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Performance verification of an on-machine optical system for measuring ball end mills

Amrozia Shaheen[1,2*] and Giuliano Bissacco[1]

[1]Technical University of Denmark, Department of Mechanical Engineering, 2800 Kgs. Lyngby, Denmark
[2]LEGO System A/S, Aastvej 1, 7190, Billund, Denmark

*amrsh@dtu.dk

Abstract

Tool presetters are optical systems used to determine the tool geometry as a prerequisite step of the machining process. Tool geometry can be established on- and off-machine; however, the on-machine tool presetting is preferred to avoid introducing clamping errors linked to the interfaces between the tool holder and the machine tool spindle. Generally, the modern computer numerical control machine tools are supplied with tool presetters (laser beam interruption systems, camera-based systems), nonetheless, traceability of such instruments is not guaranteed due to lack of the international standards. In this work, the performance of the camera-based tool presetting optical system for on-machine tool measurement of ball end mills (fine finishing tools) is evaluated. The validation process resides on ISO 15530 part 3 and established using a calibrated artefact of a simple geometry similar to a ball end mill (without the helix angle) and reference measurements using a coordinate measurement machine. The calibration artefact is used to characterise the tool presetter in actual shopfloor environment. Furthermore, the task-specific uncertainty is evaluated by considering the uncertainty contributors of measurement procedure. Results have shown the implication of the calibration artefact for characterising the parameter of interest (radius of curvature or second radius).

Tool presetter, calibration artefact, coordinate metrology, uncertainty, ball end mill

1. Introduction

These days, precision machining operations using the computer numerical control (CNC) require various parameters for ensuring the dimensional accuracy and high surface quality; therefore, accurate tool geometry estimation is essential as the surface generation is associated with offsetting the tool path according to the tool profile [1]. Tool geometry can be determined off-machine using tool presetters and by keeping the tool intact in the tool holder; however, the interface between the tool holder and the machine tool spindle introduces additional errors leading to unidentified machining errors [2]. Thus, on-machine integrated traceable measurement systems are essential for accurate tool geometry measurement.

Modern machine tools are equipped with tool presetting systems (laser beam interruption, laser scan micrometres, camera-based) for measuring tool geometry [3-5] However, traceability of the optical instruments is not guaranteed due to lack of the international standards [6]. In this work, the performance of a high-speed camera-based optical system is evaluated for measuring the ball end mills. Ball end mills play a vital role in milling operations due to their unique geometry, hemispherical cutting edge, and versatile functionality makes them suitable for machining complex 3D contours, especially in mould and die industry [7, 8].

The methodology resides on ISO 15530 part 3 which provides guidelines for evaluating the measurement uncertainty for coordinate measuring machine using calibrated artefacts or measurement standards [9]. For this purpose, an artefact resembling a ball nose cutting tool was manufactured and calibrated using a coordinate measuring machine (CMM). The method for measuring the radius of curvature (2nd radius) of the artefact was developed and the uncertainty contributors from the calibration process were quantified. Furthermore, the characterisation of the camera-based tool presetter was established by employing the artefact in the optical system and comparing the measured outcome against the reference CMM measurements.

2. Methodology and instruments details

The methodology for characterising the tool presetting system for measuring the radius of curvature of ball end mills resides on the similarity criteria (ISO 15530-3 [9]) between the dimension and the form of the actual artefact and the calibrated reference artefact, developing the artefact's calibration procedure and conducting verification tests on the camera-based optical system. The details are provided in the subsequent sections.

2.1. Reference artefact: Ball end mill shaped

The artefact is analogous to a ball end mill (without the helix) and comprises a cylindrical gauge pin (Ø6 mm ± 1 µm, length 70 mm) with a square end followed by a curved face with four cutting edges. Figure 1 shows the CAD model of the artefact. For the reference artefact, a simple geometry was chosen as the camera-based system can measure the milling tools with sharp cutting edges.

The nominal side length of the square end is 2.7 mm, and the nominal diagonal length is 3.818 mm. This is due to the field-of-view of the optical system (4.5 mm × 2.9 mm), and for two-sided measurement of the reference artefact. The artefact was manufactured from a cylindrical gauge pin, and was machined by means of wire electrical discharge machining (EDM) process on an AgieCharmilles CUT E 350 to obtain the square end and the curved face. (Figure 1).

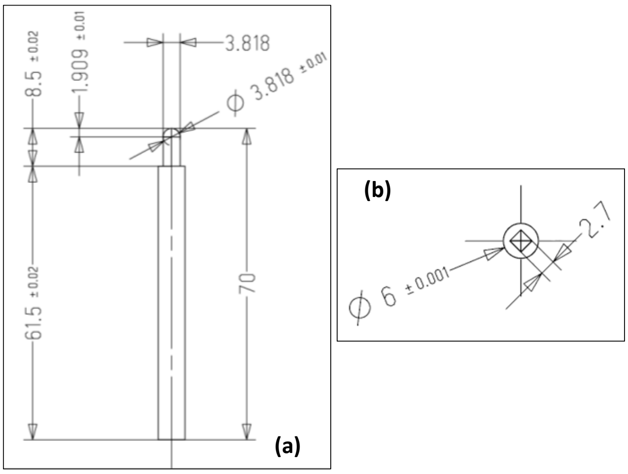

Figure 1. CAD model of the reference artefact with nominal dimensions in mm. (a) Side view, and (b) top view.

2.2. Reference measurement: CMM

Reference measurements were performed using a coordinate measuring machine (CMM-001-Zeiss-PRISMO, MPE: (0.9 + L/350) µm, L in mm) [10]. Figure 2 shows a photograph of the experimental setup; the artefact is mounted on a v-groove shaped magnetic holder which is clamped on a vise. Two probes were used; probe-1 with two horizontal styli with Ø3 mm and Ø8 mm spheres while probe-2 comprises of one horizontal stylus of Ø1 mm sphere and one vertical stylus with Ø8 mm sphere. Figure 2 and Figure 3 show the two styli used in the CMM measurements. The ambient temperature was (20 ± 1) °C, and the measurements were repeated twenty times as specified in ISO 15530 part 3.

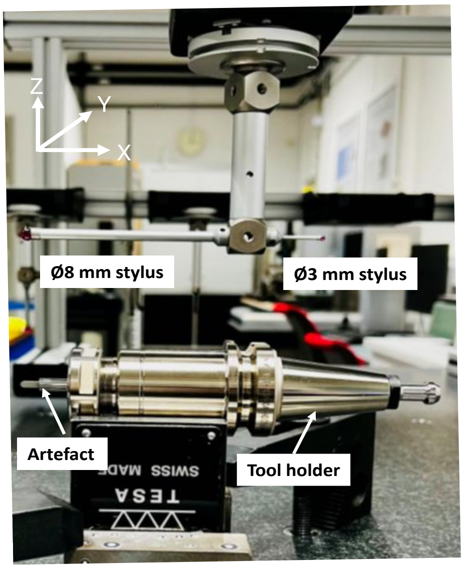

Figure 2. Experimental setup for CMM measurements (reference) with probe-1 (Ø3 mm, Ø8 mm spheres).

The reference artefact was measured while mounted in the tool holder (Figure 2) and the whole arrangement is considered as an artefact. The purpose of keeping the artefact mounted in the tool holder is to use the CMM measurements as a reference for validating the tool presetting optical system, also accounting for the total runout which is specifically dependent on the tool-tool holder assembly. The measurement strategy of determining the radius of curvature (2nd radius) is based on scanning the sphere at various heights using the CMM in scanning mode and the whole process was repeated twenty times. The details of the measurement outcome will be provided in the subsequent sections.

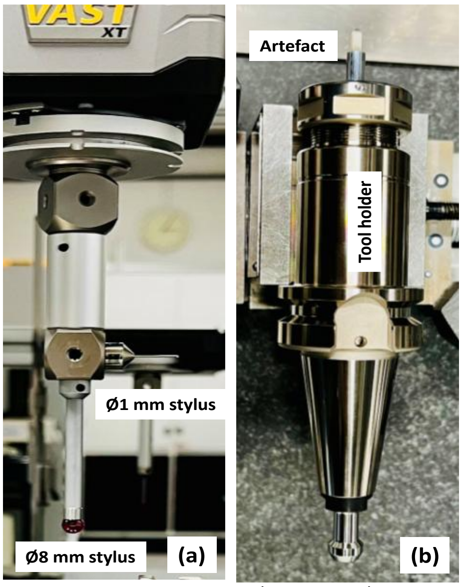

Figure 3. CMM setup. (a) Probe-2 with Ø1 mm and Ø8 mm spheres, (b) and top-view of the reference artefact.

2.3. Camera-based optical system

The camera-based system is a cost-effective, high-speed optical system and a step forward towards industry 4.0. The optical system CU2 Tool M67 (Conoptica AS, Norway) is mounted on a Fanuc Robodrill α-D21LiB5adv, and is used as a tool presetting system for cutting tool measurement in machining operations. The instrument (shown in Figure 4) is compatible with machine tool harsh conditions such as contamination by cutting fluid lubrication, metal chips from machining process and air-born coolant droplets from oil mist lubrication. The optical system comprises of a camera and an illumination unit and can perform the automated inline tool measurement of the rotating milling tool at the desired spindle speed for machining processes.

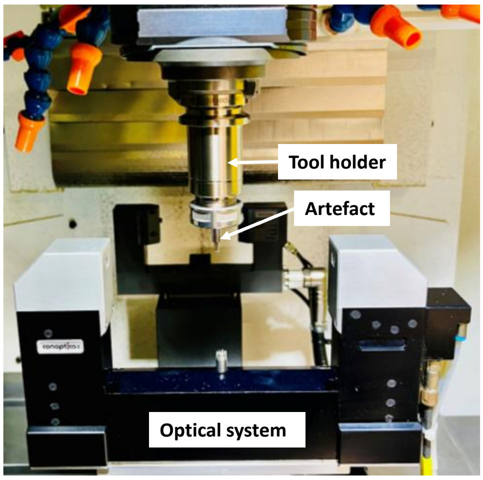

Figure 4. The camera-based optical system. The reference artefact is mounted in the spindle of the machine tool.

The camera-based system has an optical magnification x67, field-of-view 4.5 mm × 2.9 mm, and is capable of measuring the cutting tools with tool diameter less than 4mm for simultaneous measurement of both halves of the tool. The measurement procedure resides on illuminating from one side and recording images (over 200 in 4 seconds) of the rotating milling tool where millions of pixels display the contour of the cutting tool at different rotation angles. The evaluation is performed in CU2 Tool software (integrated with the camera-based system, provided by the manufacturer) based on using the reference model and the recorded images to determine the cutting tool geometry.

In this work, we have used twenty repeated measurement cycles (as recommended by ISO 15530-3) whereby each cycle comprises of creating a reference model of the clean tool followed by the measurement. The process includes identifying each cutter individually, performing digital cleaning and determining the parameters of interests (tool radius, tool length, radius of curvature, runout). This information is later used for measuring the tool geometry. We have considered the radius of curvature (2nd radius) to test the validity of the camera-based optical system for measuring in the corner and the bottom regions of the cutting tools [11].

2.4. Uncertainty budget for performance evaluation of the optical system

The measurement uncertainty is primarily determined by incorporating four key factors, each associated with either random or systematic errors. The expanded uncertainty specified in ISO 15530 part 3 [9] is defined as follows,

$$U_M = k\sqrt{u_{cal}^2 + u_b^2 + u_p^2 + u_w^2}, \qquad (1)$$

where k is the coverage factor ($k = 2$ for 95% confidence of interval), u_{cal} is the standard uncertainty of the calibrated artefact, u_b is the standard uncertainty of the systematic error linked to the measurement process ($u_b = b$ if the measurement is not corrected for systematic error, and $b = \bar{x} - x_{cal}$), u_p is the standard uncertainty related to the measurement being performed on the calibrated workpiece ($u_p = \left(\frac{s}{\sqrt{N}}\right)$, s is the standard deviation and N is the number of measurements conducted [12, 13]), and u_w is the standard uncertainty of material and manufacturing modifications of the measured object such as thermal expansion coefficient, surface texture, and dimensional errors.

The calibration uncertainty in the CMM measurements can be expressed as,

$$u_{cal} = \\ = \sqrt{U_{\text{CMM-rep}}^2 + U_{\text{CMM-probe}}^2 + U_{\text{CMM-scan}}^2 + U_{\text{CMM-system}(x,y,z)}^2} \qquad (2)$$

$$= \sqrt{(0.18)^2 + (0.2)^2 + (0.6)^2 + (0.3)^2} = 0.72\ \mu\text{m} \quad (3)$$

where, $U_{\text{CMM-rep}}$ is the uncertainty in the CMM repeated measurements, $U_{\text{CMM-probe}}$ is the uncertainty related to probe qualification, $U_{\text{CMM-scan}}$ is the scanning probing error, $U_{\text{CMM-system}(x,y)}$ is associated with systematic error in the x, y and z directions.

3. Experimental results and discussion

Figure 2 and Figure 3 depict the experimental setup for CMM measurements (reference), while Figure 4 shows the photograph of an on-machine camera-based optical system. By following the guidelines for the uncertainty evaluation (section 2.4) and using the reference calibrated artefact, we have developed a method to validate the performance of the camera-based system for measuring the radius of curvature of ball end mills. The method is based on making a complete uncertainty budget for the radius of curvature (2nd radius) by repeating the CMM measurements twenty times and afterwards utilising them to evaluate the performance of the on-machine camera-based system. The reference artefact is later placed in the spindle of the FANUC Robodrill to perform the repeated measurements (20 repeats) on the camera-based system.

The CMM measurement (serves as a reference) process comprises the probe qualification as per manufacturer's specifications, manual base alignment followed by the automated base alignment and estimating various feature characteristics. The repeatability of the features of interests (diameter, cylindricity, flatness of four faces of the square end) resides within 0.1 µm with 95% confidence of interval and listed in Table 1 . The reference coordinate system was defined on the artefact (Figure 2) and with respect to the plane at the cylindrical gauge pin face adjacent to the square cross section of the artefact.

Table 1. CMM results for measured features.

Feature characteristic	Measured value (average of 20 repeats)	Repeatability (95% CI)
Cylinder diameter	6.0015 mm	0.01 µm
Cylindricity	1.0 µm	0.01 µm
Flatness top plane	2.2 µm	0.07 µm
Flatness bottom plane	1.2 µm	0.03 µm
Flatness front plane	1.7 µm	0.03 µm
Flatness rear plane	2.0 µm	0.04 µm
2nd radius	1.9039 mm	0.36 µm

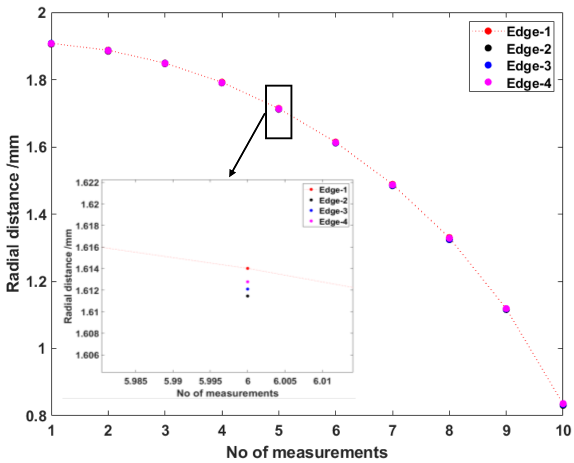

Figure 5. Radius of curvature (2nd radius) of the four edges of the reference artefact measured by CMM.

In order to determine the artefact's radius of curvature (2nd radius), a spherical feature was defined on the curved face with eleven individual circles scanned at different heights. The radial distance from the centre is computed at each individual height yielding four local maxima related to the location of the four cutting edges of the curved face of the artefact. Subsequently a theoretical feature (circle) is fitted on the extracted extreme points for each cutting edge which gives the radius of curvature (Figure 5). Among, four cutting edges' radius value, the largest (the most protruded one) is considered as the 2nd radius of the artefact coherent with the camera-based system output parameter.

Figure 7 shows the statistical distribution of the CMM measurements (reference) and the camera-based system output for two orientations of the reference artefact being placed in the machine tool spindle. The tool holder can be flipped by 180 degrees corresponding to position-1 and position-2. The on-machine tool presetting system has a relatively narrow spread relating to better repeatability of the tool presetter.

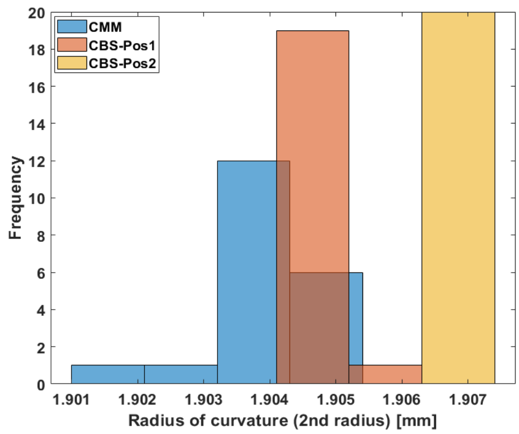

Figure 6. Statistical distribution of measured radius of curvature for reference CMM and camera-based system (CBS) for two orientations labelled as CBS-Pos1 and CBS-Pos2.

Figure 7 depicts a comparison of the measured radius of curvature (2nd radius) for reference CMM results and the optical system along with the measured uncertainty. Table 2 shows the uncertainty budget for the measured outcome of the camera-based optical system; the position-1 and position-2 have an expanded uncertainty of 2.5 µm and 6 µm, respectively (95% coverage interval).

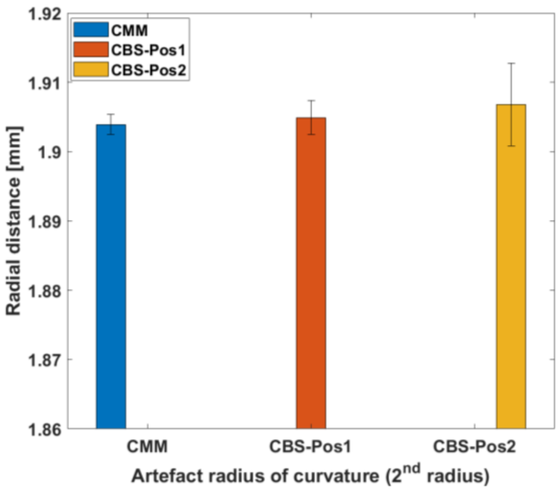

Figure 7. A comparison of measured radius of curvature for CMM and CBS for two orientations labelled as CBS-Pos1 and CBS-Pos2.

Table 2. Uncertainty budget for the measured outcome of the 2nd radius of the camera-based optical system.

Type	Artefact 2nd radius-Position 1 [mm]	Artefact 2nd radius-Position 2 [mm]
Mean value	1.9049 mm	1.9068 mm
u_{cal}	0.72 µm	0.72 µm
u_b	1 µm (1.9039 – 1.9049)	2.9 µm (1.9039 – 1.9068)
u_p	0.031 µm	0.039 µm
u_w	insignificant	Insignificant
$U_M(k=2)$	2.46 µm	5.98 µm

The measurement outcome indicates that there is a systematic error (bias) by the tool presetting optical system, and if this contribution is compensated, the measurement uncertainty of the optical system can significantly be reduced. Furthermore, the differences in the measurement results for two different orientations is related to slightly different measurement scenarios. This can be associated with the data processing strategy for computing the 2nd radius which is dependent on the region-of-interest on the curved face being considered in the evaluation process. The artefact's orientation in space, interfaces between the tool holder and machine tool spindle, and spindle thermal expansion during rotation influencing the axial position of the tool tip can be the potential influencing factors.

5. Conclusions and outlook

In this work, the performance verification of a high-speed camera-based tool presetting system is evaluated for on-machine measurement of ball end mills by following the guidelines stated in ISO 15530 part 3. For this, a reference artefact of ball nose shaped is manufactured from a gauge pin and calibrated using CMM. A complete uncertainty budget is made for the characterisation of the optical system, and the measured outcome (radius of curvature or 2nd radius) is compared with the reference CMM measurements. The expanded uncertainty for the measured 2nd radius of the artefact is for position-1 is 2.5 µm (95% coverage interval) while for position-2 is computed as 6 µm (95% coverage interval). The difference in the measurement results for the two orientations can be related to the measurement strategy, interfaces between the tool holder and the spindle and the thermal influences. An investigation is underway to generate the 2nd radius deviation results that can be used for compensation of the machine tool based on the current state of the milling tool. The future work will focus on investigating the influencing factors such as thermal errors and runout on the tool geometry estimation process.

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