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Posted Date: 28 January 2025

doi: 10.20944/preprints202501.2076.v1

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Article

Cost-Effective Surface Quality Measurement and Advanced Data Analysis for Reamed Bores

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Abstract: This paper presents a cost-effective approach for the automated surface quality measurement in reamed bores. The study involved drilling 4,000 holes into 42CrMo S4V steel, of which 3,600 underwent subsequent reaming. Utilizing a CNC-controlled gantry coupled with a mobile roughness measurement device through a compliant mechanism, surface data of every bore was efficiently gathered and processed. Additionally, analytical methods are presented that extend beyond standardized, aggregated metrics, enabling the evaluation of correlations to other quality characteristics and sensor data, such as the formation of grooves, positional deviations, and the process forces that occur during the reaming process. This approach aims to enhance understanding of the reaming process, ultimately improving bore quality, reducing component rejects, and extending tool lifespan.

Keywords: surface evaluation; reaming; drilling; automation; machining; metrology; compliant mechanism

1. Introduction

Reaming is used to achieve precise bores, demanding high standards for position, shape, and surface quality. Surface quality is critical not only to the usability of a component but also provides valuable insights into the process itself. For instance, chatter marks on a surface are a common indicator of self-excited vibrations during processing, but also tool wear—such as the formation of a built-up edge—is visible on the machined surface. Therefore, surface analysis offers a strong foundation for process optimization and interpretation of data.

This study is part of the project “KI-Span” [1]. The research project focuses on improving tool life and part quality in machining processes by analysing data, with the goal of developing robust, process-independent methods. By leveraging high-quality production data, the project aims to reduce tool-related costs, particularly in industries like aerospace, where tools account for a significant portion of production expenses.

Several studies have explored the influence of process parameters on part quality during reaming, often focusing on a specific choice of material. Key parameters that are commonly analysed include cutting speed, feed rate, tool selection, and lubrication. These studies not only examine surface quality but also investigate other critical quality characteristics such as roundness, positional accuracy, and cylindricity.

For instance, Zhang, Wang and Han [2] investigate the cutting performance, surface quality, and geometric accuracy of reaming titanium alloy Ti6Al4V using right-hand and straight-groove cemented-carbide reamers. The right-hand reamer demonstrates superior performance in terms of cutting force, tool life, surface quality, and geometric accuracy, making it a better choice for machining titanium alloys.

Lagoa Melo et al. [3] have used a statistical approach to study surface quality and form errors when reaming AISI P20 hardened steel. Their work establishes correlations between tool choice,

cutting parameters, and lubrication, and assesses their effects on surface roughness, thrust force, torque, roundness, and cylindricity.

In another study [4], Bezerra, Machado, Souza Jr., and Ezugwu investigated the reaming of an aluminium-silicon alloy (SAE 322). They examined surface finish, roundness, cylindricity, and power consumption under various cutting conditions while experimenting with different tools and process parameters.

Additionally, Zheleznov and Andreeva [5] focused on surface quality, particularly the formation of individual scratches during reaming. Their research highlights how a built-up edge or chip wedging can hinder achieving specified roughness values like Ra and Rz.

Müller et al. [6] analyse the reaming process of steel bushings made from austenitic AISI 316L stainless steel to achieve given dimensional and surface tolerances, considering economic and technical constraints. Experiments were conducted with varying cutting speeds, feeds, and lubricants to identify the optimal combination that meets all requirements. The results show that the surface finish and the occurrence of diameter bell-mouthing are less influenced by lubrication and feed rates when slow cutting speeds are used.

In [7] Müller and De Chiffre investigate the reproducibility of surface roughness under varying process conditions, including cutting fluids, cutting speeds, feed rates, and operators. The goal is to evaluate the effectiveness of the reaming process for testing cutting fluids. As in [6], low cutting speeds consistently yield high reproducibility in surface roughness, regardless of the cutting fluid used. In contrast, higher cutting speeds result in uneven and less reproducible surfaces. However, reproducibility improves when cutting fluids with higher oil content are used in water-based solutions. Furthermore, the study highlights that while Ra is not ideal for comparing machined surfaces, it serves as a reliable indicator of reproducibility and low Ra values generally correlate with better surface quality.

Other studies specifically examine the forces generated during the reaming process. Wang, Cui, Xu, and Jiang [8] have analysed the forces involved when reaming ZL102 aluminum using a PCD reamer. Their findings indicate that thrust force remains constant throughout the reaming operation. Additionally, increasing the cutting speed leads to a decrease in thrust force, whereas a higher feed rate increases it.

In [9] Bretz, Abele and Weigold present the development of a sensor-integrated reaming system for real-time straightness measurement during the machining process, eliminating the need for additional post-process measurements. This system incorporates strain gauges on the reamer shaft for data acquisition, a custom-designed telemetry unit for real-time wireless data transmission, and advanced analysis techniques utilizing artificial neural networks (ANN). The system achieves high precision in bore straightness measurement while emphasizing the need for a more compact and fully integrated solution suitable for industrial applications.

Other publications place a greater emphasis on modelling and forecast of process forces. For instance, Bhattacharyya, Jun, Kapoor, and DeVor [10] have developed a model to predict process forces during reaming, incorporating process faults and misalignments. Additionally, this model is used to predict the resulting bore diameter.

Kamath et al. [11] show a dynamic force model to predict cutting forces during reaming. It incorporates tool geometry, material properties, and vibration system elements (mass, stiffness and damping coefficients of the tool) to compute tangential, radial and axial forces, validated experimentally with less than 5% prediction error. Key findings include that torque increases with reamer size, while radial and axial forces are less sensitive to size variations. The model aids in minimizing defects like spindle misalignment and runout in reamed holes, with potential extensions to other materials and tool geometries. It highlights the importance of chip thickness variation and vibrational effects on dynamic force changes.

In [12] Rakshith, Kamath and Vijay investigate the performance of Artificial Neural Network (ANN) and Random Forest (RF) algorithms in predicting torque during reaming operations. Experimental data were gathered from reaming processes performed on various materials, with

different tool radii and rotation angles. The ANN model was optimized and its performance compared against RF and polynomial regression models. The findings demonstrate that the ANN model delivers accurate and reliable torque predictions, outperforming both RF and polynomial regression. This superior precision of the ANN model aims to facilitate better torque control, thereby enhancing surface finish quality during machining.

A significant challenge in this research area is the efficient collection of high-quality surface data, which is often time-consuming and costly, underscoring the need for automation. This paper introduces a cost-effective approach for the automated acquisition and subsequent analysis of surface data. It explores possibilities that extend beyond standardized, aggregated surface parameters, utilizing recorded profiles to identify process anomalies. Additionally, it highlights the integration of sensor, machine, and quality data, facilitating deeper insights into process dynamics and performance.

2. Materials and Methods

2.1 Reaming Process

During reaming, existing bores are drilled and then slightly enlarged, with the reamer naturally following the bore's path. In this experiment, eight plates of 42CrMo S4V steel are drilled, each with 500 holes. Out of these, 425 holes per plate are subsequently reamed, resulting in a total of 3,400 reamed holes. 600 holes are left unreamed to evaluate the drilling process, which is not discussed in this paper. After the third plate, i.e., after 1500 holes, the first drilling tool was replaced. A new drill and reamer were simultaneously inserted before plate 6.

To minimize chatter and to enhance the roundness and surface quality of the holes, coated six flute reamers with an irregular pitch angle ($\gamma > \alpha > \beta$) and internal coolant channel (ICC) are used (Ceratizit Komet Fullmax 52M.57 10H7). Pre-drilling is performed with a coated solid carbide drill featuring a 140° tip angle (Ceratizit WTX-UNI 9.80), also equipped with ICC. This results in a stock allowance of 0.1 mm. For both drilling and reaming, the sensory "spike" tool holder from the pro-micron GmbH is used, which records bending moments, as well as torque and axial forces generated by the process. A five axis DMU65 FD monoBLOCK milling machine from DMG MORI is used for the machining process.

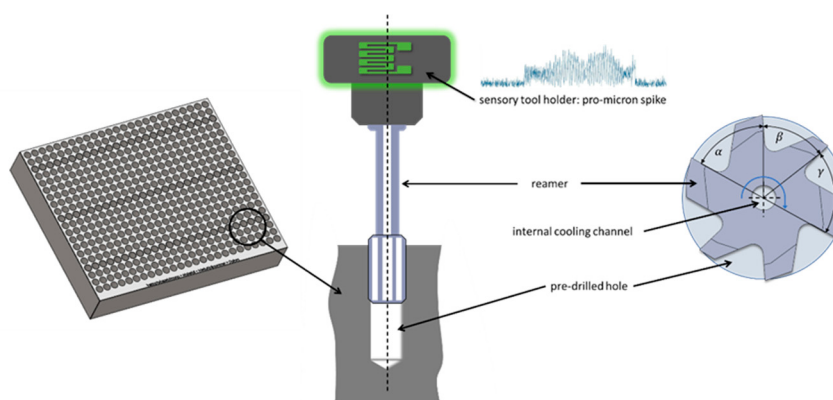


Figure 1. Reaming experiment.

2.2 Automated Surface Measurement

For automated surface data acquisition, a cost-effective mobile and hand-held surface measuring device, the MarSurf PS 10 by Mahr, is used. This stylus profilometer features a detachable feed unit that is positioned along the bore axis. It offers a measurement length of up to 12.5 mm with a profile resolution of 8 nm. Similar devices are widely used in industry and are therefore readily available. Alternatively, expensive coordinate measuring machines with surface measurement capability can

be used. The feed unit of the MarSurf is mounted on a CNC-controlled gantry, which is controlled by a PC using standardized G-code. During the measurement, the stepper motors are automatically switched off to minimise possible influences on the measurement process. The MarCom Professional software runs simultaneously on the PC to record and store measurement data in the form of aggregated values such as R_a and R_z , as well as the raw surface profile itself. The interface between the G-code and the MarCom software is implemented in Python.

The feed device holder primarily consists of two flexible, 3D-printed components—designed for this study—out of PLA plastic, functioning as a compliant mechanism. The XY stage (orange component in Figure 2) is engineered to be flexible in two translational directions while remaining rigid in all others. This, along with the two contact surfaces, ensures precise positioning within the bore and provides secure guidance to the measurement surface. The compliant design offers several advantages, including a small installation space and cost savings from eliminating linear units. Additionally, it requires no lubricants that could contaminate the workpiece or profilometer, has almost no breakaway force, and involves low maintenance effort. The second component allows precise positioning in the vertical direction by placing the unit on the component surface. It also includes a snap mechanism to protect the measuring device if a hole is missed.

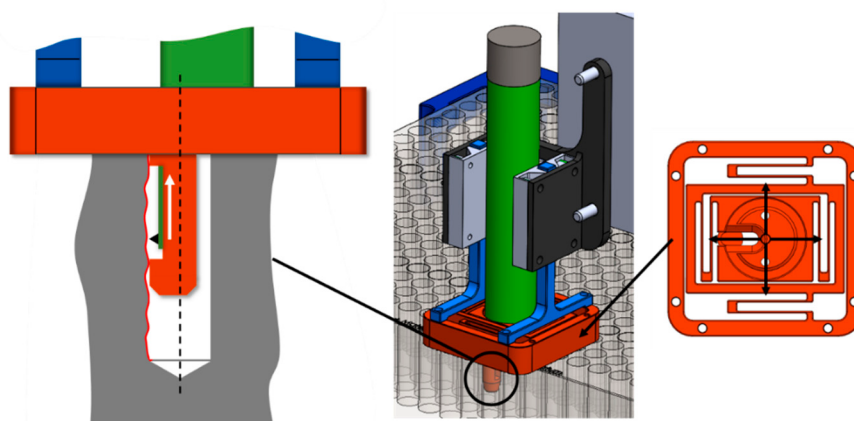


Figure 2. Automated surface measurement.

3. Results

3.1. Pre-Processing: Filtering According to Standards

The goal of pre-processing is to separate the surface profile into roughness and waviness parts, representing short-wave and long-wave components, respectively. Although both are deviations in surface shape, they arise from different mechanisms and are therefore analysed separately. Roughness is typically influenced by factors like chip formation, cutting edge geometry, or cutting parameters, whereas waviness is attributed to process dynamics, faults or misalignments.

This separation of waviness and roughness is achieved through a modified, non-linear Gaussian regression filter, compliant with DIN EN ISO 16610-31. This filter is robust against groove-like valleys, making it particularly suitable for plateau-like surfaces produced by processes such as reaming or honing. The choice of the nesting index controls the cut-off length between waviness and roughness and is usually chosen based on the expected surface roughness and measurement length. In this evaluation, the choice of measurement length and cut-off wavelength ensures in particular that enough grooves are present in the roughness profile in sufficient quality. Figure 3 demonstrates this on a reamed hole: the primary profile (representing the actual surface) from the surface measurement device is shown in black; the waviness component resulting from the regression filter is displayed in orange; and the roughness, derived from the difference between the primary profile and waviness, appears in blue. The observed trend of approximately 0.008 mm over 12 mm

measuring distance is attributed to a slight misalignment of the measuring device within the bore, which is acceptable for a 3D-printed design.

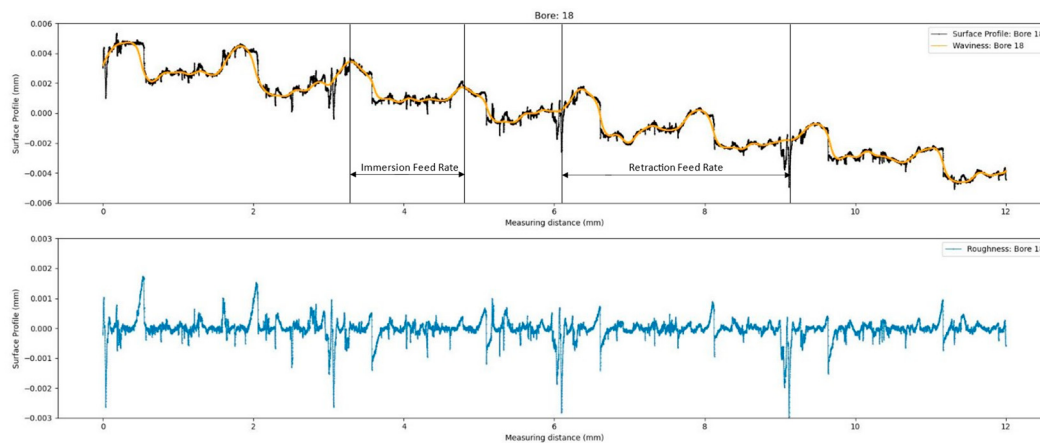


Figure 3. Surface profile (top), waviness (top) and roughness (bottom) of a reamed bore. The worn tool results in an expressive waviness and roughness profile. Additionally, the feed speeds during the immersion and retraction of the reaming tool are indicated.

3.2. Analysis of Retraction Grooves in the Roughness profile

One focus of this investigation is a groove that occasionally forms during the retraction of the reamer within the bore. This groove can increase the risk of component failure at sealing surfaces by allowing fluids, like oil, to flow along its path. To make the retraction groove distinctly visible, one bore is measured in approximately five-degree increments, creating a 360° scan of the bore surface. This scan provides a clear visualization of the surface structure, though the radial resolution does not support the derivation of 3D surface parameters. Figure 4b presents this 360° Scan visualized as a scatter plot of the roughness profiles. The darker and therefore deeper groove (in positive Z direction counter-clockwise rising) is clearly visible, corresponding to the groove formed when the reamer is retracted. Figure 4c shows a 2D heatmap of the detrended raw surface profiles, where one can additionally see the surface generated by each cutting edge.

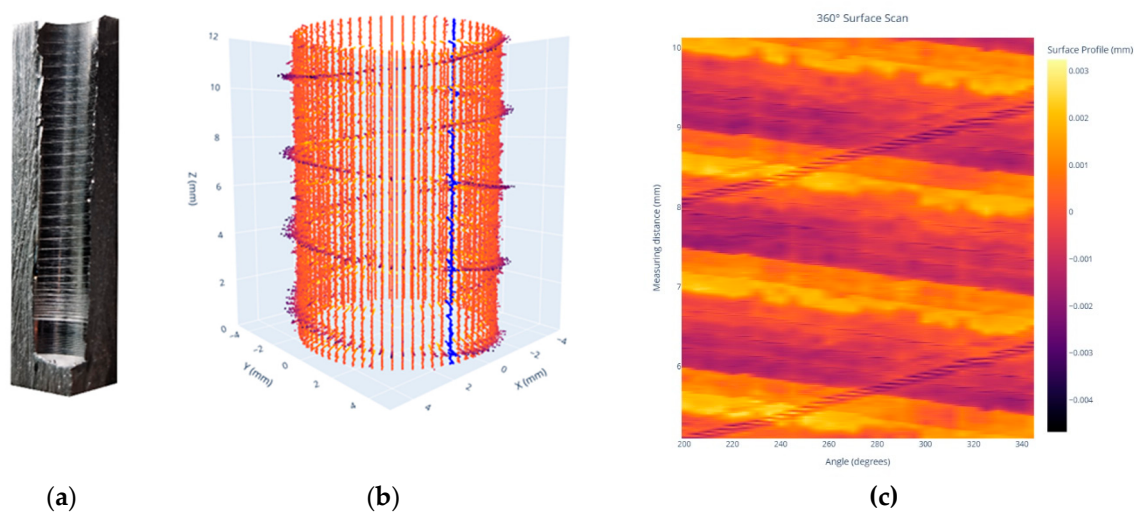


Figure 4. (a) Sectional view of a reamed; (b) 360° Scatter plot of roughness profile; (c) Heatmap section of detrended raw profile.

Figure 5 shows one profile section of Figure 4. This view does not retain information about whether the groove was created during immersion or retraction.

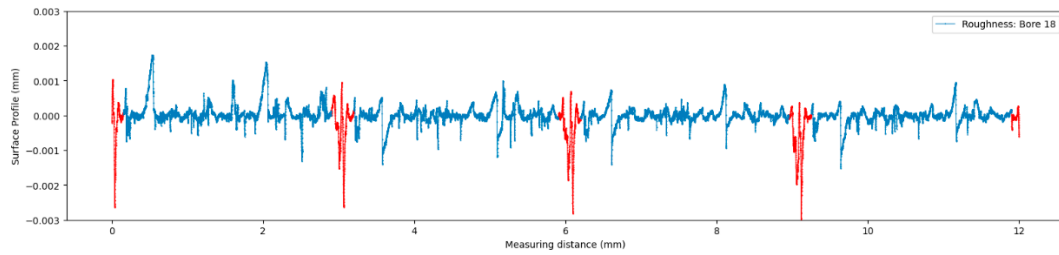


Figure 5. Retraction groove (highlighted in red) in the roughness profile.

The Abbot-Firestone material ratio curve (Figure 6a) provides a standardized (DIN EN ISO 13565-2) method for assessing the peaks, core area, and grooves of a surface. In this approach, the surface profile is organized by profile height and material content. Surface constants can then be determined through a well-defined procedure. One such constant is the R_{VK} -value, which provides a quantitative measure of the presence of grooves. However, since this method does not evaluate the periodicity of recurring grooves—which can be critical to a component’s function—a new approach, based on the autocovariance of the roughness profile is proposed. Calculated similarly to autocorrelation, autocovariance evaluates the recorded profile section and reveals how the surface features relate to each other over varying distances:

$$\hat{\gamma}_k = \frac{1}{L} \sum_{x=1}^{L-k} (z_{x+k} - \bar{z})(z_x - \bar{z}), \quad k = 0, 1, \dots, L-1 \quad (1)$$

$\hat{\gamma}_k$ is the autocovariance at lag k , L is the number of profile points, z_x is the profile height at the x -th measurement and $\bar{z}$ is the mean profile height. To evaluate the result with respect to measuring distance d as shown in Figure 6b we reparametrize the autocovariance using the known sample rate a as follows:

$$\tilde{\gamma}(d) := \hat{\gamma}_{\lfloor \frac{d}{a} \rfloor}, \quad d \in \mathbb{R}_{\geq 0} \quad (2)$$

Unlike autocorrelation, autocovariance is not normalized, providing additional insight into the amplitude of recurring features. In addition, specific areas of the roughness profile, such as heights and grooves, can be analysed individually by isolating the desired region before calculating the autocorrelation.

Figure 6b shows a high autocovariance at 3 mm, corresponding to the feed rate during retraction of the reamer. Caution is advised if the retraction feed rate is a multiple of the feed rate used to enter the hole. As an effective method for evaluating the calculated autocovariance, we propose utilizing the maximum value of the employed distance (feed rate) during extraction. If this distance happens to be a multiple of the feed rate used during immersion, the difference between the two maximum values at both used feed rates (immersion and retraction) should be utilized.

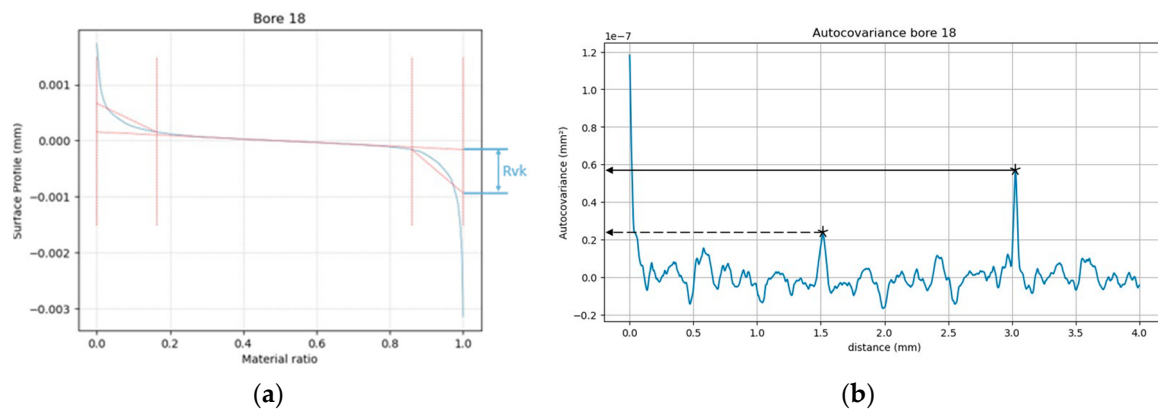


Figure 6. Assessment of retraction groove: (a) Abbot-Firestone profile; (b) Autocovariance profile.

3.3. Analysis of Phase Position in Waviness

Another focus of this investigation is the waviness of the measured bores, which displays a periodic pattern influenced by the feed rate per revolution during reaming. Comparative descriptive analysis shows that each borehole displays a distinctive pattern that spans its entire surface. While this pattern can vary from hole to hole, similar profiles tend to emerge between holes that share the same phase position of the surface profile. The phase position of the waviness—representing the location of this recurring pattern within the bore—can be converted to an angle between 0° and 360° (indicated by the blue line) using the known feed rate. Figure 7 shows an example of this calculation for one peak. To determine the phase position of one bore, the median phase location of the recurring peaks in the waviness profile (marked by red crosses) is calculated.

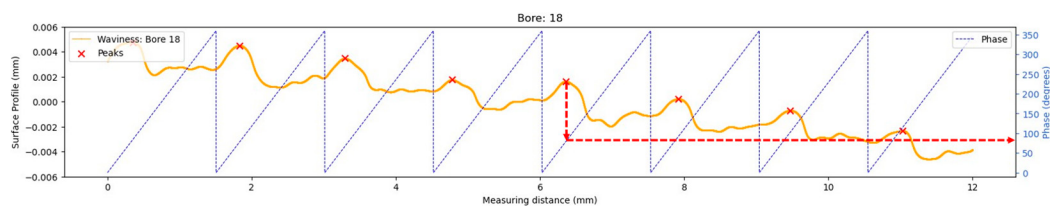


Figure 7. Phase position of waviness profile

Plotting all angles of one plate as a colourmap reveals distinct patterns within the experiment, provided the profilometer is positioned at a constant angle across all bores. This consistency arises from the highly stable rotational and traversing speeds of the machine tool. Figure 8a displays the phase angle as a colour gradient across the holes on the fourth plate in the experiment. Arrows indicate the machining sequence for the first two rows as an example. Moreover, one can see the three temporary columns in which the plate was processed.

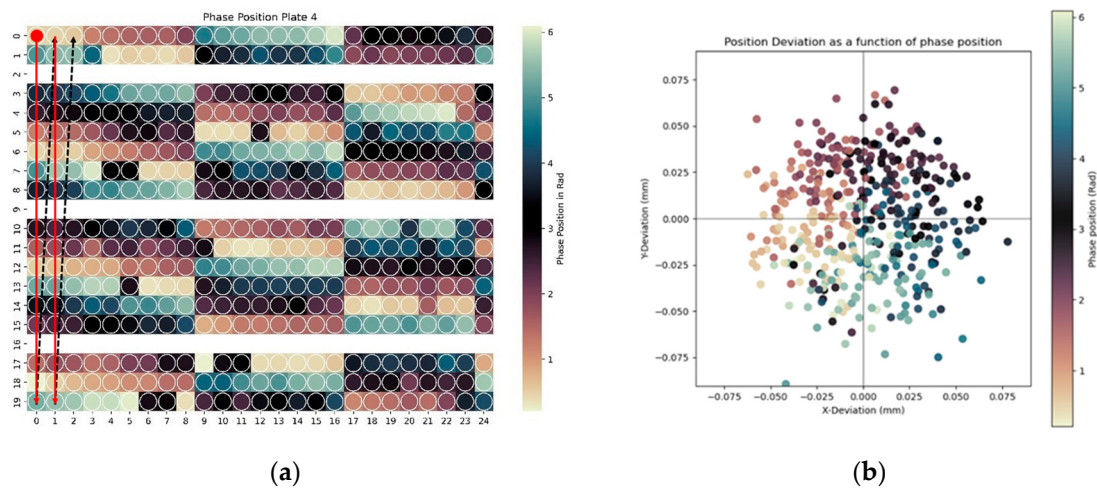


Figure 8. (a) Phase Position of worn reamer for plate 4; (b) Position Deviation of worn reamer for plate 4

If the holes are plotted around their ideal position (0,0) using measurements from a Coordinate-measuring machine rather than at their locations on the plate, another relation becomes apparent: A certain phase positions in the waviness profile results in a certain positional deviation of the bore. When examining the circular correlation between the two variables—phase position and angle of position deviation—we find that it is represented as $-0.5 - 0.5j$ for the plate shown above, resulting in a correlation magnitude of 0.7. Figure 9 shows a less worn reamer, which still results in a considerable correlation magnitude of 0.33. The different pattern on the left-hand side is due to changed travel and feed speeds, while we argue that the smaller position deviation is due to the better condition of the reamer.

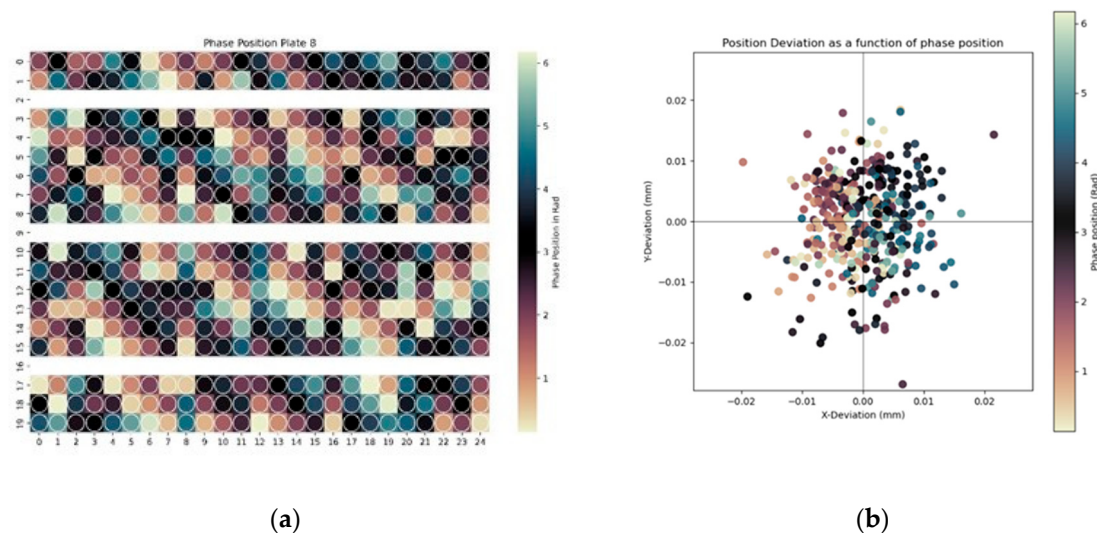


Figure 9. (a) Phase Position of worn reamer for plate 4; (b) Position Deviation of worn reamer for plate 4.

The correlation between position offset and the phase position of the waviness profile reveals a systematic positional error, especially in the case of worn tools. We propose that the phase position is directly related to the angle at which the reaming tool initially contacts the workpiece. This observation presents a promising avenue for further investigation, as addressing it could provide a method to enhance positional accuracy or extend the usable life of the reamer.

3.4. Analysis of Cutting Forces

During the experiment, process forces were measured using the 'Spike' sensory tool holder by pro-micron. It records bending moments, axial forces, and torque in a rotating coordinate system

generated during the machining process. Figure 10 displays a representative curve over a bore with a duration of approximately one second. The left ordinate shows the Z-axis position, where the zero point marks the reamer's entry depth, and the total reaming depth is 40 mm. On the right ordinate, the process forces are displayed, each with a dedicated scale. By synchronizing the axis data with the recorded process forces, specific phases of the reaming process—such as immersion and retraction—can be observed individually. It is noticeable that the bending moment (absolute values) during reaming (0 mm to 40 mm) is very similar to the bending moment after reaming (40 mm to 0 mm). This is in line with the observations of [10] where it is described that the largest component of forces in the X and Y directions, i.e. forces that cause bending moments, is caused by reaction forces due to runout error and axis misalignments.

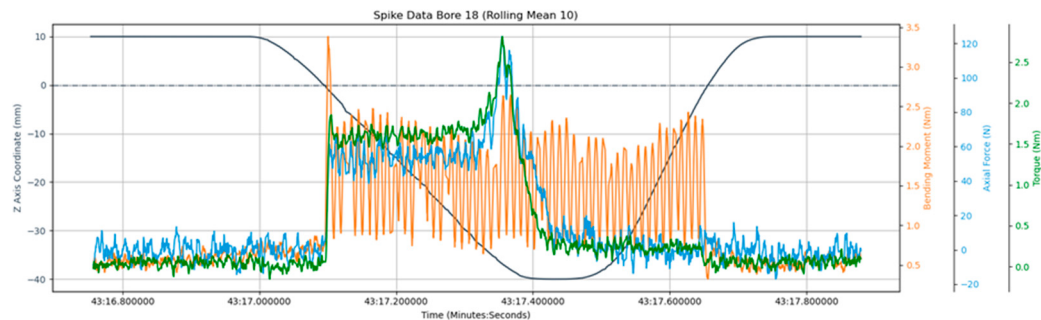


Figure 10. Measured forces (Bending Moment, Axial Force, Torque) during the reaming process of one bore.

The curves shown can be aggregated in various ways, with the mean value often generating the highest correlations to selected quality metrics. As an example, Figure 11 puts the mean bending moment in comparison position deviation of the reamed bore. The heavily worn reamer on plate 4 leads to significantly greater mean bending moments and position deviations than the less worn reamer on plate 8. Both images share a common offset, which may be attributed to the measurement or signal processing pipeline of the position deviation on the coordinate measurement machine, or to the process force acquisition in the sensory tool holder. The lowest bending moment occurs at a position deviation of around 0.02 mm in the positive Y direction.

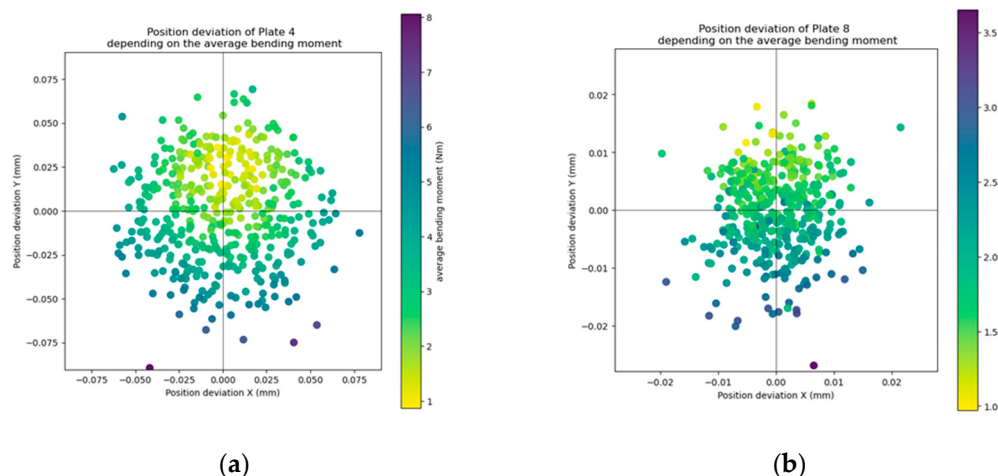


Figure 11. Bending moment based on position deviation: (a) Plate 4; (b) Plate 8; Note that the scaling of the axes varies, reflecting the fact that the position deviations for the worn tool (a) are significantly higher.

4. Discussion

The primary conclusions drawn from this work are as follows:

1. An automated, cost-effective system was developed for surface quality measurement in reamed bores, using a NC-controlled gantry and a mobile stylus profilometer.

2. The analysis of the profile data and separation of surface profiles into roughness and waviness components, according to the demanding DIN EN ISO standards, enables a more targeted analysis of process-specific issues.
3. Retraction grooves were clearly visualized using a 360° scan. An autocovariance-based approach was introduced to evaluate these grooves, offering a more specific assessment than standard metrics.
4. The phase position of the waviness profile on the reamed surface correlates with tool entry angle and position deviation. By putting this phase position into context with the bore position in the workpiece, patterns associated with tool wear were identified, allowing for potential process improvements to reduce positional deviations.
5. Process forces were measured and analysed to link bending moments with bore position deviations, revealing that bending moments increase significantly with larger positional deviations.

Despite extensive efforts to establish a link between surface data features, such as retraction grooves, and process forces, such as bending moments, no statistically significant relationship was identified. Various analyses, including feature extraction, FFT, cross-correlation, and regression modelling, yielded no clear dependency between these factors. This finding suggests that lower-order geometric defects predominantly influence the process forces, while factors impacting surface roughness do not prominently appear in the force data. Future research could explore advanced data analysis techniques and alternative measurement technologies to uncover any potential correlations that may exist. Additionally, the proposed relationship between phase angle and position deviation warrants further investigation to reduce positional errors in reamed bores in the future or to extend the reamer's lifespan.

Author Contributions: Conceptualization, T.J. and S.U.; formal analysis, T.J.; investigation, T.J, S.U and B.M.; data curation, B.M.; writing—original draft preparation, T.J.; writing—review and editing, F.S.; visualization, S.U.; supervision, F.S. All authors have read and agreed to the published version of the manuscript.

Funding: The project “AI-supported optimization of tool life and component quality on machine tools in machining production (KI-Span)” (Original: “KI-gestützte Optimierung der Werkzeugstandzeit und der Qualität der Bauteile an Werkzeugmaschinen in der spanenden Fertigung (KI-Span)”) running from August 2021 to December 2024, is funded under the Bavarian Collaborative Research Program (BayV-FP), funding line: Digitization, by the Bavarian Ministry of Economic Affairs, Regional Development and Energy (StMWi).

Data Availability Statement: The original surface profile data presented in the study are openly available at <https://zenodo.org/records/14697332>. Additional data presented in this study are available on request from the corresponding author due to restrictions within the project consortium.

Acknowledgments: The authors would like to thank Fabio Lischka for his valuable mathematical support during the development of this work.

Conflicts of Interest: The authors declare no conflicts of interest.

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