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Precision Assessment of Tactile On-Machine Inspection for Milling Operations

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Abstract

The manufacturing industry faces customer demands for increased product quality and individuality to be economically successful. Established processes on the shop floor cannot overcome resulting challenges. Due to the increased quality requirements, potentially more products must be checked regarding their requirement fulfilment. In addition, customer individuality increases the number and rate of product releases. During product releases, the quality of the product is checked. Coordinate measuring machines are usually used for the quality assessment of milling processes. However, these are only suitable in the area of high quantities per batch due to downtimes of the milling machine while assessing product quality. On-machine inspection systems show particular strengths when a high proportion of the manufactured products have to be inspected and potentially reworked. These systems are criticized for their poor precision compared to coordinate measuring machines. This paper demonstrates the precision and repeatability of a tactile system in a field test at a tool manufacturer. Based on the test results, the tactile on-machine inspection system is compared with conventional coordinate measuring machines. Finally, the application area and its limits are identified for tactile on-machine inspection systems.

Keywords

on-machine inspection; quality assessment; tactile measurement; customized products; milling

1. Introduction

Current trends in the market for machining products indicate that products are becoming more customized to individual customers while, at the same time, there are increasing demands for product quality [1-3]. The market-driven customer individuality is reflected in mass personalization, which realizes customer-specific parts at comparable costs, even for batch sizes of 1 [4]. For economical production of batch size one not only the manufacturing process but also the quality assurance processes must ensure the necessary quality [5].

1.1 Initial situation

One essential quality assurance process is product release obtained for serial parts for the first manufactured part, confirming that the manufacturing system meets the product requirements [6]. After product release, quality inspection for the series are implemented in a defined sequence. These measures can range from inspecting every part of the series (100% inspection) to a small or complete waiver of samples. Based on the customer-specific product, each part must undergo inspection for the necessary product release, as with a high number of customer-specific features, each part is a new part [7]. The standard process in the industry for product release of milled parts comprises eight steps:

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1. Unclamping from the machine (machine waits)
2. Clamping in the coordinate measuring machine
3. Programming the inspection task (can be done pre-process in a digital environment)
4. Execution of the inspection program
5. Unclamping of the work piece
6. Interpretation of the inspection results
7. Possibly rework and start of step 1
8. Product release and release of the machine tool for the next order.

The introduction of tactile on-machine inspection offers the possibility of shortening the process chain and minimizing non-value-added activities [8]. A common criticism against using tactile measuring systems for quality assurance is the perceived lower precision compared to coordinate measuring machines [9]. However, this paper will demonstrate that tactile on-machine inspection can match the precision of conventional coordinate measuring machines.

1.2 Scope

To support this claim, experiments were conducted on a machine tool using the touch probe system for reproducible measurement. The repeatability within manufacturing tolerances and the use in a productive manufacturing system were tested.

The results of these experiments show that tactile on-machine inspection provides acceptable precision that meets the requirements of manufacturing tolerances. This allows for efficient quality inspection directly on the machine without additional measuring equipment, such as coordinate measuring machines. Integrating inspection into the manufacturing process can prevent non-value-added activities such as unclamping and measuring on separate measuring machines.

It is important to note that the precision of tactile on-machine inspection depends on various factors, such as machine stability, calibration of the touch probe system, and proper programming of the measurement tasks. Therefore, careful setup and regular verification are crucial to achieve optimal results.

Overall, this paper demonstrates that tactile on-machine inspection is a promising alternative to conventional quality inspection with coordinate measuring machines. It enables efficient and precise monitoring of manufacturing quality directly on the machine, leading to shortened lead times and a reduction in non-value-added activities.

2. State of the art

The following section discusses tactile touch systems for milling. During milling, chips are generated, and coolant is used. Both can reflect when using an optical measurement system. Therefore, a more robust system is necessary to withstand environmental influences [10-11]. The touch system uses mechanical force on the probe head and is thus better suited for the machining environment.

Measurement methods for quality assurance can be divided into two groups: in situ measurement methods that measure during the process (in situ or on-machine) and measurement methods that are outsourced from the process (ex situ). Both measurement methods use the same principles (e.g., tactile, optical, etc.) [12-13]. Due to the focus on tactile in situ measurements, the corresponding offline measurement method is also presented as a reference.

2.1 Coordinate measurement machines

Generally, tactile measurement outside the machine tool uses coordinate measuring machines (CMM). These machines typically consist of a tool holder, a probe, and kinematics for multiple axes. The general use and a brief description of operating CMM can be found in [14-16].

The advantage of CMMs is their explicit use for measurements, as no high forces occur during the measurement process. Consequently, the kinematics can be designed more precisely than machine tools and the CMM wears less. A CMM can measure in 1,5 µ range [17]

Criticism of tactile in-situ measurement is based on the fact that the touch system consisting of the probe and machine is not as precise as a coordinate measuring machine. This is because the machine tool must handle the high forces of machining, which comes at the expense of precision. In addition, the machine tool is subject to higher wear and tear due to machining and possible crashes during processing. The on-machine touch system consists of the probe inserted into the tool holder and the machine tool that realizes the movement of the probe. Both the probe and the machine tool are subject to tolerances, which add up during measurement in the machine [9]. With the increasing precision of machine tools, the tolerance range of the in-situ touch system decreases.

2.2 On-machine inspection

OMI stands for on-machine inspection, a method of measuring workpieces directly on the machine tool in the same clamping situation as they were manufactured. This offers several advantages, including the ability to immediately correct the work piece based on the measurement results without re-clamping or adjusting the machine. OMI also reduces handling times compared to coordinate measuring machines, although it may reduce the availability of machinery time for other value-adding activities [18-19].

The precision and reproducibility of OMI is within the range of the machine tolerances on the installed machine tool. However, reproducibility may decrease with increasing machine wear due to crashes or axis misalignment [20]. OMI is particularly useful for correction-intensive workpieces, as tool correction is based on the machining operation and the subsequent measurement operation rather than just tool wear, resulting in improved production quality.

3. Methodology

This scientific paper aims to demonstrate the suitability of tactile on-machine inspection in a production environment. The study consists of three experimental series conducted to evaluate the effectiveness of the tactile system.

In the first series, the tactile system's repeatability is examined by testing its performance on a manufactured contour. The focus is initially on the z-axis, followed by an assessment of repeatability in the x and y-axes. The distribution of test points is based on the product manufactured by the industrial company involved in the study. Specifically, the company produces drills with indexable inserts. The contour to be inspected is the seat for the indexable inserts, and eleven points are strategically distributed on the seat for inspection purposes. The first three points are located in the seat base and are exclusively tested in the z-direction. The remaining four points lie on a straight line defined by x and y coordinates and are approached at a constant z-height (Figure 1). For this series, one seat is manufactured and inspected three times to determine the repeatability of the tactile system in both 1D and 2D by analysing the collected measurement data.

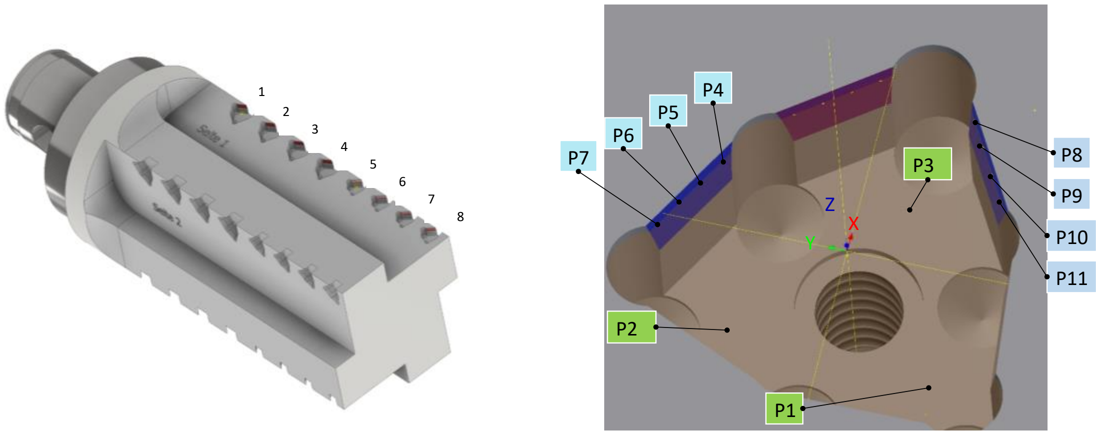


Figure 1: Test sample containing seats for indexable inserts (left) and digital model of seat for indexable inserts including inspection points (right)

The second experimental series focuses on the same geometry as the first series. However, instead of scanning a single manufactured geometry multiple times, the second series measures multiple indexable insert seats manufactured with the same machine parameters. To achieve this, the machine tool produces four seats with identical machine parameters that are shifted exclusively in the x-coordinate. This experimental setup allows an assessment of the interaction between manufacturing tolerances and the tolerance of the tactile system. By measuring multiple seats, the second series provides a more comprehensive evaluation of the system's performance and ability to handle variations in the manufacturing process. This analysis is crucial for understanding the system's limitations and identifying areas for improvement.

In this experiment, four manufactured seats will be inspected. However, the focus will be on points 4-11, which are expected to exhibit higher measurement uncertainty due to the two-axis approach. This series aims to examine the influence of a replicating manufacturing factor on the measurement results. To achieve this, eight points will be recorded for four different manufacturing operations in the experimental series.

Compared to the previous series, the third series introduces a variable manufacturing factor. Instead of producing four identical seats, the machine tool will produce seats of varying sizes. This will be accomplished by manufacturing an indexable insert seat with a negative tool setting. After each measurement, the tool setting will be adjusted to increase the radius. The intention is to observe the effect of the tool setting in the subsequent measurements. By analysing the measurement results, the sensitivity of the measurement process to manufacturing variations, such as rework due to tool wear, can be evaluated.

The three experimental series make it possible to evaluate the reproducibility of a repetitive inspection task (series 1), the precision of the machine in the interaction between manufacturing and inspection (series 2), and the sensitivity of the measurement system to tool setting (series 3). This research aims to provide valuable insights into the effectiveness and applicability of tactile OMI in a production setting.

4. Results

The experimental series were conducted at CERATIZIT Besigheim GmbH, a tool manufacturer, using a DMG CTX Beta turning and milling centre employed for special drilling tools. The milling centre operates daily to produce drills including the indexable insert seats. Equipped with a BLUM LC50 3D touch probe measurement values are provided to the machine control. The test sample consisted of hardened steel serving as the base material for the drills to be manufactured.

4.1 First series

In the first series of experiments, a geometry was repeatedly probed in one axis and afterwards in multiple axes. The measurement points for this series were outlined in the previous chapter. To ensure comparability between the experimental series, the smallest measured value for each point was set to zero, and the remaining measurement values for that point were adjusted accordingly. For the one-dimensional probing in the z-direction (P1-P3), a maximum deviation of three points from 1,2 µm was observed, indicating a high level of repeatability in a single axis (Figure 3).

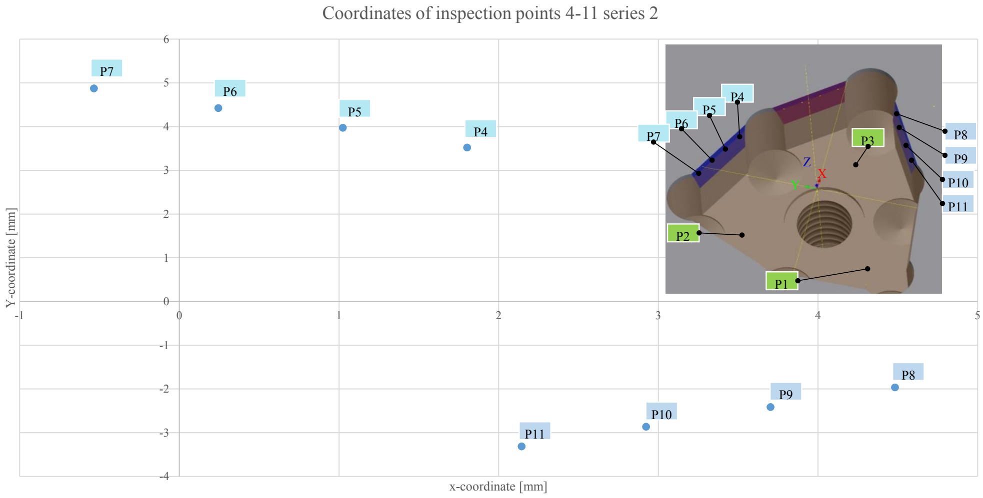


Figure 2: Distribution of inspection points

In the two-axis measurement approach, a total of eight points were utilized, four located on the contact surfaces of an indexable insert seat. The touch probe was used to probe the surface orthogonally in the X and Y directions, resulting in X and Y coordinates for each point (Figure 2). The calculation method mirrored that of the one-dimensional probing. The minimum values for each coordinate and point were recorded and subtracted from the corresponding measurement values. The assessment of the two-axis contribution involved calculating the hypotenuse of the X and Y deviations, representing the difference in both axes. The results demonstrated that the reproducibility of the measurements did not exceed 1 µm for all points, indicating the presence of a highly precise tactile system comprising the machine tool and the touch probe (Figure 3).

$$Inspection\ point\ difference\ two\ axis_i = \sqrt{(X_i - X_{min})^2 + (Y_i - Y_{min})^2)}$$

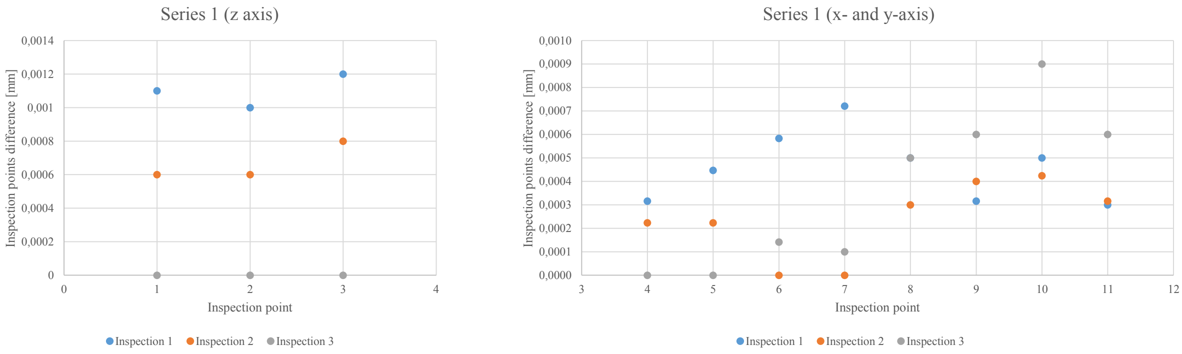


Figure 3: Inspection difference in series 1

4.2 Second series

In the second series of experiments, four indexable insert seats were manufactured on the test specimen. These seats were strategically positioned at different locations along the x-axis and produced consecutively with identical machine parameters. This setup allows for isolating the machine tool's kinematic influence during the machining process. Calculating the measurement value deviations for each point followed the same procedure as in the first series, as the same eight points were considered within the four manufactured seats.

As anticipated, the manufacturing influence resulted in larger variations among the points. The largest difference observed was 3.6 µm, although it appeared to be an outlier, as most of the measurement differences for each point fell within the range of 2 µm. When all the difference values for the eight points were analysed collectively, it was found that 50% of the differences ranged from 0.4 µm to 1.5 µm (Figure 4). This indicates that even in the presence of manufacturing influence, the tactile system exhibited high precision.

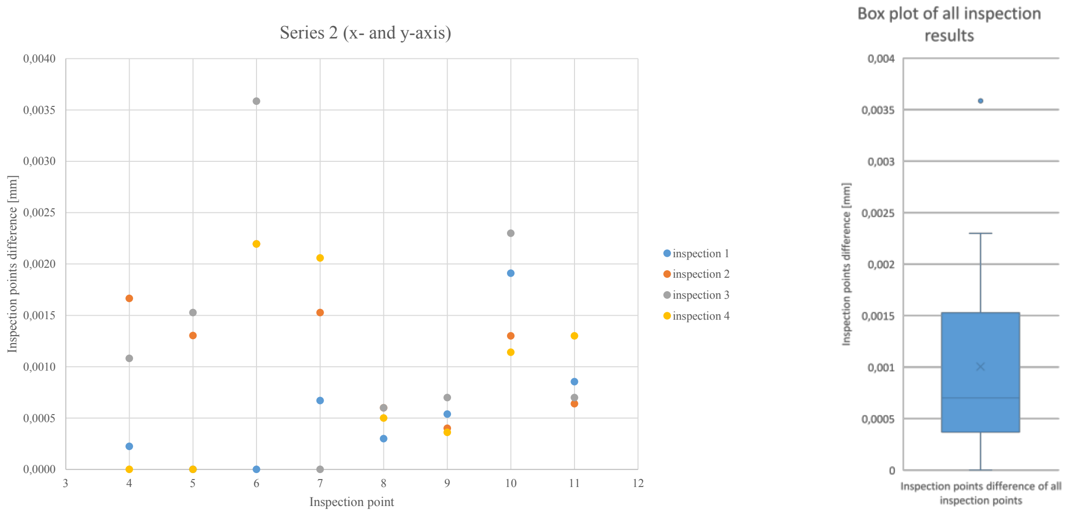


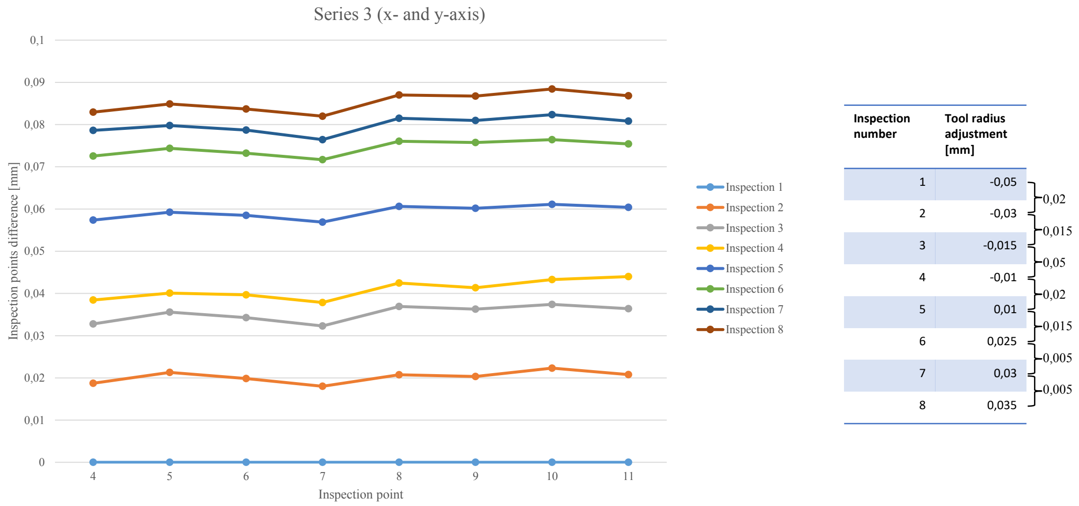
Figure 4: Inspection point difference in series 2 per point [left] and aggregated [right]

4.3 Third series

In the third series of experiments, the first seat was manufactured with a fine adjustment of -0.05 mm on the tool. This adjustment indicates that the tool was corrected by -0.05 mm on the radius, resulting in a contour that is 0.05 mm smaller than the ideal contour in an ideal system with no tool adjustment. Typically, fine adjustments are used to adjust tools based on the results of tool presetting and compensate for tool wear by making positive tool adjustments.

Within the experimental series, each seat was manufactured, measured, and then adjusted before repeating the process. Seven tool adjustments were made from the initial -0.05 mm, resulting in a cumulative adjustment of 0.085 mm to 0.035 mm. To analyse the results, the X and Y measurement values of the first measurement were subtracted from the corresponding measurement values, and the resulting vector was formed from the X and Y coordinates, as previously described. The tool adjustments are expected to be accurately reflected in the measurement results.

The results revealed a high sensitivity of the measurements to the tool adjustments. Each adjustment was clearly visible in the measurements, with the points fluctuating around the applied adjustment within the low µm range (Figure 5).



Inspection number	Tool radius adjustment [mm]
1	-0,05
2	-0,03
3	-0,015
4	-0,01
5	0,01
6	0,025
7	0,03
8	0,035

Figure 5: Inspection point difference in series 3 per point including tool adjustment

In summary, the tactile system demonstrated a reproducibility of 1 µm and a sensitivity to manufacturing operations within a few µm range. It is important to note that this analysis focused solely on 2D probing and the involvement of two machine axes. The sensitivity of the on-machine inspection solution is comparable to that of coordinate measuring machines and will be assessed for its suitability in further applications.

5. Critical assessment

The measurement precision of coordinate measuring machines is typically in the range of 1.5 µm, as described in the state of the art. However, the presented on-machine inspection solution showed a reproducibility difference of only 3,6 µm for the same manufacturing task with the same machine parameters. Most of the measurement values fluctuated within less than 2 µm and were sensitive to the manufacturing influence of the tool adjustment. Therefore, the on-machine inspection solution is a viable alternative to established coordinate measuring machines.

The high sensitivity to tool adjustments makes on-machine inspection suitable for quality monitoring and deriving necessary tool corrections. By transferring the measurement values to the machine control, there is the possibility of adaptive process control based on the measurement values.

It is important to note that the experiments did not involve probing in three dimensions. However, this consideration was not pursued since no increased uncertainty was observed between 1D and 2D probing. The results strongly depend on the equipment used in the experimental series. However, based on the results obtained, a comparable touch probe on a machine tool would provide sufficient quality for the intended use and sensitivity for quality assurance within the machine. This assumption is supported by the fact that the test machine is used for the daily production of drills.

6. Conclusion

This study demonstrated the comparability of the sensitivity between an on-machine inspection solution and a conventional coordinate measuring machine. The reproducibility of the on-machine measurements and their sensitivity to manufacturing influences were investigated through three experimental series conducted at a special tool manufacturer. The results revealed excellent reproducibility of the measurement outcomes within the chosen experimental setup. The on-machine inspection system accurately detected tool adjustments within a few µm, offering a competitive alternative to coordinate measuring machines and laying the groundwork for a self-regulating machine tool. Looking ahead, future considerations should focus on topics such as tool regulation based on on-machine inspection and the necessary work preparation, including the generation of measurement points. Addressing these aspects will unlock the full potential of using on-machine inspection for high-customized parts.

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Biography

Jonas Krebs (*1995) is a research associate at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA. He joined the Department Factory planning and production management in early 2021. He finished his Masters in production engineering at RWTH Aachen University with a background in mechanical engineering.

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Jan Prochnau (*1986) is employed as a project engineer in the production technology department at CERATIZIT Besigheim GmbH. After completing an industrial apprenticeship and working in production for several years, he moved to the administrative area of work preparation and production control in 2010. Since 2017 he has been responsible for the supervision and coordination of improvement projects and since 2022 for the machine procurement of the machining production at the CERATIZIT site in Besigheim.

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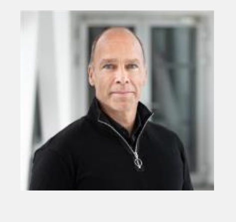

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