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X-ray computed tomography for dimensional measurements of threaded parts

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Abstract

X-ray computed tomography (CT) is and advanced measuring technique capable of performing holistic dimensional verification of both internal and external threaded elements. The contactless and non-destructive nature of CT measurements makes them suited for evaluating also screw threads and threaded features that are internal, small in size, or made of easily deformable materials, overcoming the limitations of conventional contact and optical measuring techniques. This work presents a CT-based methodology for measuring the geometry and local form errors of threaded products applied to (i) additively manufactured metal dental implants (characterized by significant form errors and complex surface topography) and (ii) injection molded polymeric threaded components (fragile, deformable and characterized by high form errors). The accuracy of CT dimensional measurements is investigated through comparison with reference measurements.

X-ray computed tomography, thread measurement, dimensional metrology, accuracy, injection molding, additive manufacturing

1. Introduction

Threaded parts are extensively used in many industrial applications and account for approximately 50 % of all joints produced in mechanical systems [1]. The dimensional verification of screw threads is nowadays performed mainly using contact and optical measuring instruments, or through limit gauges [2]. However, these methods are limited by the fact that (i) they are based on the detection of a relatively small number of points or profiles and (ii) they are not suitable for the measurement of threads that are internal, small in size, or made of materials that can be easily deformed under the action of mechanical probes (e.g. polymers). X-ray computed tomography (CT) is an advanced measuring technique increasingly used for several industrial metrology applications [3]. For the application of screw threads measurements, it is capable of overcoming the limitations of the conventional measuring techniques mentioned above. In particular, CT allows holistic non-destructive and non-contact evaluations of both internal and external threaded elements, even in cases when these elements are included in fragile or deformable parts (e.g. fiber reinforced polymeric parts) or in parts characterized by significant form errors and complex texture (e.g. additive manufacturing parts). This work presents a CT-based methodology for measuring the geometry and local form errors of threaded products, with particular attention to: (i) additively manufactured (AM) dental implants and (ii) injection molded polymeric threaded components. The accuracy of CT dimensional measurements is investigated through comparison with reference measurements.

2. Materials and methods

2.1. Components and instrumentation

Three components with different form errors and different surface topographies were investigated in this work.

The first one (Sample 1) is a calibrated thread gauge with standard thread geometry (UNC 5/16''-18) and very low form errors. The second component (Sample 2), shown in Fig. 1-a, is a dental implant made of Ti6Al4V, produced by laser-powder bed fusion (L-PBF). It is characterized by: (i) an external thread with non-standard geometry, very high form errors and highly complex surface texture, and (ii) a standard internal thread produced via micro-drilling and threading process [4]. The third component (Sample 3) is an injection molded part (see Fig. 1-b) characterised by an internal thread with non-standard geometry and significant form errors.

All components were scanned by means of a metrological micro-CT system (Nikon Metrology MCT225). The maximum permissible error (MPE) for length measurements is equal to $9 \pm (L/50)$ µm, with measured length L expressed in millimetres.

CT data were elaborated by means of the analysis and visualization software VGStudio MAX 3.1 (Volume Graphics GmbH) and by a newly developed Matlab (MathWorks) routine.

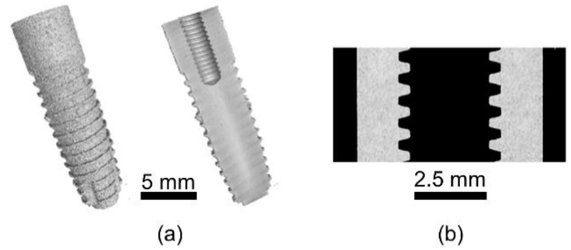

Figure 1. (a) CT volume reconstruction and virtual sectioning of dental implant produced by L-PBF of Ti6Al4V; (b) CT virtual section of injection molded polymeric part with internal thread.

2.2. Procedure for CT thread measurement

The procedure for performing thread measurements from CT data consists in the following main steps:

1. Acquisition of X-ray projection images keeping the scanning parameters as similar as possible (e.g. voxel size equal to 7.4 µm) for the calibrated gauge (Sample 1) on one side, and for the other parts (Samples 2 and 3) on the other side, in order to obtain comparable scanning conditions;
2. CT reconstruction of the 3D model of the scanned samples;

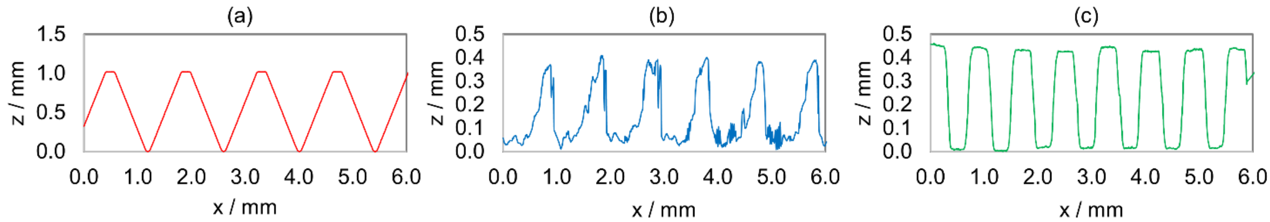

Figure 2. One of the 360 profiles extracted from the point cloud of: (a) Sample 1, (b) Sample 2 and (c) Sample 3.

3. Surface determination using the local adaptive thresholding algorithm available in VGStudio MAX 3.1.
4. Registration of the 3D model with respect to the axis of the least-squares cylinder fitted to the external diameter;
5. Extraction of high-density point-cloud;
6. Extraction of points belonging to *n* axial profiles (using the newly developed Matlab routine; see Fig. 2), in order to analyse *n*/2 different longitudinal sections of the part. In this work *n* is equal to 360 (i.e. one profile for each rotational degree);
7. For each single considered section, measurement of the thread geometrical parameters of interest (this work presents results on minor diameter *dmin* and major diameter *dmax,* defined according to ISO 5408:2009 [5]).

2.3. Systematic errors and uncertainty evaluation

The systematic errors (i.e. difference between the average of *N* repeated measurements and the corresponding calibrated value) and the uncertainty of CT measurements conducted in this work were determined by applying the approach defined in the guideline VDI/VDE 2630-2.1 [6], which is based on repeated measurements of a component calibrated with low uncertainty, similar to the actual components (with similarity conditions as reported in [6]). The measurement result *Y* is corrected for the systematic error (*b*) and expressed as:

$$Y = y - b \pm U \qquad \text{(Eq. 1)}$$

where *Y* is the corrected measured value, *y* the uncorrected measured value and *U* the expanded measurement uncertainty.

3. Results

Fig. 3 shows the CT measurements results of *dmin* (Fig. 3-a), and *dmax* (Fig. 3-b) for the three samples, plotted as difference between measured and mean values in order to enable a better visualization of variability. The variability considering 180 different sections is far lower for Sample 1 than for Sample 2 and 3. For both *dmax* and *dmin*, the range is below 3.1 µm for Sample 1, around 57 µm for Sample 2 and below 26 µm for Sample 3. Such variability is due to the very different form errors and surface texture of the analysed samples. Concerning Sample 3, a specific trend can be observed, due to a significant form error for which the part section tends to be two-lobed rather than circular. Sample 1 is calibrated, hence the mean systematic errors (*b*) can be evaluated and corrected as per equation (Eq. 1). They were found to be equal to -1.7 µm and -1.2 µm for *dmin* and *dmax* respectively. The expanded measurement uncertainties (95 % confidence level) related to Sample 1 were determined as explained in Section 2.3., by considering the results obtained from 10 repeated CT scans. The determined final expanded measurement uncertainties are reported in Table 1. For Sample 2 and 3, additional uncertainty contributions had to be considered to take into account the differences with respect to Sample 1, in terms of material, form and surface texture. Moreover, to cope with the particularly high form errors of Sample 2 (see Fig. 2-b), the profiles extracted from the CT scan were smoothed, before applying the algorithm employed to measure the thread parameters. In this case, the uncertainty contribution associated to the smoothing filter effect was included as well. All the final expanded measurement uncertainties are reported in Table 1.

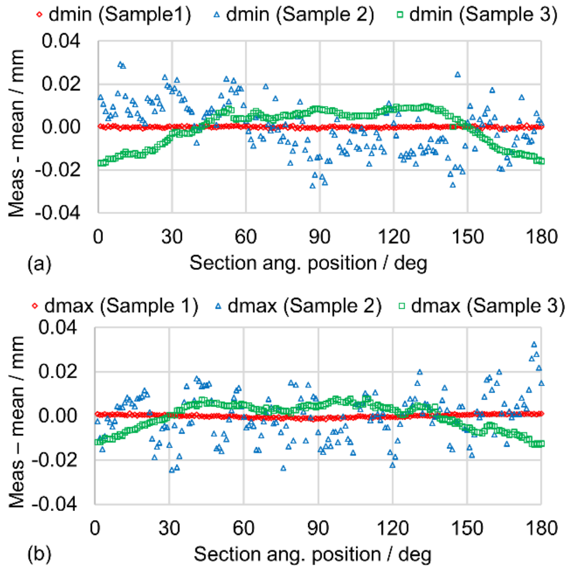

Figure 3. CT measurement of (a) minor diameter *dmin* and (b) major diameter *dmax*, for Sample 1, Sample 2 and Sample 3, plotted as difference between measured and mean values. 180 sections are considered (i.e. 360 profiles).

Table 1 Expanded uncertainties (95 % confidence interval) determined for *dmin* and *dmax* measured for Sample 1, Sample 2 and Sample 3

U	Sample 1	Sample 2	Sample 3
dmin	3.2 µm	138.0 µm	10.9 µm
dmax	3.2 µm	70.1 µm	10.9 µm

4. Discussions and conclusion

This work proposed a CT-based methodology to measure the geometry and local form errors of two threaded parts, one fabricated via additive manufacturing and the other via injection molding. The errors and uncertainty of such measurements were determined by comparison to a calibrated component with standard threaded geometry. Results demonstrated the measurement capabilities of CT in performing a local evaluation of both thread dimensions and form errors, for threaded parts characterized by high form errors and complex surface topography.

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