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On-Machine Measurement as a Factor Affecting the Sustainability of the Machining Process

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Abstract: One of the key aspects of the automation of machining processes is the elimination of manual measurements. This is crucial in the production of precision parts, where the absence of in-process control can lead to an increased number of non-compliant parts, resulting in financial losses for the company. In addition to economic considerations, environmental care is a fundamental requirement for manufacturing companies. While many efforts focus on finding environmentally friendly coolants or reducing machining time, researchers often overlook the impact of the measurement method on the balanced development of machining. The conditions inside CNC machines are quite demanding in terms of maintaining measurement stability. For this reason, this paper presents a comparative study of two types of machine inspection probes. The influence of the measurement axis and the effect of returning the probe to the magazine on the accuracy of the measurement were examined. This study revealed that the probe with a kinematic resistive design has a higher measurement uncertainty (2.7 µm) than a probe based on strain gauges (0.6 µm). This paper emphasizes the positive impact of the conducted activity on the sustainability of machining, highlighting benefits such as resource savings, energy savings, and positive effects on the health and safety of operators.

Keywords: kinematic resistive probe; strain gauge probe; on-machine measurement; sustainable production; CNC

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1. Introduction

The integration of the measurement process with the manufacturing process has been a highly developed activity in recent years. Terms such as in-process metrology [1], on-machine measurement [2], or the cyber–physical manufacturing metrology [3] are integral to the concept of the Industrial Revolution, concerning the computerization and automation of manufacturing processes, including machining processes. These concepts are classified in the document [4] according to their place and moment of occurrence in the process.

With the widespread use of touch-trigger probes, also known as inspection probes, dimensions are controlled directly in the machining space. Data collected through probes allows for the automatic setup of the workpiece zero point, measurement of geometry [5], and active correction of cutting tools, ensuring process stability. It is worth emphasizing that probes are used not only during the manufacture of simple parts but also for technologically advanced components made of difficult-to-cut materials, as seen in the aerospace industry [6]. This is crucial because automating the machining of expensive aerospace parts helps maintain process repeatability, ultimately affecting the quality of products.

Among the leading manufacturers of measuring probes, such as Renishaw, Blum, Metrol, and Marposs, touch-trigger probes are dominant. Depending on the measurement system, these probes are categorized as kinematic resistive, strain gauge, and scanning probes. The first type, known as electrocontacting probes, includes an electrical circuit in their construction. As the contact force on the stylus increases, the resistance also increases until it reaches a threshold trigger value, at which point a trigger signal is generated. Strain gauge probes utilize a series of strain gauge sensors to measure the contact force acting on the stylus and generate a signal with a lower trigger force. These probes enable the measurement of three-dimensional surfaces, such as conical ones, where the trigger force acts on the measurement system in multiple axes. Scanning probes are highly sensitive to changes in surface shape and can detect submicron displacements at the tip of the stylus. They record points in time at a specific frequency, generating a considerable amount of data. This necessitates a large working memory in the machine tool controller for their effective use.

Inspection probes used in machine tools feature a modular design, allowing for customization to suit specific applications. It is also possible to order a specially designed stylus to meet customer needs. The primary benefits of using these devices include reduced machine downtime and enhanced safety in unattended production. The main disadvantage lies in the high cost of purchase, prompting the exploration of various alternative methods. Examples include a simple probe for measuring diameter from a single point [7] or a measurement system based on a cutting tool, as described in [8]. This system operates by generating an electrical impulse as a result of contact between the insert and the workpiece.

Reviewing the results of the research conducted by the scientific community reveals numerous articles on the integration of measurement processes into manufacturing processes [9]. An important aspect addressed in the research is the influence of environmental conditions on the accuracy of 'in situ' measurement, i.e., on the production line [10]. The authors of [11] confirmed the differences in measurement accuracy with the same probe under laboratory conditions and on the machining station. In [12], the measurement process with a probe on a CNC machine was assessed, and the results were compared with typical methods. Differences in the obtained results for 2D features were approximately 0.04 mm, whereas for 3D measurements, they exceeded 0.2 mm. Importantly, due to the multitude of potential factors, identifying the cause of the error is not an easy task. Mathematical models aimed at predicting measurement errors and compensating for them can be a helpful solution, as discussed in [13]. Certainly, the presence of coolant and chips contributes to random errors. Thermomechanical deformations impact both the workpiece [14] and the machine itself. In [15], it was proven that stiffness and the quality of the measured surface are factors causing incorrect measurement results. The authors of [16] reached similar conclusions, emphasizing that measurements after rough machining deviate more from actual measurements than measurements after finishing machining. These articles also emphasize the importance of the machine tool's condition and the necessity for its diagnostics. The control of the accuracy of axis positioning, as well as volumetric errors resulting from their summation, plays a key role in measurement accuracy, as presented in [17]. Problems with obtaining correct results can also arise from the measurement system, the selection of the stylus, or the adopted measurement strategy. In [18], attention was given to the influence of filtration and the method of signal transmission on the delay in information transfer between the moment of contact and receiving the result. It has been shown that signal filtering generates greater delays than wireless transmission itself. The publication [5] demonstrated that the delay increases with the length of the stylus and a decreased feed rate. For this reason, manufacturers recommend a minimum measurement speed. The effect of speed on forces during measurement was studied in [19]. To minimize hysteresis, it is recommended that successive measurement points be collected in the same direction rather than in the opposite direction.

During the study, it was observed that the discussed issue not only aligns with Industry 4.0 concepts and its metrological counterpart, Metrology 4.0 [20,21], but also contributes to the sustainable development of CNC manufacturing. This aspect has been extremely significant in recent years, particularly for manufacturing companies, as this sector is responsible for 40% of global energy consumption and 25% of resource consumption [22]. Therefore, optimized processes that minimize the negative impact on the environment are becoming increasingly important in modern manufacturing [23]. Trends include, among others, the search for new materials, such as ecological composites [24]. The authors of [25] describes a case study that allows for the evaluation of a manufacturing process in terms of environmental friendliness. Taking into account machining processes, an important aspect often discussed by scientists is the study of the impact of cooling and lubricating liquids on the environment [26]. An overview of the most commonly used cooling methods, along with the determination of their impact on the environment, can be found in [27]. Looking only at ecology, the best solution is machining without the use of coolant, but the authors note that this solution is not possible for machining at high temperatures, i.e., in materials that are difficult to cut. Therefore, alternative solutions are being sought, such as the use of a biodegradable emulsion. Another issue is energy consumption; researchers attempt to optimize processes by selecting cutting parameters or using innovative methods like high-speed ultrasonic vibration cutting [28,29]. An interesting and increasingly common solution is the use of machine learning [30], genetic algorithms [31], or big data analysis [32] to optimize processes for energy consumption. However, it is worth noting that the measurement method can also contribute to the improvement of machining programs, thereby reducing machining time. Improving the quality of manufactured components reduces the number of corrections and scrap parts [16]. Manufacturing processes for difficult-to-machine materials are extremely time-consuming, and the characteristics of these materials lead to rapid tool wear [33]. For instance, the process of machining an aircraft engine shaft made of Inconel 718 alloy takes approximately 20 h on a CNC machine, equivalent to an electricity consumption of about 300 kWh. Considering geometric requirements within hundredths of a millimeter, the lack of adequate precision results in a non-compliant product unsuitable for installation in the engine [34]. The process has to be repeated, consuming not only energy but also resources such as workpiece material and cutting tools. In addition to the typically economic aspects, it is crucial to produce quality compliant parts the first time. Measurement automation is a significant improvement in this matter [35].

Figure 1 presents a concise summary of the factors that characterize sustainable machining. These factors certainly concern environmental aspects, but it is also important not to overlook the health and safety of CNC machine operators. Manufacturing is a highly complex process and, as mentioned in the earlier paragraph, is responsible for high energy and resource consumption [23]. On one hand, the presence of many factors offers a wide field of optimization opportunities. On the other hand, any attempt to improve the process involves the risk of deteriorating the quality of the manufactured components. For this reason, before implementing any changes, it is crucial to prioritize the need to maintain process stability.

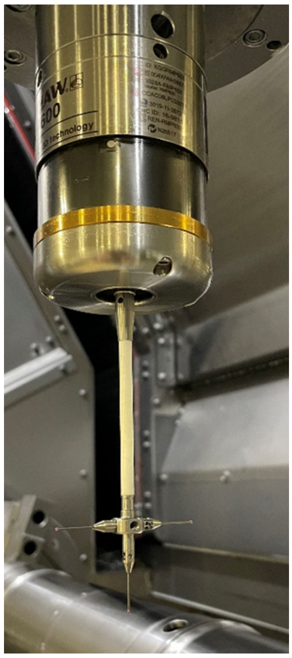
This paper serves as an introduction to the development of a method for measuring selected features of external threads directly on a CNC lathe. Currently, thread turning requires stopping the machine after a semi-finishing pass for manual measurement by the operator using the three-wire method. During measurement, the operator is exposed to harmful fume emissions from the cooling emulsion and the potential for injury from sharp edges and chips. Subsequently, the operator manually corrects the cutting tool, a critical step prone to mistakes, ultimately leading to the production of a non-compliant part. The implementation of automated measurement is expected to enhance overall quality. Thread profiles are traditionally measured via contact on a coordinate measuring machine (CMM) by scanning with a self-centering tip. However, attempts to measure threads directly on a CNC machine, as found in the literature, primarily use optical methods [36–39]. Ensuring repeatability and stability in automated measurements within a shop floor environment poses a challenge addressed in Metrology 4.0, as outlined in [40]. Determining the measurement uncertainty resulting from the combined errors of the machining machine and the measuring device is also a complex task [41,42]. To verify the repeatability of measurements under production conditions and assess the suitability of using the more expensive but also more accurate strain gauge probe, comparative tests of two types of touch probes were conducted. The positive impact of this endeavor on the balanced development of machining was noted. The authors identified various benefits of on-machine measurement in terms of sustainability.

Figure 1. Characteristics of sustainable machining.

2. Materials and Methods

The tests were conducted on a WFL M40 horizontal multitasking machining center equipped with Siemens Sinumerik 840D control. It is essential to note that the discussed workstation is situated on the production floor, where shaft-type components for the aerospace industry are produced daily. Due to limited testing opportunities associated with machine availability and equipment constraints and considering the study's purpose—to select a probe for measuring external threads—a comparative test of two types of Renishaw contact probes with configurations available on the station was undertaken. The RMP40M transmission system, combined with the LP2 probe, equipped with a stylus of length L = 50 mm and a ball diameter of Ø = 2 mm, represents a kinematic resistive probe. On the other hand, the RMP600 probe, paired with a stylus of length L = 75 mm ending in a star-type adapter, featuring two horizontal tips (D2) and one vertical tip (D1), each with a length of L = 20 mm and a diameter of Ø = 1 mm, operates based on strain gauges. Table 1 lists parameters such as repeatability and trigger force at factory settings for both probes, both of which utilize radio signal transmission. Measurement cycles developed by the WFL machine manufacturer were employed based on standard Sinumerik 840D cycles. Measurements were programmed in NC code and run in a loop in automatic mode. The measured points were recorded in a table of R variables, available in the Sinumerik controller, and downloaded from the NC machine after the experiment. The temperature inside the machine was measured using a TERMIO recorder from Termoprodukt with a resolution of 0.1 °C. Despite the presence of vibrations, coolant, lubricating emulsion, and microchips, which could potentially interfere with measurements, it is important to note that the measuring elements and machine were cleaned, minimizing the possibility of errors arising from contamination, even under production conditions.

Table 1. Comparison of selected parameters of measurement probes.

	RMP40M + LP2	**RMP600**
Unidirectional repeatability	1 μm 2σ	0.25 μm 2σ
Stylus trigger force in XY	0.5 N	0.2 N
View of the probe		

The single tip in the RMP40M+LP2 and RMP600 D1 probes was calibrated to the ring using a four-point measurement. In contrast, the RMP600 D2 probe, equipped with two horizontal styluses, was calibrated on the ring using a two-point measurement. The correction value is determined by calibrating the stylus on a ring with a precisely defined inner diameter. To ensure the accuracy and repeatability of these calibration methods, the calibration ring must be cleaned before calibration and be at the same temperature as the machine. The stylus used must be recalibrated from scratch after each installation or replacement of the measuring tip and after a collision. It is crucial that the adjustment screws of the probe are always securely tightened since the tool is exposed to vibrations. While the reproducibility of the engagement sections is typically very high and consistent during normal use, the stylus is calibrated at regular intervals, at least once a week. The first two contact measurements, used solely to detect the center of the ring, are taken only twice. All other contact measurements are taken five times, and the reproducibility of the attachment points within 1 μm must be ensured. Calibration data for each position and probe are stored in the machine, and specific calibration data numbers for the selected probe must be recalled depending on the measurement position.

Several series of measurements were conducted using each touch probe. Diameters were measured on a ground steel ring with an inner diameter of Ø = 58.004 mm (with a form error of 5 μm) and on a ground Inconel shaft with an outer diameter of Ø = 115.918 mm, earlier confirmed with manual measurement. Depending on the measurement possibilities related to the limitations of the probe configuration, machine tool, or available measurement cycles, the dimensions were determined from two or four points. Standard measurements of external diameters on shaft-type parts on the discussed machine tool are typically measured during the production process from two points in the direction of the Y-axis.

In the first test, a series of 15 alternating measurements were made with the RMP600 probe. The inner diameter of the ring was measured using a four-point D1 tip and a two-point D2 tip. The measurement via 15 repetitions primarily aimed to check the correctness of the probe calibration. According to the manufacturer's recommendations, the reproducibility of the results is verified by five consecutive measurements. In the next step, a series of 50 two-point measurements were taken of the same ring with the D1 tip, once in the *Y*-axis direction and once in the Z direction. A constant temperature between 23.2 and 23.5 °C was recorded during the measurements.

In another test, the outside diameter was measured on a fabricated shaft-type part using a two-point measurement in the *Y*-axis direction. Measurement series were carried out without returning the probe to the tool magazine and with returning it. The RMP40M+LP2 probe was compared with the RMP600 D2 probe. Four measurement series of 50 repetitions were conducted on one day, where the temperature varied from 23.5 to 23.7 °C. Two subsequent measurement series were carried out the following day after the machine was stopped overnight. The temperature recorded inside the machine ranged from 22.8 to 23.1 °C.

Temperature fluctuations during the tests were negligible. Certainly, stability in temperature on the shop floor, inside the machine, and coolant temperature is essential. Considering the thermal expansion of metals, it affects machine components, the workpiece, and measuring instruments. To ensure accurate measurements, each of these elements should have the same temperature, which should also correspond to the temperature in the quality control facility. External temperature is important, but drives are also subject to temperature changes during their movements, hence the need for warm-up programs to thermally stabilize the drives. This is particularly crucial in the aerospace industry, where CNC machine tools sometimes perform features with tolerances as tight as +/− 6 μm.

The collected results were analyzed using Excel. The analysis included determining the average value (Avg.), minimum (Min.), maximum (Max.), the difference between extreme values (Max.–Min.), standard deviation from the average value (σ), and the 2σ value, which can be identified with the expanded measurement uncertainty (U) for a 95% confidence range.

3. Results and Discussion

The results of measuring the inner diameter of the gauge ring Ø = 58.004 mm with the RMP600 probe are presented in Table 2 and in the chart (Figure 2). The results for both the vertical probe tip D1 and the horizontal tips labeled D2 are similar. In both cases, average values close to the nominal dimension were obtained, confirming the correctness of the probe calibration. It was observed that the strain gauge measurement system was highly precise, and regardless of the type of stylus, the uncertainty value for 2σ was U = 0.8 μm. The scattering of the results was random, and no linear trend in the change in the obtained values was observed.

Table 2. Values obtained for measurements of the inner diameter of the ring Ø = 58.004 mm.

	Avg. [mm]	**Min. [mm]**	**Max. [mm]**	**Max.–Min. [mm]**	**σ [mm]**	**2σ [mm]**
RMP600 D1	58.0044	58.0039	58.0052	0.0013	0.0004	0.0008
RMP600 D2	58.0048	58.0040	58.0057	0.0017	0.0004	0.0008

To assess the impact of measurement direction on the obtained results, a series of 50 two-point measurements of the inner diameter of the ring were conducted—once in the *Z*-axis direction and once in the *Y*-axis direction. The results are presented in Table 3 and illustrated in the graph (Figure 3). Variances in measurements for individual axes were observed, with the average values between the two measurement series differing by 1.7 μm. This discrepancy could stem from errors in the shape of the ring and potential calibration issues with the D1 tip itself. As mentioned earlier, it was calibrated using a four-point measurement, whereas in the test, the diameter was determined from two points. Notably, while the measurement uncertainty for the *Y*-axis was comparable to the previous one, for the *Z*-axis, it was twice as large, amounting to U = 1.8 μm. The reason for this could be attributed to wear on the *Z*-axis, which has a much larger range of motion and is also subjected to heavier loads during longitudinal turning.

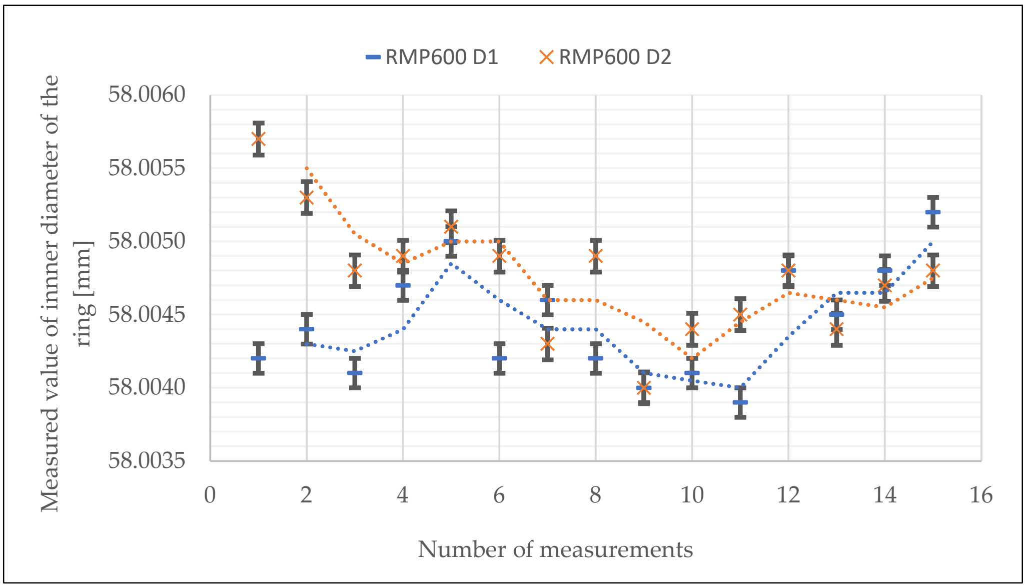


Figure 2. Results of a series of measurements of the ring Ø = 58.004 mm using the RMP600 probe with D1 and D2 tips.

Table 3. Values obtained for measurements in the Y and Z axes of the inner diameter of the ring Ø = 58.004 mm.

	Avg. [mm]	Min. [mm]	Max. [mm]	Max.–Min. [mm]	σ [mm]	2σ [mm]
Z axis	58.0036	58.0019	58.0056	0.0037	0.0009	0.0018
Y axis	58.0053	58.0037	58.0061	0.0024	0.0005	0.0009

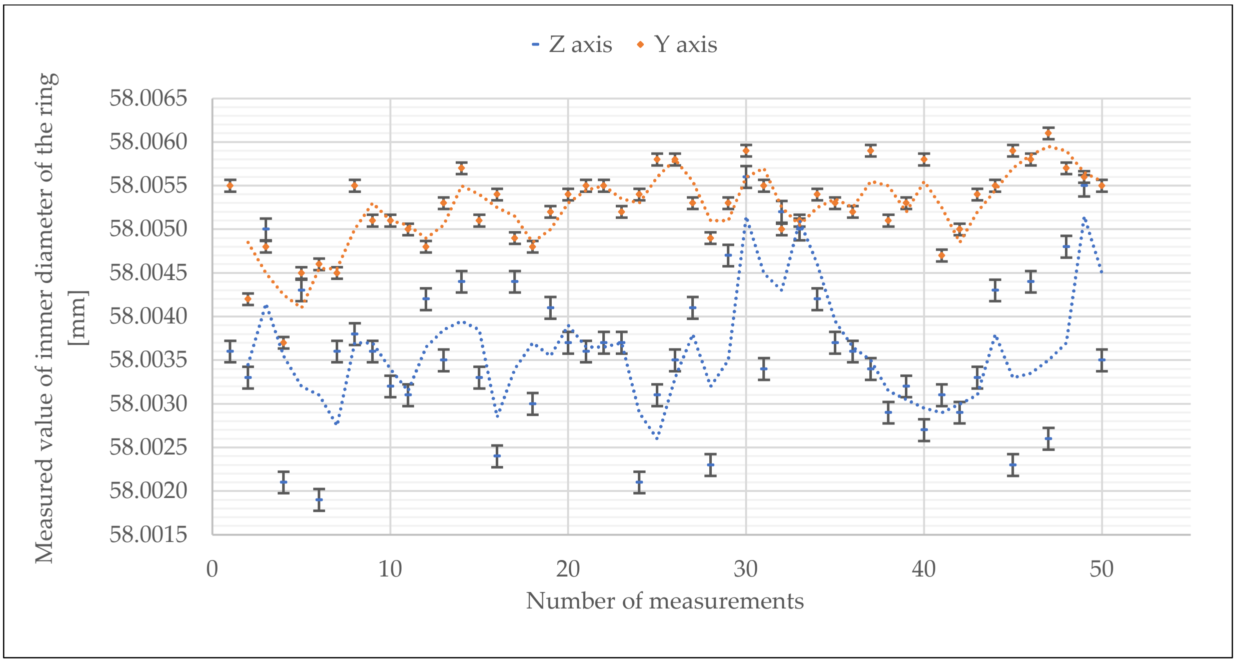


Figure 3. Results of a series of measurements in the Y and Z axes of the inner diameter of the ring Ø = 58.004 mm.

Figure 4 displays the results obtained from a series of 50 measurements on the external diameter of the shaft Ø = 115.918 mm. A visual analysis of the graph reveals that three out of the six measurement series deviate significantly from the nominal dimension. These include two series of measurements after machine downtime and a series of measurements with a kinematic resistive probe with the probe being returned to the tool magazine.

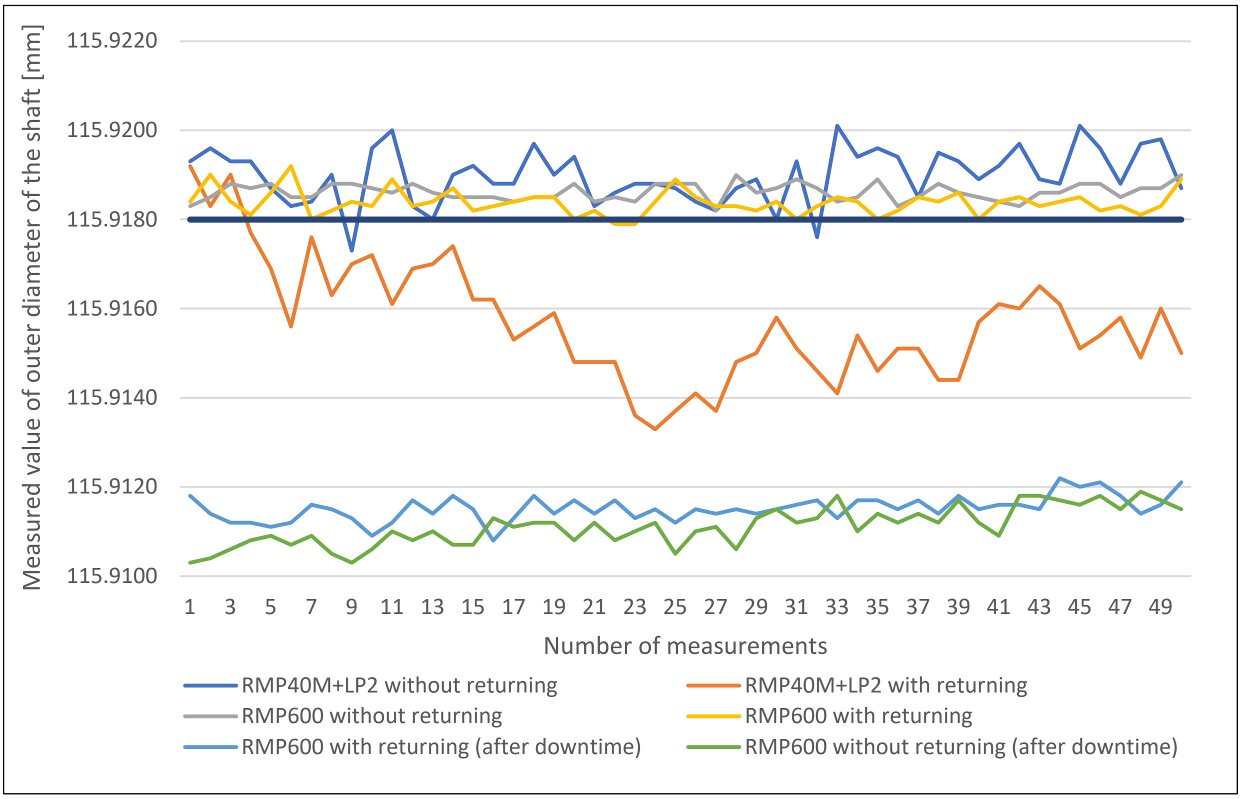


Figure 4. Results obtained for measuring the external diameter of the shaft Ø = 115.918 mm.

Table 4 and Figure 5 summarize the results for the measurement series conducted on the outer diameter of the shaft-type production part. When comparing the kinematic resistive probe with the strain gauge probe, notably lower values of the obtained measurement uncertainty (U) for RMP600 are evident. The lowest value achieved was U = 0.4 µm for a confidence interval of 95%. Importantly, a negative effect of returning the probe to the tool magazine was observed for both RMP40M+LP2 and RMP600. Differences in the repeatability of probe mounting in the tool head resulted in more than twice the uncertainty for the RMP40M+LP2 probe and one and a half times the uncertainty for the RMP600. Measurement with an electrocontact probe and returning the tool to the magazine turned out to be particularly sensitive. In this case, the uncertainty value (2σ) was obtained at the level of U = 2.7 µm. Discrepancies were also observed in the average values obtained for a series of 50 measurements. As for the strain gauge probe, returning the tool to the magazine did not cause significant differences, while for RMP40M+LP2, the average result when returning the probe was 3.3 µm lower than without it.

An extremely important test proved to be the repetition of measurements with the RMP600 probe on a thermally unstable machine. A machine downtime of several hours resulted in lower measured diameter values than for the heated machine. The differences were about 7 µm, which is significant, especially in the production of precision parts for the aerospace industry. This study confirms that warming up machine drives before machining after a prolonged shutdown is crucial. This should also be kept in mind before the probe calibration process.

Table 4. Values obtained for measuring the external diameter of the shaft Ø = 115.918 mm.

	Avg. [mm]	Min. [mm]	Max. [mm]	Max.–Min. [mm]	σ [mm]	2σ [mm]
RMP40M+LP2 without returning	115.9190	115.9173	115.9201	0.0028	0.0006	0.0012
RMP40M+LP2 with returning	115.9157	115.9133	115.9192	0.0059	0.0013	0.0027
RMP600 without returning	115.9186	115.9182	115.9190	0.0008	0.0002	0.0004
RMP600 with returning	115.9184	115.9179	115.9192	0.0013	0.0003	0.0006
RMP600 without returning (after downtime)	115.9111	115.9103	115.9119	0.0016	0.0004	0.0009
RMP600 with returning (after downtime)	115.9115	115.9108	115.9122	0.0014	0.0003	0.0006

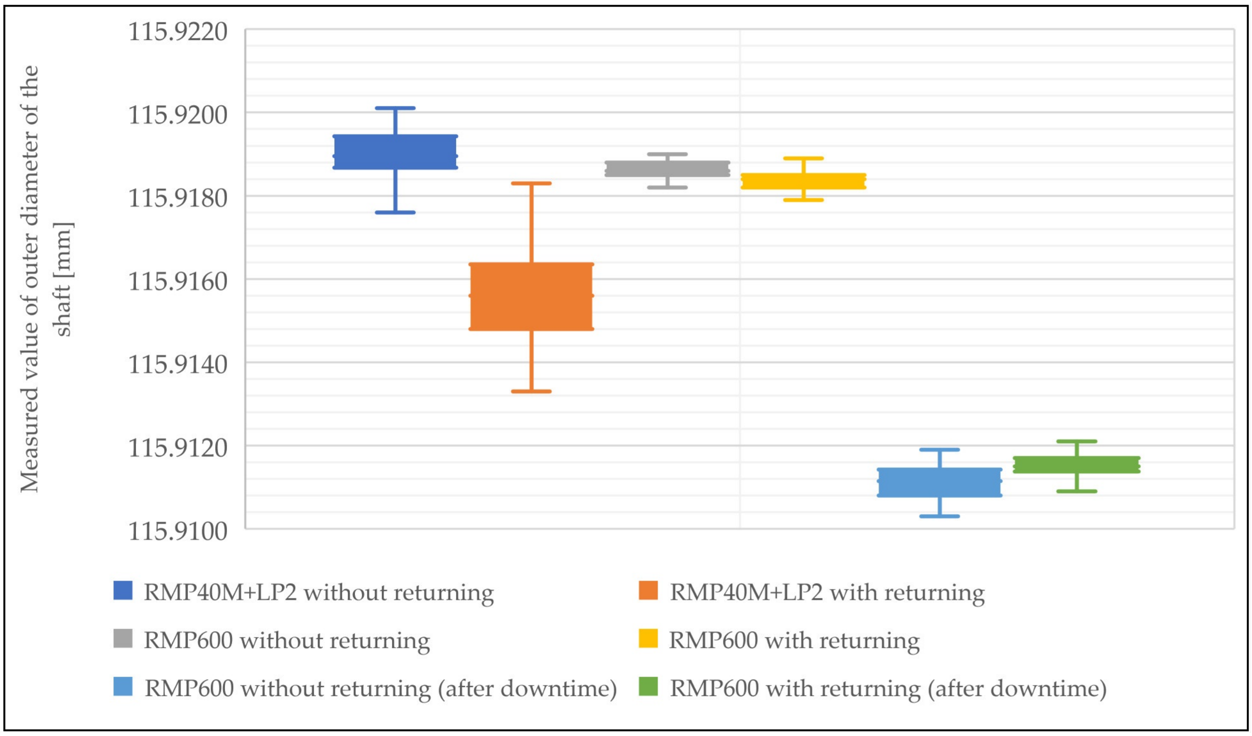


Figure 5. Box plot for the data obtained for measuring the external diameter of the shaft Ø = 115.918 mm.

Upon obtaining satisfactory results, it can be assumed that on-machine measurement will not contribute to the deterioration of product quality compared to manual measurement. Based on the experiment, we decided to isolate the factors influencing the improvement of sustainability due to the introduction of measurement touch-trigger probes directly on the CNC machine. These sustainability features essentially represent standard lean waste improvements [43]. The summary is presented in the form of a graph (Figure 6).

The benefits of introducing on-machine measurement primarily yield financial effects for the company. Nevertheless, Table 5 evaluates in detail the impact of individual factors on sustainability. Quantitative benefits can be estimated based on experience and case study examples, indicating that the use of probes increases machine utilization by about 20% [44]. Assuming 250 working days per year and a labor cost of 120 USD per hour, subtracting time for downtime and maintenance, we have about 5000 h per year (working three shifts). As a rough estimate, with on-machine measurement, we gain an additional 1000 h for machining per year, translating to USD 120,000. The cost of purchasing a contact probe is an expense of about USD 7000. The financial balance in this case is influenced by many factors. Certainly, such calculations are more common in high-volume industries. In the aerospace industry, machining time is important, but the quality of manufactured parts and the avoidance of nonconforming parts are key as these are the biggest financial losses. Therefore, the introduction of on-machine measurement mainly aims to prevent the production of a scrap part where, for example, the cost of a workpiece made with Inconel can be as high as USD 5000. Thus, just one operator's mistake during the compensation of the cutting tool equals the cost of purchasing the probe itself, considering working time and additional initial costs. Of course, the calculation is not so straightforward because we need to take into account the cost of manual instruments relative to the universal probe, the cost of CMM operation and transportation, and the wait time of the measurement [45]. As mentioned at the beginning of this article, the test stand is monitored for energy consumption. Based on the average consumption, it can be concluded that the machine consumes 15 kWh per hour, which, taking into account the previous calculations (i.e., 1000 h), results in 15 MWh of savings per year.

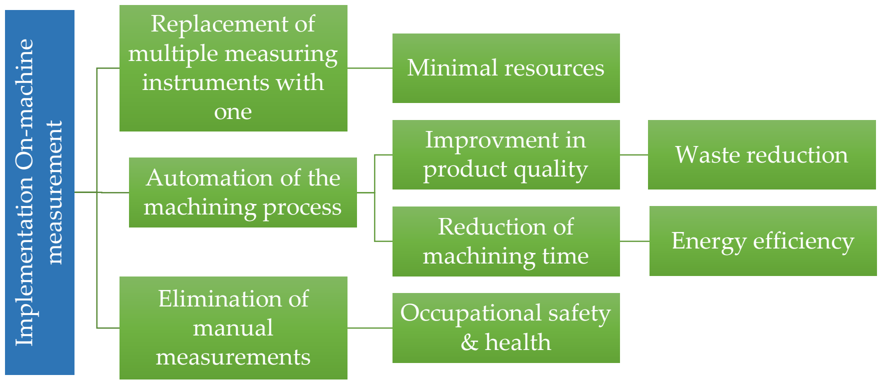


Figure 6. Key factors resulting from the implementation of on-machine measurement.

Table 5. Assessing the benefits of on-machine measurement in terms of sustainability.

Benefit of Introducing On-Machine Measurement	Impact on Sustainable Development
Replacement of multiple measuring devices, e.g., calipers and micrometers with specific measuring ranges, for a single, universal touch-trigger probe	Saving resources needed to manufacture multiple measuring instruments. Reduction in the space required for instrument storage.
Reduction in machining time.	Saves energy by reducing machine run time. More will be produced with less resources, which is one of the characteristics of lean manufacturing.
Elimination of the human factor in measurements. Active control during machining.	Minimize the risk of producing a non-compliant part. Consequently, less rework, remanufacturing of parts. Saving resources like workpiece material and cutting tools. Reduction in energy. When machining complex aerospace parts made of hard-to-machine materials, the machining time and tool wear are of great importance.
Automation of measurements in CNC programs.	No need for the operator to open the door. The person operating the machine does not inhale harmful fumes from the cooling and lubricating emulsion.
Elimination of manual measurements.	Operator safety. Reduce the risk of injury from sharp edges.

Understanding the actual production environment, we realize that, despite machine tools being equipped with many safety systems, there are still harmful factors affecting the operator. Firstly, when the operator takes manual measurements directly on the machine, they are exposed to an uncomfortable position and back strain. The parts being machined contain numerous sharp edges, posing a significant risk of injury. Additionally, there are less obvious factors with long-term effects. Contact with the emulsion can lead to skin problems due to the presence of many allergenic substances [46]. Vapors from the coolant and generated material can cause various diseases, including cancer [47]. Transitioning from manual to automatic measurements in a closed-door machining environment reduces the risk of inhaling harmful substances and physical contact with them.

In conclusion, the use of on-machine measurement offers significant benefits in terms of the sustainability of machining. The choice of measurement method is generally not considered in terms of its impact on the environment and occupational safety and health. Nevertheless, as demonstrated in this paper, the use of touch-trigger probes can influence sustainable development. The authors acknowledge that the current research indicates the potential benefits of introducing on-machine measurement; however, detailed figures have not been determined, and the conclusions presented are general in nature. In conclusion, the current work notes and identifies the benefits of introducing on-machine measurement, providing a solid basis for further research to determine the detailed impact and numerical benefits of changing the measurement method. These benefits are determined by the knowledge of specific work in the aerospace industry, where complex parts made of hard-to-machine materials are produced. This production is low volume. Each industry, however, shows slight differences in approach [48]. It can be assumed that in the case of the automotive industry and aluminum alloy machining, the benefits of on-machine measurement would not be as obvious. These on-machine measurements increase machining time, and, as already mentioned, the benefit is no downtime for manual measurements and no rework. In the automotive industry, it seems better to invest in expensive diamond tools that will provide repeatable dimensions in aluminum, and only statistical control is sufficient.

4. Conclusions

In the present study, two types of touch probes were examined under production conditions. The validity of using the more expensive strain gauge probe for manufacturing precision parts was proven in accordance with the manufacturer's assurances. The influence of factors such as the direction of measurement or the returning of the probe to the magazine on the repeatability of the results was determined. The total uncertainty of the measurement system has not been determined because it is a very complex task involving many factors. Manufacturers of these probes usually specify unidirectional repeatability (2σ) as a parameter characterizing the inaccuracy. This is only one of many components of the uncertainty budget. Other components may include the direction of the probe's arrival at the workpiece, the repeatability of the probe's mounting in the machine tool spindle, the technical condition of the machine tool, the type of drive and position measurement system, the probe's measurement system, and the selection of probe stylus. These also include the rigidity of the entire system, the type of measurement strategy, filtration, signal transmission, and, of course, the external factors related to the environment and contamination. The difference observed in the Z-axis was probably influenced by the technical condition of the machine tool, as this axis is the most heavily loaded during turning, which can cause increased backlash in the drive system. It is also certainly the axis with the longest range of motion, several times longer than the Y-axis. The importance of introducing on-machine measurement from CNC machines for the development of green manufacturing in social, environmental, and economic contexts was noted and emphasized.

In summary, the following conclusions can be drawn:

1. Measurements taken with the strain gauge probe feature about 65% lower measurement uncertainty values than with the kinematic resistive probe, ignoring the impact of returning the probe to the tool magazine. In the case of both probes, satisfactory results were obtained, allowing them to be successfully used interchangeably with classic, manual measuring instruments. This saves resources because a number of devices and gauges are replaced with a universal probe.

2. Eliminating manual measurements shortens the process and thus saves energy. It also represents a health benefit for the operator, as each time the machine is opened, toxic fumes from the coolant are released and enter the respiratory system.
3. Improving process quality through the use of probing reduces the number of scrap parts. This results in a reduction in the consumption of resources such as workpiece material and cutting tools for rework. Avoiding corrections or reworking an entire part means eliminating power consumption.
4. Putting the probe in the tool magazine has a negative effect on the repeatability of measurements (2σ increase by 125% for RMP40M+LP2 and by 50% for RMP600). The direction of measurement affects the accuracy of the results obtained (2σ received two times higher for the Z-axis than the Y-axis).
5. Several hours of machine tool downtime caused significant differences in the results obtained for measuring the same feature. The value of the measured diameter decreased by 7 μm.

Although the measurements took place on the production floor, the measurement conditions were somewhat different from the actual machining environment. It would certainly be worthwhile to repeat the test while turning an actual part where contaminants exist in the form of microchips, or the presence of coolant and lubricant on the measured surface is present. Certainly, a paper describing the case study of a real example of implementing on-machine measurement and quantifying the benefits of this measure, both in terms of finance and sustainability, would be of great added value.

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Nomenclature

2σ	twice standard deviation
σ	standard deviation
Ø	diameter symbol
Avg.	average
CNC	computerized numerical control
CMM	coordinate measuring machine
D1	tool offset number 1 in Sinumerik controller
D2	tool offset number 2 in Sinumerik controller
L	length
Max.	maximum
Min.	minimum
U	measurement uncertainty

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