

Inline Wear Detection in High-Speed Progressive Dies Using Photometric Stereo

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Abstract. The progressive forming of complex components, including blanking, deep-drawing, and bending, represents an economically efficient sheet metal processing method. Wear control is crucial for ensuring product quality by preventing defects and minimizing material waste. The integration of optical sensors for qualitative wear detection, driven by advancing digitisation and miniaturisation, supplements conventional monitoring techniques. This study introduces a modular, agile camera-based measurement system that records component geometry and allows cause-specific feedback on wear progression. By assigning anomalies to distinct process stages, the system enhances defect diagnosis. The employed photometric stereo analysis relies on multiple images captured under varying illumination angles. Photometric reconstruction enables the calculation of normal maps, facilitating the assessment of surface characteristics through pixel-wise brightness variations. Deviations from predefined standards allow for the precise identification of irregularities. By delivering real-time, non-intrusive insights into the forming process, this approach establishes a foundation for efficient, reliable, and adaptive manufacturing. Its contributions to intelligent forming technologies enable enhanced process control and quality assurance, advancing the state of modern industrial production. Through the fusion of optical monitoring and computational analysis, the proposed methodology represents a significant step towards data-driven, self-optimising manufacturing systems.

Keywords: Photometric Stereo; Inline wear detection; Progressive dies; Process interaction

1 Introduction

The production of complex components through stamping, deep-drawing, and bending operations is one of the key manufacturing processes in the sheet metal industry [1, 2]. These components are used in various fields such as mechanical and automotive engineering, medical technology, electrical engineering, and consumer goods, covering a wide range of applications—from the smallest plug contacts to large body parts for the automotive industry [3]. Due to high stroke rates and low process costs for serial products, unit costs are relatively low [4]. The international competition in this technological field forces companies to ensure the cost-effectiveness of their processes by maximising productivity. Even short downtimes or deviations from component surface quality can have significant negative impacts. Therefore, a central objective is, therefore, the minimization of both, planned and unplanned downtimes [5]. Conventional monitoring approaches for multi-stage forming processes are usually based on time-series force signals and anomaly detection, often with a focus on protecting

against excessive strain in machines and tools [6, 7]. There are already successful approaches that have realised wear monitoring during shear cutting [8]. However, this approach does not allow the user to draw any conclusions about the optical condition of the mould and identify potentially critical areas. To address the challenge of wear detection in high-speed forming processes, this study presents an optical sensor designed for inline wear analysis on a stroke-by-stroke basis. Image data and its fusion with time-series hold significant potential for identifying errors, their causes, and their localisation in complex processes. However real-time processing remains a major limitation, especially for multi-stage processes exceeding 1,000 strokes per minute [9, 10]. Conventional image-based monitoring systems struggle to keep up with the data processing demands of such high-speed operations [11]. To overcome these challenges, this work introduces an optical soft sensor that acts as a scanning module within the production processes in a progressive die. The soft sensor with photometric stereo presented here is a real-time capable system that processes data in real time without a machine learning approach. It not only

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monitors a single work tool but also distinguishes between different production steps by leveraging domain-specific knowledge [12]. This enables it to provide the operator with precise feedback on the individual production stages and efficiently support the production process. The initial implementation integrates the soft sensor into a sub-tool of a modular progressive die as a separate module. By comparing the actual and target reflective properties of component surfaces through photometric stereo technology, the system enables the assessment of surface changes from stroke to stroke. These variations provide insights into the wear behaviour of both the punch and the die, as well as the condition of the workpiece's surface roughness, enabling a more precise assessment of tool wear and ensuring that more effective monitoring and maintenance can be achieved. In addition to the conceptual introduction, the functionality of the system is experimentally validated in a progressive die, evaluating its reliability and accuracy under real operating conditions. This publication represents an extension of the system presented in Moske et al. and enables a differentiated analysis of the process-specific defects that occur during deep drawing and ironing [13].

2 Methods and procedures

In order to evaluate the compatibility and effectiveness of the scanning module within an industrial context, it was methodically incorporated into an existing progressive die. The experimental procedures were executed using a high-performance Bruderer BSTA 410-110 stamping press, operating at a stroke rate of 200 strokes per minute, with each test series comprising 200 strokes. The materials utilised in these trials comprised sheet made of DC04 with a thickness of 0.5 mm and a width of 50 mm.

2.1 Description of the progressive die

The progressive die consists of several modules, each performing one or two cutting operations and specific forming processes. The first module includes two cutting operations: a pilot cut and a blanking geometry cut. The sheet metal is pre-processed by a pilot cut to align it precisely and prepare it for the subsequent steps. A specific shearing process creates a blanking geometry that remains connected to the sheet metal strip at designated attachment points, allowing further transport within the die to subsequent forming processes. This blanking geometry cut is necessary to enable deep drawing on the sheet metal strip without failure modes and to produce without punching waste. The second module performs the deep-drawing process, forming the sheet metal into a cup. Deep-drawing is defined as a metal forming process in which a sheet metal blank is radially drawn into a forming die by a punch, thereby creating a hollow, cup-like shape while maintaining material continuity and minimising thinning [1]. The following module combines drawing with ironing. Ironing combines material stretching and controlled flow along the tool surface [1]. In this process, the

material is drawn over a stretch-glide drawing slope, specifically at the wall of the cup rather than at the bottom. As a result, the material thickness is reduced at the wall. However, during this forming process, wear on the drawing edge can occur, leading to the formation of draw marks—individual or multiple parallel grooves appearing adjacent to each other [1]. After this, a scanning module performs an inline quality inspection of the outer surface of the cup using an optical scanning module. It analyses the surface reflection of the components through photometric stereo analysis, generates normal maps, and it identifies wear phenomena such as scratches, waviness or material transfer. In the final module, the formed workpiece is separated from the sheet metal strip. To ensure precise monitoring and analysis of the forming process, force measurement sensors are implemented within the progressive die. The force measuring rings directly capture the process forces generated by each punch in a module, while quartz shear force sensors indirectly measure the forces exerted by individual stages. These sensors are integrated into the deep drawing and ironing modules to provide real-time data on process forces. Specifically, piezoelectric quartz shear force sensors 9240A and force measuring rings Kistler 9051C are utilised for this purpose. In the following figure (Fig. 1), the sequence and feed direction of the modules and operations in the progressive die, along with the processed sheet metal strip, are visualised.

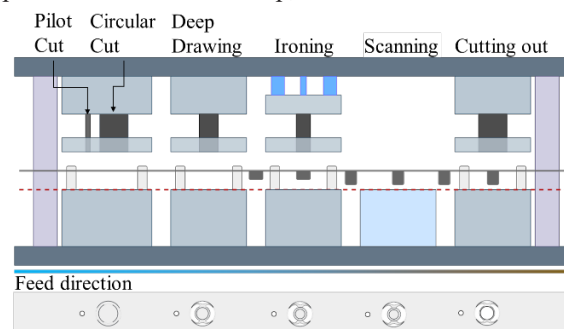


Fig. 1. The progressive die

Two types of dies were used in the wear tests: unworn and synthetically worn matrices; the unworn matrices represent a new condition, while the synthetically worn matrices were modified by artificial roughening so that they correspond to a worn condition. The measured roughness values clearly show this difference: unworn surfaces exhibited a roughness of $R_z = 4.65 \mu\text{m}$, $R_a = 0.74 \mu\text{m}$ in the deep-drawing stage and $R_z = 0.35 \mu\text{m}$, $R_a = 0.11 \mu\text{m}$ in the ironing stage. Synthetically worn dies, on the other hand, exhibited a roughness of $R_z = 10.8 \mu\text{m}$, $R_a = 1.58 \mu\text{m}$ in the deep-drawing stage and $R_z = 8.32 \mu\text{m}$, $R_a = 1.36 \mu\text{m}$ in the ironing stage. Four different test series were performed to analyse different combinations of die wear. The specific conditions of these test series are shown in Table 1. The tests are carried out without additional lubrication so that the scanning module can pick up the surface. In the first series of tests, both the deep-drawing die and the ironing die were used in an unworn state. A defined target surface was achieved and recorded by the scanning module for the subsequent wear tests. In the second series of tests, an unworn deep-drawing die was

combined with a synthetically worn ironing die. In the third series of tests, a synthetically worn deep-drawing die was combined with an unworn ironing die. In the fourth series of tests, both the deep-drawing die and the ironing die were synthetically worn.

Table 1. Combinations of the forming tools in the wear test series

Test series	Deep Drawing die	Ironing die
1	unworn	unworn
2	unworn	synthetically worn
3	synthetically worn	unworn
4	synthetically worn	synthetically worn

2.2 Description of the built in scanning module

The 3D reconstruction of objects, along with the subsequent processing of this data, is computationally expensive, which poses a challenge in relation to the demands of a progressive die. Consequently, the surface structure of the components is assessed based on their reflection properties. Photometric Stereo (PS) is particularly well-suited for this application as it provides rapid capture and processing capabilities. PS encodes the surface of the object using the corresponding normal vectors, a method also referred to as 2.5D reconstruction. This approach facilitates an actual versus target analysis between a fault-free reference component and the currently produced component, based on the normal vectors at corresponding surface points. If the normal vectors at a given a point on the surface do not align within a predefined tolerance, it can be concluded that tool wear becomes measurable at that equivalent point on the cup surface. The corresponding pixel position of the examined surface point is then color-coded according to the deviation between the normal vectors. In cases where no deviation is detected, the pixel position is marked in black. By applying this methodology to all surface points/pixel positions, a wear mask is generated, which visually represents the location and severity of tool wear on the cup surface through discolouration. There are various methods for performing a Photometric Stereo reconstruction [11]. In the presented setup, both the object and the camera are fixed. Multiple light sources illuminate the object sequentially, while the camera captures the shadow and reflection behavior of the object. If the directions of the light sources illuminating the object are known, the normal vector $N(x,y)$ at the pixel position (x,y) can be computed as follows, provided that at least three distinct light directions are available [13]:

$$N(x,y) = \frac{(L^T L)^{-1} L^T I(x,y)}{\rho(x,y)} \quad (1)$$

where $I(x,y)$ represents the pixel intensity of the captured images, $\rho(x,y)$ denotes the albedo, and L indicates the direction of the incident light on the object. Thus, there is a closed-form expression for calculation of the normal vectors based on simple matrix operations, which is particularly advantageous in terms of computational run times within the production of progressive dies. Using the closed-form equation (1),

the hardware specifications can be designed accordingly, as illustrated in Fig. 2. Multiple individually controllable 3W white light LEDs are arranged in a known pattern, allowing for a calibration of the direction of the incident light on the object. A 1 MP high-frame-rate camera capable of capturing 140 frames per second is utilised, which accommodates the speeds of the progressive die. Additionally, both the camera and the LEDs within the scanning module can be rotated around the object from 0° to 50° .

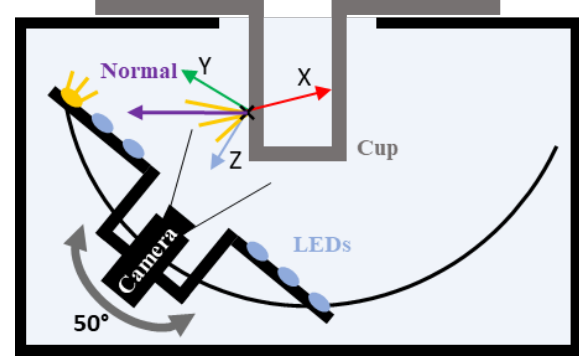


Fig. 2. Inside the scan module

The angle must be set prior to installation and scanning. The scanning module has an opening to securely hold the cup within the scan area. Additionally, a position sensor is installed at the bottom dead center of the progressive die to get a trigger signal to initiate the scan, as well as a Raspberry Pi 5 to control the presented subcomponents and process the acquired data. To enhance the user-friendly operation of the scanning module, an autonomous pipeline has been developed, as illustrated in Fig. 3, enabling users to easily initiate the scanning process. In this setup, the data acquisition and processing phases are separated. This design eliminates the need for a communication protocol, ensuring that the failure of one of these components does not block the entire scanning module. A local server is installed on the Raspberry Pi 5, where all acquired data is initially stored. A separate processing computer retrieves data from the local server and computes the normal maps and wear masks for the currently produced components. This autonomous, non-communicating structure allows data to continue to be processed on the local server if the scanning module fails, or additional data to be collected if the scanning module is operational but the processing computer fails.

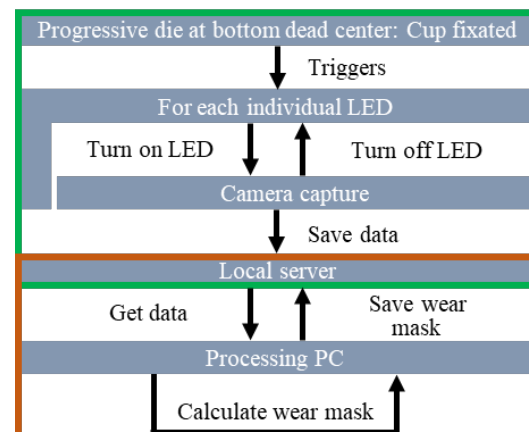


Fig. 3. Autonomous workflow of scanning module

The overall workflow, illustrated in Fig. 3, starts with the progressive die reaching the bottom dead centre which triggers the position sensor. This signal is then received by the Raspberry Pi 5 which initiates the scanning procedure. The Raspberry Pi systematically activates and deactivates each individual LED, while a camera captures the reflections and shadows of the object. The acquired data and the computed wear mask of the component are stored on a local server, with a separate processing PC retrieving the data to calculate the wear mask based on the component's actual target. The green and orange boxes highlight the acquisition and processing units of the entire autonomous, non-communicative workflow, where each module operates independently. Fig. 4 shows a real-time capture of the scanning module in action while a produced cup is secured within the opening. One LED illuminates the object while the camera captures the reflections of the cup.

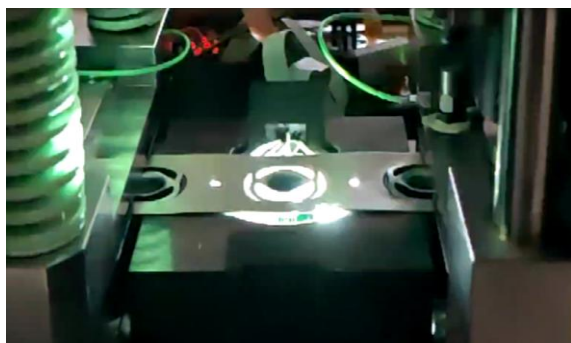


Fig. 4. Presented scanning module in a progressive die during a scanning process

3 Results and discussion

During the life cycle of a progressive die, adhesive and abrasive wear occurs on the active parts, especially on the dies and drawing punches, due to the mechanical and thermal loads acting during the process. The dies used are most affected by these phenomena, as this is where the highest frictional and pressure loads occur, which favour the introduction of defects on the semi-finished product. The influence of die wear can be seen in the undesirable effects on the components manufactured with a synthetically worn die.

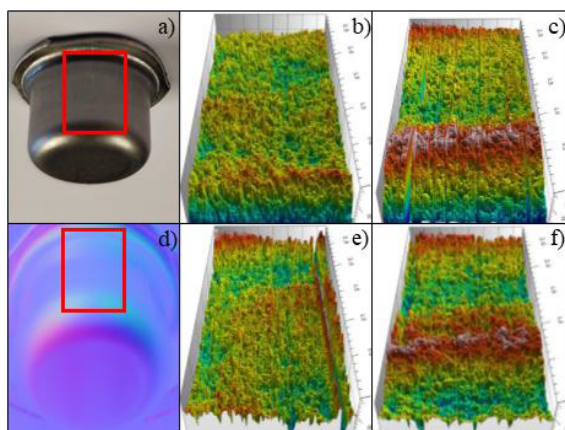


Fig. 5. Images of the cup surface: a) Photo of the cup; b), c), e) and f) images from the surface in the red rectangle with a

confocal white light microscope; d) normal map from the scanning module

The progressive die under consideration comprises the two main forming stages of deep drawing and ironing to produce a 'cup'. Different production-related defects can occur in each of these stages, which can be both inherent to the process and wear-related. While the deep drawing process is primarily responsible for the formation of scoring and localised material accumulations, the influence of the ironing process often manifests itself in the form of waviness on the component surface. Fig. 5 illustrates examples of the error patterns described above. The series of tests carried out focused on specific types of defects that are relevant both for the evaluation by the scanning module and for the feedback of defects into the production process. The test series are based on synthetically generated wear patterns in the matrices, as described in detail in chapter 2.1. The figure illustrates the effects of different states of deep-drawing and ironing dies on the surface quality of a cup. Fig. 5 a) shows an overall view of the bowl, with the relevant area under investigation marked by a red rectangle. This area serves as a reference for the detailed analyses of the surface structures shown in figures b) to f) which are produced through the utilisation of a confocal microscope. Fig. 5 b) shows a three-dimensional surface image of a cup that was manufactured using an unworn deep-drawing and an unworn ironing die. This configuration represents a fault-free cup that is characterised by a homogeneous and uniform surface structure. Fig. 5 c) illustrates the influence of synthetic wear on the ironing die with an unworn deep-drawing die. This clearly shows pronounced differences in roughness and irregular surface structures. Fig. 5 d) shows a normal map that is the result of the surface reconstruction performed by the built-in scanning module to create the wear mask. Fig. 5 e) shows the surface structure of a cup with a synthetically worn deep-drawing die and an unworn ironing die. Clear line structures and elevations are visible indicating the dominant influence of wear on the deep-drawing die. Fig. 5 f) shows the effects of combined wear of both die components, which manifests itself in strongly pronounced grooves, increased roughness and an overall uneven texture. The colour scale of the 3D surface images visualises the topographical height differences: red marks the largest elevations with a height of around 15 μm , while blue represents the base plane at 0 μm . Fig. 6 presents various normal maps that were generated as part of the present study. In a), a normal map of a fault-free cup from the reference test series is depicted, while in d) an exemplary normal map from test series 4 is shown in which the die is synthetically worn in the deep-drawing and ironing stage. A visual analysis of these two representations hardly reveals any differences. In b), the comparison between the fault-free cup images is shown, with the mask appearing almost black, indicating the use of identical data and the associated inability of the method to detect changes.

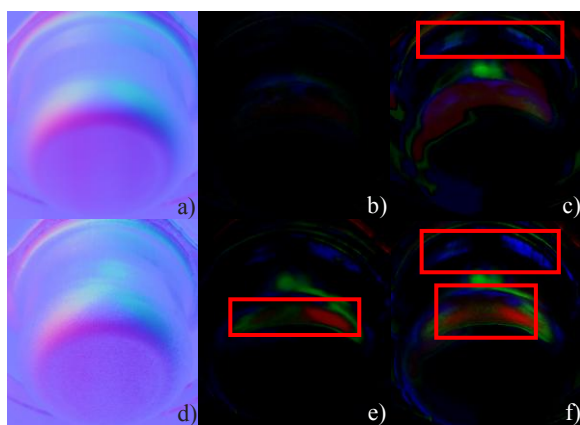


Fig. 6. Comparison normal map from the scanning module and wear mask of the 4 wear test series: a) normal map of a fault-free cup; b), c), e) and f) are wear mask of the test series; d) normal map of a bad cup

Fig. 6 c) shows the case where the deep-drawing die is synthetically worn, and the ironing die is unworn. Fig. 6 e) illustrates the reverse scenario, i.e. an unworn deep-drawing die in combination with a worn ironing die. Finally, f) shows the comparison with a simultaneously worn deep-drawing and ironing die. It is clear to see that different areas of the normal maps can be assigned to specific production steps. The figures clearly (highlighted with red boxes in the illustrations) identify the areas where surface defects are due to specific forming processes. If the areas marked in Fig. 6 b), c), e) and f) are compared with the corresponding areas in Fig. 5, it can be clearly seen that the wear masks mark the same areas in colour. The corresponding areas can also be assigned to the deep drawing or ironing process. Thus, a clear assignment of cause and effect can be derived via the soft sensor. For example, scoring and scratches can be seen in the upper part of the image, which indicate the deep-drawing stage, while waviness caused using the ironing die can be seen in the lower part of the cup. This means that a clear allocation is demonstrated. The quality of the surface finish is a pivotal aspect of this technology, with the condition of the mould exerting a predominant influence on this parameter. Given the extensive range of production parameters, surface quality necessitates a process- and product-specific empirical definition, as opposed to a generalised tolerance framework. The internal characteristics of the production process and the product itself play a key role in determining acceptable deviations and quality requirements. To ensure reliable performance, a sound database is created with a limited number of data collections. With less than 200 semi-finished products recorded, the system reaches its full operational capability after a short teaching phase. This teaching data allows qualitative comparisons of changes to the component surface, enabling efficient implementation and seamless customisation to specific application requirements. Fig. 7 shows the progression of the direct deep-drawing process force for the four different test series, which differ in terms of the different combinations of deep-drawing die and ironing die. The blue and orange curves represent combinations with an unworn deep-drawing die (Tp_Ax), while the green and red curves represent those with a synthetically worn

deep-drawing die (Tv_Ax). The force curve shows the typical pattern for a deep drawing process: the process force initially increases, then reaches a plateau and finally decreases again until the end of the forming process. In the series of tests with synthetically worn deep-drawing dies (green and red curves), a slight wave formation or two local maxima can be seen within this plateau. These can be interpreted as indicators of altered friction conditions and modified material flow characteristics as a result of tool wear.

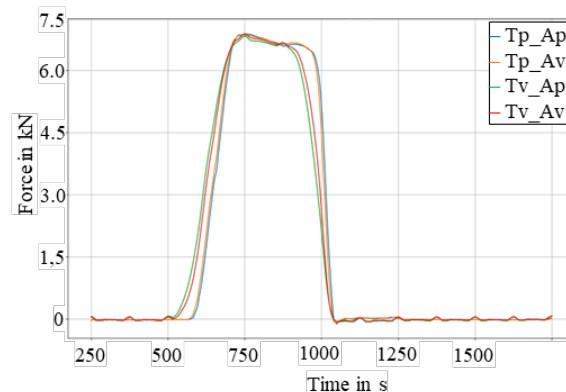


Fig. 7. Force curves of the direct process force during deep drawing for the time of one stroke

Fig. 8 shows the progression of the indirectly measured process force in the ironing process for four different test series. The blue and green curves represent combinations with an unworn ironing die (Tx_Ap), while the orange and red curves represent those with a synthetically worn die (Tx_Av). The force curve shows a characteristic development: At the beginning of the process, the force increases with increasing material deformation until a maximum is reached. This is followed by a symmetrical decrease in the force until the end of the process, at which point it can be seen that an increase in force can be measured with a synthetically worn ironing die, which is comparatively low at approximately 5 % of the maximum force.

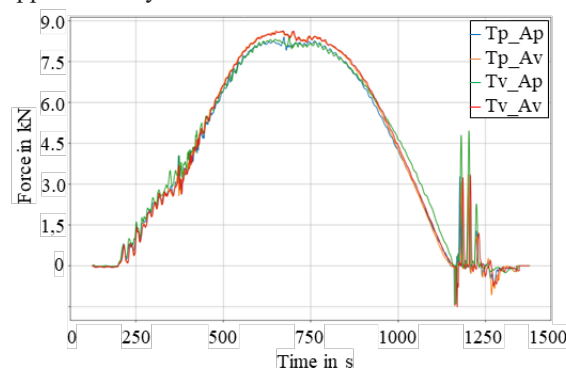


Fig. 8. Force curves of the indirect process force during ironing for the time of one stroke

Despite the differences in the process stages, the deviations between the individual curves are marginal overall, and simply analysing the process force during regular production operations would not reliably detect these subtle deviations, meaning that creeping tool wear or an increased scrap rate could go unnoticed. This emphasises the need for a more detailed analysis of process forces and additional methods for monitoring

tool conditions to enable early detection of wear and quality deviations. Compared to the measured force signal, the wear mask derived from the scanning module data contains significantly more relevant information. This emphasises the added value of image-based analysis approaches for wear assessment. Furthermore, it has been shown that despite the simplifying assumptions made within the photometric stereo reconstruction, valid and reproducible results can be obtained. The suitability of the presented scan module for the digitisation of component surfaces can therefore also be confirmed at the high process speeds of 200 strokes per minute tested in the trial. This underlines its potential for use in industrial applications in conjunction with powerful hardware with even higher clock frequencies.

4 Conclusions

This study analyses the accuracy and suitability of methods for wear detection in continuous operation of high-speed multi-stage forming processes. It is shown that force monitoring alone is not capable of providing precise statements about the cause, severity and exact localisation of faulty conditions in the progressive die tool. This limitation reveals a significant gap in the industrial inline monitoring of forming processes. The method presented in this paper demonstrates the potential and effectiveness of photometric stereo analysis in high-speed forming processes. This method allows not only the detection of surface features with high precision, but also cause-specific feedback between detected component surface features or wear marks and the existing tool wear within its installed forming steps. This correlation can be carried out locally at the respective process steps, enabling precise and situation-specific analysis of critical areas of the forming process. In addition, photometric stereo analysis offers the possibility of specifically identifying the causes of quality deviations if the measuring points in the die are accessible. This significantly improves process understanding and helps to make forming processes more efficient and resource-saving. Another key advantage of the method presented is the possibility of carrying out 100% quality control at far more than the 200 strokes per minute tested here. With slightly adapted hardware, 1000 strokes per minute are possible. Continuous inline monitoring enables critical wear conditions to be recognised at an early stage before significant amount of scrap are produced. This not only increases process reliability, but also reduces costs by minimising rework and scrap rates. It is also possible to use different light waves to enable precise quality control of semi-finished products, even when using lubricants. This will be the subject of future research work.

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