Wear 570 (2025) 205928

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Integrated measurement of tool wear in punching processes using a pneumatic gauging system

Maximilian Lorenz *, Johannes Epple, Christian Donhauser

University of Applied Sciences Kempten, Bahnhofstraße 61, Kempten, 87435, Germany

ARTICLE INFO

Keywords:
Punching
Blanking
Wear monitoring
Predictive maintenance
Pneumatic gauging

ABSTRACT

Punching is an essential production process for manufacturing large volumes of uniform, cost-effective parts. Despite its widespread use, the efficiency and quality of this process are highly sensitive to numerous parameters, many of which are not fully understood. Achieving optimal, reproducible, and transparent process control, it is crucial to have a detailed understanding of the wear condition of the punching tool. Currently, direct methods for measuring tool wear are unavailable, leading to reliance on indirect measurements through physical surrogate variables. These techniques predominantly focus on indirectly monitoring the quality of the punched parts after processing. In this study, we developed an innovative pneumatic gauging system capable of periodically measuring punch wear directly. We demonstrate the feasibility of integrating a measurement nozzle into the cutting tool, which enables direct assessment of the cutting edge wear. Additionally, we have developed a dedicated measuring transducer and conducted a comparative analysis against an industrial standard. Our methodology includes a comprehensive calibration process within the punching operation. To validate our approach, we performed a series of tests and cross-validation to demonstrate that tool wear degradation can be effectively measured. We explored the potential of this monitoring approach for predicting tool wear. Our findings indicate that real-time measurement of the punch's cutting edge wear in punching and blanking operations is achievable, which paves the way for advancements in process control and maintenance.

1. Introduction

For nearly a century, pneumatic gauges have been known as tools for precise length measurement and in-process control [1]. The key advantages of these instruments include high accuracy, high sensitivity, and self-cleaning of the measured surface, which collectively make them adaptable to a wide range of applications [2]. This technique operates by directing compressed air into a gap between a nozzle and a workpiece, creating back-pressure for small distances, which indicates the gap size. The principal advantages include non-contact measurement with resolutions in the submicrometer range [2]. Furthermore, air gauges provide unique metrological advantages, including minimal gauging force, the capacity for variable and attribute inspections, and high amplification [3]. In terms of functionality, these gauges exhibit no wear on the gauge parts or the workpiece, a rapid response time, and a compact size. Air gauges are ideal for final checks on machine components, e.g., shafts [4]. Additionally, they are utilized for tool wear monitoring in grinding [5] and turning [6]. However, the high accuracy of pneumatic gauges requires a precise guidance system to position the measured part correctly. Additionally, the measurement range is typically limited to a few hundred microns. Another drawback is that the system provides only a single, averaged measurement over the area of the nozzle. Moreover, the use of compressed air increases operational costs.

1.1. Punching, blanking

Punching and blanking are manufacturing methods widely used in the automotive industry. These operations often serve as the foundation for subsequent processes, such as bending, enabling the production of a wide range of products, including electrical connectors and fuses [7]. Additionally, these processes are cost-effective for producing large quantities of parts [8]. The quality of the punching process is largely determined by the accuracy of the cutting line and the characteristics of the cutting surface, such as the presence of burrs [9]. These quality parameters can vary due to factors like tool wear and variations in material properties, including thickness and hardness distribution within a material batch [10]. Despite the considerable effect these variations have on process reliability, quality in practice is frequently limited to manual, random inspections by employees and therefore remains heuristic. Kubik et al. [11] identified the main reasons for this to be:

* Corresponding author.
E-mail address: punchdata@gmx.de (M. Lorenz).

https://doi.org/10.1016/j.wear.2025.205928
Received 26 August 2024; Received in revised form 16 January 2025; Accepted 3 February 2025
Available online 23 February 2025
0043-1648/© 2025 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

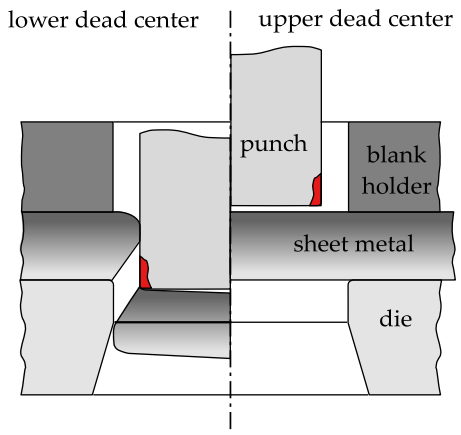

Fig. 1. Punching process in lower dead center (left) and upper dead center(right) of the punch, wear region in red [7]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

- Standardization of the cutting surface and consequently detailed definitions of cutting surfaces is limited,
- Data-based evaluation relies solely on classification methods,
- Latency between the occurrence of cutting surface defects in the process and their detection in an offline measurement system.

The manufacturing process itself involves a tool, consisting of a punch, a die, and a blank holder (see Fig. 1). First, the punch hits the sheet material and deforms it elastically. As the movement of the tool continues, the material is deformed plastically. When the maximum shear stress is reached, cracks begin to form at the edges of the punch and the die, and the sheet material breaks without chipping. The scrap part is pushed into the die by the punch, and the elastic energy is released, resulting in a clamping of the punch. On the backstroke, the punch is withdrawn from the material. As a consequence, the edges of the punch and its lateral surface experience wear. This process forms a characteristic surface on the part [12], which defines its quality [13].

Multiple studies have investigated the influence of wear on the quality of cutting surfaces, as tool wear significantly impacts both the dimensional accuracy and surface characteristics of blanked parts [14,15]. While these studies have provided valuable insights, the current methods for measuring tool wear face significant limitations. Existing approaches can be broadly categorized into those focusing on the punch itself and those analyzing the blanked part, linking it to wear. However, these methods struggle with indirect measurement reliance, complex setups, and insufficient adaptability to industrial conditions.

1.1.1. Measurements on the punch

Directly measuring wear on the punch is particularly challenging. Cutting tools require high stiffness, often achieved by using thick metal plates, and any structural weakening to accommodate sensors must be carefully evaluated. Additionally, micron-level guidance tolerances, combined with oiled debris, make simple optical setups impractical.

As a result, indirect methods are often employed, relying on surrogate variables such as force [16], acceleration [17], or acoustic emission [18,19]. These variables are typically measured at the punch mounting point or outside the cutting tool. While these methods avoid direct modifications to the cutting tool, they have notable drawbacks: they require large datasets, and the connection between the measured signals and actual wear is often ambiguous. Furthermore, these approaches frequently rely on data-based models that demand labeled training data, which is time-consuming and resource-intensive.

Efforts to develop direct measurement methods have also been made. For example, Schlegel [20] presented a system capturing images of the punch at the upper dead center. Labeled data were derived from microscope scans of the cutting surface, and convolutional neural networks (CNNs) were trained to predict wear from these images. However, this method is limited by the tool setup, as industrial cutting tools are typically not accessible at the upper dead center, making implementation in industrial applications difficult.

1.1.2. Measurements on the blanked part

Instead of measuring wear directly on the punch, other approaches attempt to link wear to the quality of blanked parts, as the surface characteristics of the blanked part are directly influenced by the condition of the punch. Hernández [9] explored the modification of blanked surfaces caused by tool wear, emphasizing how surface characteristics like the burnish zone or rollover correlate with the condition of the punch. These methods illustrate how the blanked part can serve as an indirect indicator of tool wear. Lorenz [21] proposed an optical method that examines every cutting surface after it leaves the tool, providing indirect insights into tool wear. Similarly, Kubik [11] used machine learning to predict wear by analyzing the cutting surface of blanked parts. However, relying solely on blanked surface measurements has limitations. Variations in material properties, lubrication, or misalignment can obscure the relationship between punch wear and surface quality, leading to inaccurate or unreliable predictions. Additionally, these methods lack the ability to monitor wear progression directly.

1.2. Motivation for a pneumatic gauging system

Given the limitations of existing methods, there is a need for a system capable of directly measuring tool wear under industrial conditions within the tool. Pneumatic gauging offers a promising solution by enabling periodic measurements of the wear condition or material buildup on the punch during the manufacturing process. Unlike indirect methods, this approach allows for direct measurements of the punch wear, leveraging the precise guidance already integrated into the cutting tool. The use of compressed air provides additional benefits, such as self-cleaning of the measurement area, which minimizes interference from debris or oil.

This study describes the development of a pneumatic gauging system designed to measure punch wear with micron-level resolution over the area of the nozzle. Firstly, nozzles and a measurement transducer are developed and validated through comparison with a commercial measuring system. After successful testing, the measurement technology is integrated into a shear cutting tool, and a calibration process is implemented in the machine control system.

Finally, experiments are conducted on a production system under industrial conditions. The recorded wear values are compared with geometric measurements of the punch, demonstrating the system's accuracy. Additionally, the potential of this approach for predicting tool wear is explored, showcasing its ability to enhance process control and maintenance strategies.

2. Material and methods

2.1. Pneumatic gauging

The performance of a back-pressure pneumatic gauge is primarily determined by the airflow through its key components, including the inlet and measuring nozzle, measuring chamber, and flapper-nozzle area, see Fig. 2a,b. Compressed air flows from a constant pressure supply (typically 300 kPa to 500 kPa absolute) through an air filter and a pressure reducer, entering the system at the desired inlet pressure. The air then flows into a pre-chamber with a sufficiently large cross-section to reduce flow velocity. The pressure p_z in this chamber is recorded by a sensor before the air passes through the inlet nozzle into the measuring chamber, where a second pressure measurement is taken. The pressure p_M in the measuring chamber, which depends on the displacement

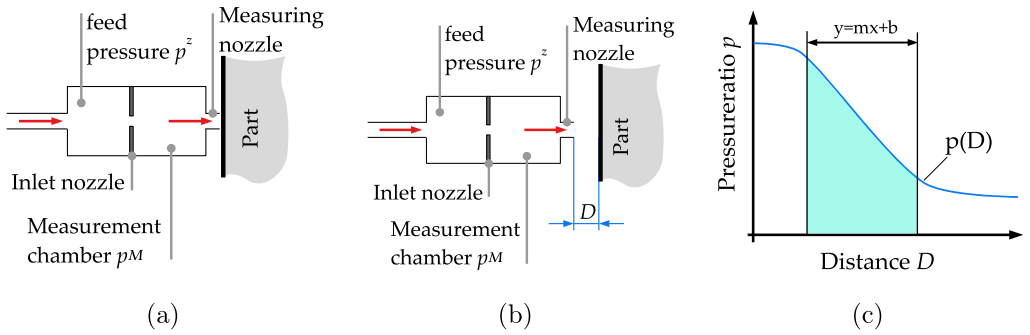

Fig. 2. Principal of pressure measurement for air gauging. (a) closed measuring nozzle, (b) open measuring nozzle with air gap with distance D (c) characteristic curve of the pressure development in respect to distance D. The cyan area marks the linear segment, which is used for measurement. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 3. Measurement nozzle in steel rod and inlet nozzle.

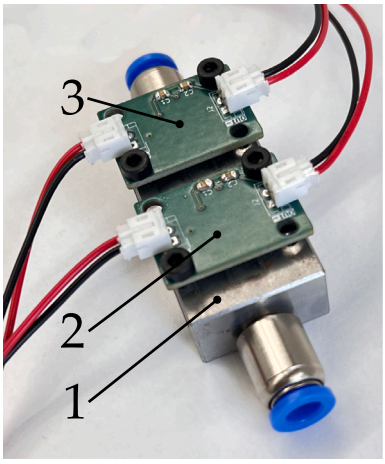

Fig. 4. Developed measurement transducer: (1) body with integrated inlet nozzle between the pressure sensors, (2) pressure sensor for feed chamber, (3) pressure sensor for measurement chamber.

between the nozzle and the measured surface, is crucial for determining the measurement range. This pressure is proportional to the displacement within a certain range, enabling accurate measurements and representing the average distance over the nozzle surface. Beyond a critical displacement, the pressure drops to atmospheric levels. The air ultimately exits through the gap between the measuring nozzle outlet and the workpiece. A sensor characteristic can be seen in Fig. 2c. Typically, the pressure ratio $p = p_M / p_z$ is calculated. The characteristic depends on the ratio of inlet nozzle and measuring nozzle and their geometry. Calibration of the static characteristics is typically performed using masters of known dimensions to ensure accuracy [22].

2.2. Nozzles

The nozzles used in this study cannot be purchased off the shelf, as they must be matched to the measurement transducer. Consequently, custom nozzles were manufactured. These brass nozzles were inserted into a steel rod with a diameter of 6 mm. The nozzle geometry was based on the designs published by [1,22,23]. Since the penetration depth of the punch is only slightly greater than the sheet thickness of 0.5 mm, a bore diameter of 1 mm was required. In addition to the measuring bore, an outer cylinder with a diameter of 1.4 mm was also fabricated to create the measurement gap. A radius was added at the entrance to the bore to ensure smooth airflow. Furthermore, inlet nozzles for the transducer with a bore diameter of 0.7 mm were manufactured, see Fig. 3.

2.3. Measurement transducer

The transducer converts pressure changes into electrical signals, with several types of transducers available for this purpose. Mechanical-electrical transducers, for example, consist of two measuring chambers separated by a diaphragm. The diaphragm deforms in response to the pressure difference between the chambers, and this deformation is recorded via displacement measurement [24]. While this design is robust and exhibits low measurement noise, its large size renders it unsuitable for integration into a cutting tool.

In contrast, electrical transducers are better suited for such applications. In these systems, separate pressure sensors are installed for both the feed pressure and the measurement pressure. To accommodate this, a compact transducer was developed with a continuous bore into which the inlet nozzle was pressed, see Fig. 4. The pressure sensors were mounted and connected to the continuous bore via orthogonal bores, resulting in a compact design with dimensions of 50 mm×20 mm×10 mm. This compactness allows the transducer to be integrated directly into the cutting tool, offering a distinct advantage over existing alternatives.

The signals were processed using a 16-bit analog-to-digital converter, accessed via a Python script. The achieved pressure resolution was 10.7 Pa, corresponding to a displacement resolution of 0.1 µm.

2.4. Calibration and sensor characteristic

Firstly, to accurately establish the linear segment for the developed inlet and measuring nozzles, it is necessary to determine the characteristic curve of the respective nozzle combination. This process begins

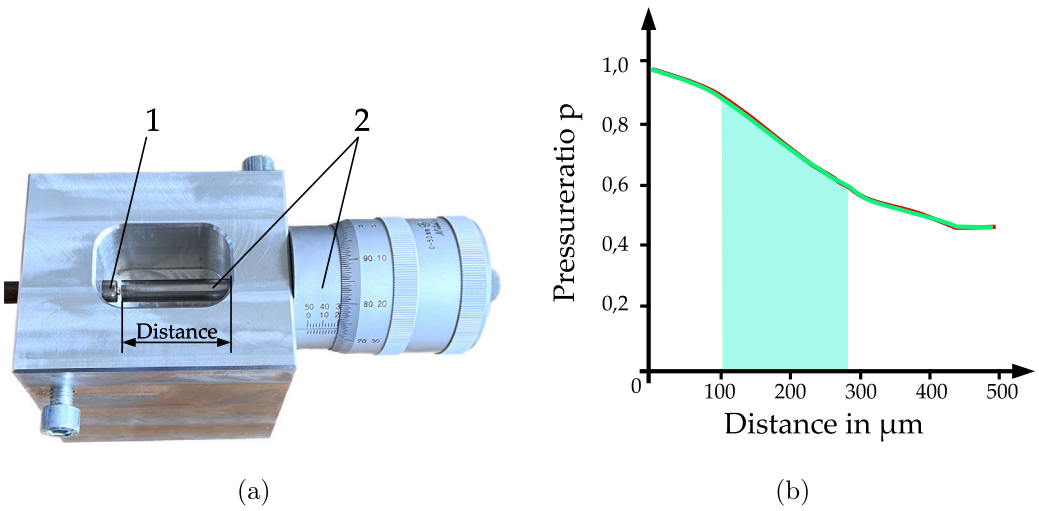

Fig. 5. Setup for measurement of the sensor characteristic (a) 1 Measuring nozzle; 2 depth micrometer (b) Sensor characteristic for multiple trails. (inlet nozzle 0.7 mm, measuring nozzle 1 mm, $p_z = 4$ kPa, linear segment in cyan). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

by attaching a depth micrometer with a one-micrometer resolution directly opposite the nozzle (see Fig. 5a). The nozzle is initially closed with the spindle rod of the micrometer and then gradually opened, allowing for the precise recording of pressure values for both the inlet nozzle and the measuring nozzle.

Through this procedure, the characteristic curve is determined, and it has been consistently observed that the curve remains stable across multiple trials (see Fig. 5b). The linear region of the curve is clearly identifiable, extending over a range of 185 µm. Across these trials, the mean and standard deviation for each distance value were calculated. A linear function was fitted to the mean values, and the uncertainty for the distance values based on the standard deviation was calculated, resulting in an uncertainty of ±0.55 µm. Additionally, both the custom-manufactured nozzles and the commercially sourced nozzles were subjected to rigorous testing, with no significant discrepancies detected between them.

As the linear measuring range was determined, calibration masters were produced. For this purpose, the measuring distance was placed in the center of the linear range at 200 µm. Calibration masters with +55 µm and −55 µm were produced. During calibration, both masters are measured and the linear equation is created from the known distance values. This configuration allows calibration without the need to measure the sensor characteristic itself and can be repeated if external influences change, ensuring consistent results. To ensure accuracy, the measuring range was ultimately restricted to 110 µm, as values at the boundaries are generally more prone to instability.

Subsequently, the calibrated sensor was subject to an analog test bench evaluation, see Fig. 6. This test bench was developed to simulate the physical relationships involved in the cutting process, while allowing for easy adjustments of manufacturing parameters such as cutting clearance and interchangeable dies. It is capable of replicating the stroke movement of the press, and an additional distance sensor utilizing laser triangulation was installed to provide supplementary verification of the stroke movement by precisely measuring the punch distance.

In the initial stage of the experiment, various dies were used to securely position the measuring nozzle. These dies were designed with a cutting clearance identical to that of the tool. Initially, exhaust holes with a diameter of 0.5 mm were drilled in a manner that directed the exhaust air — potentially contaminated with debris — upwards and away from the sheet metal. While the measurement technology provides functional results with a single sensor aiming at one surface of the punch, a symmetrical setup was chosen to ensure that production-related tolerances were averaged out, thereby yielding

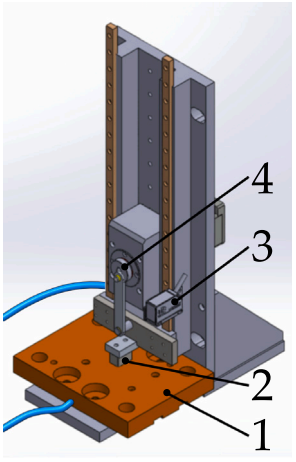

Fig. 6. Analog test bench: (1) die - in this case holder of the cutting tool (2) mounted punch (3) distance sensor (4) drive and mechanics for the punch movement.

stable measurement results.

A punch was mounted at a defined distance, with material removed from the cutting edge by grinding to simulate wear. The measurement of this ground step was then tested using both measurement transducers. The measured values were compared against the step values obtained through a microscope, and after repeated tests, no deviation was found for either transducer.

In a further test, a combination of cutting oil and abrasive dust was applied to the punch surface to simulate real-world process conditions. The measurements were repeated under these conditions, and it was observed that the air stream effectively cleaned the measurement area, resulting in no detectable deviation in the measurements.

In conclusion, the developed nozzles and transducers proved effective, although the signal collection time takes up to 2 seconds. This delay may be due to the long lengths of tubing used in the setup. In contrast, commercially available transducers can achieve measurement times as short as 15 µs, indicating that faster signal collection is feasible [25]. With this measurement time over the course of a stroke, a 3D geometry of the punch could be measured. However, there are restrictions: the punch must move slowly and only a strongly averaged surface area is determined, as a measured value always represents the average distance over the entire nozzle surface.

Table 1
Manufacturing parameters of the experiment.

Press	Bihler GRM-NC
Press velocity	250 Stroke per Minute
Coil width b	35 mm
Coil thickness s	0.5 mm
Coil material	X12CrNi177
Tensile strength R_m	1600–1800 MPa
Lubrication	Oil Zeller+Gmelin Multicut HSC20
Punch die clearance u	0.025 mm (5%)
Punch material	Powder Metallurgy Tool Steel (SPM30)
Die material	Carbide metal K40 (CFH40S+)
Punch geometry	5 mm × 5 mm
Punch edge radius	20 µm
Blank holder force	23.6 kN

2.5. Experimental setup

After the successful completion of these tests, a cutting tool with integrated pneumatic measurement technology was constructed for the experimental investigation of the system. Precision holes were machined into the blank holder of the tool, and the sensors were installed in place (see Fig. 7a). During the assembly process, the distance between the measuring nozzle and the punch surface was adjusted. The measurement chain, consisting of tubing, transducer, and nozzles, was calibrated using calibration masters. Given the high precision required and the influence of external factors such as temperature and air pressure, regular calibration is essential.

This calibration relies on the presence of a reference feature in the process. At the lower dead center of the punch movement, the punch surfaces are positioned in front of the nozzle outlet surfaces. These surfaces do not contact the sheet metal and are therefore not subject to wear, allowing them to serve as a reference point (see Fig. 7b). The measurement process is thus divided into two distinct stages: first, establishing the reference, and second, positioning the cutting edge beneath the sensor to measure the wear point. By repeating this process for every measurement, thermal expansions are equalized under the assumption that the punch itself maintains a uniform temperature. It is also assumed that the temperature of the punch does not change during the measurement time.

Given the constraints on measuring time, a measurement at production speed is not possible. Therefore, a measuring sequence was incorporated into the system. Initially, the machine is decelerated from production speed, and the measuring air is activated 10 strokes before the measurement interval is reached to clear any potential obstructions in the measuring area. Once the measurement interval is reached, the machine first returns to the reference position to set the reference value. After a period of 2.5 s, the punch is moved to the measurement position, and the deviation is determined. Finally, the machine is accelerated again.

A new punch is installed in the cutting tool and the described measurement is carried out at a defined interval. The punch is removed at defined intervals and a confocal microscope was used to measure the geometry of the punch. Matching the number of measurements was impractical due to the time-consuming process of removing and reinstalling the punch. Repeatable positioning of the punch during measurement was ensured by indexing, allowing the identical position to be measured as with the pneumatic measurement technology. A repeatable mounting position of the punch in the cutting tool is guaranteed by pins in the mounting setup. All manufacturing parameters of the experiment are detailed in Table 1.

3. Results

In order to evaluate the behavior of the measuring nozzle within the cutting tool, a series of repeated tests was conducted. A damaged punch was installed in the cutting tool for this purpose. Two positions were selected for further analysis: Position $X1$, where the punch is at the lower dead center, undamaged, and measuring 5 mm, and Position $X2$, where the measuring nozzle is aligned over the damaged surface, measuring 4.996 mm. Ten repeated measurements over the course of 5000 Strokes were carried out to determine whether the measurement technology is capable of coping with the vibrations inherent to the process and whether the developing temperature in the process influences the measurement results. Table 2 shows that there is no significant influence of temperature or the manufacturing process on the measurements. The mean values differ by a standard deviation of ±0.0002 mm.

Table 2
Results of repeated measurements with the cutting tool and integrated air measuring nozzles.

Stroke	X1 in mm	X2 in mm	Δx in mm
500	4.9997	4.9960	0.0037
1000	4.9996	4.9959	0.0037
1500	4.9997	4.9960	0.0037
2000	4.9999	4.9963	0.0036
2500	4.9999	4.9962	0.0037
3000	5.0000	4.9965	0.0035
3500	5.0000	4.9964	0.0036
4000	4.9999	4.9963	0.0036
4500	5.0000	4.9965	0.0035
5000	5.0002	4.9967	0.0035
Mean	4.9999	4.9963	0.0036
std	±0.0002	±0.0002	±0.0001

After that, an experiment over the lifetime of a punch was carried out. A total of 100 000 strokes was performed. A measurement by the pneumatic transducer was carried out every 1000th stroke. Over the course of the experiment, wear was observed, but no fatal failure, such as chipping of edges, occurred. The results of the tests on the punch's lifetime are presented in Fig. 7c. The curves demonstrate the degree of deviation from the initial thickness of the punch, which was 5 mm.

The blue curve represents the geometry data of the punch obtained from the confocal microscope ("Ground Truth") at defined intervals (0, 5000, 10 000, 25 000, 50 000 and 100 000 Strokes). Additionally, the curves for the OctaGauge and the custom transducer are presented. It can be observed that the initial measurements obtained through the pneumatic measurement technology remain at the initial dimension. Despite the presence of wear on the punch's cutting edge, the area of the measuring nozzle outlet covered in the measurement position is insufficient to generate a signal.

As the number of strokes increases, wear progresses along the punch axis and begins to cover more of the measurement nozzle, starting from a stroke count of 10 000. The curves of the two pneumatic transducers exhibit a comparable trend, with minor deviations of 0.3 µm. The discrepancies, with a mean of 1.2 µm between the reference curve and the measured values, can be attributed to the fact that the measuring surface should ideally be parallel to the nozzle outlet surface. However, the wear develops at an angle to the punch axis. Additionally, the signal is derived by averaging over the entire measuring area, which results in a tendency for the measured value to be smaller than the actual value.

Since the stopping position of the machine also varies by ±1 µm, this leads to slight deviations, as observed between strokes 75 000 and 100 000. Within these limitations, both pneumatic measurement systems are capable of measuring tool wear during the process. No influence of vibrations or contamination from the process could be observed.

3.1. Predictive maintenance

The analysis of material wear often follows a characteristic pattern, where linear wear is expected to occur after an initial running-in phase. However, this is not universally applicable. Based on the available data, this can be tested under the assumption that the running-in phase is not

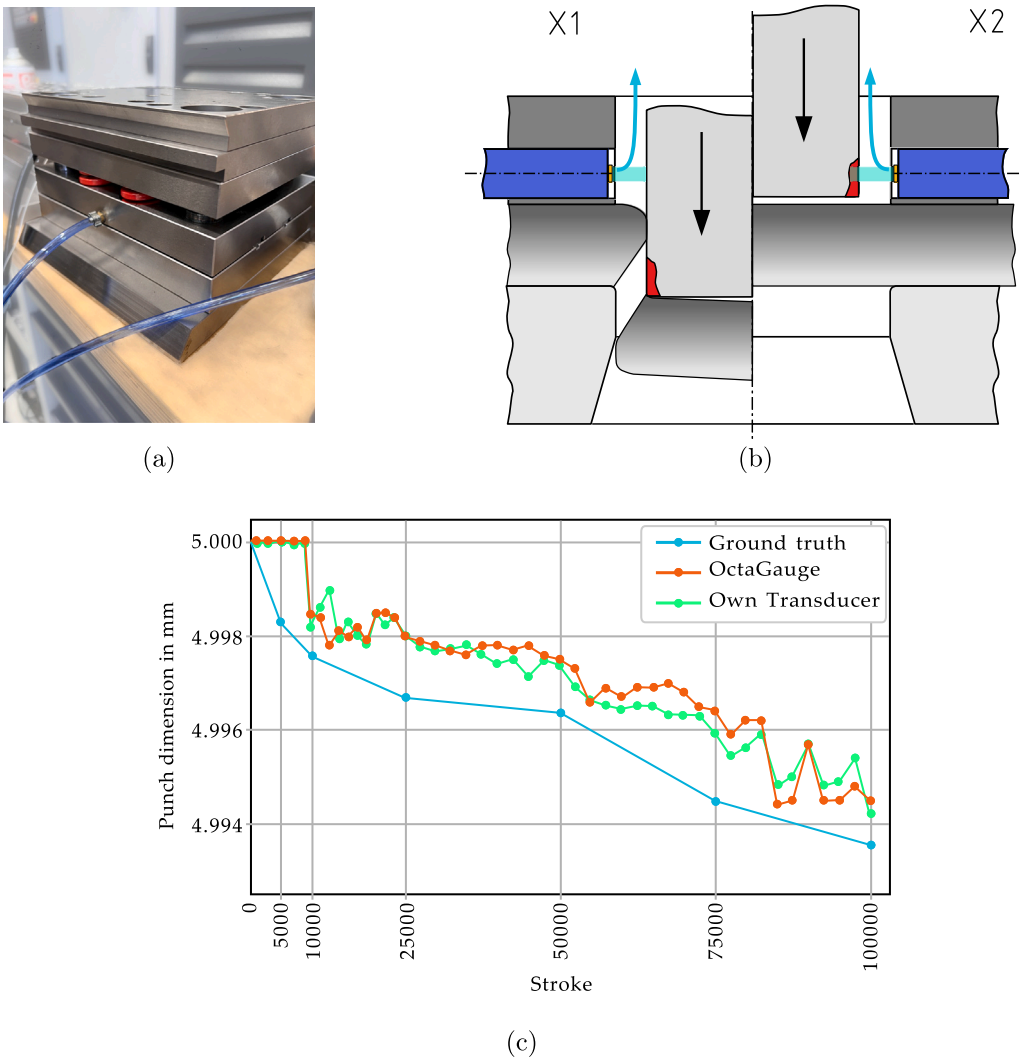

Fig. 7. Experimental setup: (a) cutting tool with mounted measuring nozzle, (b) punch positions with measuring position $X1$ and reference position $X2$ (c) Results of the measurement of the punch wear for the OctaGauge-System (red) and the developed transducer (green) in comparison with the ground truth (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

captured by the sensor, meaning the wear data should exhibit linearity across the strokes.

Firstly, the rolling mean value of the wear is calculated using the obtained measurement results, compensating for any positioning inaccuracies of the machine. Subsequently, a linear regression is applied to the data, yielding an R^2 value of 0.96, indicating a significant result (see Fig. 8). This suggests that a linear regression can be constructed during the test series once the running-in phase is over. Additionally, wear forecasting can be performed using the resulting equation. A check for punch failure can also be conducted via the sensor system. If the R^2 value deviates significantly, it indicates that the punch has reached the end of its service life.

Another way to evaluate the lifetime of the punch is to define a lower limit for the geometry of the punch. The drawing tolerance of the punched part can be used for this. If this is exceeded, the service life is reached. Once the linear function has been determined, it can be extrapolated, and the number of strokes at which the service life is reached can be calculated, provided that this remains within the linear wear range.

However, this threshold does not account for the detailed condition within the cutting surface, such as the burnish part and the cutting surface itself. To assess these aspects, further measurements of the cutting surface would be required.

4. Discussion

This measurement technique is designed for periodic operation and requires the machine to stop momentarily at predefined positions to perform the measurement. This approach can also be applied at higher production speeds, as modern punching machines, such as those from Bruderer, are equipped with clutch systems that allow precise stopping without deceleration. This enables the pneumatic gauging system to be integrated seamlessly into high-speed processes while maintaining accuracy and reliability.

During testing, one challenge identified was the potential for cleaning the measuring point on the punch to introduce irregular wear patterns. Although lubricant removed during cleaning is reapplied with each stroke — thanks to the continuous addition of lubrication to the sheet metal — this effect requires further investigation. While no irregular wear patterns were observed in the conducted tests, additional long-term studies are recommended to evaluate potential impacts.

Furthermore, the current nozzle designs measure wear along straight sections of the cutting line but only cover a small portion of the overall surface. To address this limitation, slit-shaped nozzles could potentially be used to cover larger areas of the straight sections of the cutting line. However, these nozzles would still provide only an

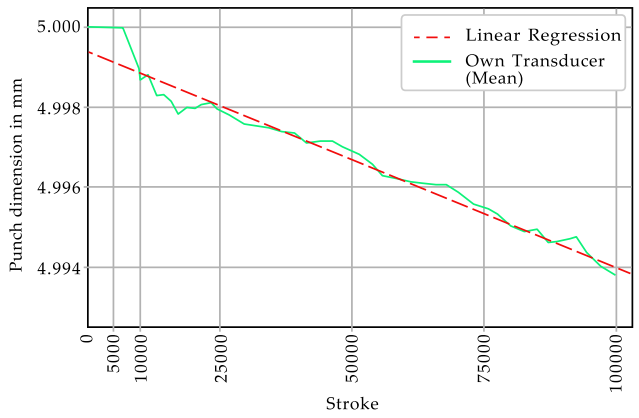

Fig. 8. Signal of the wear measurement with rolling mean (green) and linear regression of the signal with $R^2 = 0.96$, which can be used for rough estimation of the remaining lifetime of the punch. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

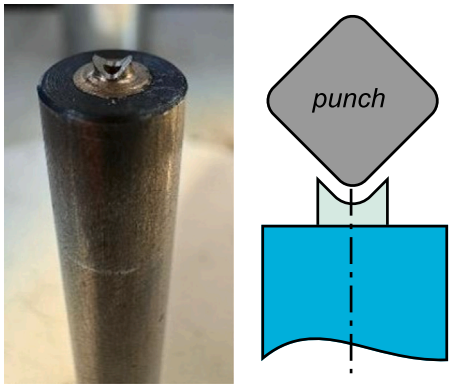

Fig. 9. Modified nozzle geometry for measurement of the cutting wear on corners of the punch.

averaged measurement over the covered area and would not be capable of capturing localized wear.

Additionally, the highest wear typically occurs at the corners of the punch or in regions with the smallest radii, where stress concentrations are greatest. To specifically target these critical areas, a specialized nozzle was developed (see Fig. 9). This nozzle was designed to match the geometry of the punch and covers half of the determined measuring range. Testing of this configuration was conducted on a dedicated test bench, which included a die with mounting holes positioned in the corners. A damaged punch was installed, and measurements were performed using both the specialized nozzle and existing systems. The tests showed measurable values for the damage, and over ten measurements, a repeatable result with a standard deviation of ± 0.001 mm was achieved. This demonstrates that the method is capable of reliably detecting localized wear in critical areas. Although compressed air is a relatively expensive medium, the machines require it anyway. The periodic measurements ensure that costs are kept to a minimum.

5. Conclusion

An integrated pneumatic gauging system and measurement transducer for cutting tools was successfully developed in this study. The results demonstrate that the pneumatic gauging system is capable of measuring the dimensional reduction of the punch due to wear within the cutting tool during the manufacturing process. The typically high demands for the guidance of measured parts are already integrated into the cutting tool, as it provides precise guidance for manufacturing geometrically defined parts.

In contrast to state-of-the-art methods, which measure wear using surrogate variables or offline techniques, this technology offers several benefits and potential applications. These include monitoring punch wear with greater precision and density, without the need to dismantle the cutting tool. This capability allows for a direct correlation between the condition of the punch and the quality of the component to be determined at the point of origin.

The developed system achieves a theoretical resolution of 0.1 µm, with a practical measuring range of 110 µm and a distance measurement accuracy of ±0.55 µm. The developed nozzles and measurement transducer have been validated for functionality on a test bench. The results from this custom setup showed no deviations compared to the true measured geometry (“ground truth data”) within the expected precision range.

Moreover, a functional prototype for integration into a cutting tool was developed and validated through a series of tests. The measurement technology successfully recorded the actual punch wear, enabling the creation of a wear curve that reflects the punch’s service life. When compared to the true geometry measured using a microscope, a deviation of 1.2 µm was observed. This deviation can be attributed to the measurement of non-parallel surfaces, which slightly affects the system’s accuracy under these specific conditions.

Despite this limitation, the developed system offers significant advantages, including a smaller construction footprint and the ability to be integrated directly into the cutting tool. This integration results in shorter tubing lengths and a shorter response time. Additionally, the results demonstrate that process lubrication and abrasion do not affect the measurement technology. Furthermore, the system allows for monitoring punch breakage, as pressure drops to atmospheric levels, leading to high deviations or indicating material build-up on the punch.

A specialized nozzle was also developed to address localized damage, particularly in critical areas such as the corners of the punch or regions with small radii. Testing demonstrated reliable and reproducible results, with a repeatability standard deviation of ±0.001 mm over multiple measurements.

In addition to these possibilities, this measurement technology facilitates the implementation of new processes. By understanding the wear curve, artificial intelligence methods can be applied to determine optimal times for predictive maintenance (e.g., punch replacement). A preliminary application using linear regression has been demonstrated. The main drawback of the developed method is that the measuring time could not be reduced to the desired level, necessitating a production stop of five seconds.

Further work should focus on analyzing this method with varying cutting line geometries. For simplicity, straight lines were tested during the experiment, but initial tests with geometrically adapted sensors showed promising results. Additionally, the results should be verified through more test series over the lifetime of different punches. With a larger dataset available, the principal test of predicting wear based on surrogate variables should be repeated and extended.

Furthermore, efforts should be made to reduce the response time of the transducer. Since commercially available transducers in the industry can achieve measurement times as short as 15 µs, improvements in this regard are possible. The presented method could also be adapted to other cutting processes, such as fine blanking.

CRediT authorship contribution statement

Maximilian Lorenz: Conceptualization, Methodology, Software, Data Curation, Writing – original draft. **Johannes Epple:** Methodology, Resources, Formal analysis, Visualization. **Christian Donhauser:** Project administration, Funding acquisition.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to improve the readability and language of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Funding

The project 'Pneumatic measurement technology for inline wear determination in stamping processes (PneuInSta)' (10/2022-03/2024) is funded by the Bavarian State Ministry of Economic Affairs, Regional Development and Energy (StMWi) as part of the Bavarian program to promote the validation of research results and inventions (validation program).

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Maximilian Lorenz, Christian Donhauser has patent FERTIGUNGSWERKZEUG, VERFAHREN ZUM BESTIMMEN EINES VERSCHLEISSZUSTANDS UND VERWENDUNG EINES PNEUMATISCHEN SENSORS licensed to Inventor. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available from the corresponding author on reasonable request.

References

[1] W. Lotze, Kritische Einschätzung und Beiträge zur Entwicklung der Pneutmatischen Längenmesstechnik, Habilitation, Technische Universität Dresden, Dresden, Germany, 1968.
[2] M.A. Curtis, Handbook of Dimensional Measurement, fourth ed., Industrial Press, New York, NY, 2011.
[3] C.P. Keferstein, M. Marxer, C. Bach, Fertigungsmesstechnik, Springer Fachmedien Wiesbaden, 2018, http://dx.doi.org/10.1007/978-3-658-17756-0.
[4] M. Rucki, Recent development of air gauging in industry 4.0 context, Sensors (4) (2023) http://dx.doi.org/10.3390/s23042122.
[5] V.T. Thang, N.A. Tuan, N.V. Tiep, Evaluation of grinding wheel wear in wet profile grinding for the groove of the ball bearing's inner ring by pneumatic probes, J. Mech. Sci. Technol. (2018) http://dx.doi.org/10.1007/s12206-018-0234-5.
[6] J.G. Baldoni, S.T. Buljan, V.K. Sarin, Continuous Tool Wear Monitoring in Turning, Springer US, 1983, http://dx.doi.org/10.1007/978-1-4684-4319-6_54.
[7] H. Hoffmann, R. Neugebauer, G. Spur, Handbuch Umformen, Carl Hanser Verlag, 2012, http://dx.doi.org/10.3139/9783446430044.
[8] M. Kolbe, Stamping Practice: High Performance Stamping, Springer Fachmedien Wiesbaden, 2022, http://dx.doi.org/10.1007/978-3-658-34758-1.
[9] J. Hernández, P. Franco, M. Estrems, F. Faura, Modelling and experimental analysis of the effects of tool wear on form errors in stainless steel blanking, J. Mater. Process. Technol. (2006) http://dx.doi.org/10.1016/j.jmatprotec.2006.05.015.
[10] B.-A. Behrens, R. Krimm, Q.T. Nguyen, Robuste Schnittflächencharakterisierung und Prozessbegleitende Schnittgratmessung, first ed., in: EFB-Forschungsbericht, Europäische Forschungsgesellschaft für Blechverarbeitung e.V. (EFB), Hannover, Germany, 2018.
[11] C. Kubik, D.A. Molitor, S. Varchmin, D.S. Leininger, J. Ohrenberg, P. Groche, Image-based feature extraction for inline quality assurance and wear classification in high-speed blanking processes, Int. J. Adv. Manuf. Technol. (2023) http://dx.doi.org/10.1007/s00170-023-12653-x.
[12] V.D. Ingenieure, Schnittflächenqualität beim Schneiden, Beschneiden und Lochen von Werkstücken aus Metall Scherschneiden: VDI2906, Beuth Verlag GmbH, Berlin, 1994.
[13] E. Doege, B.-A. Behrens, Handbuch Umformtechnik: Grundlagen, Technologien, Maschinen, Springer Berlin Heidelberg, 2016, http://dx.doi.org/10.1007/978-3-662-43891-6.
[14] M.J. Hirsch, Einfluss von Leichtbauwerkstoffen in Schnelllaufenden Stanzwerkzeugen auf das Verschleißverhalten (Ph.D. thesis), Technische Universität München, München, 2012.
[15] A. Toussaint, Einfluss des Werkzeugverschleißes auf die Teilequalität beim Scherschneiden von Elektroblechen (Ph.D. thesis), in: utg-Forschungsberichte, Technische Universität München, München, 2000.
[16] C. Kubik, S.M. Knauer, P. Groche, Smart sheet metal forming: importance of data acquisition, preprocessing and transformation on the performance of a multiclass support vector machine for predicting wear states during blanking, J. Intell. Manuf. (2021) http://dx.doi.org/10.1007/s10845-021-01789-w.
[17] J. Breitling, B. Pfeiffer, T. Altan, K. Siegert, Process control in blanking, J. Mater. Process. Technol. (1997) http://dx.doi.org/10.1016/S0924-0136(97)00167-2.
[18] A.S. Mardapittas, Y.H.J. Au, BETS: An Expert System for Tool condition Monitoring in Blanking, in: Proceedings of the International Conference of Sheet Metal, IOP Publishing, London, 1992.
[19] M. Unterberg, M. Becker, P. Niemietz, T. Bergs, Data-driven indirect punch wear monitoring in sheet-metal stamping processes, J. Intell. Manuf. (2023) http://dx.doi.org/10.1007/s10845-023-02129-w.
[20] C. Schlegel, D.A. Molitor, C. Kubik, D.M. Martin, P. Groche, Tool wear segmentation in blanking processes with fully convolutional networks based digital image processing, J. Mater. Process. Technol. (2024) http://dx.doi.org/10.1016/j.jmatprotec.2023.118270.
[21] M. Lorenz, M. Menzl, C. Donhauser, M. Layh, B.R. Pinzer, Optical inline monitoring of the burnish surface in the punching process, Int. J. Adv. Manuf. Technol. (2021) http://dx.doi.org/10.1007/s00170-021-07922-6.
[22] P. Schäfer, Modellbasierte Entwicklung Pneumatischer Abstandssensoren für Prozessintegrierte Messungen, in: Berichte aus dem Lehrstuhl für Messtechnik und Sensorik, Universität Kaiserslautern, Kaiserslautern, Germany, 2016.
[23] A. Wiemer, Pneumatische Längenmessung, VEB-Verlag Technik, 1970.
[24] Nirschl Präzisionsmechanik Held & Plaschke GmbH, Manual: OctaGauge, 2019.
[25] Datasheet: Gageline transducer TPE200. JENOPTIK Industrial Metrology GmbH.