A novel approach for characterising the cause of disc formation by the shear cutting process in a punching machine

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Abstract. The objective of this paper is to validate a method for identifying the cause of disc formation by numerical and experimental investigations for a single-stage shear cutting process in a tool-bound punching machine. To this end, first a 2D simulation model for the deep-drawing steel DC01 is developed, which enables the sophisticated requirement of tracking the material flow behaviour in the cutting process to be met by using the FEM Software DEFORM. Furthermore, the plastic flow behaviour is measured in an equivalent experiment with strain gauges near the cutting process. Then, the measurement results from the experimental investigation are contrasted with those from the simulation and compared for reliability at the measuring position of the strain gauges. The main contribution of this paper is a numerically and experimentally performed comparative study, in which the verified results of the first investigation near the shearing process are transferred into the cutting area and are validated subsequently.

1. Introduction
As a result of the growing globalization of markets and the demand for digitalization concepts regarding autonomous production, flexible sheet metal manufacturing industry is currently facing a multitude of challenges. In recent years, special efforts have thus been made to steadily accelerate process digitalisation, which is becoming increasingly important not only in production, but also in the development departments. Especially in process development, FEM simulations are being used progressively and established as a permanent institution. Hence, forming operations such as deep drawing or bending have been modelled and calculated by modern FEM simulation for several years [1]. In this context, the pre- and post-production processes that are required for the manufacture of technical products are also gaining in significance. Especially in the processing of sheet materials, shear cutting has to be mentioned as one of the most common techniques with which almost every technical product is processed at least once in its production chain. Here, conventional shear cutting is the most frequently used process variant in the industry. This process is often used on single-acting presses or on machine tools in flexible sheet metal production for the manufacturing of entire workpieces. In contrast to the firmly established use of FEM simulation in deep drawing and bending in industry, shear cutting could not participate in this trend similar. Existing studies have often concentrated in their simulation requirements on the cut surface characteristics of the shear-cut components [2] [3] [4] [5]. In addition to the high-quality requirements for the cutting surface for shear cut components, the flatness in the flexible production of sheet metal parts is of crucial importance [6]. This flatness is significantly
influenced by the prevailing residual stresses in the sheet material. In the mechanical cutting process, which includes normal shear cutting, it is the elastic and plastic deformations in the cutting influenced zone next to the cutting line that result in the residual stresses in the sheared part. In this case, the stresses that have been introduced extend to different degrees in the thickness direction of the sheared sheet and cause a deforming force effect in the component activated by the stress asymmetry. By a multitude of performed operations, which are common in flexible sheet metal production, the resulting accumulation of the stress states can be measured on the finished component resulting in an elastic and plastic deformation. In the following, these deviations from the flat component are referred to as disc formation and are caused by the plastic flow behaviour of the material in the cutting area. As the disc formation directly correlates with the introduced mechanical stress states, the simulation of them is of particular interest for cutting processes. Previous research in this context has been carried out mainly in the field of electrical sheet production, as the electromagnetic properties are negatively influenced by the introduced stress states [7] [8] [9] [10] [11]. Here, the comparison of the simulation with the experimental results has mainly been carried out on the basis of the electromagnetic properties or cutting surface characteristics obtained. However, previous studies do not offer a method to compare the stress inducement during the cutting process with those of the simulation based on the stroke movement. Another aspect not shown in previous studies, is the description of the exact flow behaviour of the material during the cutting process. By comparing a simulation model with these experimental characteristics, significant advantages would not only arise for the prediction of the resulting disc formation. In fact, the FEM simulations could be validated in the sheet thickness direction. This also offers the opportunity to identify more precisely the critical stages in the shearing process, in which the stress imbalance is induced. Subsequently, mechanisms could be developed for the cutting process to reduce or even avoid such effects. Therefore, it is important to gain more specific understanding on this topic, which is given in this paper as a first approach.

2. Experimental setup

2.1. Machine design

For the experimental investigation in this article, the hydraulically driven punching machine TruPunch 5000 with a flexible tool system was used. In this system, force is applied to the punching process via a hydraulic unit that operates at two pressure levels. The frame of the machine itself consists of a C-frame, to which the hydraulic unit is attached at the back end. On the open side of the frame the upper and lower tool holders for punch and die are installed. The concentricity of the punch and die is determined by the alignment of the tool holders in the C-frame, and they are fixed in their horizontal position. The position of the metal sheet in the machine is fixed by a pin, that moves out of the machine table during insertion. At production, the metal sheet is held by clamping claws and moved to the correct position in the C-frame. The flexible tool concept basically consists of the four elements punch, alignment ring, stripper and die. The machine and tooling concept are shown in Figure 1. In contrast to press tools, where the wear of the top and bottom tools is usually considered as a set, the two tool components in flexible manufacturing are freely interchanged.

![Figure 1](image.png)  
**Figure 1.** a) Punching machine TruPunch 5000; b) Tooling concept
2.2. Applied Material
The test material investigated in this study was the deep-drawing steel DC01 (EN-AW 1.0330) having nominal sheet thickness of 2.0 mm. Table 1 shows the chemical composition of the material.

| Material       | C   | Si  | Mn  | P   | S   | Cr  | Al  | Ni  |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|
| EN-AW 1.0330   | 0.035 | 0.044 | 0.209 | 0.009 | 0.010 | 0.026 | 0.037 | 0.020 |

To characterise the mechanical properties of the mentioned material, uniaxial tensile tests were carried out with various orientations to rolling direction. The resulting mechanical properties are displayed in Table 2. The lowest value of ultimate tensile strength occurred against rolling direction. Diagonally to the rolling direction, the value was significantly higher. The extrapolation of the yield curve was calculated with the values of uniaxial tensile tests under an orientation of 90° to the rolling direction. The followed procedure was based on the common method of Ludwik-Hollomon and Swift, as described in [12].

| Material       | Rolling direction [°] | E-Modul E [MPa] | Yield strength $R_{p0.2}$ [MPa] | UTS $R_m$ [MPa] | Uniform elongation $A_e$ [%] | Fraction elongation $A_{100}$ [%] |
|----------------|-----------------------|-----------------|---------------------------------|----------------|-------------------------------|----------------------------------|
| EN-AW 1.0330   | 0                     | 199272          | 183.702                         | 307.190        | 23.25                         | 41.83                            |
|                | 45                    | 216689          | 200.563                         | 324.311        | 20.76                         | 36.73                            |
|                | 90                    | 205556          | 191.198                         | 301.162        | 22.62                         | 40.41                            |

2.3. Measurement methods and setup
In order to implement the method for characterising the cause of disc formation by the shear cutting process presented below, an experimental setup was designed, that can map the material flow behaviour in the cutting process. Therefore, an experimental measurement of the elastic and plastic flow behaviour in the sheet thickness was developed. To measure the flow behaviour, strain gauge sensors were integrated on a cut-out area in the sheet. For this purpose, the depth value for the cut-out area was set to 0.5 mm. This value results from the trade-off between measuring as close as possible to the bottom surface of the sheet and the integration thickness of the strain gauge sensor. The distance of the strain gages sensor system has been designed that the elongation measurement can be carried out as close as possible to the cutting process. The cut-out area for the application was made symmetrically to the punched geometry in the sheet and the residual bar width was chosen at 0.45 mm. Thus, it was ensured that the force was distributed symmetrically over the sheet and no asymmetrical deformation was promoted in the cutting process. In addition, this resulted in an advantage for the calculation speed of the simulation, as the FEM calculation could be carried out symmetrically [13]. In the present study, C2A 06 G1350-120/SP70 type strain gages from Vishay were used. The foil was applied at the edge of the cut-out area on the bottom side of the sheet. The measuring points P1 and P2 represent the grid length of the strain gauge sensor with a length of 1.1 mm. The bottom side of the prepared sheet with the applied strain gauge sensors is shown in Figure 2. The numbered sections from 1 to 4 mark the areas that have been prepared similarly for the measurements on the bottom side of the sheet.
Figure 2. Bottom side of the prepared sheet with the integrated strain gauge sensor and the two labelled measuring points P1 and P2, that represent the grid length of the applied strain gage sensor.

The study was carried out with the objective of obtained information about timing and cause of the resulting disc formations gained by the stress curves during the cutting process. In both the simulation and the experimental investigation, two punches with different wear conditions were compared with each other. In general, the propagation of wear was assumed to extend further along the lateral surface than at the front surface, what is affirmed in [14]. Consequently, a preparation contour with a chamfer length of 1 mm x 60° seemed appropriate for the final wear state. As counterpart, a tool without a preparation contour was used. The cutting parameters of the experimental measuring are summarized in table 3. In addition to the strain gages measurements, the stroke movement of the punch was measured using a linear measuring system on the ram rod. To ensure comparability of the measuring signals detected by the different sensors, time synchronicity of the measuring signals had to be guaranteed. For this purpose, the imc measuring system PL8 was used, which allowed all required signals to be recorded simultaneously.

Table 3. Setup summery of investigated parameters.

| Factors                  | Settings                                      |
|--------------------------|-----------------------------------------------|
| Cutting clearance        | 10%                                           |
| Punch diameter           | 8 mm                                          |
| Cutting edge             | No preparation and chamfer 1mm x 60°           |
| Stripper force           | 0 kN (approx. 0.6 mm above the sheet metal surface) |
| Sheet metal material     | DC01                                          |
| Sheet metal thickness    | 2 mm                                          |
| Sheet metal format       | 400 x 400 mm                                  |
| Blanking operations      | 2 for each cutting edge                       |

2.4. Analyses of the experimental investigation

For comparing the real data with the simulation results, a previous data preparation was required to ensure comparability on an equal basis. As only the workpiece itself was considered as an elastic-plastic element in the simulation, which led to the advantage of shorter calculation times in the simulation, the elastic parts of the machine have to be considered subsequently. For this purpose, the elastic components of the machine were extracted from the measured stroke movements on the ram rode. For measuring the elastic components of the machine strain gauges were applied to the C-Frame of the machine. The strain gauge sensors were calibrated in advance to reflect the resulting distance between punch and die as a
function of the measured strain in the C-frame. Besides, it was shown in [15] that the stroke movement of high dynamic machine tools show certain fluctuations in time series. To avoid falsification of the results due to these effects, the signal series had to be processed prior to the final comparison. Therefore, the remaining time latencies were eliminated from the signals. The time synchronous data sets of the stroke movement and the strain gauge measurements were transformed as strain over stroke movement and scaled by the maximum strain value of the simulation. The scaling values that were used for the 4 respective measurements are summarised in table 4. This was a necessary step, as many influencing factors had a major impact on the measurement results, making a comparison of absolute values inappropriate. The most important influencing factors in the presented setup were (sorted in descending order of their influence):

- deviations of the grid position on the foils of the strain gages - deviations of up to 0.2 mm
- fixing the sheet in the machine
- application of the strain gages in the cut-out area
- manufacturing of the cut-out areas for the strain gauges
- deviations in concentricity of the tools due to the tool change

Therefore, in the final comparison only a qualitative comparison of the strain curves was possible. Although the comparison allowed no longer any conclusion about the absolute values, the exact course description of the flow behaviour of the material during the cutting process was still possible.

Table 4. Scaling vales for data preparation.

| Measurement                                      | Scaling value |
|--------------------------------------------------|---------------|
| real experiment 1 – no preparation               | 0.46222       |
| real experiment 2 – no preparation               | 0.25772       |
| real experiment 1 – cutting edge 1.00 mm x 60°   | 0.86032       |
| real experiment 2 – cutting edge 1.00 mm x 60°   | 0.65629       |

3. Modelling approach and simulation setup

In general, the simulation of shear processes due to damage modelling and element separation/erasure models as well as missing material properties is very challenging in this field. As a first approach for consideration, a numerical 2D calculation therefore appears to be usefully, since the shear cutting process mainly concentrates on operations in sheet thickness direction and the geometries are rotationally symmetric. The software DEFORM 2D from SCTF has been used in many scientific papers and is today one of the most common software for numerical analyses of shear cutting processes. The advantage of this software is the sophisticating representation of elastic-plastic material properties by considering local and global springback effects. The investigated sheet metal material DC01 with a nominal thickness of 2 mm was meshed with solid elements and an elastic-plastic material law was chosen. For plasticity, the von Mises model was selected and as integrations scheme, the Newton-Raphson method was chosen. This algorithm reduced in each load step the resulting error by adding an internal stiffness. In the calculation, all other components such as the punch, the stipper and the die were defined as rigid. To avoid excessive deformation of the FE mesh from large plastic deformations during the cutting process, an integrated algorithm in the software was used for remeshing and a Coulomb contact with a value of $\mu = 0.1$ was chosen at contact between the tool parts and the sheet. The elongation between the two measuring points P1 and P2 was determined in DEFORM 2D by using the point tracking method. Here, two node elements were selected on the meshed workpiece’s surface (P1 represents the beginning of the measuring grid of the strain gauge and P2 the end) and these points were tracked via the simulated stroke movement. The tracking of the change in distance between P1 and P2 showed the elongation across the measuring grid of the strain gauge. The resulting simulation setup for this study is shown in Figure 3.
Figure 3. Simulation setup of the investigation showing the method for measuring the elongation across the measuring grid of the strain gauge using point tracking method.

Figure 4. Comparison of the cutting surfaces of the real experiment and the simulation for the chosen setup (punch with no preparation of the cutting edge).

For modelling damage in the simulation, the normalised Cockroft & Latham criterion was applied. The model is based on the theory that the energy absorption capacity of the control volume in the material is limited and will fail if a specific value is exceeded [16]. It is one of the most frequently used models in FEM simulations for shear cutting. This caused a local failure of a mesh element as soon as the cumulative real-time value \( C_{\text{normC&L}} \) of the plastic work reached a critical limit of \( C_{\text{crit}} \). Thereby, a fixed number of adjacent elements must fail before the programme starts to delete extremely deformed elements. The number of adjacent elements represents the control volume of the used damage model.

For this study, the best results were achieved for a value of 3 adjacent elements in combination with \( C_{\text{crit}} = 2.7 \). These values were calibrated by comparing the smooth cut zone of the simulation and experiment. For this, several damage values with different numbers of adjacent elements were simulated and then the cut surfaces were compared of the real part and the simulation. The used "normalised Cockroft & Latham" criterion is formulated by the following equation:

\[
C_{\text{normC&L}} = \int_0^{\varepsilon_f} \frac{\sigma^*}{\sigma_v} \, d\varepsilon.
\]  

(1)

Here the maximum principal stress \( \sigma^* \) refers to the equivalent stress \( \sigma_v \). The comparison of the cut surfaces for the selected values of the damage criterion is shown in Figure 4.

4. Comparison of the simulation and experimental results

4.1. Comparison for a punch with no preparation at the cutting edge

The following results in Figure 5 show the measured difference in the elastic-plastic material behaviour of the workpiece derived from comparing the real cutting process and the simulation for a punch diameter with 8 mm and no preparation at the cutting edge. The flow behaviour of the material in the shear cutting process is mainly influenced by the properties of the material, the cutting edge contour and the measuring position. All these parameters were kept constant in the first investigation. As shown in Figure 5, the difference of the quantitative comparison of the real cutting process and the simulation emerges mainly in the elastic stage of the cutting process. It can be seen that the increase in elongation of the real cutting process is slightly delayed from the simulation. Furthermore, it can be noticed that the springback behaviour of the real experiment is less pronounced. The cause for this effect could be a small deviation of the concentricity of the top and bottom tool. The one-sided narrowing of the cutting gap favours increased grid deformation of the material and consequently reduces the elastic component after the cutting process. In addition, this anomaly could be caused by the fact that only the penetration of the punch into the sheet was considered in the measurements. Therefore, an obvious explanation is that the punch is still restraining the full springback of the sheet at that point. Overall, the simulation and the real experiment show a close agreement in their elongation course.
4.2. Comparison for a punch with a cutting edge 1.00 mm x 60°

For validation of the experimental investigations, a second comparison was examined for a different punch with a cutting edge of 1.00 mm x 60°. Figure 6 shows the comparison results of the elongation measurements for the second survey. The progression of the curve even shows a slightly closer agreement between simulation and real experiment as in Figure 5. Especially in the increase of the elastic stage, the curves are clearly closer to each other. Both the measured variance and the absolute values correspond for all elongation curves in the second investigation. The fluctuations that occurred during the entire investigation in the real measured elongations probably resulted from process intrinsics that could not be reproduced within the 2D simulation. These include positional accuracy of the sheet, asymmetric force requirements for ejecting the slug and variations in the cut surface characteristics along the punched geometry.

Figure 5. Comparison of the real measurement and the simulation results of the elongation between P1 and P2 for a punch with no preparation at the cutting edge.

Figure 6. Comparison of the real measurement and the simulation results of the elongation between P1 and P2 for a punch with a cutting edge of 1.00 mm x 60°.
5. Validation of the results
In order to obtain precise information about the plastic flow behaviour of the material during the cutting process and the resulting disc formation gained by the presented method, a transfer to the cutting area was necessary. For the simulation transfer, 1100 points with equal spacing were arranged in 11 layers across the sheet thickness. The respective point layers were horizontal arranged from 0.2 mm below the punch to 0.2 mm behind the die. The changes in distance and orientation of the points in the layers were compared with corresponding grains in etched samples. Therefore, samples were produced at different process steps and compared with those of the simulation. The samples of the process steps were generated by punching to the respective penetration depth of the punch into the sheet. The results for a stroke movement of 1.3 mm for both punch preparations are shown in Figure 7. The left side presents the etched micrographs and the right side the corresponding simulation results with the point tracking method. The dashed red lines show examples of the excellent correspondence and were set to grain and point orientation for better comparability.

![Figure 7. a) Punch with no preparation; b) Punch with a cutting edge of 1.00 mm x 60°](image)

6. Conclusion
In the experimental investigations carried out as part of this paper, a new approach for characterising the cause of disc formation by the shear cutting process in a tool-bounded punching machine was investigated. To this end, first a simulation model was developed, which enables the sophisticated requirement of tracking the material flow behaviour in the cutting process. Furthermore, the plastic flow behaviour was measured in an equivalent real experiment with strain gauges near the cutting process. In this investigation, many influencing factors on the measurement results of the real experiment were noted, making a comparison of the absolute values unsuitable. Nevertheless, the results enabled a qualitative comparison of the material flow behaviour in the cutting process. The measurement results from the experimental investigation were contrasted with those from the simulation and were compared for reliability at the measuring position of the strain gauges. Notable differences in the quantitative comparison of the real cutting process and the simulation consisted mainly in a small delay in the increase of the elastic phase. To confirm and ensure transferability of the results, the experiments were carried out with another punch and a cutting edge preparation of 1.00 mm x 60°. Based on the good results of the first investigation within the scope of the comparison of the plastic flow behaviour near the cutting zone, the presented material tracking method was transferred to the cutting zone. Thereby, the simulation results were validated by comparing the tracked flow behaviour with corresponding etched samples and their grain orientation gained by real experiments. As a result, it has been demonstrated that excellent matches could be obtained with the presented method for both punch preparations. Thus, it was shown that the flow behaviour of the material, which is decisive for the disc formation of shear-cut components, could be modelled excellently for the entire punch movement across the sheet. Here, the presented method has been shown that it offers an excellent opportunity to describe...
the material flow behaviour based on the changes in distance and orientation of the points in the layers. As a conclusion, it is proposed to apply the presented method in future investigations in order to analyse precise information about timing and cause of the emerging disc formation. A further field of applicability, that could be modelled with this method, might be in the domain of surface hardening and sheared edge formability.

7. References

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