Identification of process limits for punching with a slant angle

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Abstract. In order to experimentally identify process limits during punching with slant angle, a test tool was manufactured at the Institute for Metal Forming Technology (IFU) for in-situ measuring the horizontal punch deflection. The modular design of a test tool enabled the variation of numerous cutting parameters such as the "cutting clearance", the "punch length" or the "slant angle". Considering current lightweight construction trends in automotive industry, sheet metal materials HC340LA, DP600 and DP1000 were investigated, since these high-strength steel materials allow the use of relatively thin sheets in modern car body designs. As a result of investigations carried out in single stroke testings, a cutting parameter-dependent overview of maximum possible slant angles could be obtained, which was not yet available according to the current state of the art. Based on gained results, design guidelines for tools for punching with slant angles were derived, which were subsequently validated by endurance tests performed under lab conditions. In summary, the research work carried out does not only show a list of the maximum possible slant angles. Rather, it was possible to work out the insight that the process limits for punching with slant angle are assumed to be too conservative in industrial practice. For example even the high-strength sheet material DP1000 was punched reliably with a punch diameter of \( d = 5 \text{mm} \) up to a slant angle of \( 17.5^\circ \). In industrial practice, a cost-intensive cam solution would have been used from a slant angle of approx. \( 5^\circ \).

1. Introduction
The competitiveness of manufacturing companies nowadays largely depends on the quality, reliability and manufacturing costs of manufactured products [1][2]. In addition, industrial companies are facing continuously increasing technological, economic and ecological challenges [3]. The consideration of suitable manufacturing possibilities and alternatives therefore directly influences the manufacturing costs of a product [1][4]. However, when manufacturing processes are used, there are always process windows, which restrict their applicability from a technical or economic point of view. For economic or process related reasons, punching of structural sheet metal components in production often is realized by punching directions deviating from the optimum angle of attack of \( 90^\circ \) [5]. By punching with a slant angle, expensive cams can be saved and it is possible to keep the number of manufacturing operations low. The challenge posed by this process arises from the fact that the transverse forces acting horizontally on the punch increase as the slant angle increases. These transverse forces cause a horizontal punch deflection, which in worst cases can exceed the size of the cutting clearance and thus lead to immediate failure of the cutting tool. For the design of cutting tools, exact information on maximum possible slant angles is therefore required.
2. State of the Art

In recent years, extensive research work has been carried out on trimming with a slant angle at open cutting line. This research work revealed findings about achievable surface qualities [6], amounts of transverse forces occurring [7], the expansion of the cutting clearance [8][9] and information about the maximum possible slant angles [9]. In contrast, no empirically determined values for maximum possible slant angles have been published so far for punching with a slant angle at closed cutting line. However, information about the maximum possible slant angle is equally important for this process variant, since horizontal transverse forces are also applied to the punch causing a horizontal punch deflection [10][11][12][13]. This deflection leads to inaccuracies in the cut part geometries and increased tool wear [5][14][15]. In extreme cases, an inadmissibly large punch deflection causes the cutting tool to fail as the punch collides with the die [5]. In industrial practice, for these reasons, cutting with larger slant angles is preferably avoided. In order to ensure series suitability, maximum possible slant angles are often estimated on the basis of conservatively designed empirical values [11]. As a consequence, cam tools are already used for relatively small slant angles in order to realize a vertical hole direction, especially when punching high-strength sheet metal materials [5][11][13]. Depending on the type and size of a cam, however, costs of 500 to several thousand euros could be saved per slide unused. In order to reduce tooling costs, a research project funded by the AiF (German Federation of Industrial Research Associations) was carried out at Institute for Metal Forming Technology for investigating the process limits of punching with slant angles in more detail.

3. Definitions and Symbols

Punching with a slant angle describes the cutting process in which workpieces are cut on surfaces that are not perpendicular to the punch movement. Thus, the punch hits a surface inclined to the horizontal. Figure 1 schematically shows the “punching with slant angle” process and lists the formula symbols used in this paper.

$$\beta = \text{Slant angle}$$
$$L = \text{Length of punch}$$
$$u = \text{Cutting clearance (rel.)}$$
$$s = \text{Thickness of sheet metal}$$
$$WS = \text{Sheet metal material}$$
$$d = \text{Punch diameter}$$

**Failure Criterion:**
Deflection $\geq$ Cutting gap $u$

![Figure 1. Punching with a slant angle (overview)](image)

4. Experimental investigations

The experimental investigations reported about in this paper were performed using a modular test tool allowing the measurement of the horizontal punch deflection. The principle structure of the tool is shown in Figure 2 by a schematic sectional view. For the in-situ measurement of the punch deflection an eddy current sensor was integrated into the downholder of the tool. The eddy current sensor enabled recording of approx. 34000 measured values per second in order to ensure a high resolution of the measured punch deflection. Finally, a load cell was installed into the tool in order to record the punch force curves.
In the experimental investigations, all punches were firmly clamped over a length of 22mm in the shaft area. The punches used in the experiments were standardized according to ISO8020 having a shaft diameter of 13mm.

4.1. Parameters for single stroke measurements

Table 1 provides an overview of the different experimental parameters investigated with the modular test tool.

| Parameter | Number of variations | Description                        |
|-----------|----------------------|------------------------------------|
| $\beta$   | 7                    | 10° to 25° (steps of 2.5°)         |
| $L$       | 3                    | 80mm, 90mm, 100mm                  |
| $u$       | 2                    | 10%, 15% (refers to $s$)           |
| $WS$      | 3                    | HC340LA, DP600, DP1000             |
| $s$       | 0                    | 1mm                                |
| $d$       | 2                    | 10mm, (5mm)                        |

By exchanging die and downholder combinations in the testing tool, the slant angle was varied in the range from $\beta = 10^\circ$ to $\beta = 25^\circ$. The variation of the slant angle was carried out in steps of $\Delta \beta = 2.5^\circ$. The smallest slant angle investigated was determined according to conservative design using the following equation.

$$ \beta_{\text{max}} \approx 1.0 \ldots 1.5 \times d $$

(1)

Formula (1) is used in industrial practice in order to estimate the maximum possible slant angle of punching operations [11]. Since the formula does not include the length of the punch, a variation of this parameter (80mm, 90mm, and 100mm) was performed in the experiments. According to VDI3374 design guidelines, the punches were firmly clamped over a length of 22mm in the shaft area. The punch diameters examined were defined as $d = 5\, \text{mm}$ and $d = 10\, \text{mm}$. By using the test materials HC340LA,
43. DP600 and DP1000, high-strength materials were deliberately chosen to follow the current lightweight construction trend in automotive industry. The size of the cutting clearance selected for the investigations was based on standard industrial values. Usual values for the size of the cutting clearance are 10% and 15% of the sheet thickness \( s \). A variation of the sheet thickness \( s \) was not carried out within the scope of the investigations presented here. Selection of the sheet thickness \( s = 1 \)mm was based on the maximum sheet thicknesses of automotive car components. In order to identify maximum possible slant angles, the parameters shown in table 1 were subjected to a full factorial test plan and the size of the slant angle was successively increased until the measured punch deflection exceeded the size of the cutting clearance. The results of the experimental investigations are described below.

4.2. Experimental results of single stroke tests using a punch diameter of \( d = 10 \)mm

Figure 3 shows examples of a punch force and a punch deflection curve measured during the single stroke tests performed. The curves shown here are characteristic for punching with a slant angle. Thus, punch force curves measured show two peaks. First peak marks the first penetration of the cutting punch into the sheet metal material. The second peak represents the point in time at which the slug is completely separated from the sheet metal. Furthermore, figure 3 shows that the maximum of the punch force curve (second peak) and the maximum of the (horizontal) punch deflection correspond vertically on the time axis in good approximation.

![Figure 3](image)

**Figure 3.** Example for a recorded measurement chart \((d = 10 \)mm\)

During all measurements, positive punch deflections were detected - independent of the parameter combination. This means that the orientation of the horizontal punch deflection occurs in the direction of the eddy current sensor (see figure 2). The slant angle \( \beta \) was successively increased until the (measured) maximum horizontal punch deflection exceeded the size of the cutting clearance \( u \) (see figure 4). Figure 4 shows an example of the maximum horizontal punch deflection measured with this method for the specified test parameters. Each of the measuring points shown in figure 4 represents the mean value of five repeated measurements. These measurements showed a high repeatability, since they only exhibited deviations of \( \pm 5 \mu m \).
Figure 4. Experimental determination of max. possible slant angles

The diagram in Figure 4 shows, for example, that the process limit for DP1000 material lies between $\beta = 17.5^\circ$ and $\beta = 20.0^\circ$. In the case of DP1000, process-safe punching can thus be performed up to a slant angle of $\beta_{\text{max}} = 17.5^\circ$. The following table provides a complete overview of the maximum slant angles $\beta_{\text{max}}$, which were experimentally determined for the sheet materials considered using a punch diameter of $d = 10\,\text{mm}$:

Table 2. Experimental results (d=10mm)

| WS          | L[mm] | u [%] | $\beta_{\text{max}}$[°] |
|-------------|-------|-------|-------------------------|
| HC340LA     | 80    | 10    | 17.5°                    |
|             | 80    | 15    | 20.0°                    |
| (R_m = 460MPa) | 90    | 10    | 15.0°                    |
|             | 100   | 10    | 15.0°                    |
|             | 100   | 15    | 17.5°                    |
| DP600       | 80    | 10    | 17.5°                    |
|             | 80    | 15    | 17.5°                    |
| (R_m = 625MPa) | 90    | 10    | 15.0°                    |
|             | 90    | 15    | 17.5°                    |
|             | 100   | 10    | 15.0°                    |
|             | 100   | 15    | 17.5°                    |
| DP1000      | 80    | 10    | 15.0°                    |
|             | 80    | 15    | 17.5°                    |
| (R_m = 1100MPa) | 90    | 10    | 12.5°                    |
|             | 90    | 15    | 15.0°                    |
|             | 100   | 10    | 12.5°                    |
|             | 100   | 15    | 12.5°                    |
The process limits determined show, for example, that the test material DP1000 can be punched up to a slant angle of $\beta_{\text{max}} = 17.5^\circ$ with favourably selected cutting parameters ($L=80\text{mm}, u=15\%$). With unfavourable selected cutting parameters ($L=100\text{mm}, u=10\%$) punching is possible up to a slant angle of $\beta_{\text{max}} = 12.5^\circ$. A measurement of the cutting heights showed no significant differences between the achievable hole qualities at $u=10\%$ and $u=15\%$. When designing tools for punching with a slant angle, therefore, the use of short piercing punches and a comparatively large cutting clearance is recommended. The listed results also show that the horizontal punch deflection increases in relation to the tensile strength of the sheet material.

4.3. Experimental results of single stroke experiments with a punch diameter of $d=5\text{mm}$

In addition to the investigations presented above, experiments with a punch diameter of $d=5\text{mm}$ were also carried out. Based on the test results shown in Table 2, cutting dies up to a slant angle of $\beta=17.5^\circ$ were manufactured and integrated to the test tool. Figure 5 depicts the force and deflection curve of the experiment considering the most unfavourable parameter combination. The most unfavourable parameter combination includes the longest investigated punch length and the smallest investigated cutting clearance ($L=100\text{mm}, u=10\%, \text{material DP1000}$). Here, the measured maximum punch deflection of about $80\mu\text{m}$ is considerably smaller than the cutting clearance ($u=100\mu\text{m}$). Thus, the process limit is not yet reached when using the parameter combination mentioned at a slant angle of $\beta = 17.5^\circ$. Considering in this context the results obtained when punching using a punch diameter of $d=10\text{mm}$ (see Table 2), the following inference is gained for punching with a slant angle:

$$\beta_{\text{max}}(d = 5\text{mm}) > \beta_{\text{max}}(d = 10\text{mm})$$  (2)

Due to lower process forces, the measured horizontal punch deflection at a hole diameter of $d=5\text{mm}$ is smaller than the measured deflection at a hole diameter of $d=10\text{mm}$. A buckling of the piercing punches having a diameter of $d=5\text{mm}$ did not occur during the experimental investigations.

According to the state of the art, in this case, cost intense cam-solutions would have been used from a slant angle of $\beta = 7.5^\circ$ at the latest (see formula 1). In contrast, the experimental results presented in figure 5 show that the process limit defined by the cutting clearance is not yet exceeded at a slant angle of $\beta = 17.5^\circ$.  

![Figure 5. Example for a recorded measurement chart (d = 5mm)](image-url)
4.4. Experimental results of endurance tests

For verifying the maximum possible slant angles identified in single stroke, endurance tests were additionally carried out for punching with slant angle. In these endurance tests, only selected test parameters were examined based on the findings from the single stroke tests (see figure 6). In order to promote wear on the cutting punch due to higher process forces, a sheet thickness of \( s = 1,2\, mm \) was selected. The main focus of these investigations was on the measurement of the (maximum) horizontal punch deflection as a function of the number of press strokes and the associated punch wear. Figure 6 shows the measured values of the maximum punch deflection for the materials DP600 (black) and DP1000 (blue).

![Figure 6. Experimental results of endurance tests](image_url)

The linear compensation lines in Figure 6 show that for both test materials a slight increase in punch deflection occurs with increasing number of press strokes. With regard to the process limit (cutting clearance), however, this increase is not critical since the punch deflection does not exceed the size of the cutting clearance. In contrast, cutting edge breakouts which occurred at the piercing punches after 38000 press strokes or 50000 press strokes are more critical.

5. Summary and further research

This paper contains important findings on punching with slant angle, which have been obtained from extensive experimental investigations. Thereby, occurring horizontal punch deflection was measured in situ by integrating an eddy current sensor into the hold-down device of a test tool. As a result of the investigations carried out in single stroke tests, a cutting parameter-dependent overview of maximum possible slant angles could be obtained, which was not yet available according to the current state of the art. Based on gained results, design guidelines for tools for punching with slant angles were derived and subsequently validated by endurance tests performed under lab conditions. In summary, the research work carried out does not only show a list of the maximum possible slant angles. Rather, the insight was gained that the process limits for punching with slant angle are assumed too conservative in industrial practice. Future research at Institute of Metal Forming Technology will focus on the numerical investigation of the process "punching with slant angle". In order to further expand the numerical investigations known from Senn [16], a measurement of the occurring transverse forces will be realized. These measured transverse force curves, will lead to a fine calibration of cutting simulations for punching with slant angle in the future.
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