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Non-contact measurement of grinding pins by means of a 2D laser micrometer

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Abstract

Grinding is one of the most important processes for producing discrete components of advanced materials with high precision. The macroscopic and microscopic analysis of surface topography becomes an essential activity to ensure accurate machining results. Most of the methods used traditionally are carried out off-line so expensive equipment and time consume are required. The present work proposes the use of a 2D laser micrometer to perform on-machine macrogeometric measurement and analysis of grinding pins in order to overcome non-productive time with a fast, precise and reasonably economical inspection equipment, which is easy to integrate in a CNC grinding machine.

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Keywords: Non-contact measurement; On-machine measurement; Laser micrometer; Grinding pin; Grinding

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1. Introduction

Grinding is one of the most important processes for producing discrete components of advanced materials with high precision, and it accounts for about 20% to 30% of the total expenditure on machining operations in industrialized nations [1]. The advances in the use of super-abrasive (CBN and diamond) grinding wheels have opened new

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possibilities to industry, such as improvements in surface integrity, surface finish and productivity in the manufacturing of difficult to machine materials [2], such as ceramics, silicon carbide or glass.

Grinding pins are small diameter grinding wheels widely used in different machining tasks performed on CNC grinding machines, including hybrid machining processes with the assistance of tool vibration [3]. The grinding wheel plays a key role in a grinding process for obtaining high accuracy machining and good surface finish of the workpiece. When wear appears, dressing and truing operations become necessary for shaping and sharpening the wheel face [4] in order to prevent flaws in products [5]. Thus, a rigorous control of the tool geometry will help to compensate the tool paths in CNC grinding, determine the time to perform the tool dressing, reconstruct the tool shape or eliminate the process errors.

Many attempts have been made to describe the surface topography of a grinding wheel and to correlate it with the result on the workpiece. The geometrical quality features of a grinding wheel which describe the types of tool wear are divided into macroscopic (diameter deviation, radial runout, ovality, waviness) and microscopic features (grain breakage and flattening, wheel loading grain, drop-out, roughness). Examples of microgeometric sensors are inductive wheel-loading sensors, scattered light sensors, reflection sensors or laser triangulation sensors. On the other hand, macrogeometric sensors often consist on tactile probes, pneumatic, capacitive, acoustic or electromagnetic sensors [6].

Furutani *et al.* [7] used an in-process method for measuring changes in the topography of a grinding wheel, but the method lacked repeatable accuracy on the measurement. Other researchers used acoustic emission sensors to monitor wheel wear [8]. Lachance *et al.* [9] used a scanning electron microscope for measuring the wear flat area, but the technology was very expensive and not practical for repeated and automatic measurements. Sodhi and Tiloquine [10] used digital images of a wheel surface captured by a charge-coupled device (CCD) in order to measure wear flats, although there was no uniformity on the sample surface and the presence of dust degraded the optical readings. A non-contact optical measuring method was used by Young and Chen [4] to evaluate the grinding wheel wear by comparing the wheel profile before and after the grinding process. Accuracy of 1 μm was achieved. Su and Tarng [11] provided a simpler indirect method to measure wear of a grinding wheel from a specimen with a gap ground by the grinding wheel. They processed the 2D image of the specimen profile. Repeatable accuracy of ±3 μm was achieved. Chen *et al.* [12] developed a compensation approach for grinding of tungsten carbide aspheric moulds based on on-machine measurement of the ground profile by using a contact microprobe so that a profile accuracy of 177 nm and Ra 1.7 nm were met. Magdziak and Wdowik [3] presented the results of off-line contact and non-contact measurements of external profiles of two selected grinding pins by using a contact CMM and a tool presetter, respectively. They concluded that the contact method presented a lack of repeatability whereas the non-contact one was the most appropriate to predict the accuracy of machined workpieces and the wear of grinding pins.

Taking into account the necessity of performing a grinding wheel surface control on the grinding machine to overcome non-productive time if the inspection were carried out off-line, as well as the necessity for a fast and economical inspection method, the present work will analyse the feasibility of using a 2D laser micrometer (LM) for on-machine macrogeometric measurement of grinding pins. Differently to other sensors, laser micrometers stand out by their capability to measure directly the diameter of a part with accuracy by projecting a parallel beam on the part and its shadow on a CCD [13]. They are capable of acquiring two dimensional parameters simultaneously up to 2400 Hz what make it ideal for continuous processes or for measurement of moving parts.

2. Methodology and experimental procedure

Two CBN grinding pins (Urdiamant, reference BS-32-6-8-B251-H-7-0001), with 6 mm of cutting diameter, 8 mm of cutting length, 4 mm of shaft diameter and 45 mm of total pin length, were considered in the study. The grit size was B251 (according to ISO 6106:2013) using a bonding resin B-VII. One of the pins was new and the other one was used for grinding a prismatic DIN 41Cr4 alloy steel part, using a federate of 1000 mm/min, 20000 revolutions per minute, 0.002 mm of radial depth of cut and 3 mm of axial depth of cut. Thus, a notable wear appeared on the pin. This grinding wear test was performed at Rzeszów University of Technology on Ultrasonic 20 linear machine tool (Fig. 1a). Then, the pins were measured at University of Oviedo with a laser micrometer LS-7070 by Keyence (Fig. 1b). Many close sections were measured consecutively along the tool axis. The tool profile was generated and the form errors calculated for both pin states to compare each other.

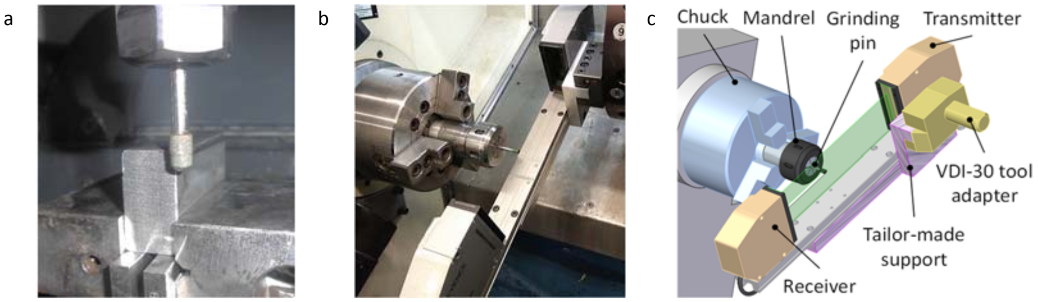

Fig. 1. (a) Machining with a CBN grinding pin; (b) Measuring the grinding pin with a Laser Micrometer; (c) Set up of the Laser Micrometer in the CNC lathe.

2.1. Features of the LM

The portable instrument considered for non-contact on-machine measurement of the grinding pin was a high-accuracy digital 2D micrometer Keyence LS-7000, consisting on a LS-7070 measuring head (transmitter and receiver) connected to a LS-7601 controller and using LS-H1W PC software for setting operation, real-time monitoring and recording of measured values.

The LM is a very fast optical system which consists of a transmitter and a receiver units. The transmitter is responsible for the emission of a high intensity light produced by a nitride gallium green led unit (GaN led), which is changed into uniform parallel light through the special diffusion unit and collimator lens and emitted to the target in the measuring range. Once in the receiver, the shadow image of the target appear on the high-speed linear HL-CCD through the telecentric optical system. The output incident signal of the HL-CCD shall be processed by the digital edge-detection processor in the controller and CPU. As a result, the dimensions of the target are displayed and output. The main working features of this LM are shown in Table 1.

Table 1. Main measuring characteristics of the Keyence LS-7000 micrometer.

Feature	Value
Measuring range	0.5 to 65 mm
Measuring accuracy	± 3 μm
Repeatability (2σ)	± 0.2 μm
Max. Sampling	2400 Hz

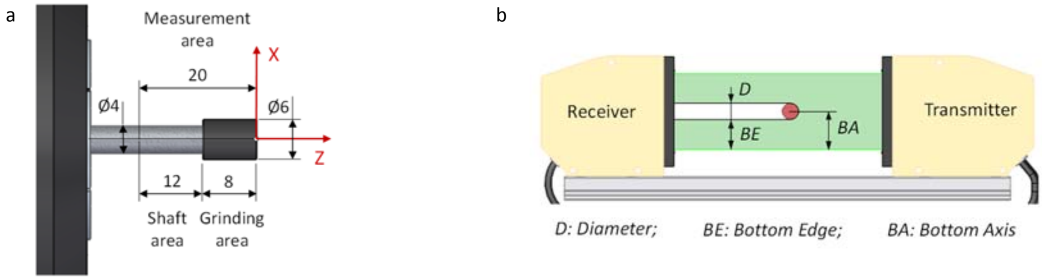

Fig. 2. (a) Measurement origin and characteristic areas; (b) Measured parameters.

2.2. Measuring process with the LM

Before starting the measurement tests, the LM was calibrated according to the European co-operation for Accreditation (procedure EA-4/02 for the Expression of the Uncertainty of Measurement in Calibration) by measuring several cylindrical gauges of different diameters within the working range, meeting an expanded uncertainty $U = \pm 3.17$ µm for a coverage factor $k = 2$. Once calibrated, and taking into account previous studies [13], the LM was switched on more than 14 minutes before performing each measurement test in order to ensure thermal stabilization of the laser and to avoid any thermal influence on the measurements.

Measurements of the grinding pin were performed in a CNC lathe. The pin was hold in a mandrel which was clamped in the chuck of the CNC lathe. On the other hand, the LM was set up in the lathe turret by means of a standard VDI-30 tool adapter (Fig. 1c).

The origin for measurements was set at the right edge of the grinding pin (Fig. 2a). Two different measurement procedures were performed to capture the geometrical parameters. Each type of test was repeated 5 times to ensure repeatability.

In the first procedure, the value of diameter (*D*) and bottom edge distance (*BE*) (Fig. 2b) were acquired each 0.05 mm along 20 mm in the negative Z direction. This way, measurements were extended over the whole cutting length and partially along the pin shaft to be able to perform a geometrical analysis between both elements (Fig. 2a). Measurements were taken in a discrete way, so that the LM was moved from one position to an adjacent one at a speed of 150 mm/min. Once stopped at the target position, a triggering signal caused the micrometer to acquire both parameters and they were registered externally in a PC, together with the *Z* position extracted from the lathe controller. Measurements were performed along the grinding pin under eight angular orientations (θ) with increments of 45°, covering a complete rotation. This way, four diameters were measured at each section under two opposite orientations (phase difference of 180°).

In the second measurement procedure, the pin was measured repeatedly several times at each *Z* position while it was rotating at a constant speed. In this case, the parameters measured were the ranges of *D* and *BE* for analysing roundness and coaxiality between the shaft and the grinding areas. The adjustment of the test parameters was set to take one measurement per degree of rotation. This way, considering an acquiring frequency of 1024 Hz, the rotational speed resulted 171 rev/min.

Besides, to get reliable data, measurements were taken for several rotations of the pin at each *Z* position. The time required for that was considered in the numerical control program as a delay between repositioning movements along the pin. In order to avoid excessive time consume to perform all the tests but being careful not to miss any data in the process acquisition-transmission, it was decided to spend 0.8 s i each position. Then, the number of revolutions calculated at each section was 2.28 rev.

3. Analysis of results

The geometrical features analysed in this work were the tool diameter (pin profile), pin roundness and coaxiality between the grinding area and the pin shaft, corresponding to the new and the used pins. A comparison between both states was done to compare the tool wear additionally. The tool profile was directly the evolution of pin diameter (*D*) along the tool length. Roundness was analysed from the values of pin diameter (*D*) at each section for different angular orientations of the pin. The extension along all the tool length will allow for comparing the roundness at the grinding area and the pin shaft.

On the other hand, coaxiality between the shaft axis and the grinding zone axis was determined. For this, it was necessary to calculate the distance between the axis and the bottom edge of the laser (parameter *BA*) as:

$$BA = BE + \frac{D}{2} \tag{1}$$

The variation of *BA* along the tool length was used to compare the tool axis between the shaft and the grinding zones. Since the tool attachment is carried out in the mandrel through the shaft, this was the reference zone to analyze the tolerance with respect to.

3.1. Grinding pins profile

Fig. 3a and 3b show the representation of the pin profiles for the new and the used grinding pins corresponding to the eight angular orientations in which the measurements were performed during the first experimentation procedure. The profile corresponding to each orientation is calculated as the average value of *D* measured in each of the five repetitions. In order to ensure reliability of these profiles, it was also included in Fig. 3c and 3d the standard deviation of the five values of *D* measured at each section. The *Z* axis was represented in the negative scale, since the measurement origin was set at the right edge of the grinding pin.

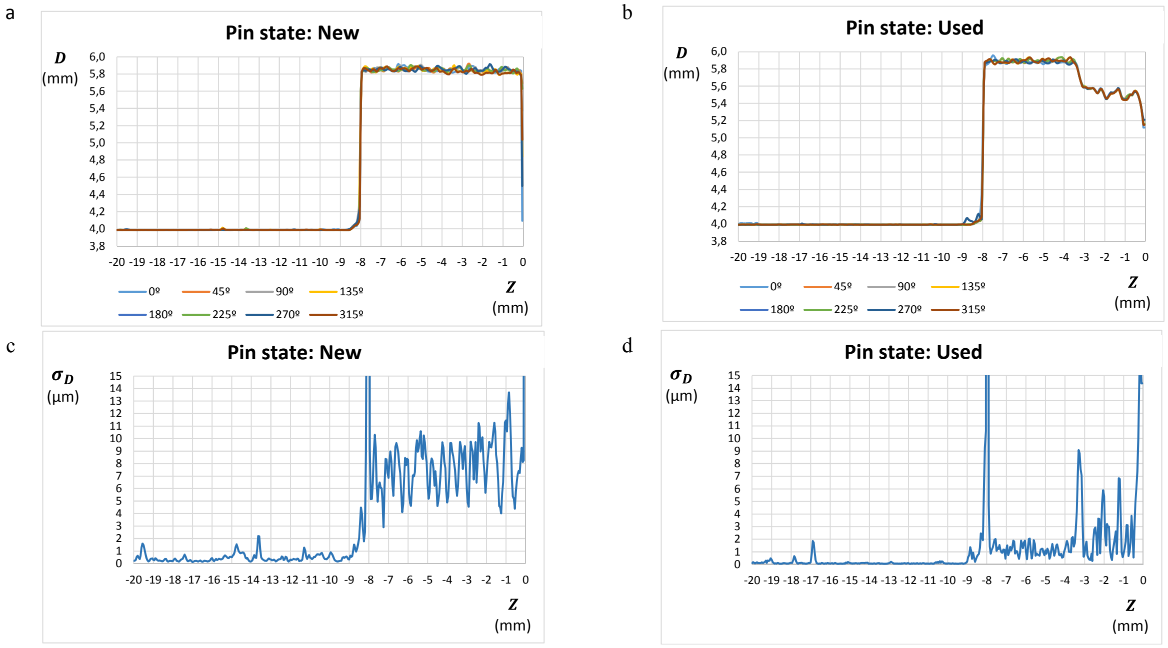

Fig. 3. Average diameter (D) and standard deviation (σ_D) of the new and the used grinding pins along 20 mm, for eight angular orientations.

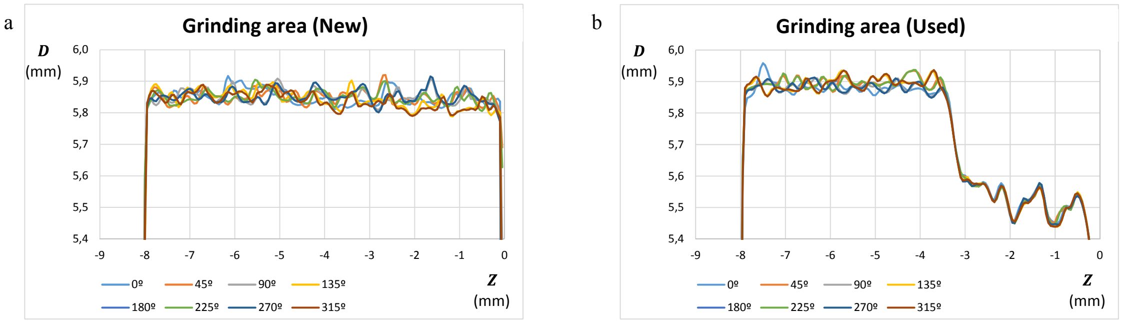

Fig. 4. Profiles of the grinding area of the new (a) and the used (b) pins for eight angular orientations.

According to the graphs of standard deviation (Figs. 3c and 3d), it can be seen that measurements of the tool shaft have got very high repeatability, being $\sigma_D \leq 1.6$ μm for the new pin and $\sigma_D \leq 0.9$ μm for the used one. On the contrary, worse repeatability was met at the grinding zone, being $4 \leq \sigma_D \leq 11$ μm for the new pin, $0.3 \leq \sigma_D \leq 9.8$ μm for the used one at the worn zone and $0.3 \leq \sigma_D \leq 2.1$ μm for the used one at the unworn zone. All of these values are expressed for a confidence level (CL) of approximately 95%. The different behaviour of repeatability between the new and the used pins can be explained by the different method used for the angular orientation of the grinding pin in each case. It was done manually in the case of the new grinding pin but automatically in the case of the used one, by using the spindle orientation capability of the CNC lathe, which provided better precision in the orientation.

It can also be noticed in Fig. 4 that there exists a certain variation between the different orientations in the grinding area not used. This is probably due to the grit size and its random distribution in the bonding resin, which causes a small surface irregularity. On the contrary, in the worn area there exists a fine coincidence of values for all the orientations. This can be explained since the tool wear takes place symmetrically around the grinding pin as it rotates when machining, and affects to both the grits and the bond. Additionally, it can be observed in Fig. 4b an important wear in the first 3.5 mm of the used tool.

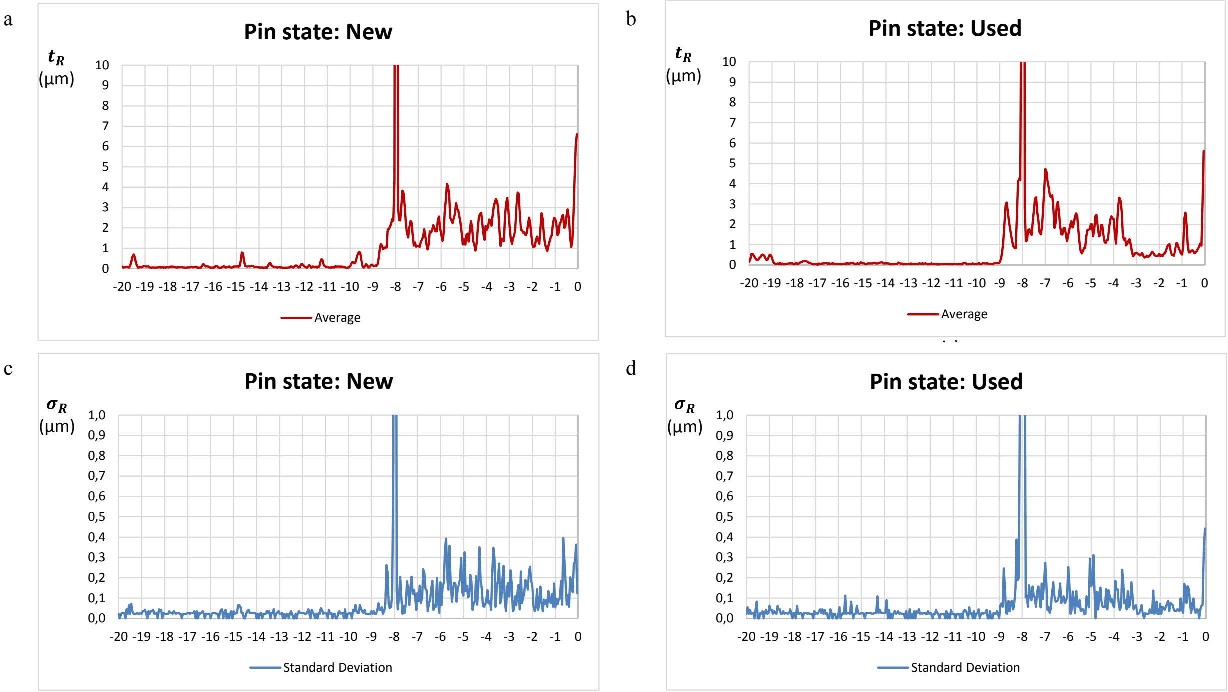

Fig. 5. Average Roundness tolerance (t_R) and its standard deviation (σ_R) for the new and the used grinding pins.

3.2. Roundness

According to ISO 1101:2017, the roundness tolerance zone at each section is limited by two concentric circles with a difference of radii equal to the tolerance value specified in a drawing. Considering this, the roundness tolerance at each section could be expressed as:

$$t_R = \frac{1}{2} \cdot (D_{max} - D_{min}) \tag{2}$$

where D_{max} and D_{min} are, respectively, the maximum and minimum value of diameters measured while rotating the grinding pin several turns, as it was described in Section 3.1.

Fig. 5 shows the value of the average roundness tolerance (t_R) for the five repetitions of the trials, corresponding to the new (Fig. 5a) and used (Fig. 5b) grinding pins. Fig. 5c and Fig. 5d show the standard deviation (σ_R) for each grinding pin. The low value of σ_R along all the tool length ($\sigma_R \leq 0.3$ µm for both pin states, with a 95% CL) demonstrates that the average value of the roundness tolerance is very reliable. Then, from the graphs of this parameter, it can be stated that the roundness at the shaft area is very good ($t_R \leq 0.4$ µm for both pins, with 95% CL) and in the grinding area it is a little worse but still quite good ($0.6 \leq t_R \leq 3.9$ µm in the non-used area for both pins and $0.3 \leq t_R \leq 1.3$ µm in the worn area, with 95% CL). The better roundness in the worn zone can be explained because the tool wear takes place symmetrically around the grinding pin and it improves roundness.

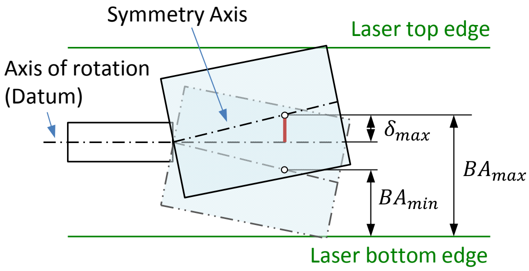

Fig. 6. Sketch for determining deviation δ of the symmetry axis with respect to the rotation axis.

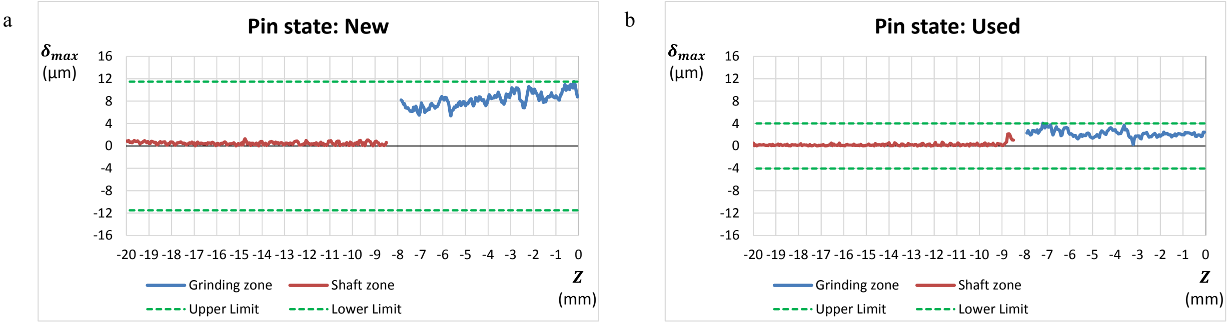

Fig. 7. Maximum deviation (δ_{max}) of the tool axis with respect to the rotation axis for the new (a) and the used (b) grinding pins.

3.3. Coaxiality

The coaxiality tolerance of the grinding area with respect to the grinding pin shaft was determined according to ISO 1101:2017. In this case, the tolerance value (t_C) is the diameter of a cylinder which axis is the one of the shaft zone, in which the axis of the grinding zone should be completely located.

The parameter used for determining the location of both axes (shaft and grinding zones) was the one defined in equation (1) and denoted as *BA*. Nevertheless, since this parameter represents the distance between the axis and the bottom edge of the laser, its value is influenced by the angular orientation of the grinding pin when performing the measurements. It can be seen in Fig. 6 that each point on the symmetry axis of a cylinder which is not coaxial with the datum, turns around the rotation axis describing a circle of radius δ_{max}, which can be calculated as:

$$\delta_{max} = \frac{1}{2} \cdot (BA_{max} - BA_{min}) \tag{3}$$

By determining δ_{max} for all the positions along the grinding pin, it is possible to determine the axis profile of both the shaft and the grinding zones to analyse coaxiality. This way, Fig. 7 shows the representation of this parameter for the new and the used pins.

It can be realized that the shaft zone has a very good coaxiality with the rotation axis whereas the grinding area has not in any case, although the lack of coaxiality is greater in the new pin ($t_C = 23$ µm) than in the used one ($t_C = 8.2$ µm). The difference between them is because they were different pins instead of the same. In the case of the used pin, the coaxiality of the worn area with respect to the shaft is slightly better than in the rest of the grinding zone, but not significantly.

4. Conclusions

This work analyses and demonstrates the feasibility of using a 2D laser micrometer (LM) for on-machine macrogeometric measurement of grinding pins. This way, it is possible to overcome non-productive time, required if the inspection were carried out off-line, and becomes a fast and economical inspection method easy to be integrated in a CNC grinding machine.

Measurement experiments were performed on two different grinding pins, one completely new and the other after a certain use, so that it was partially worn in the grinding zone. For that purpose, the laser micrometer was set up in a CNC lathe and the grinding pins in a mandrel clamped in the chuck. The measurement procedures were automated by specific CNC programs.

The micrometer was able to take two dimensional parameters simultaneously, from which it was possible to analyse three geometrical features for each pin: profile, roundness and coaxiality between the shaft and the grinding area. The high repeatability found in all the experiments ensure the reliability of the measurements.

Although in this case the study was performed in a CNC lathe, the ease of integration of the Laser micrometer with machine tools make it possible to apply it directly in a CNC grinding machine, where the grinding tool were held in the machine spindle, and the LM were set horizontally on the machine tool table. In order to automate the measurement process and the analysis, it would be necessary to develop some specific routines with an easy to use interface for the operator to input data and to get the results of the inspection. The application could also be extended to the measurement of other type of tools, such as mills or drills.

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