Theoretical aspects of analysis of selected sources of errors in profile measurements of surface asperities

Teoretyczne aspekty analizy wybranych źródeł błędów w profilowych pomiarach nierówności powierzchni

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In the paper theoretical background regarding selected errors in profile methods of surface asperities measurements were presented. The influence of a tip was discussed for stylus (including geometry, pressure and flight) and optical probe basing on confocal chromatic effect. Problems connected with translation tables was described. Basic assumptions regarding accuracy parameters in topographical analysis was shown.

KEYWORDS: profile measurement, surface topography, errors

The work of instruments for surface topography analysis is based on one of two basic methods, i.e. scanning or surface method. Scanning methods can in turn be divided into profile and image [12]. Profile scanning methods evaluate the inequality on the basis of the set of profiles, and image scanning - based on the sequence of images. Surface methods assess inequalities based on averaging and adopting a model describing measured inequalities. Evaluation of unevenness on the basis of a set of profiles uses horizontal scans and is reduced to profilometry involving a series of profiles, most often in parallel planes. Scanning takes place in the *X* axis, followed by a step shift in the *Y* direction. Among the profile methods are: contact profilometry, point autofocus, use of profilometric confocal probes, scanning tunneling microscopy, and atomic force microscopy. Profiling methods are susceptible to abnormalities due to their specificity [5, 7], which cannot be neglected in the analysis of measurement results.

Impact of measuring tip

Surface mapping by means of profile methods has a significant effect on the fidelity of the results obtained, whether it is a contact tip made of synthetic diamond, or an optical tip, based on interferometry or confocal. The tip geometry of the contact profilometer is characterized by two main parameters: vertex and apex. This is a cone shaped diamond needle with a rounded tip, 90° or 60°.

The radius of the rounding of the vertex is more significant, with both the curvature of the vertex and its local changes. Under laboratory conditions, a much lower rounding radius of the tip can be achieved, but the smaller the diameter, the higher the tip cost and the lower the shear life.

The tip shape changes the actual value of the inequality - as a result, the relationship between the measuring tip and the surface geometry measured at each point of the profile is very complex. The basic approximate model of the tip contact with the surface is shown in fig. 1 [11].

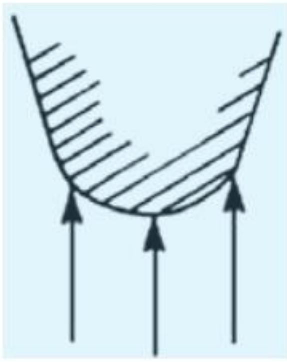

Fig. 1. Approximate rounded contact tip of the profilometer probe with the surface

This model is considered as a three-point, which does not mean that three points of contact must occur - most often we deal with one or two point contact. As is evident from the tests, for a typical ground surface, a reduction of *Ra* at a rounding radius of 2 µm (relative to the ideal tip) is approximately 2%. This difference increases with greater radius value and is visible especially for fine surfaces. Examples of the effect of the rounding radius of the measuring tip on the shape of the imaged profile are shown in fig. 2 and fig. 3.

The actual impact of the apex angle on the fidelity of the profile is relatively simple to establish. In order for this angle to affect the roughness mapping (assuming the tip is infinitely sharp), the angle of the profile edge would have to be larger than the tip of the tip (> 45°). This would mean the presence of undetectable recesses within the sampling interval, of a width of the order of 0.05 µm.

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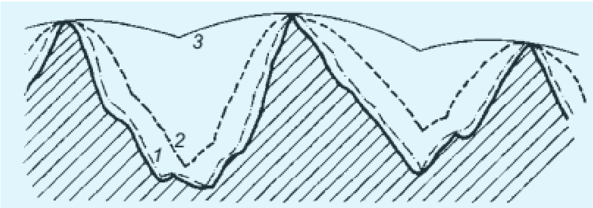

Fig. 2. Changes in the mapped profile when changing the radius of rounding of the measuring tip ($r_1 < r_2 < r_3$) [8]

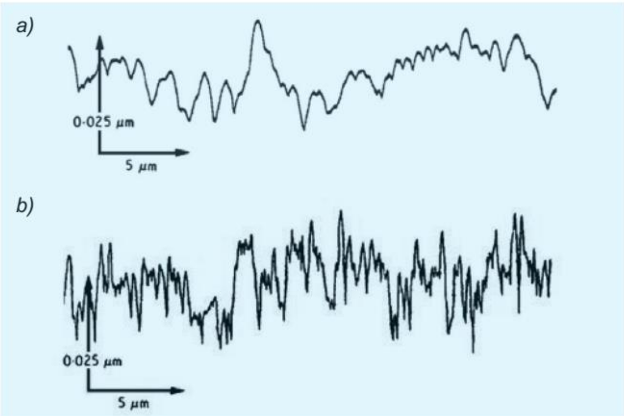

Fig. 3. Profile of the cut surface obtained by the traditional profilometer (a) and the same profile but obtained with a laboratory measuring tip with a rounding radius of tip approximately 0.3 μm (b) [2]

In practice, for a typical ground surface, these values are 20÷50 times higher. Hence, it is concluded that the geometry of the measuring tip only the radius of the rounding affects the smoothing of the profile. It is somewhat misleading to present a surface in the form of a profilogram where the vertical magnification is much larger than the horizontal. The actual appearance of the profile and its image distorted by uneven magnifications are shown in fig. 4.

Nevertheless, the contact tip is shaped by its averaging, mechanically filtering the profile. It consists in the non-metering of narrow micro-gaps or inequalities with a pitch less than the radius of the measuring needle.

Very important factor in the surface roughness measurement is also the pressure of the measuring tip. The case (the most unfavorable) of the contact of the rounded measuring tip with the tip of roughness is shown in fig. 5.

According to Hertz's theory, the radius of the contact area of two surfaces is [10]:

$$a = \sqrt[3]{\frac{3\pi}{4}\left(\frac{1-\nu_1^2}{\pi E_1} + \frac{1-\nu_2^2}{\pi E_2}\right)\frac{F r_1 r_2}{r_1 + r_2}}$$

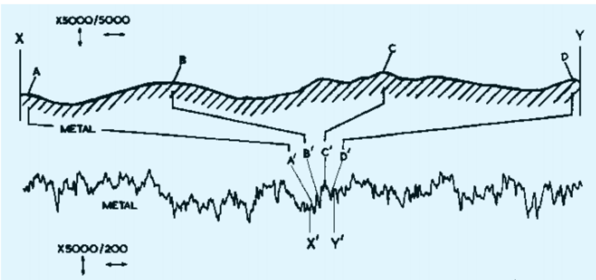

Fig. 4. The actual appearance of the profile and its image distorted by uneven magnification [9]

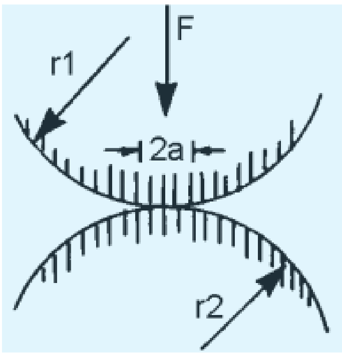

Fig. 5. Contact of rounded tip with roughness tip

where: v_1, v_2 - Poisson's numbers; E_1, E_2 - modules of elasticity of materials in contact.

The total susceptibility of the measured surface under the pressure of the measuring tip is:

$$\delta = \frac{a^2(r_1 + r_2)}{r_1 r_2}$$

In the case of typical pressure applied to the measuring tips and the typical minimum values of the contact area, the surface pressure is less than the yield strength of most materials used in machine construction, which is a prerequisite for the measuring tip to damage the surface being measured. However, the yield point of the material core differs from the yield point of the top layer with which the measuring tip is contacted. In many situations where it seems that the measuring tip should seriously damage the surface, nothing happens - only the tip itself wears off faster. Surface damage through the measuring tip is more common for relatively soft materials, such as copper or aluminum, and less often for steel. It is the larger, the sharper the vertex, which in a way contradicts the two requirements for the tip. Similarly, susceptibility does not in itself distort the surface image if it is approximately constant and relatively small as compared to the geometric structure of the surface to be measured.

Probable source of error in profilometric surface analysis is also the kinematics of the measuring tip [1]. It moves on the test surface at a certain speed, which - if it is large enough - can cause the tip to tear away from the surface, i.e. the so-called *flight* (fig. 6). The moment in which this happens depends not only on the kinematic system but also on the geometry of the surface. McCool [4] developed a simulation model for tip behavior, taking into account the rounding radius of its tip and flight. Errors arising from the detachment of the tip from the surface are important in the case of topographic multi-profile analysis by contact devices, a tendency is often to increase the scanning speed to reduce the time consuming process.

An interesting study on the estimation of the distortion caused by flight of the tip is presented in [6]. The degree of deterioration of individual parameters was analyzed here. The result of the work was a simulated model, which allows to assess the distortion of the flight profile.

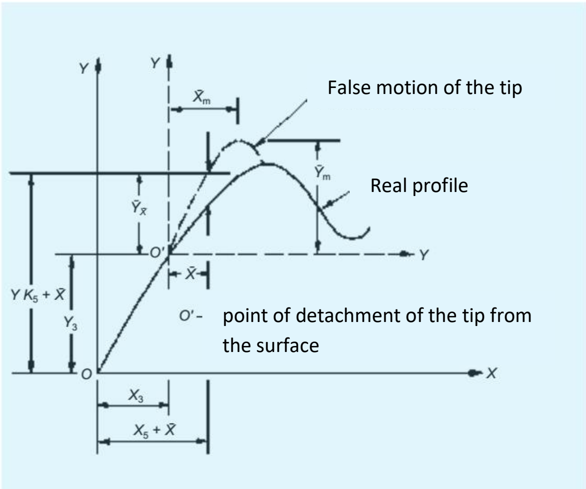

Fig. 6. Path of the measuring tip after breaking away from the surface

In recent years, white light confocal heads have become increasingly popular, working in the profilometric system. At present, it is not possible to design entire confocal profilometers, but only heads that can be installed in special constructions that allow relative motion in the *X* and *Y* axes or even in commercial profilometers - as contact head substitutes. White light confocal heads use a confocal effect, so that the photo-detector observes at one point at any one time. This point is illuminated by a small, focused spot, while the entire system remains insensitive to other light rays. Apart from the movement of the profilometer table, this measurement method does not require any moving parts, and the range is determined by the spectrometer, the length of the photodiode ruler, and the instrument parameters. Chromatic technology combined with chromatic confocal sensing (CCS) is based on splitting light onto individual colors in the optical axis. Chromatic aberration is therefore used (fig. 7).

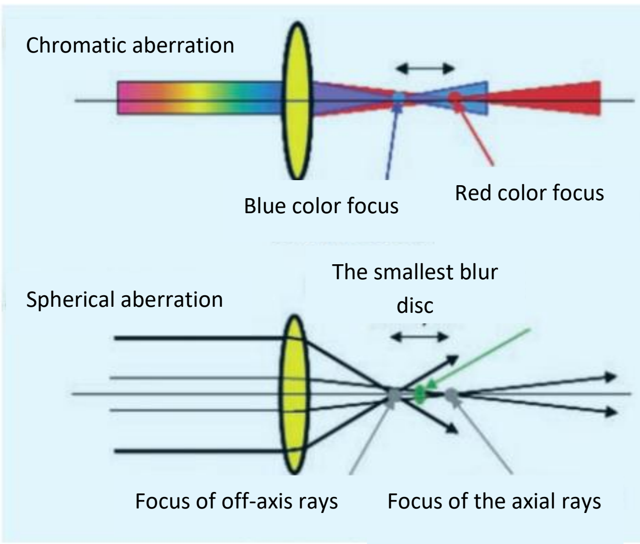

Fig. 7. Chromatic aberration

An example of a profilometric head working on the basis of the chromatic confocal effect is shown in fig. 8. The white light beam incident on the surface is split into a colored spectrum. Only one specific frequency, which is dependent on surface unevenness, focuses on the surface. For this wavelength, a sharp image is obtained, which then reaches a photo-detector - a precise spectrophotometer that reads the wavelength or frequency, giving the height of the measured inequality.

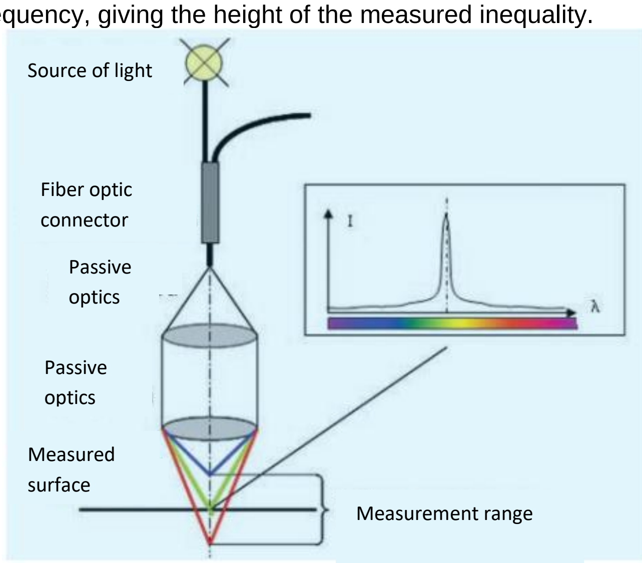

Fig. 8. Schematic diagram of white light confocal head [13]

Errors in topography measurements

In surface topography measurements, similar problems exist as in 2D measurements. In addition, it is necessary to:

- maintain an accurate height reference base between transitions,
- maintain an accurate sampling intervals on each track relative to other tracks,
- adequate compensate the angular deviations of the measurement head movements - vertical, transverse and longitudinal (from the line of travel),
- adopt an appropriate numerical methods,
- adopt a suitable sampling grid to measure a given area within a reasonable time and at an acceptable cost,
- use an appropriate image processing algorithms and extracting features of functional interest,
- maintain an adequate resolution to detect defects and other non-standard features of the surface,
- maintain a right temperature conditions.

Maintenance of the necessary reference base can theoretically take place in one of three ways [3], ie by using a slider, a reference element not associated with the surface being analyzed, or an external reference element from the instrument. Measurements using a slide head are analogous to the profile analysis, but in a stereometric base the surface becomes complex and difficult to determine, which disqualifies this option. The use of a reference element not associated with the surface being analyzed is based on the additional passage of the tip by a surface of nominal shape and a considerably smaller roughness, e.g. by an interferential plate. This lengthens the measurement procedure, but the base obtained in this way is the most accurate. These were, for example, Williamson's first major surface mapping attempts [14]. In this case, the reference base between the individual passes was obtained by means of a non-surface element, by referencing each path to the polished plane at the beginning and end of the plane (fig. 9).

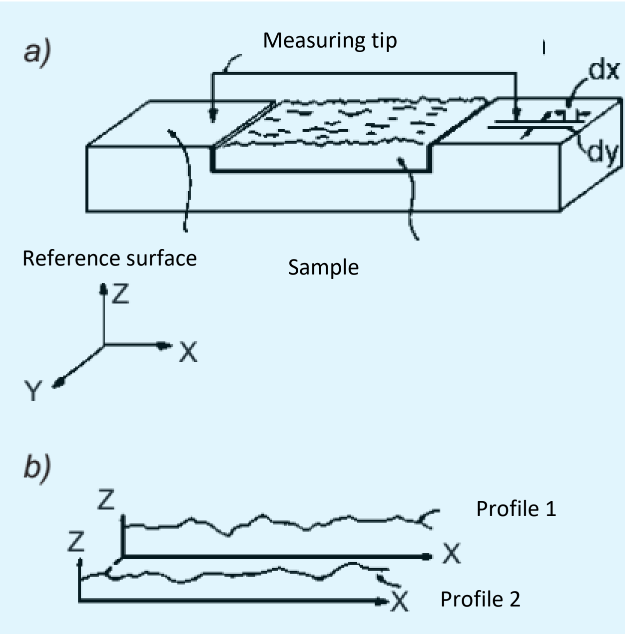

Fig. 9. Diagram of topography measurement with element not connected to the surface: a) reference element not related to the surface being analyzed, b) cross-correlation

The innovation introduced by Williamson was also the cross correlation of each path with the previous one to obtain spatial data consistency. If, therefore, on the z_2 path, a vertex shifted by the value of *s* relative to the corresponding vertex of the path z_1 is obtained, the z_2 profile is shifted by this value to provide spatial coherence. Due to these two simple measures, reliable surface mapping was achieved. When the object was wedge-shaped, it was visible in the image and the incline was corrected with the corresponding simple regression. Experiments of this type, however, had disadvantages. For example, if the surface showed the direction of the structure, the use of the correlation method sometimes did not make sense because the displacement *s* could come from both inaccuracy and machining.

The external reference element of the instrument is used in topographic systems in two ways:

- In systems with a measuring tip moving only in the *Z* axis and with a table moving in the *X* and *Y* axes, the reference element is a very smooth, flat and accurate guide, after which the table moves in the *X* and *Y* directions;
- In systems, where the measuring tip moves in the *Z* and *X* axes, and the *Y* axis table, one reference element is the table guides (*Y* axis) and the other - the drive unit, i.e. the guide system for the measuring head (*X* axis).

In the devices using the external reference element, there are two types of construction solutions for the table. The first is a table driven by a linear motor with a non-contact position transmitter and a feedback loop in the control circuit to minimize positioning errors. An additional element is the system that reduces angular errors and rectilinearity errors. The second option is a stepper table and a lead screw. This way of removing measurement points from the surface is called *static sampling*. In this case, additional accuracy conditions are imposed, such as that the table must have a two-way tilt adjustment. As a rule of precision, it can be further assumed that the variance of the sampling interval should not exceed 0.1 of the value of the interval, i.e., for a 1 μm interval, it is 0.1 μm. Moreover, the total error of the sum of the sampling interval should not exceed half the length of the interval.

Further development of measurement techniques led to the contractual adoption of recommendations and criteria for obtaining a topographic image of the surface. First, the mechanical system and sampling procedure must be such that the scattering of the sampling step (or sampling interval) for each path is only a fraction of its value (not exceeding 1/4 of its value). In addition, individual paths must be correlated (fig. 10).

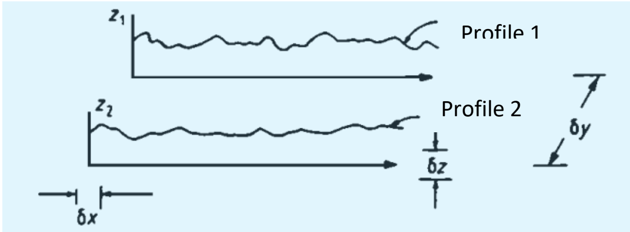

Fig. 10. Deviations in the X, Y and Z directions, distorting the mechanical integrity between successive paths

Mechanical reference base between z_1 and z_2 must give very little uncertainty as compared to the actual height of the geometric surface structure. The typical accepted value is 0.1 *Rq*. This does not mean that the mechanical reference element can not be continuously higher (or lower) at each subsequent path in the *Y* direction (or *X*), since such effects can always be removed by selecting the appropriate median plane. Designing it cannot, however, be fraught with too much uncertainty. From the standpoint of this criterion, it is obvious that the smoother the surface being measured, the harder it is to measure its inequality. Due to the increasing demand for surface roughness and the accuracy of such measurements, mechanical correlation becomes increasingly difficult. Currently, the link between paths is accomplished by applying an abstract reference element, e.g. by fine adjustment of the tip position.

Conclusions

Roughness measurements are based on a variety of instruments developed over decades by professionals from a number of industries. Machine tools are the most popular instruments in the machine construction are contact profilometry. Over the years, they have been modified, resulting in extremely versatile construction solutions of sub-nanometric resolution and millimeter measuring range. In conjunction with an additional element providing the third axis, these instruments allow the surface topography to be measured.

The topographic analysis of surfaces presented here shows how important and common this problem is. It is worth emphasizing that measurements of inequality

The surface is considered to be the most complex, and the actual roughness of the surface is so complex that its recognition and description is currently impossible. Localizing potential sources of errors and, where possible, eliminating them is therefore a must when analyzing surfaces in two and three dimensions.

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