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Medium term stability investigation of polymer step gauges for CT scanner verification

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Abstract
A miniature step gauge fabricated using a material for dental applications was previously used at DTU as a reference object for instrument verification in optical 3D scanning and Computed Tomography (CT). Initial material investigations had indicated a good metrological compatibility but a later stability investigation showed that the material was not hard and stable enough to be used for reference objects. In order to achieve better performance mechanical properties and stability, two other polymer materials, polyetheretherketone (PEEK) and polyphenylene sulphide (PPS), were selected. Five miniature step gauges of each material were manufactured using milling. A tactile CMM and grade I steel gauge blocks were used for calibration. A practical approach inspired by the PUMA method was used for uncertainty estimation, as a simplification of the GUM approach. The long term stability of the step gauges was monitored through reproduced measurements of 10 groove distances for each step gauge, both uni-directionally and bi-directionally, carried out eight times over approximately one year. The stability investigation showed for PPS deviations below 3 µm and expanded uncertainties (k=2) below 5 µm while 4 µm and 7 µm, respectively, were obtained for PEEK. The E_n value normalised with respect to the estimated uncertainty was computed according to ISO 17043 guidelines. The estimated $|E_n|$ values are generally in the acceptable range for both polymer materials, with a calculated average of $|E_n|$ = 0.2.

Keywords: Computed Tomography, Coordinate Measuring Machine, miniature polymer step gauges, long term stability, deviations, uncertainties

1. Introduction

A miniature step gauge fabricated using a material for dental applications (Luxabite) was previously used at DTU as a reference object for instrument verification for uni-directional and bi-directional distances in optical 3D scanning and Computed Tomography (CT) [1, 2, 3]. Initial material investigations had indicated a good metrological compatibility but a later stability investigation showed that the material was not hard and stable enough to be used for reference objects [4]. In order to achieve better performance in terms of material density, X-ray penetrability, hardness, mechanical properties, surface cooperativeness, and stability, two other polymer materials, polyetheretherketone (PEEK) and polyphenylene sulphide (PPS), were selected [4, 5]. A key issue has been to document that these step gauges are stable and controllable, and useful as reference objects for evaluating dimensional measurements using optical and CT scanning, in terms of detecting systematic errors and estimated uncertainties. Some of the challenges taken into consideration are form errors, temperature sensitivity, and lower material stability over time, which degrade the metrological compatibilities and increase measurement uncertainty. Material characteristics such as density and thermal expansion coefficient data for PEEK and PPS are shown in Table 1. The step gauges are manufactured with a short (7 mm) and a long edge (9 mm) for identification of position and direction for the alignment, as shown in Fig. 1.

Table 1 Material characteristics of the step gauges.

Material	Density [g/cm³]	Thermal expansion coefficient [10^{-6} K^{-1}]
PEEK	1.31	50
PPS	1.65	30

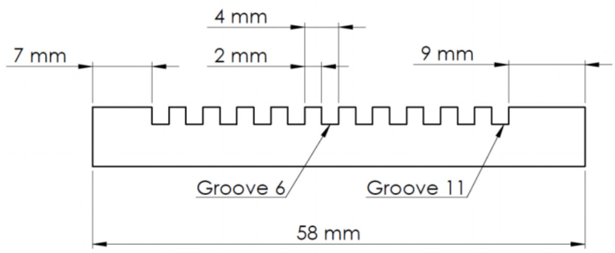

Figure 1. Step gauge with nominal dimensions.

2. Step gauge manufacturing

Five PEEK (PEEK #1 to #5) and five PPS (PPS #6 to #10) step gauges were manufactured using milling. Roughness measurements on the vertical planes on the grooves were carried out and the resulting average roughness lies in the range Ra = 0.8-1.0 µm for both material types, see Table 2. Examples of corresponding roughness profiles are shown in Fig. 2. The roughness is of big importance in CT, because the quality of the surface can influence the threshold determination [6] on the CT scanned model.

Table 2 Roughness on the vertical planes on the grooves. All values are in µm and based on 12 measurements for each material.

	PEEK #1		PPS #7	
	Ra	*Rz*	*Ra*	*Rz*
MAX	1.211	7.537	1.090	8.218
AVG	1.014	5.905	0.820	6.191
MIN	0.738	4.710	0.645	4.587

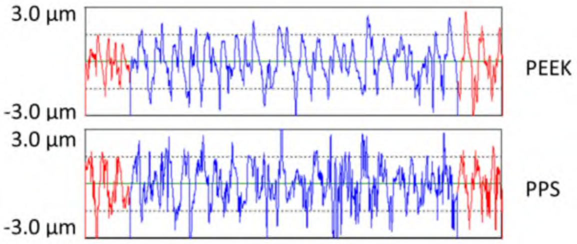

Figure 2. Examples of roughness profiles.

3. Step gauge calibration

A tactile CMM of the type Zeiss OMC 850 with a maximum permissible error of MPE_{U3} = (3+L/250) µm (L in mm) and grade I steel gauge blocks were used for calibration and transfer of traceability, see Fig. 3. A practical approach inspired by the PUMA method was used for uncertainty estimation, as a simplification of the GUM approach. The calibration uncertainty resulted from five main contributors: 1) reference artefact u_r, 2) instrument MPE u_m, 3) workpiece form error u_w, 4) temperature effects u_e, and 5) reproducibility u_p where the parts were repositioned and measured again five times. The temperature contribution was divided into three sub categories: 4.1) temperature difference for instrument $u_{e(1)}$, 4.2) temperature difference for artefact $u_{e(2)}$, and 4.3) deviation from the standard reference temperature $u_{e(3)}$. Calibration uncertainties were assessed at a confidence level of 95 %, corresponding to k=2 and the uncertainty model was defined

as $U = k \cdot \sqrt{u_r^2 + u_m^2 + u_w^2 + u_{e(1)}^2 + u_{e(2)}^2 + u_{e(3)}^2 + u_p^2}$.

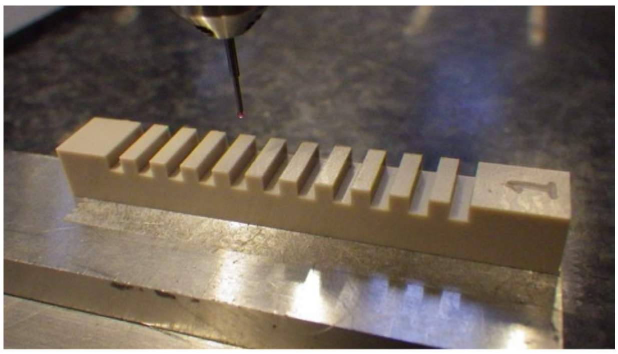

Figure 3. Calibration of PEEK miniature step gauge on CMM.

4. Stability investigation

It is of high importance to test and document the stability of polymers over a period of time, since they are sensitive to environmental changes such as humidity and shrinkage [7, 8]. The medium term stability of the step gauges was monitored through reproduced measurements of 10 groove distances for each step gauge, both uni-directionally and bi-directionally, carried out eight times over approximately one year. The stability investigation showed for PPS deviations below 3 µm and expanded uncertainties (k=2) below 5 µm while 4 µm and 7 µm, respectively, were obtained for PEEK. Improved results were obtained for PPS compared to PEEK and for all distances due to the glass fibre content in PPS. In order to judge the agreement between reference values over a period, the E_n value normalised with respect to the estimated uncertainty was computed according to ISO 17043 [9]. The estimated $|E_n|$ values are generally in the acceptable range for both polymer materials, see Fig. 4, with a calculated average of $|E_n|$ = 0.2.

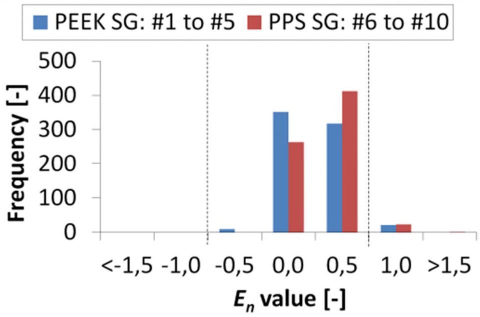

Figure 4. E_n values for all measurements covering all 10 step gauges.

5. Conclusions

The medium term stability of two new polymer step gauges was monitored through reproduced measurements of 10 groove distances for each step gauge, both uni-directionally and bi-directionally, carried out eight times over approximately one year. The stability investigation showed for PPS deviations below 3 µm and expanded uncertainties (k=2) below 5 µm while 4 µm and 7 µm, respectively, were obtained for PEEK.

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