Determination of the properties of semi-finished parts in blanking processes

S Wiesenmayer, P Frey, M Lechner and M Merklein

Institute of Manufacturing Technology (LFT), Friedrich-Alexander University Erlangen-Nürnberg (FAU), Egerlandstraße 13, 91058 Erlangen, Germany

sebastian.wiesenmayer@fau.de

Abstract. Deviations of the properties of semi-finished sheet metal parts affect the finished part’s geometry and its properties. With knowledge of the deviations, forming processes can be adjusted to a certain degree in order to maintain the part quality. Typically, in mass production, the sheets are blanked before deep drawing. Within the blanking processes, the necessary cutting force and cutting stroke are both influenced by the properties of the material. Thus, by the analysis of the process data, which is obtained in blanking processes, deviations of the properties of semi-finished parts could be determined. Within the scope of the work, it is analyzed to which degree process data, which is gained during blanking processes, can be used for the determination of the properties of semi-finished parts and their deviations. For this purpose, a blanking process is investigated for two different batches of the dual phase steel DP600 with a nominal sheet thickness of 2.0 mm and varying mechanical properties. In addition, the sheet thickness of the specimens is reduced by 5 and 10 % for one batch. The recorded process data from the blanking process is correlated with the properties of the sheet materials, which are determined with uniaxial tensile tests.

1. Introduction

The properties of semi-finished parts are subject to deviations, which influence forming processes as well as previous and subsequent manufacturing steps. Thus, they determine the properties and the quality of finished components. With regard of the increasing complex geometries and thinner wall thicknesses of car body parts, process windows become smaller and forming processes more challenging [1]. Knowledge of the deviations and their influence on the processes and part properties allows the use of adaptive tool systems for the compensation in order to maintain the part quality and avoid rejection. Requirements are the identification of the deviations and the data exchange between the different manufacturing steps. However, by common destructive characterization methods, the properties of semi-finished parts can only be determined for random samples and extrapolated, based on statistics, as the properties cannot be measured continuously in mass production. An approach for the non-destructive inline determination of mechanical properties is the use of eddy current [2]. Since the microstructure of the material influences its electromagnetic and mechanical properties, these characteristics can be correlated [3]. However, next to additional measurement equipment, mathematical models are needed for the correlation of the eddy current and the mechanical properties [2]. Moreover, the calibration of the setup is necessary for each material. Another approach is the use of data, which is generated during the production process. Until now, processes are mostly monitored individually, while the obtained data remains unused [4]. In [5] it was principally shown how information on the tensile strength of the sheet materials can be gained during blanking and bending processes and used for the adaption of the blank
holder force in a deep drawing operation. However, only maximum forces from the blanking and the bending process were considered in order to calculate the tensile strength of the used materials. Yet, for a full process control, knowledge of the flow behavior and the ductility as well as the sheet thickness of the used materials is also important.

Blanking the initial shape of the semi-finished parts from a coil is often the first step in the manufacturing chain of formed sheet metal components. Thus, within the scope of this work, it is analyzed to which degree data, which is gained during blanking processes, can be used for the determination of the properties of semi-finished parts and their deviations. For this purpose, a round hole punching process is investigated, which is typical for the production of holes for locating pins in progressive dies. The mechanical properties of the used material DP600, which is common within the automotive industry for deep drawn complex structural parts, are determined with uniaxial tensile tests. Afterwards, the properties are correlated with the force-displacement curves, which are obtained during the blanking process. While process parameters like the cutting clearance are held constant, the material properties and sheet thicknesses are varied in order to determine the influence of deviations of the properties.

2. Materials and setup

Within the investigation, a round-hole punching process is analyzed. The experiments are conducted on a universal testing machine RM400 from Schenck-Trebel with a punch velocity of 100 mm/min. The blanking tool consists of a punch, which has a diameter of 10 mm, a blank holder and a die with an inner diameter of 10.4 mm. Therefore, a cutting clearance of 0.2 mm is set, which equals a relative cutting clearance of 10 % for the investigated sheet thickness of 2.0 mm. The blank holder is connected via springs with the inner punch. The springs have a stiffness of 2200 N/mm and a pre-load of circa 0.7 kN. The specimens are quadratic and have a width of 45 mm.

A force-displacement curve, which is gained in the round-hole punching process, is depicted in figure 1. In the initial phase (1), the sheet is only elastically deformed. The force, which is necessary for the plastic deformation of the material depends on its properties and the geometry of the cutting line. Due to work hardening, the force increases during the actual cutting phase (2). In this phase, the maximum of the process force $F_{\text{max}}$ is reached and cracks are initiated. With further movement of the punch, the force slightly decreases as the cracks propagate, until the remaining cross section breaks and the force instantly drops. Afterwards, the cut out slug is pushed out from the die (3).

![Figure 1](image.png)

**Figure 1.** Force-displacement curve of a round hole punching process with blank holder

Due to the tool setup, the applied blank holder force also contributes to the measured process force. In order to extract the actual cutting force and work, the force-displacement curves are corrected. The linear increase of the force, which is caused by the compression of the blank holder springs as well as the pre-load of the springs are subtracted from the curve. Moreover, the curves are only considered until the actual cut, which is indicated by the steep decline of the force. The phase, in which the slug is pushed through the die, is not taken into account for the calculation of the cutting work $W_{\text{cut}}$. Next to the maximum cutting force $F_{\text{cut max}}$, the displacement at the cut $s_{\text{cut}}$ and the cutting work $W_{\text{cut}}$, the punch displacement $s_{\text{contact}}$, which marks the initial contact between the punch and the sheet is also taken into
account for the correlation. In order to determine $s_{\text{contact}}$ from the original, uncorrected force-displacement curves, a regression line is defined for the initial elastic deformation in a section, where the process force is between 4 and 12 kN and linear behavior can be assumed. Therefore, influences from the initial compression of the blank holder springs before the contact of the punch and the sheet and the plastic deformation of the specimen for higher forces are avoided. The intercept of the line and the x-axis is defined as $s_{\text{contact}}$ and marks the starting point of the displacement for the corrected curves. The correlation of the maximum cutting force $F_{\text{cut max}}$ and the properties of the semi-finished parts is based on equation (1), which is commonly used for the calculation of blanking processes [6]. The tensile strength $TS$, the length of the cutting line $l$ as well as the thickness $t$ are considered with a linear relationship in the equation. The equation is based on empirical observations and shows a good correlation, although material properties from the tensile tests are obtained under a uniaxial stress state, while blanking is dominated by a multiaxial stress state. The shearing constant $c$ accounts for the dissimilar forming behavior of different materials and has to be determined experimentally in order to increase accuracy. Beside the influence of the material, the shearing constant $c$ is mixed with influences of the sheet thickness, the cutting clearance and tool wear [6]. It is therefore not possible to separate those influences and determine a general shearing constant $c$ for each material without considering the circumstances of the blanking process. However, for the estimation of cutting forces a shear factor $c$ in the range of 0.6 is applied for harder materials whereas 0.8 is used for ductile materials [6].

$$F_{\text{cut max}} = t \cdot c \cdot TS$$

(1)

For the investigation, the cold rolled dual phase steel DP600 with a nominal sheet thickness of 2.0 mm is used. For the analysis of the influence of deviations of the mechanical properties of the semi-finished components on the blanking process, two different batches of DP600 with zinc coating are used. In order to simulate the variation of the sheet thickness while maintaining the mechanical properties, specimen from batch A with an original thickness of 2.0 mm were grinded to 1.9 mm and 1.8 mm. Thus, deviations of the mechanical properties due to different material batches can be avoided. With this method it is intended to separate influences of the sheet thickness and the material batch on the blanking process. However, due to grinding the zinc coating was removed on both sides from the specimens of batch A with a thickness of 1.9 mm and 1.8 mm. The true stress-true strain curves in figure 2 and the mechanical properties of the materials, which are displayed in table 1, were determined with uniaxial tensile tests according to DIN EN ISO 6892. The samples from batch A have a similar yield strength and elongation at break. However, despite the almost equal uniform elongation, the grinded specimen with a thickness of 1.9 mm and 1.8 mm have a slightly higher tensile strength and hardening behavior than the original material with a thickness of 2.0 mm which is attributed to the removed zinc coating and favorable surface conditions of the grinded specimen. Considering the standard deviation, the properties of the specimens with a thickness of 1.9 mm and 1.8 mm are equal. Batch B has a distinctly higher strength, a higher work hardening and a lower ductility than batch A.
Table 1. Mechanical properties of used materials (n = 5)

| Batch | Sheet thickness (mm) | Yield strength (MPa) | Tensile strength (MPa) | Uniform elongation (%) | Elongation at break (%) |
|-------|----------------------|----------------------|------------------------|------------------------|------------------------|
| A     | 2.0                  | 379 ± 3              | 604 ± 4                | 16.5 ± 0.3             | 25.0 ± 0.5             |
| A     | 1.9 (grinded)        | 378 ± 1              | 623 ± 2                | 16.2 ± 0.2             | 24.5 ± 0.7             |
| A     | 1.8 (grinded)        | 378 ± 3              | 622 ± 4                | 16.1 ± 0.2             | 24.6 ± 0.3             |
| B     | 2.0                  | 391 ± 2              | 666 ± 2                | 13.9 ± 0.1             | 21.7 ± 0.2             |

3. Results and discussion

In figure 3 the corrected force-displacement curves of all conducted experiments are shown. For the variation of the sheet thickness as well as for the different batches, there is no significant difference in the elastic deformation behavior in the beginning of the process. However, higher forces are necessary for the plastic deformation of sheets with a higher thickness due to the larger shear area. In addition, specimen with smaller sheet thicknesses are cut at lower punch displacements. When the mechanical properties are considered, there is also no significant difference in the initial elastic behavior. However, for batch B, which has a higher initial flow stress and work hardening behavior, higher forces are necessary for the plastic deformation of the sample. Due to the reduced uniform elongation and elongation at break of batch B, the specimens are cut at lower punch displacements. The extracted information from the force-displacement curves regarding the properties of the semi-finished parts and the limits of the accuracy are discussed in the following.

![Figure 3](image.png)

Figure 3. Force-displacement curves in dependence of the sheet thickness (a) and different mechanical properties (b)

In figure 4 a detailed analysis of the influence of the properties of the semi-finished parts on the maximum process force is given. The maximum process force increases almost linearly with the sheet thickness with a coefficient of determination of $R^2 = 97.7\%$ which is in good accordance with the linear relationship postulated in equation (1). Since changes in thickness and mechanical properties occur gradually in rolled sheet metal coils it is appropriate to compare the mean values of a sample. Due to the compensation of random scatter, the differences are more robust compared to single values. In this study, a sample size of $n = 10$ is used. Therefore, the sheet thickness and its deviations can be correlated with the maximum process force. Deviations from this linear correlation can be attributed to a change in mechanical properties which is shown in figure 4 b).

The maximum force increases from $28.7 \pm 0.1$ kN for batch A, which has a tensile strength of $604 \pm 4$ MPa to $30.7 \pm 0.2$ kN for batch B, which has a tensile strength of $666 \pm 2$ MPa. Therefore, deviations of the mechanical properties, in particular of the tensile strength, also lead to a change of the maximum process force, which allows the correlation of the tensile strength and its deviations and the maximum process force. The mechanical properties were determined with uniaxial tensile tests with a representative sample size of $n = 5$ due to the low scattering of the experiments. For the maximum
cutting force a significant difference of more than 0.235 kN at a reliability level of 99.9 % can be detected for a sample size of \( n = 10 \). However, the cutting constant \( c \) varies in dependence of thickness and other conditions, thus no satisfying linear correlation can be derived.

Another factor, which is influenced by the properties of the semi-finished parts, is the punch displacement at the actual cut. It therefore also allows the correlation of the gained data with the properties of the semi-finished parts and their deviations. Figure 5 displays the cutting stroke \( s_{\text{cut}} \) in dependence of the semi-finished part’s properties, which gives an estimate of the fracture behavior. A longer cutting stroke indicates higher formability.

The necessary cutting stroke \( s_{\text{cut}} \) increases almost linearly with the thickness of the sheet, with a mean standard deviation of ± 0.0105 mm. Therefore, the cutting stroke \( s_{\text{cut}} \) also allows the determination of the sheet thickness and its deviations through correlation with the obtained process data. However, in case of the cutting stroke, a distinct effect can be detected for a difference of 0.039 mm at a reliability level of 99.9 %. Requirement for the determination of the sheet thickness is also the knowledge on the mechanical properties of the semi-finished part, since the cutting stroke is also influenced by the elongation at break of the material. Therefore, for batch B, which has a 13 % lower elongation at break, the cutting stroke is reduced by 8 % in comparison to batch A. The low scattering of the data allows the correlation of the cutting stroke and the ductility of the material. The third factor, which can be deducted from the force-displacement curve, is the cutting work \( W \), which equals the integral of the process force \( F \) over the punch displacement \( s \). The comparison in figure 6 a) for the different sheet thicknesses from batch A, shows a linear increase of the cutting work with the sheet thickness, which allows the correlation of the factor with the sheet thickness and its deviations. When the specimen from batch A and B with a thickness of 2.0 mm are compared, there is no significant difference between the batches.
regarding the cutting work. Higher forces are necessary in order to cut the samples from batch B. However, due to the lower elongation at break, the specimen are cut at lower displacements, which results in an almost equal work for both batches in figure 6 b). Therefore, no significant information can be derived for different mechanical properties.

Since the factors maximum cutting force, cutting stroke and cutting work depend on the sheet thickness and the mechanical properties of the material, knowledge on either of the properties is required in order to determine the other. A simple approach to determine deviations of the sheet thickness is the consideration of punch displacement at the initial contact of the punch and the sheet $s_{contact}$. For the different materials, the displacement at the contact was determined with the original, uncorrected curves and the presented approach (figure 7). While for the specimen of batch A with a nominal sheet thickness of 2.0 mm a displacement at the contact of $1.304 \pm 0.005$ mm was measured in average, this value increases to $1.413 \pm 0.002$ for the specimen with 1.9 mm thickness and to $1.503 \pm 0.003$ mm for the samples with 1.8 mm thickness. Therefore, the difference in the punch displacement at $s_{contact}$ correlates with the difference of the sheet thicknesses. For the specimen of batch B an average $s_{contact}$ of $1.275 \pm 0.006$ mm was measured. When the displacement $s_{contact}$ is calibrated for one sheet thickness, the actual sheet thickness can be recalculated for each specimen. Given the variance of the recalculated sheet thickness, deviation of more than 0.008 mm of the mean value of a sample size of $n = 10$ can be detected with a reliability level of 99.9%.

With knowledge of the sheet thickness, deviations of the mechanical properties can be determined. Therefore, the process force is normalized with the cutting area, which equals the product of the length of the cutting line l and the sheet thickness t in figure 8 a). For this purpose equation (1) is rearranged, resulting in equation (2), which allows the calculation of the cutting resistance, which equals the product of the shear constant c and the tensile strength TS.

\[ y = 20.577 \cdot x - 19.664 \]
\[ R^2 = 0.946 \]
For the normalization, equation (2) is also used for the currently prevailing process force and not only for the maximum $F_{cut\ max}$. Following the approach in uniaxial tensile tests, the force is related to the initial cutting area. The deformation induced reduction of the cross section is not considered. Also, analogous to the determination of the yield strength in uniaxial tensile tests, the end of the first phase and therefore the beginning of the plastic deformation of the specimens is determined with the intercept of the corrected force-displacement curve and a regression line for the elastic deformation, which was parallel shifted. For the shift a value of 0.01 mm was chosen.

\[ c \cdot TS = \frac{F_{cut\ max}}{t \cdot l} \quad (2) \]

For the beginning of the plastic deformation of the sheets, there is almost no difference between the different specimens from batch A. All three sheet thicknesses are plastically deformed at normalized forces of 232 to 234 MPa, which is in good accordance with the tensile tests, which have shown, that despite the grinding process, all sheet thicknesses of batch A have a similar yield strength. In contrast, for specimens from batch B, which has a higher yield strength, an average stress of 260 ± 5 MPa is necessary for the plastic deformation of the sheet. Therefore, there is a correlation between the beginning of the plastic deformation of the sheets in the blanking process and the yield strength. However, the deviation of the flow stress between the batches cannot be quantified reliably, as for batch B, a 12 MPa higher yield stress leads to a 27 MPa higher begin of the plastic deformation in the blanking process, which contradicts the calculated relation of the normalized process force and the yield strength of circa 232 MPa / 378 MPa = 0.62 to 260 MPa / 391 MPa = 0.66. The cutting resistances, which equal the maximum cutting force $F_{cut\ max}$ related to the cutting area, differ slightly for the different sheet thicknesses from batch A. This is in good accordance with the findings of [6], as a smaller sheet thickness leads to an increase of the shear constant $c$. For batch B, which has a 60 MPa higher tensile strength, a 31 MPa higher cutting resistance of 482 ± 2 MPa was determined. The reason is that the shear constant $c$ is also influenced by the ductility of the material, which is lower for batch B. Therefore, with knowledge of the sheet thickness deviations of the mechanical properties can be determined. However, the accuracy is also limited, as the shear factor $c$ is influenced by the properties of the semi-finished part and therefore not constant.

4. Conclusion

Within the scope of this work it was analyzed to which degree information on the properties of semi-finished parts can be obtained from process data, which is gained during a blanking process. Considering the information, which was obtained from the force-displacement curves, the following statements on the correlation of the data with the sheet thicknesses as well as with the mechanical properties of the semi-finished parts and their deviations can be made:

Figure 8. Normalized force-displacement curve (a) and properties of the semi-finished part (b)
The sheet thickness and its deviations indicates a linear correlation with the maximum cutting force, the cutting stroke and the cutting work. These factors are interdependent with the mechanical properties which can lead to deviation of the linear correlation, which indicates a variation of the properties. However, for the cutting work no a significant deviation is observed neither for the linear correlation nor for the direct comparison, thus rendering this parameter inappropriate for the conclusion of mechanical properties.

An independent factor without influences of the mechanical properties is the displacement at contact of punch and sheet, which is based on the increase of force at contact. The derived displacement at contact can be used to recalculate the sheet thickness. However, this requires the calibration of the system based on known sheet thicknesses of one sample group. Without calibration at least deviations of the sheet thickness can be obtained with high accuracy.

Deviations of the ductility of the material can be correlated with the cutting stroke and changes of the strength with the process force. In comparison to the sheet thickness, the sensitivity is reduced.

With knowledge of the sheet thickness, the flow behavior of the sheet material can be estimated from the normalized process force-displacement curve.

The accuracy of the determination of deviations and their quantification are limited due to the interdependence of the sheet thickness and the mechanical properties.

Due to the gradual variation of properties of sheet metal, a moving average is suitable in order to increase robustness of the measured effects and to discover small variations.

Since the force-displacement curve is influenced by the mechanical properties and the sheet thickness, knowledge of one of the characteristics is required in order to determine the other reliably. A simple approach for the determination of the sheet thickness and the mechanical properties was shown. In future investigations the presented approach for the determination of the properties of semi-finished sheet metal parts and their deviations will be investigated for further materials and sheet thicknesses.

Acknowledgements
The authors gratefully acknowledge the support of the European Research Association for Sheet Metal Working (EFB) and the project-related committee for funding the project “Konzeption einer adaptiven Prozesskette für das mechanische Fügen - Mechanisches Fügen 4.0” (EFB 02/217).

References
[1] Hora P, Heingärtner J, Manupolo N, Tong L, Hortig D, Neumann A and Roll K 2011 On the Way from an Ideal Virtual Process to the Modelling of the Real Stochastic, 4th Forming Technology Forum 2011 (Zurich: ETH Zürich) pp 3-14
[2] Heingärtner J, Born M and Hora P 2010 Online Acquisition of Mechanical Material Properties of Sheet Metal for the Prediction of Product Quality by Eddy Current 10th European Conf. on Non-Destructive Testing (ECNDT 2010) vol 3 (Red Hook: Curran)
[3] Ružovič M 2004 Die zerstörungsfreie Ermittlung von genauen Zugversuchsdaten mit dem Wirbelstromverfahren (Zurich: ETH Zürich)
[4] Hagenah H, Schulte R, Vogel M, Hermann J, Scharrer H, Lechner M and Merklein M 2018 4.0 in metal forming – questions and challenges Procedia CIRP 12th CIRP Conference on Intelligent Computation in Manufacturing Engineering ed R Teti and D M D’Adonna (Gulf of Naples) vol 79
[5] Schulte R, Frey P, Hildenbrand P, Vogel M, Betz C, Lechner M and Merklein M 2017 J. Phys.: Conf. Ser. 896 012037
[6] Spur G and Stöferle T 1985 Handbuch der Fertigungstechnik Band 2/3 Umformen und Zerteilen ed G Spur (Munich, Vienna: Carl Hanser Verlag) chapter 9.2 pp 1384-96