Modelling approach and simulative setup

Within the scope of this presented research work, different influencing factors such as the cutting clearance and punch length were numerically investigated with regard to the punching process considering different sheet position angles. For this purpose, a simulation model was developed within the commercial FEM software DEFORM 3D and by this horizontal punch deflection was investigated numerically first, see Figure 2.

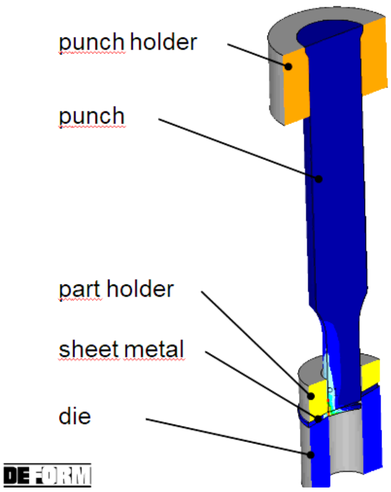

Figure 2. Simulative setup of piercing with slant angle

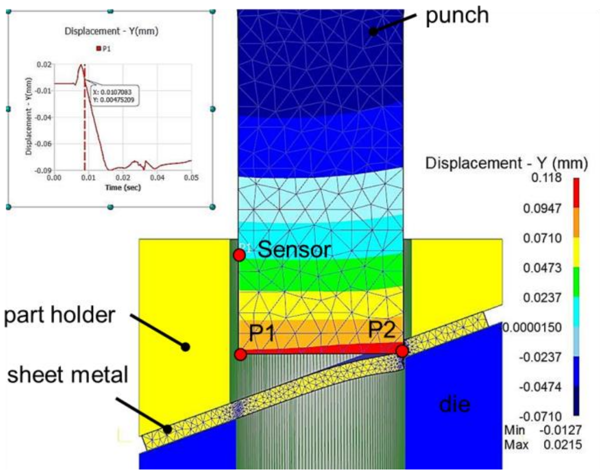

Figure 3. Method to measure lateral punch deflection using point tracking method

Due to the non-planar part position, the model was created in the 3-dimensional state. Investigated sheet metal material D600 was finely meshed and a plastic material law was chosen. A pure elastic

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material behaviour was applied to the punch and was defined as such in simulation. All other components such as the part-holder and the die were defined as rigid. A Coulomb contact algorithm with $\mu = 0.1$ was chosen at contact between tool parts and sheet metal material. The horizontal punch deflection was determined in DEFORM 3D by using the point tracking method. Here, a node element was selected on the meshed punch surface (Figure 3) and then the point was tracked via the simulated punch stroke. The tracking in X-direction showed horizontal punch deflection, which could be described as purely elastic.

In this simulation, the normalized Cockroft & Latham criterion for damage modelling was used. This caused a local failure of a mesh element as soon as the cumulative real-time value of the plastic work reached a critical limit $C_{\text{krit}} = 2.0$, calibration of this value was done at Institute for Forming Technology by comparing the smooth cut zone of simulation an experiment. According to [21], two to five neighbouring elements must fail before the program starts deleting elements. Element deletion is a method of modeling ductile material failure from crack initiation and expansion to global fracture. It is known as the "Normalized Cockroft & Latham" criterion and formulated as below:

$$C_{\text{normC\&L}} = \int_0^{\bar{\varepsilon}_f} \frac{\sigma^*}{\sigma_v} d\bar{\varepsilon}$$

The first main stress σ^* refers to the equivalent stress σ_v. This is a common model, which is mainly used in simulation of shear cutting and cold forming processes. The investigated cutting parameters are summarized in Table 1. One of the most important parameters of course is the slant angle β, which was varied by 7 amounts between 10 and 25° with an increment of 2.5°. The punch length obviously gives an important influencing factor though its mainly induce horizontal punch deflection. In relation to the manufacture of real tool sizes, piercing punches were tested according to DIN ISO 8020/B having a punch length of 80 mm, 90 mm and 100 mm. The punch diameter was chosen to D = 10 mm and the cutting edges were not rounded. Investigated cutting clearance levels were determined to 10% and 15% of the sheet thickness and were defined as the standard cutting clearance for the considered material D600 having a sheet thickness of t = 1 mm. The part holder load was assumed constant at 8 kN during the study.

Table 1. Design summary of investigated parameters

Factors	**No. of steps**	**Amount of steps**
Slant angle	7	10°; 12,5°; 15°; 17,5°; 20°; 22,5°; 25°
Punch length	3	80 mm; 90 mm; 100 mm
Cutting clearance	2	10 %; 15 %
Sheet thickness	1	1 mm
Sheet metal material	1	DP600
Part holder load	1	8 kN
Cutting edge	1	No rounding of cutting edge
Punch diameter	1	10 mm

Punch material	1	1.3343 (HSS); ASTM A 600-1992 M2 regular C; hardened at 64 ± 2HRC

3.2. Results of numerical investigation
The following results show the influence of parameters such as punch length, cutting clearance and slant angle on the horizontal punch deflection for a circular punch having a diameter of D = 10 mm. The analysis was performed according to the point tracking method described in section 3.1, which was calculated at point P1 (Figure 3). This point showed the highest deflection and, therefore, represents the critical case of a collision between punch and die.

3.2.1. Influence of the punch length on horizontal punch deflection. Deflection of punch in case bending loads applied mainly depends on the punch material, punch diameter and punch length. In this study, the influence of the punch length on the punch deflection was investigated, the punch material (1.3343) and the punch diameter were kept constant. As shown in Figure 4, the difference of the horizontal punch deflection between punch length of 100 mm and punch length of 80 mm emerges around 0.02 mm. In the case of a cutting clearance of 10%, study shows to extend process limits by 20% when using shorter punches. It can be seen that the increase in horizontal punch deflection is relatively linear with increasing punch length. In all three cases investigated, the maximum deflection limit value of 0.1 mm was not achieved, thus the punching process doesn't appear critical in terms of investigated parameters. The maximum deflection limit value of 0.1 mm is given by theoretical cutting clearance of u = 10% of sheet thickness t = 1 mm.

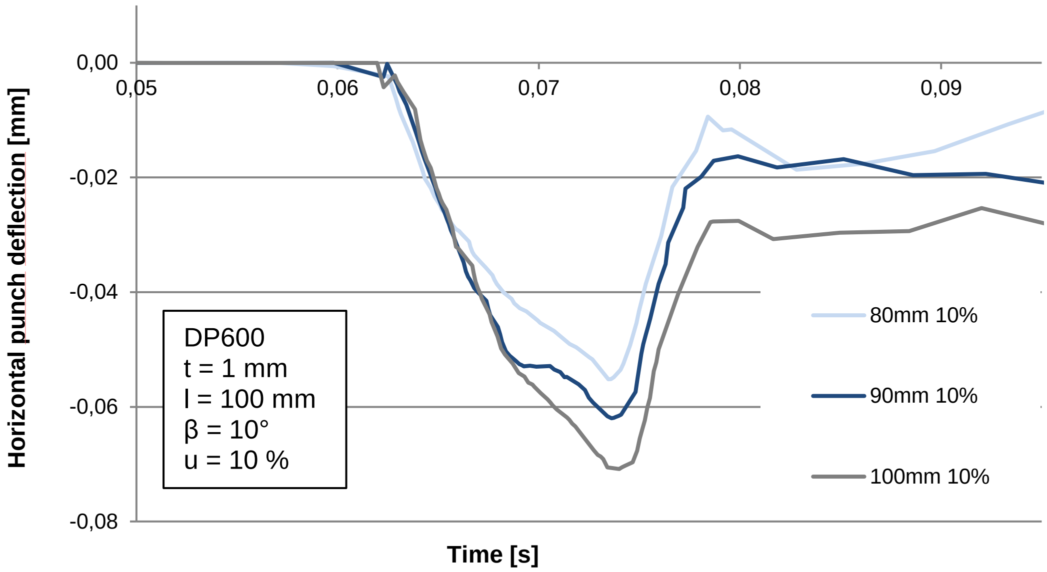

Figure 4. Influence of punch length on horizontal punch deflection

3.2.2. Influence of the cutting clearance on horizontal punch deflection. One of the most investigated influencing factors in the cutting process is the clearance. The selection of the cutting clearance influences both quality of the cut surface and required amount of force and cutting work. A cutting clearance that is too large may cause incipient cracks parallel to the surface, especially in case of higher-strength steel grades, due to unfavorable stress conditions in the clearance. Part quality is also influenced by clearance.

Figure 5 shows six graphs exhibits results gained by simulation, performed with different clearance settings during cutting of DP600 material (thickness t = 1 mm) with a slant angle of β = 10 °. The progression of the curve emerges similar to Figure 4. The influence of an increasing clearance caused a maximum offset of 0.01 mm from 0.05 mm to 0.06 mm when utilizing a punch length of 80 mm.

In general enlarged cutting clearance indeed expand process limits of cutting process. Thus, when increasing clearance up to 15% then the deflection of punch nearly appears unchanged. All thow the cutting clearance was enlarged by 50%, which is a lot. The results of the punch deflection (Figure 5) for the punch lengths 80 mm and 90 mm corresponds to each other. The results of the punch deflection for punch length 100 mm doesn't show a difference between cutting clearance of 10% and 15%.

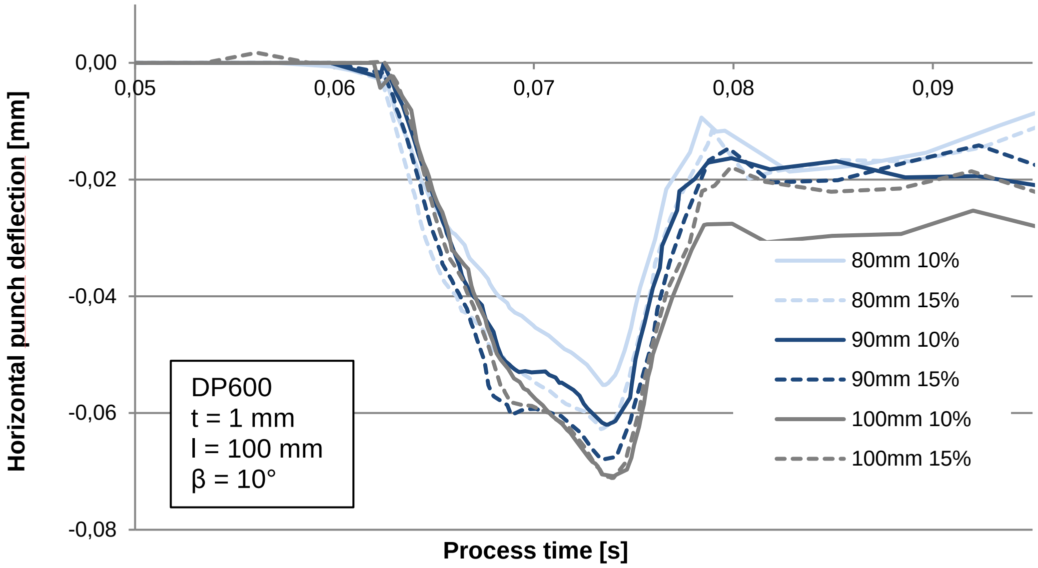

Figure 5. Influence of cutting clearance on horizontal punch deflection

3.2.3. Influence of the slant angle on horizontal punch deflection. As described in the previous section, determination of critical slang angle is very important for robust shearing process layout. In this study, seven different slant angles (10 °-30 °) were investigated as shown in Figure 6. The progression of each graph looks different. As already mentioned, the maximum horizontal punch deviation was measured around 0.07 mm when considering a slant angle of β = 10 °. The increase of the slant angle up to β = 25 ° caused a maximum punch deflection of 0.03 mm. All of these calculated punch deflections at the end did not cause punch failure during piercing.

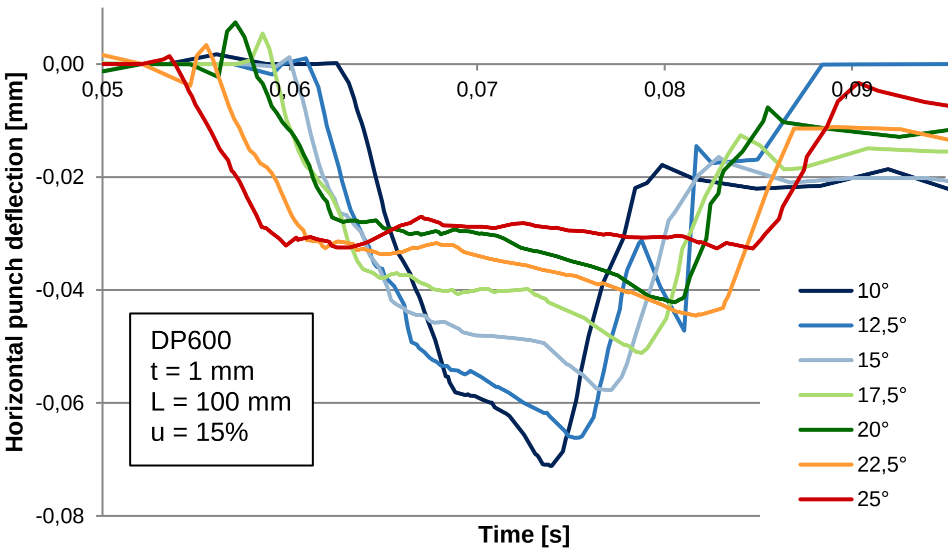

Figure 6. Influence of slant angle on lateral punch deflection

As shown in Figure 6, an unstable system is to be expected when piercing with slant angle. The higher the slant angle is chosen in the tool, the lower punch deviation was measured in the process. This is in contrast to the results presented in [12], where punch deflection was measured experimental by eddy current sensor. The influence of the slant angle in numerical investigation was found significantly high, too. The meshing of the sheet metal causes the reason of the counterproductive statement. The mesh was finely adjusted in the shear zone by using mesh windows and the damage model according to normalized Cockcroft and Latham. By using remeshing and deleting the element methods, individual elements were deleted after reaching a critical value C_{crit}. This means that no horizontal force is transmitted to the punch. In Fig. 6, for example, the influence of the horizontal punch deflection caused by bending moment is shown and is generated by the off-center load transmission. It should also be noted that the cutting line, which actively interferes with the punch, decreases as the slant angle increases. A reduction of cutting line concludes a reduction of cutting force and with it a reduction of lateral punch deflection. Releasing the degree of freedom in the X-direction of the sheet metal, which allows sliding of the sheet metal and was noted on the experimental investigation in [12], will affect the results of lateral punch deflection and will be explored in future scientific work.

4. Conclusion

This study presented in this paper shows different influence factors while piercing DP600 with a slant angle. The most important factors are clearance, punch length and slant angle. In order to evaluate these factors, a numerical model set up was designed and lateral punch deflection was measured using a point-tracking method. The results showed that the highest punch deviation is caused by the slant angle. In relation to slant angle, punch length and clearance have a lower influence on the measured punch deflection.

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