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Optical micro-metrology of structured surfaces micro-machined by jet-ECM

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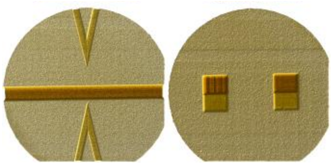
Abstract
A procedure for statistical analysis and uncertainty evaluation is presented with regards to measurements of step height and surface texture. Measurements have been performed with a focus-variation microscope over jet electrochemical micro-machined surfaces. Traceability has been achieved using as reference contact measurements from a calibrated stylus instrument. A statistical analysis has been carried out and the method of least squares has been implemented to correct for systematic behaviours. The combined uncertainty has been evaluated accordingly and the expanded uncertainty has been finally calculated as the confidence interval of 95 %. Results show that agreement within single digit micrometre (dimensional measurements) and tenths of micrometre (surface parameters measurements) can be achieved with the proposed methodology.

Keywords: Step height, roughness, micro-machining, uncertainty, ISO GUM

1. Introduction

Measurements of step height and surface texture (*Sa* and *Sq* parameters) have been performed with a focus-variation microscope over two micro cavities (see figure 1), made of steel, which have been produced by additive manufacturing and successively structured by Jet Electro-Chemical Machining (Jet-ECM) [1]. Traceability has been achieved using as reference contact measurements of the same specimens from a calibrated stylus instrument [2]. Taking advantage of these measurements a procedure for statistical analysis and uncertainty evaluation has been determined, which is consistent with [3].



(a) (b)

Figure 1. Overview of the surface specimens. (a) Straight-lined grooves. (b) Sectioned surfaces at different heights.

In a past work [4], Mattsson et al. already showed that agreement among surface roughness measuring instruments is limited mostly by: (a) Inaccuracies in repositioning the different instruments in the same measurement area. (b) The data set evaluation or post-processing.

The current investigation aims to establish a general method for analysing and correcting possible divergences among instruments which are due to systematic differences. Eventually, the measurement uncertainty is evaluated as a consequence of the least squares method used to correct systematic differences among the measurements and to estimate discrepancies between the optical instrument measurements and the contact ones (reference measurements).

2. Pre-processing of measurements raw data

The raw data have been pre-processed using the same image processing tool to reduce software influences [5].

Disturbances inspection is of paramount importance when comparing several measurements. For example, spikes can be sometimes so extended that the related surface texture is represented completely distorted. Under such circumstances, those measurements have been eliminated even though an exclusion principle has been applied in the successive statistical analysis. Such principles, in fact, act on the value of a measure but they are not able to detect the surface texture distortion.

Other kinds of disturbances have been separated from the main data set and discarded using inspection windowing. In addition, in case of voids, i.e. incomplete image acquisitions, the null pixels were reconstructed by interpolation using surface prediction values from available neighbouring pixels. Nevertheless, these practices are to be avoided as far as possible because they can result in an underestimation of the measured values and, consequently, contribute to the so called systematic effects in the experimental distribution of the data (see § 3).

At the short length scales (i.e. sub-mm), subjects of the present investigation, the cut-off wavelengths normally used for filtering waviness become comparable with the quantities to be measured. As a consequence, filters can jeopardize the final results. For this reason, no filter has been applied and waviness has been instead put in connection with its RMS value extracted by the Fourier transform of an average profile and, subsequently, compared with the overall surface texture measured by *Sq* parameter. Further details can be found in [6].

3. Statistical analysis and uncertainty evaluation

The measurements have been preliminarily examined for discordant observations (or accidents of measure or, as generically called, outliers) which can be misleading later in the statistical analysis. Values evidently outside the experimental distribution can be eliminated using an exclusion principle. The Chauvenet's criterion has been applied in the investigation.

Deviances from the normal distribution can be successively evidenced running several normality tests and then corrected. Such deviances are called systematic effects and can be related to the factors involved in the measurements. They are, in fact, consequences of the measurement operations due to the non-ideal behaviour and use of the measuring instruments in the actual environmental conditions. The time sequence of the measurement events (occurrences) is strictly related to the generation of such effects. Organising the data in the exact time sequence can allow describing and correcting them by regression models. Descriptions and details of the techniques used can be found, e.g., in [7].

The method of least squares has been implemented to correct for systematic discrepancies between optical and contact measurements, i.e., the references. The model equation which has been found consistent with the experimental data is a straight line for step height values and a parabola for the surface texture ones. In association with each model equation, the combined uncertainty u has been evaluated considering the contribution of the accuracy of the stylus profilometer [2], the standard deviation of the coefficient of the model equation in the best fit regression, the reproducibility (standard deviation of the residuals) and the precision of the image processing software [5]. The standard uncertainty has been obtained by applying the law of propagation of uncertainty and the expanded uncertainty has been calculated as the confidence interval of 95 % [3].

4. Results

Two measurands, step height and surface texture, have been considered over the specimens with average values h = 162.3 µ, Sa = 4.12 µm and Sq = 5.19 µm. Twenty-five replications have been acquired for step height measurements and thirty replications for the surface texture ones. Two examples are shown in figure 2.

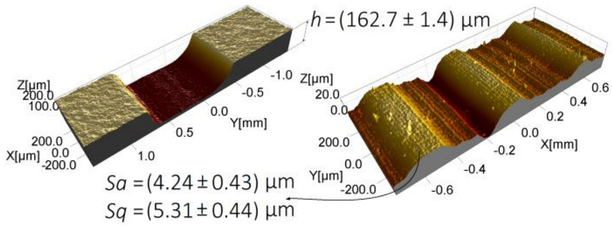


Figure 2. Illustration in 3-D of two examples of acquired surfaces.

The correction for systematic factors has been performed with respect to the time sequence of the replications and then corrected for the accuracy with respect to the contact measurements. The expanded uncertainty evaluated is 1.4 µm for step height and respectively 0.44 µm and 0.46 µm for Sa and Sq parameters.

As an example, the experimental distribution for Sq parameter is reported in figure 3 together with the least squares regression model used for the correction. The same distribution is shown in figure 4 after correcting for the systematic behaviour, with the expanded uncertainty interval evaluated per each replication. The corresponding reference value and the related expanded uncertainty interval are also shown in figure 4.

5. Conclusions

A statistical analysis has been outlined and it has been also shown how the correction of systematic behaviours in the experimental data distribution can be effective for an accurate evaluation of the measuring uncertainty.

Considering the figure 2, the quantities measured spread over several length scales but the related uncertainties are included in only one order of magnitude. Hence, the main impact on the final uncertainty seems to be due to the instrument and the reference used. Even though the calibration of tactile instruments is well stated by the ISO standards, establishing the traceability of optical instruments using contact ones inevitably leads to an overestimated uncertainty which can be additionally dependent on their results. Such considerations suggest that a stand-alone calibration of optical instruments appears as a crucial future development of the proposed methodology.

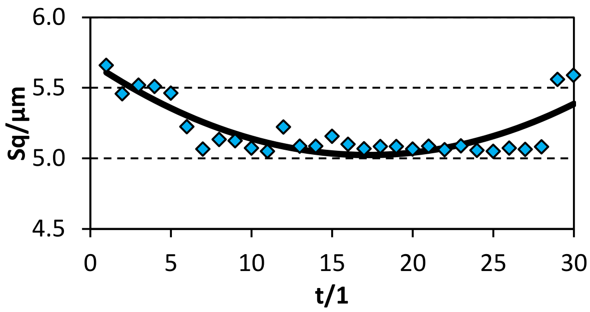


Figure 3. Graph of the experimental distribution of the Sq parameter (lozenges) and least squares regression model (line).

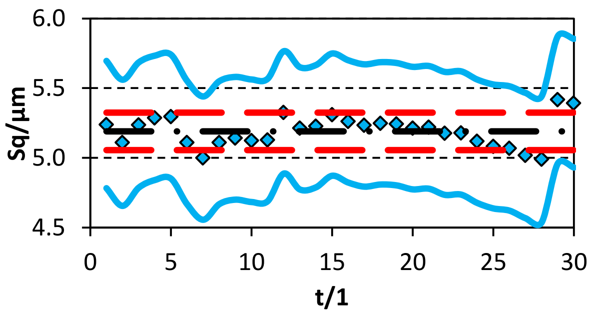


Figure 4. Graph of the experimental distribution of the Sq parameter after the correction (lozenges) and reference value (dotted-dashed straight line in the middle). The limits related to the expanded uncertainty are also indicated for the reference (dashed red lines) and for the corrected experimental distribution (external blue lines).

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