Identification of methods for the in-situ measurement of cutting forces in a tool-bound punching machine

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Abstract. With the increasing implementation of industry 4.0 technologies in production plants, issues such as control and monitoring as well as feedback control of plants and processes are becoming more and more important in current development trends. Thereby, potential approaches to such issues are generally accompanied by an increased use of sensors in production systems, aimed at gaining operation-, product- and process-specific data. In this respect, this paper focuses on the shear cutting process of a tool-bound punching machine. One of the most important parameters for the evaluation of shear cutting processes is the cutting force required. However, the precise measurement of this highly dynamic process parameter proves to be relatively challenging. The limited installation space within the tools and the loads caused by highly dynamic axis movements decisively restrict the options for sensor-based process monitoring. In order to face these challenges during sensor implementation in such punching machines, issues regarding measuring concept, localization and resulting measurement deviation of the sensors have to be solved simultaneously. In this paper, relevant measurement concepts and their properties are discussed, and the most favourable integration possibilities are derived. Based on this, several measurement concepts are identified that could be suitable for the application considered. These measuring methods include hydraulic pressure sensors, strain gauges or piezoceramics. The major contribution of this paper is an experimentally conducted systematic comparative study of these methods, in which the accuracy of the sensors used is evaluated and the influence of different integration positions on the measurement result is investigated.

1. Introduction
As a result of the increasing globalization of markets and the demand for digitalization concepts regarding autonomous production, flexible sheet metal manufacturing industry is currently facing a multitude of challenges. Here, one challenge arises from the continuous enhancement of the degree of automation of corresponding manufacturing processes in order to ensure economical production. The key to this lies in the metrological acquisition of process data, enabling data-driven monitoring systems and process control systems to be integrated into production processes. In case of shear cutting processes, efficiency of the processes is particularly influenced by deviations in the cutting geometry caused by built-up edges, rounding and edge breakout [1]. If these deviations exceed a certain level, quality of the cut part is impaired in the area of the cutting surfaces. By means of suitable measuring technology, the influences of the cutting geometry deviations can be detected in-situ via changes in the process data. Here, the process force applied for the cutting process is of essential
importance and is therefore used as an elementary parameter for monitoring and controlling punching machines [2]. The added value of the acquired process signals depends on the signal quality, the measurement concept and the localization [3].

In the past, various methods have already been presented for the signal acquisition of highly dynamic cutting processes in automatic punching presses [3] [4]. The measurement concepts used differ in measurement position and the measurement method. The integration of individual sensor systems based on strain gages, piezoceramics or thin-film technology at different measuring positions is addressed in [5] [6] [7] [8] [9] [10]. However, a comparison of the various measuring methods and the effects of different measuring positions on the quality of the measurement results has not been carried out so far. Therefore, in this paper simultaneously applicable measuring concepts and measuring positions for a tool-bound punching machine TRUPUNCH 5000 are identified and compared by quantifiable quality measurements.

2. Experimental setup

2.1. Machine design

In the investigation reported about in this paper, a hydraulically driven punching machine with a flexible tool system was used. The machine and tooling concept are shown in Figure 1. The force is applied to the punching process via a hydraulic unit that operates at two pressure levels. For the vertical movement of the stroke, pressure is applied to the two differently sized surfaces on the top and bottom side of the ram in the punching head of the machine. Depending on the pressure ratio exerted, the ram will move up or down. To position the ram in starting position a small amount of pressure, is always applied to the bottom surface. The flexible tool concept basically consists of four the elements punch, alignment ring, stripper and die.

![Figure 1. a) Punching machine TruPunch 5000; b) Tooling concept](image)

2.2. Applied Material

The test material investigated in this study was the deep-draw 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 |

Table 1. Chemical composition of the test material.

To characterise the mechanical properties of 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 occurs against rolling direction. Diagonally to the rolling direction, the value is significantly higher. However, since only rotationally symmetrical tools were used in the investigations presented here, the deviations for the tested orientations had no effect on the measured values.
Table 2. Mechanical properties of the test material gained by tensile tests.

| Material         | Rolling direction [°] | E-Modul E [MPa] | Yield strength $R_{p0.2}$ [MPa] | UTS $R_m$ [MPa] | Uniform elongation $A_g$ [%] | 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

For the investigation, three measuring methods were chosen for comparing at three different integration positions. These measuring methods include hydraulic pressure sensors, strain gauges and piezoceramics. In addition to the force measurements, the stroke movement of the punch was measured using a linear measuring system on the ram rod.

2.3.1. Strain gauges. The idealized load case of a cutting punch during a punching operation corresponds to that of a tension/compression rod. For this reason, the cutting force was measured using strain gauge sensors (SG) applied to the outer surface of the cutting punch. Superimposed bending strains as well as thermal expansions were compensated by a suitable bridge circuit for mirror-symmetrical rod cross-sections [11]. In the present study, N2K-06-S5038P-10C/DG/E5 type strain gages from Vishay were applied to the punch. The measuring concept, the applied circuit and the equipped punch are shown in figure 2.

![Figure 2](image)

Figure 2. a) Strain measurement on a compression bar [11], b) Circuit diagram of the applied Wheatstone bridge circuit ($U_B = $ bridge supply voltage, $U_A = $ output voltage); c) Punch with applied strain gauges and soldered bridge circuit

2.3.2. Piezoceramics. According to [3], piezoelectric elements show a higher sensitivity than the strain gauges for the same mechanical strains and compressions. Therefore, such piezoelectric elements are superior to strain gages when measuring smaller forces on the same part and can provide more precise measurement results on stiff components showing smaller strains. In the field of application considered here, a concept has been developed for both the punch and the die in order to integrate piezoceramics in the force flow of the cutting elements. The tool construction including the piezoceramics is shown in figure 3. Three rotationally symmetrically arranged load cells (KISTLER type 9021A) were integrated in the die between die holder and cutting unit. For mounting the load cell in the punch, the punch was divided into two parts and the piezoceramic (KISTLER type 9061A) was clamped in between. Both piezoceramic sensors were installed with a preload force of 20 percent of the measuring range.
2.3.3. Hydraulic pressure. Force measurements were additionally carried out via the hydraulic pressures of the hydraulic press. Therefore, pressure sensors were applied to the upper (Baumer type PDRB E002.S14.B440DE) and lower pressure chamber (Baumer type PDRB E002.S14.B416DE) of the machine ram. Under consideration of the deviating area size of the pressure chambers $A_1$ and $A_2$, the resulting force $F_{HYD}$ could subsequently be determined by the following equation

$$F_{HYD} = p_1 A_1 - p_2 A_2$$

with $p_1 =$ pressure in upper chamber $A_1 =$ area size upper chamber (9976 mm²), $p_2 =$ pressure in lower chamber $A_2 =$ area size lower chamber (4661 mm²).

2.3.4. Setup for the experiments. In order to ensure comparability of the measuring signals detected by the different measurement methods, time synchronicity of the measuring signals had to be guaranteed. For this purpose, imc measuring system PL8 was used, which allows to record all required signals simultaneously. The cutting parameters and combinations of measuring methods examined are summarized in table 3.

| Factors                      | Settings                                                   |
|------------------------------|------------------------------------------------------------|
| Cutting clearance            | 10%                                                       |
| Punch diameter               | 8 mm, 16 mm, 32 mm                                        |
| Cutting edge                 | No rounding                                               |
| Stripper diameter            | 10 mm, 18 mm, 34 mm                                       |
| 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           | 1000 x 1000 mm                                            |
| Blanking operations          | 4000 per measurement series                               |
| Measurement combination 1    | Punch piezoceramic, die piezoceramics, HYD pressure       |
| Measurement combination 2    | Punch strain gauges, die piezoceramics, HYD pressure       |
For the experimental investigation, the two measurement combinations (1 and 2) were compared directly with each other. Therefore, the corresponding experiments were carried out using the same punch diameter (8 mm, 16 mm and 32 mm). This resulted in a total of six test series, each with 4000 cutting operations. The tools applied with strain gauges as well as the tools built up with piezoceramic sensors were separately calibrated in the punching machine using a pre-stressed load cell before the examination.

3. Analyses of the experimental investigation
All 4000 signal curves of each test series are superimposed for evaluation. Due to the large number of individual signals, the superimposition results in an enveloping surface that represents the signal quality of each measurement method. In addition, the mean values of all individual signals are inserted into the diagram. The range of variance of the signals for each measurement method is represented by the distance between the mean values and the border areas of the enveloping surfaces. The signals of the stroke movement are presented in the same way and can be used to explain possible irregularities in the force curves. For an improved understanding of the signal curves the characteristic phases of a cutting process are marked numerically in the evaluation diagrams. The simple numbers represent the digits for the tool integration measurement methods. For hydraulic force determination, the numerical values are marked with an apostrophe. The following nomenclature was used for representing the characteristic phases in the analysis:

\[
\begin{align*}
0 & = \text{start of the vertical stroke movement} \\
1 & = \text{penetration of the punch into the sheet, the force increases continuously} \\
2 & = \text{transition from elastic to plastic deformation, shearing starts} \\
3 & = \text{peak of cutting force} \\
4 & = \text{the incipient cracks expatiate and separate sheet and shearing part} \\
5 & = \text{the shearing force decreases rapidly} \\
6 & = \text{the vertical stroke movement reached the return point}
\end{align*}
\]

3.1. Comparison between the two measuring method combinations for 8 mm punch diameter
In this first study, the influence of the localization and the measurement methods were investigated for a small load level. Therefore, the punch diameter with 8 mm was chosen and the sheet metal material were kept constant. As shown in Figure 4 the tool-based measuring methods (punch piezoceramic, die piezoceramic) show a very similar course and a rather small variance. In addition, no significant difference between the measurements of the upper and lower tool part can be determined. In the case of hydraulic force measurement, it is to be noted that the initialization of the vertical stroke movement already leads to a signal increase. Furthermore, hydraulic force measurement shows a delayed rise about 0.7 ms in the signal curve and the peak value is approx. 50% above the peak of the piezo-based measuring methods. The hydraulic force signal also shows a larger scattering. It is also noticeable that the force signal of the hydraulic measuring method assumes negative values after reaching the return point of stroke movement.
When comparing the signal curves of measurement combination 2 in figure 5 with the curves of combination 1, no significant difference between the curves measured with piezo elements and those measured with strain gauge can be noted. Both the measured variance and the absolute values correspond for all tool-bound measuring methods in the first investigation. The hydraulic force signal also shows an identical course.

3.2. Comparison between the two measuring method combinations for 16 mm punch diameter
As described in the previous section, the measurement combinations were subjected to a validation study in which larger load conditions were applied. In this investigation, cutting clearance, sheet material and sheet thickness were unchanged. Figure 6 shows the signal characteristics of measuring combination 1 with piezoceramics in die and punch and hydraulic pressure sensors for a punch diameter of 16 mm. Again, the two tool-bound measuring methods show an accurate agreement of their signal characteristics. Only in the area of the maximum force the measurement on the die side shows slightly higher values. For the hydraulic force curves, similar characteristics as in 3.1 can be noted. The premature increase in force due to the downward movement of the punch, the delayed response behaviour and the stronger signal fluctuations are still visible. However, in contrast to the previous investigation, the approach of the hydraulically determined force signals approximates to the tool bound.
The detected difference in the maximum values is less than 20%. In addition, it is notable for all measuring methods that the range of the signals increases strongly after achieving the peak value. Comparing the current stroke movement with the one in 3.1, it is noticeable that it varies considerably after reaching the peak force. As a result, the scattering in the signal curves after the decrease in force increases.

When comparing the signal curves of measurement combination 2 in figure 7 with the curves of combination 1, no significant difference between the curves measured with piezo elements and those measured with strain gauge can be noted. Also the difference registered in Figure 6 between the use of sensors on punch or on die is no longer visible. Both the measured variance and the absolute values are the same for all tool-related measuring methods, as in the first investigation. The hydraulic force signal also shows an identical course.

3.3. Comparison between the two measuring method combinations for 32 mm punch diameter

Figure 8 shows the signal characteristics for measurement combination 1 with a punch diameter of 32 mm. In principle, the trends in curve characteristics identified in 3.2 are continuing. The curves of
the two measurement methods on tool are in proximity and only show a small deviation in the peak value. The approximation of the hydraulically determined force curves to the tool-bound measuring methods is particularly distinctive. Except for the already known delay in the response behaviour, there is almost no difference to be identified. The collapse of all force signals in the elastic range is due to the pressure switch over. This is also shown by the delayed downward movement of the punch in the stroke movement at this area. Due to the low strains on the 32 mm diameter punch, no suitable results could be gained for measurement method using strain gages under these load conditions. The results of measurement combination 2 were therefore excluded from the evaluation.

![Figure 8. Force signals for measurement combination 1 for 32 mm punch diameter: punch piezoceramic (green), die piezoceramics (red), HYD pressure (yellow).](image)

4. Conclusion and Outlook
In the experimental studies carried out within the scope of this paper various possibilities for measuring the highly dynamic force signals during shear cutting processes in a tool-bound punching machine were investigated. Here, three measurement methods with various localizations were analysed regarding their influence on the resulting measurement deviation. For the experimental comparative study, two possible combinations with alternative measurement concepts were identified, allowing three measurement methods to be integrated into the tool system simultaneously. In parallel, the measurement methods under investigation were validated for different load levels with regard to their continuous signal quality. Based on these results, it could be stated that the proximity of the sensor to the main cutting operation is of major importance for the quality of the measurement signals, especially in lower load conditions, and the resulting deviations become less significant with increasing load. This is particularly visible for hydraulic force measurement, which only achieves close approximation to the signal quality of other force measurement methods at higher load conditions. This is due to the fact, that with increasing load levels, the signal-distorting influence of additional tolerance chains and mass dynamics lose significance and the measured sensor signals increasingly resemble each other. The consistently observed signal delays with the hydraulic force measurement correspond in their extent to the manufacturer's specifications, but can possibly be reduced by using faster responding sensors. A detectable distinction between the force signals using sensors on the punch or die could not be recorded in the study. Likewise, the advantage of the piezoceramic sensors mentioned in 2.3.2 could not be determined in relation to the measuring method with strain gauges. Depending on the specific requirements and load cases, under which the force signals have to be detected, each of the presented measurement methods might produce usable measurement results. However, it is essential to be aware of the signal deviations occurring as a result of the measurement method and localization. Suitable measurement signals are only obtained if the combination of method and localization is suitable to the application. This is also the basic requirement for use in the context of industry 4.0. In field of Industry 4.0, sensors and instrumentation
are one of the central driving forces for innovation. Intelligent decisions of complex systems are based on the knowledge of the system as well as ambient conditions and influence factors provided with high accuracy by sensors. Therefore, the importance of sensors, measurement science and smart evaluation, as presented in this paper for a specific application, will gain an increasingly major role for Industry 4.0.

5. References
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