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Roughness measurements using optical coherence tomography: A preliminary study

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ABSTRACT

To determine the roughness is an important aspect in both industrial and biomedical applications. We propose and utilize for roughness evaluations, a non-destructive evaluation methods, Optical Coherence Tomography (OCT). For the metallic surfaces investigated from this point of view, the Ra and Rz parameters are utilized, according to ISO 4287/1988. Also, according to ISO 4280 and ISO 3274 standards, the measurements have been made on 12.5 mm portions. In order to accommodate such evaluations with the specific OCT field-of-view, four consecutive OCT images have been made for each sample, and an appropriate processing of the data collected from the surface profiles has been made. A validation of the results obtained with OCT has been completed with the gold standard for such evaluations, using a contact mechanical method, with a Mitutuyo profiler.

Keywords: Optical Coherence Tomography (OCT), roughness, metallic materials, non-contact measurements, imaging methods, handheld probes, manufacturing, dental medicine.

1. INTRODUCTION

The shape and dimensions of imperfections in processed parts depend on several factors, including: the processing operations, the shape of the cutting tool, the cutting cycle (particularly the cutting feed), and the manner in which the chip/splinter is formed – the latter aspect including its cycle, geometry/shape, and material.

These imperfections or profile ruggedness are standardized by ISO 11562-1996 and ISO 16610-21/1996 into the Primary Profile, the Waviness profile and the Roughness Profile. Surface profiles of processed parts bring about disadvantages, such as: a diminishing of the contact surface, an increase in wear, a decrease of the fatigue endurance limit, etc.

The measurement methods for surface roughness profiles are specified in specific standards. Thus, the ISO4287-1998 standard provides methods for determining the surface profile evolution using stylus profile meters; they register the profile along a profile length of several millimeters. ISO 4287 is part of the Geometrical Product Specifications (GPS), which also comprises the following standards: ISO 3274, ISO4287, ISO4288, ISO11562, and ISO16610-21. These standards specify the contact characteristics of the stylus, provide rules and procedures for surface certification, specify parameters defining surface roughness and filters to be used, etc.

ISO 4287 and ISO 4288 classify the parameters that define the surface evolution in the following way:

(a) Field parameters R_a, R_q, R_{sk}, R_{ku}, R_p, R_v, and R_z; amplitude parameter R_t;

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(b) Feature parameters R_c (peak-valley) and RS_m (spacing).

In order to control roughness profiles, the following methods can be used:

(a) comparative determination of roughness using roughness specimens made of steel, cast iron, etc.;

(b) quantitative determination of roughness achieved by using specialized probing equipment (profile meters, profilographs, atomic force microscope);

(c) non-contact classical optical methods and equipment (optical microscopes or interferometers);

(c) non-contact optical methods that have been less used before for such applications, like Optical Coherence Tomography (OCT) – as we explore in this study.

The latter two categories, of optical non-contact methods are currently used for the measurement of surface roughness, and they include: measurement of reflectance [1, 2]; laser speckle techniques [3-8]; two wavelength holographic interferometry [9]; reflected step edges [10]; laser measurements [11, 12]; white light interferometry [13-18]; scattering [19]; terahertz reflection spectra [20]; adaptive optics [21]; low coherence interferometry [22]; OCT based on vertical scanning interferometry (VSI) [23]; spectrophotometric measurements [24].

Comparisons between values of roughness measured through mechanical versus optical methods have been made since 1962. An "Optical Measurements Procedures Guide" was thus edited in 1988 in order to explain in simple terms how several basic optical measurements are made.

Experiments have been carried out on glass, composite materials, metallic materials (steel, aluminum, nickel, bronze, etc.). All these materials were processed through a variety of mechanical procedures like grinding, polishing, milling, belt sounding, etc. The non-contact methods have been used to determine three parameters: mean height of roughness (Ra); root mean square height of roughness (Rq); maximum height of roughness (Rz).

Depending on the material analyzed and the processing operation to which it was previously submitted, the values of these parameters may vary in the Å, nm, or µm range.

Measurements made using optical methods have been compared with those made using for example the stylus [14, 17] and there were always variations in the parameter values measured by the stylus and those obtained by non-contact methods. The roughness of the measured surfaces in such investigations has been low (i.e., Rz < 3µm). The lengths of the surfaces analyzed by non-contact methods have been situated in the µm range.

The standards specifying surface roughness evaluation through mechanical methods stipulate that roughness should be determined on different length depending on the roughness of the surface: for Rz > 50 µm – 40 mm; for Rz = 10-50 µm – 12.5 mm; for Rz = 0.5…10 µm – 4 nm; for Rz = 0.1…0.5 µm – 1.25 mm; for Rz < 0.1 µm – 0.4 mm.

2. MATERIALS AND METHODS

2.1 Samples

In the present study a steel, mechanically milled Commercial Roughness Standard has been used (Fig. 1). The nominal values of its roughness parameters have been R_z = 10 µm and R_a = 2.4 µm.

2.2. OCT System

The surface microstructures have been analyzed using an in-house developed Swept Source (SS)-OCT system with a 10 µm resolution [25]. A Scanning Electron Microscope (SEM) system with a 4 nm resolution has been used to validate some of the OCT investigations.

The schematic diagram of the SS-OCT imaging system is similar to the one reported in [25, 26]. A SS (Axsun Technologies, Billerica, Massachusetts), with a central wavelength of 1060 nm, a sweeping range of 106 nm (quoted at 10 dB), and a 100 kHz line rate has been used. A low coherence interferometer with a balance detection receiver (Thorlabs, Newton, NJ, model PDB460C) was used, and a dual axis XY galvanometer-based scanner (Cambridge Technology, Bedford, Massachusetts, model 6115) [27] was used to scan the IR laser beam over the sample.

Figure 1. Commercial Roughness Standard with a R_z nominal value of 10 μm and a R_a nominal value of 2.4 μm.

2.3 Roughness Parameters

The parameters used to determine the surface roughness are shown in Table 1. The following well-known mathematical formulas have been used for the calculus of R_z and R_a [28]:

$$R_a = \frac{1}{n}\sum_{i=1}^{n}\left|Z_i - Z\right| \tag{1}$$

where n is the number of the points within a sampling length, Z_i is the height value of a point i, and Z is the arithmetic mean of Z_i within a sampling length:

$$R_z = Z_p - Z_v\,, \tag{2}$$

where Z_p is the largest profile peak height and Z is the largest profile valley depth within a sampling length.

Table 1. Roughness parameters.

Parameters	Specific standard	Definition
R_a	ISO 4287/1998	Arithmetic average deviation of the profile
R_z	ISO 4287/1998	Maximum height of the assessed profile

2.4 Applying the OCT method

The Commercial Roughness Standard shown in Fig. 1 has been investigated using the SS-OCT system in order to determine the roughness parameters R_a and R_z. According to ISO 4288 and ISO 3274, the measurements for a value of R_z of 10 μm have to be made along a length of 12.5 mm. For this Commercial Roughness Standard with R_z equal to 10 μm, several consecutive scans have been made, and the corresponding OCT images have been obtained. The area of the scanned surface has been 3.125 x 3.125 mm and 1000 OCT B-scans (cross-section, i.e., height profiles) were performed on this surface, each of the B-scans having 1000 points.

2.5 The procedure used to determine Roughness Parameters from OCT B-scans

In order to determine the value of parameters R_z and R_a, the processing of the B-scans obtained using OCT has been performed using ImageJ, Matlab, and Excel.

For this Commercial Roughness Standard with the nominal value R_z equal to 10 µm several B-scans have been analyzed: 1, 250, 500, 750, and 988 (somehow equally spaced B-scans on the surface of the sample, out of the total of 1000 B-scans). An illustration of one of these analyses is given in Fig. 2 - for the B-scan 250. After scanning, the B-scans have been imported in Matlab; using this, the values of the coordinates *x* and *y* have been determined for each of the 1000 points of the B-scan. The *x* and *y* coordinates obtained using Matlab have then been transferred to Excel – Fig. 3, where the graph (*x*. f(*y*)) has been plotted.

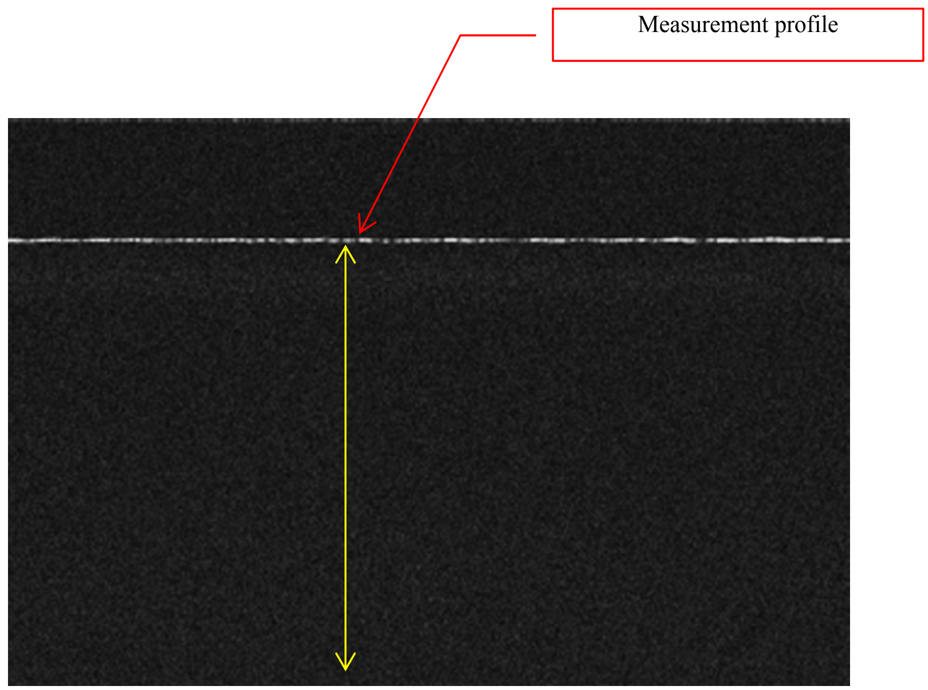

Figure 2. OCT B-scan number 250 – considered in order to determine the values of Rz_5 and Ra_5

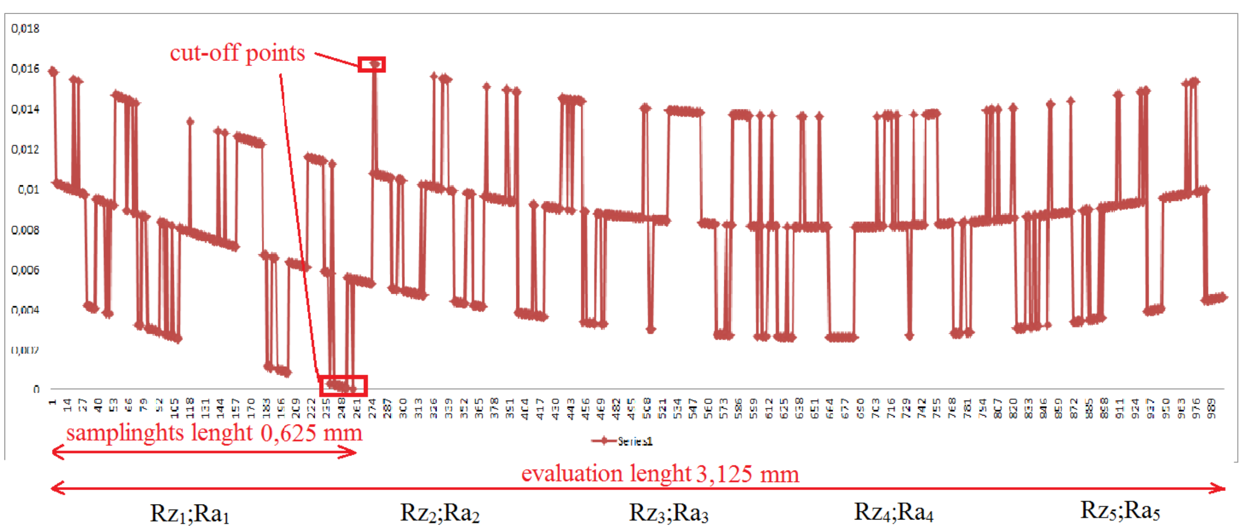

Figure 3. Graph of the measured values of the height profile for the B-scan number 250.

2.6. Determining R_z and R_a for the Commercial Roughness Standard with R_z of 10 µm and R_a of 2.4 µm

The B-scans 1, 250, 500, 750, and 998 have been processed using ImageJ, Matlab and Excel in accordance with the steps described in section 2.5.

Four consecutive scans have been carried out on the commercial Roughness Standard using OCT. After each scan the five B-scans mentioned have been analyzed.

Tables 2 and 3 show the results of these OCT B-scans, processed, i.e. the values of the parameters R_z and R_a.

Table 2. Rz values obtained using OCT.

B-scan / Nr.	1	250	500	750	998	Average
1	12.66	13.32	12.07	12.91	12.06	**12.60**
2	12.33	11.96	12.34	14.94	12.63	**12.84**
3	12.46	12.28	13.54	12.36	13.31	**12.79**
4	13.79	13.11	13.16	11.85	12.83	**12.94**
Average	**12.81**	**12.66**	**12.77**	**13.01**	**12.70**	

The average value of R_z for a B-scan ranges between 12.66 µm and 13.01 µm, while the average value of the five B-scans is 12.79 µm.

Table 3. Ra values obtained using OCT

B-scan / Nr.	1	250	500	750	998	Average
1	2.84	2.95	2.97	2.73	2.66	**2.83**
2	2.86	2.82	2.81	3.20	3.08	**2.95**
3	3.04	2.72	3.16	3.03	3.13	**3.01**
4	3.05	3.04	2.98	2.80	3.18	**3.01**
Average	**2.94**	**2.88**	**2.98**	**2.94**	**3.01**	

The average value of R_a for a B-scan ranges between 2.94 µm and 3.01 µm, and the average value of the five B-scans is 2.95 µm.

3. CONCLUSIONS

The average R_z value measured by the OCT is 12.79 µm, with 27.9% bigger than the R_z value of the Commercial Roughness Standard (10 µm), while the R_a value is 2.95 µm, with 22.91 % bigger than the R_a value of the Commercial Roughness Standard (2.4 µm).

The following remarks can be made: (i) If we consider B-scans 1, 250, 500 performed on the four scans, the average values obtained are an average R_z of 12.74 µm and an average R_a of 2.93 µm; (ii) If we consider B-scans 1, 250, 750 performed on the four scans, the values obtained are an average R_z of 12.82 µm and an average R_a 2.92 µm; (iii) If we consider B-scans 1, 250, 998 performed on the four scans, the values obtained are an average R_z of 12.72 µm and an average R_a 2.94 µm; (iv) If we consider B-scans 250, 500, 750 performed on the four scans, the values obtained are an average R_z of 12.81 µm and an average R_a 2.93 µm; (v) If we consider B-scans 250, 500, 998 performed on the four scans, the values obtained are an average R_z of 12.71 µm and an average R_a of 2.95 µm; (vi) If we consider B-scans 500, 750, 998 performed on the four scans, the values obtained are an average R_z of 12.82 µm and an average R_a of 2.97 µm.

The conclusion is that in the cases when the measurements are carried out on three B-scans, the values of R_z and R_a are close to the values obtained on the five B-scans. However, if only the first scan of 3.125 mm is taken into account, there are significant differences between the R_z and R_a values measured using OCT and those of the Commercial Roughness Standards. In order to obtain the R_z and R_a values closer to the Commercial Roughness Standard values, the scanned length has to be 12.5 mm – which confirms the standards in use, according to ISO 4288/1988.

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