Experimental research of selected sources of errors in profile measurements of surface asperities

Badania doświadczalne wybranych źródeł błędów w profilowych pomiarach nierówności powierzchni

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In the paper experimental results of research regarding selected errors in profile measurements of surface asperities were presented. Influence of synchronization of measurement tracks, errors coming from rotation and possibilities of measurement devices as well as interference from conditions in both: high and low frequencies were discussed. It was shown that repeatability of the first point and even slow temperature changes around a measurement device have a great influence on fidelity of results.

KEYWORDS: profile measurement, surface topography

For proper selection of technological process, it is necessary to understand the structural requirements for the surface to ensure getting specific properties and performances. An integral part of this procedure is the metrological analysis of the surface during and after the process. Therefore, the selection of control method and a measuring device for the analysis of the resulting surface is important. Tool selection is generally a function of purpose, to which it is to serve. On the one hand, it is important to restore the credibility of the surface with functional parameters (resolution, measurement range, etc.), and on the other hand, the cost of the tool and its usefulness counts.

Currently, the most widely used instruments for measuring the geometric surface imbalance [14] are profilometers (especially contactors). Traditionally, they measure the surface of the measurement tip through a single profile, which is insufficient if the purpose is to properly reflect the nature of the inequalities present. On the basis of such profilometers, contactless object gauges are created - by adding optical heads - where the contact of the measuring tip with the surface is unacceptable. Measurements using contactless methods are fraught with errors, both internal and external, such as vibration or temperature changes. Some interfering factors can be eliminated by hardware or software. It is important for the person performing the measurement to be aware of the source of the disturbance and to what extent they can distort the measurement signal - only then the result is logically justified [4, 6].

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Track sync errors

From the point of view of fidelity to surface topography, it is important to keep the sampling grid as good as possible. This in turn is possible provided the least value of the so-called *flows*, when specifying sampling intervals (value instability). The reason for the flow is, for example, the lack of thermal equilibrium which may occur as a result of the operation of the motors of the measuring device. To stabilize the operating conditions profilometer should be allocated to at least a few hours from the start and that the moving elements corresponding to a displacement of the head or a table for each axis. The speed at which the data is collected must be much higher than the flow value, but it must not exceed the limit, at which the measuring tip will peel off the surface. In addition to the positioning accuracy of the first point of each track important is the accuracy of the sampling. Errors in the synchronization path (fig. 1) can often lead to serious inaccuracies.

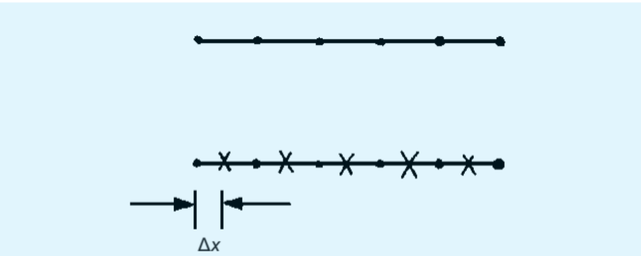

Fig. 1. Errors in synchronizing consecutive tracks

Traditional sampling plans are based on a rectangular grid. If, for example, the second track is offset with respect to the first by Δx and this value is in the order of half the sampling interval, the entire plan is subject to major changes. This will cause changes in the expected locations of vertices occurrence and distortion of the properties of the surface to be measured. In practice, the maximum permissible offset can not exceed 1/4 of the sampling interval. Evaluation of how rigorous this criterion is, depends on the sampling step and its value as compared to the surface correlation t_L (correlation length is the delay value, above which the autocorrelation function falls to a small value - typically 50%, 10% or 1/e × 100 %). The smaller the sampling step, the tougher the condition, and the more serious the consequences of any error. Since the typical sampling step values are 1 ÷ 2.5 μm, the permissible error of the first point - affecting the whole sampling - cannot exceed 0.25÷0.63 μm, although in practice, the safety assumption is 0.2÷0.5 μm. These values - especially in industrial equipment - are very difficult to obtain.

The starting point (but not necessarily all sequential recorded values of the *x* coordinates) is influenced by several factors, including:

- quality of mechanical components - reproducibility of measurement and movement of recurrence after changing the direction of motion, size and repeatability as well as hysteresis clearance elimination;
- quality of electronic components - resolution and repeatability of the element defining the data reference point (ruler, rotary decoder);
- software - method of controlling the 3D measurement cycle, i.e. measurement and return movement, including elimination of the effect of reversal and reversal hysteresis and loops occurring in mechanical systems (clearance procedure and release at reference point).

In structures related to displacement in the *X* axis, there are two solutions: based on an incremental line and not containing this element. If the device has an incremental ruler, the starting point will be recorded with much better repeatability, and the differences in the value of *x*-coordinate of the start point will be relatively small. This situation is illustrated in fig. 2 showing the surface map of the sinusoidal pattern of type C.

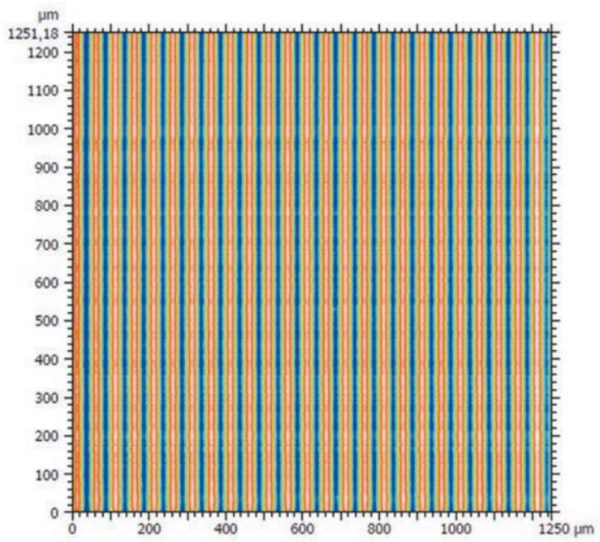

Fig. 2. A sinusoidal pattern contour map collected using a ruler in an X-axis drive unit.

Fig. 3 shows the differences between successive overlapping profiles (expansion of the map into a series of profiles). They are so small that visible is basically one profile, the deviations are not visible.

Fig. 4 shows an enlargement of fig. 3 with two extreme profiles. The cutoff is approximately 0.05 μm and this value is most acceptable.

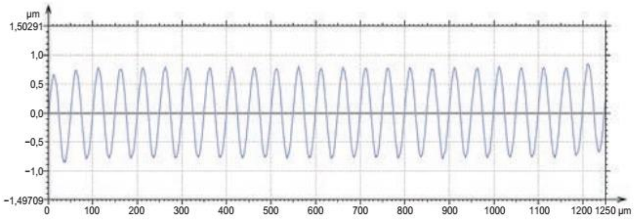

Fig. 3. Profiles collected from the map of fig. 2

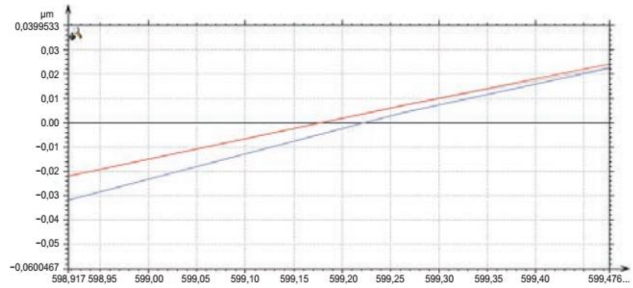

Fig. 4. Enlarged extreme profiles from fig. 3

If the profilometer does not have an incremental ruler, the starting point is either from the limit switch or from the motor rotation. At that point, the repeatability of the starting point is much worse and may reach up to several micrometers in specific situations. Such a situation is shown in figs. 5-7. The first of them - just as before - presents a contour map of the standard surface of type C.

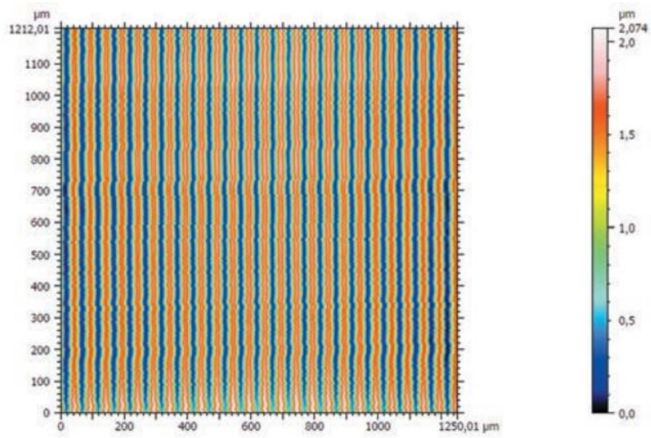

Fig. 5. Standard C-type contour map collected without a ruler in the X-axis drive unit

In this view, the movement between the profiles is noticeable. This can be seen as the width of the graph in fig. 6, which is the expansion of the surface into a series of profiles.

Enlarging a portion of the chart with extreme profiles indicates a difference in abscissa of more than 5 μm. Such value causes very clear distortion and loss of correlation between successive paths.

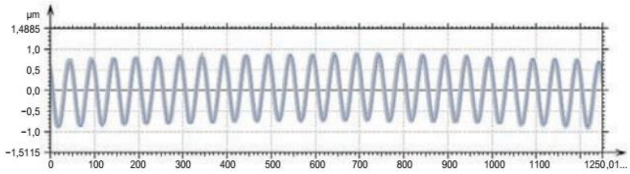

Fig. 6. Profiles collected from the map of fig. 5

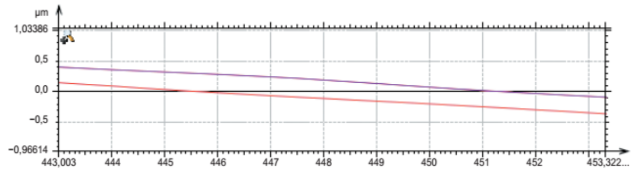

Fig. 7. Enlarged extreme profiles of fig. 6

These situations were related to the solution of contactors with a drive unit mounted on a column and a *Y*-axis displacement table. In optical profilometers, solutions are often more frequent with a table that implements both displacements, i.e. in the *X* and *Y* axes. In this case, the starting points may also exhibit some displacement although their values are usually small. This can be seen in figs. 8-11. The first map shows again sinusoidal pattern, but this time collected with confocal head.

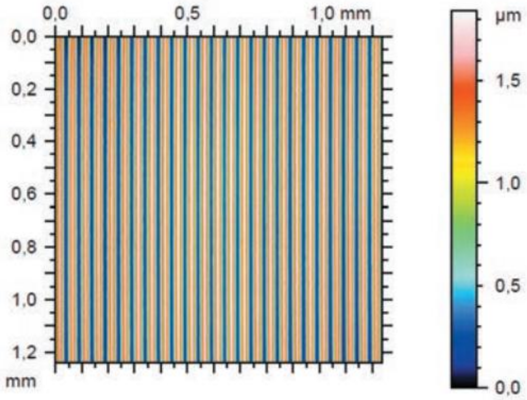

Fig. 8. Contour map of the C type collected by the chromatic confocal head

The development of this map in a series of profiles is shown in fig. 9. In-depth analysis of the course reveals the subtle differences between successive profiles.

Zoom in on part of the image is given in fig. 10. Here, the differences of the form of band are already far clearer.

Fig. 11 shows the extreme profiles. The difference between their abscissa values does not exceed 0.1 µm.

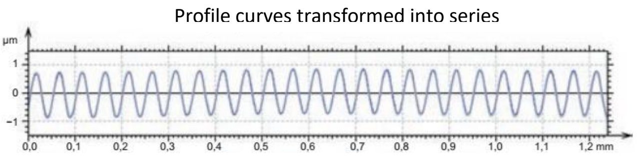

Fig. 9. Profiles collected from the map of fig. 8

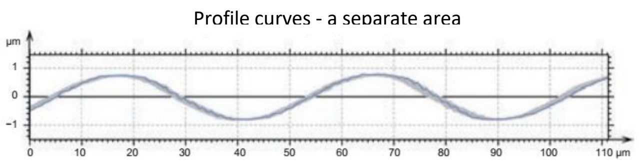

Fig. 10. Magnification of the series of profiles from fig. 9

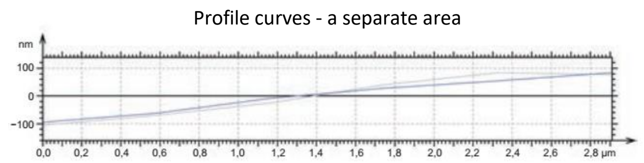

Fig. 11. Enlarged extreme profiles of fig. 10

The method of triggering the start signal of each track should be at least as accurate as the repeatability of the starting point. Otherwise, further tracks will be offset relative to one another and relative to the intended position. This requires diligence in designing a triggering system that, in extreme cases, goes beyond the limits of standard interferometers. In turn the hysteresis of the mechanical part must be limited to the values of the errors assumed for the synchronization of consecutive tracks, or the collection of subsequent profiles should be carried out in the same direction (positive), which, however, prolongs the measurement time. For bidirectional measurements, the effective start is shifted due to the same direction changes or the presence of frictional forces. Loads or gaps are eliminated by means of springs, and precision drive devices now allow hysteresis and clearance reduction to approximately 0.3 µm. Repeatability tracks after resetting should not be worse than 0.2 µm. It is often assumed that the repeat profile measuring feeler moves on the same line. But the reality is different, as shown in fig. 12. The area was covered with a thin layer of soft material abraded during the measurements. The white box shows the actual passage of the contact tip several times in the same place (in theory).

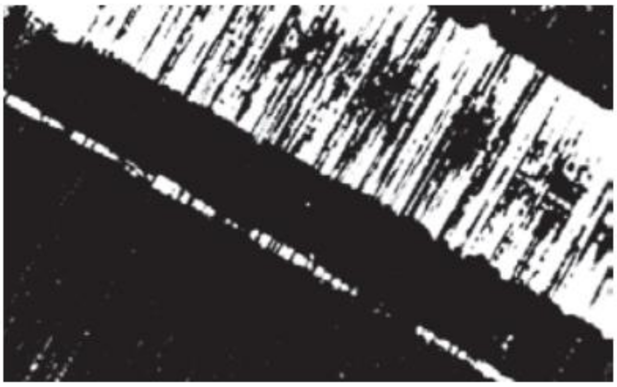
Fig. 12. Repeatability error in Y direction [2]

Spiral errors and abilities of measuring instruments

Another important factor is to ensure linear travel only in one axis, so guides must be made without local tilt errors. Typical acceptable values should be of the micro-radians order. At the same time another path should be as parallel to each other (fig. 13). Furthermore, the entire measuring system should be as close to linear as possible to avoid Abbe's error.

In order to ensure the correct measurement plane, the two axes should be as perpendicular to each other so that for large values of *x* and *y*, the grid does not "fall out of phase". For example: for a square sample with a side of 10 mm the perpendicular should not be worse than 0.25 µm (these errors in practice are rather small values). When moving the table in the Y direction, and even more in the *X* and *Y* directions, the weight of the moving parts can not be ignored. Moreover, as a shift in some propulsion systems, a leverage effect can occur, increasing with increasing distance from the origin of the coordinate system. The drive of the measuring head should be just enough to offset it as it is defined by the jargon of the builders. Too strong drive system may cause side effects in the form of elastic deformation.

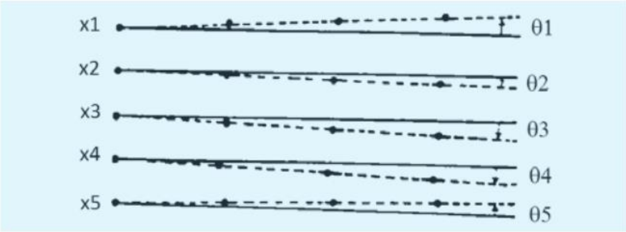

Fig. 13. Parallel errors of successive data collection tracks

Achievement of the stated assumptions was presented in the literature already at the end of the 20th century. In [3], a three-part system for scanning and gathering ordinates, consisting of: an independent automatic travel table, a control-calculating unit, and a profilometer as a mechanical part, has been described. A similar system is presented in [11] and [7], where an inversion is also used, ie the inversion of the image with respect to the median plane with respect to the axonometric surface image. A design based on an independent reference element was proposed in [10]. By analyzing the inaccuracy of the system with respect to topographic surface analysis, the authors [8] found that it is the result of two components: the inaccuracy of determining the x and y coordinates and the inaccuracy of measuring the elevation of the ordinate z. The total mean squared error of the data collection point was expressed by the formula:

$$SH^2 = Sx^2 + Sy^2 + S1x^2 + S2x^2 + S3x^2 + S3y^2 + Su^2$$

Each system variable had the following values:
- linear error of determining the point in the *X* axis: Sx = 0.28 µm,
- linear error of determining the point in the *Y* axis: Sy = 0.28 µm,
- twist error with respect to *Y* axis affecting *X* position error: $S1x$ = 0.25 µm,
- twist error with respect to *X* axis affecting position error in *Y* axis: $S2y$ = 0.25 µm,
- twist error with respect to the *Z* axis affecting the position error in the *X* axis: $S3x$ = 0.50 µm,
- twist error with respect to the Z axis affecting Y axis position error: $S3y$ = 0.50 µm,
- error of measuring tip deflection as a result of inequalities: Su = 0.3 µm.

The total mean square error of *SH* was approximately 0.93 µm. Graphic diagrams of particular components of the error are shown in fig. 14 and fig. 15.

The authors [12] have identified a track synchronization error as an important component of the disturbance. In their instrument, it reached a value of about 5 µm, thus the data from each track was collected three times and an average version was selected for analysis. This shows how difficult it turns out to minimize confusion sometimes associated with the first sample point.

Similar problems were signaled in [9] - the authors, taking into account the electronic disturbances, the influence of the environment, as well as the errors of the table and the measuring tip, reached the total uncertainty of the height indications (vertical axis coordinates) over the entire surface of the sample (164 × 164 points at sampling interval 2.5 µm) at 1.25 µm. The sampling area included a rectangular grid of 164 × 164 points. The measuring tip was stationary, while the table moved in the *X* and *Y* axes. After that construction, commercial 3D profilometers were developed up to the present day. The scheme of action does not deviate substantially from the presented research structures, although in great detail has changed a lot. Over the years, the accuracy of the mechanical parts has been improved by the use of computer-aided precision systems, which consisted of accurately mapping the error map of the entire system and its insertion into memory and use in the course of measurement as the correction of indications. Due to the development of computer science, the electronic part and data processing system have naturally changed [15].

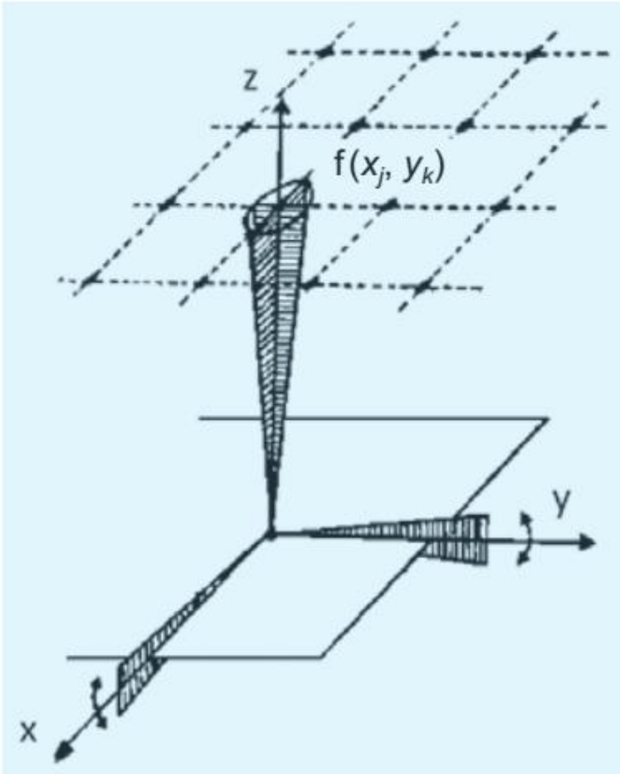

Fig. 14. Twist errors with respect to X and Y axes

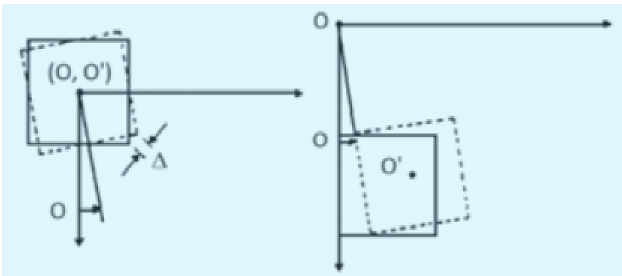

Fig. 15. Twist errors with respect to Z axis

Interference from the environment

The last of the discussed factors affecting the surface imaging errors is the temperature. Overall, the analysis of the topographic surface of a very significant impact on the results of the measurements are ambient noise. In case of profilometric measurements it is often related to how the environment affects the instrument, or rather with - following the philosophy of D.J. Whitehouse - how well the device is isolated from the environment [13]. Interference may be changes in the nature of low or high frequency. High frequency changes are the result of mechanical vibration of the drive system or simply periodic changes affecting the drive-to-drive loop. The effects of vibration coming from sources such as motors, drives and transmissions, are a very important part of a disturbing, filtering some hardware and - increasingly - additionally by software. However, changes of the low frequency are generally temperature variations.

In single-profile measurements it is assumed that the entire instrument should be in an air-conditioned room and that slow temperature changes are not detrimental to the measurement results - provided that the change time is long compared to the measurement time. This last condition for 3D measurements with a large number of single passes of the measuring tip is very difficult to meet. From the metrological point of view, both the absolute change of dimensions and the effects of the temperature gradient, which can lead to errors due to geometric changes and shape changes, are both important. Air conditioning - switched on by the regulator after exceeding a certain upper limit value and disconnected after a drop in temperature to the lower limit - results in distortion of the near-period surface. This is shown in fig. 16 illustrating the profiles collected in the same place (without moving the axis *Y*) on the plate interference.

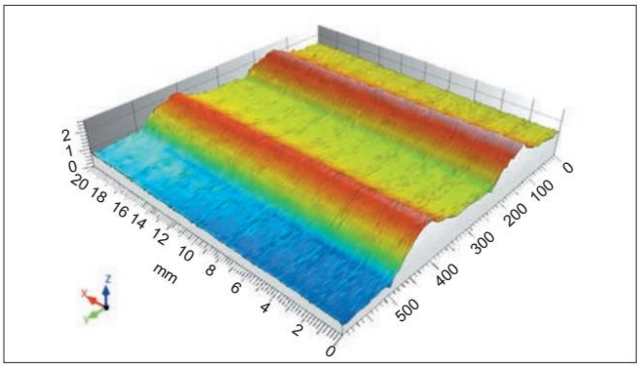

Fig. 16. Changes in surface mapping under air conditioning

Fig. 16 shows that after the initial stabilization profilometer he began to warm up, which resulted in extension of mechanical components and increase the value of the signal (the first ridge marked in red). Then the air conditioner came on and the signal from the profilometer was lowered - the mechanics shortened (the signal dropped between the ridges). After switching off the air-conditioning, temperature began to rise again (second ridge). These changes are cyclical, and the period is consistent with the periodic switching on the air conditioning.

Fig. 17 illustrates the size of changes in surface mapping over time. The amplitude of the received sinusoid exceeds 1 μm, which for the smooth surface will result in a falsification of the actual measurement signal.

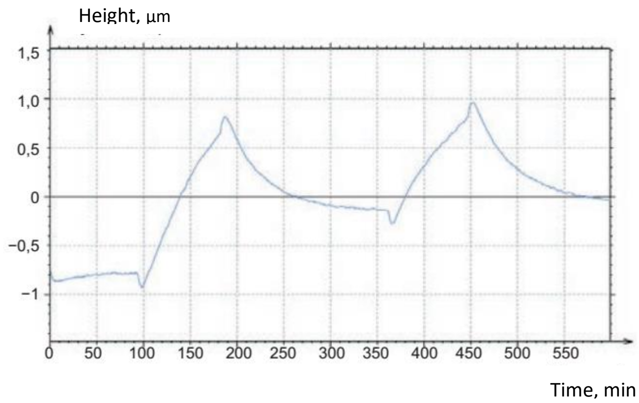

Fig. 17. Changes in profile height due to air conditioning

Correlation analysis of this phenomenon as a function of time is shown in [5]. Temperature changes are not necessarily gradual. Serious complications can be caused, for example, by the effects of sun rays temporarily falling on the instrument. Even the presence of the person in the device can interfere with the measurement and introduce errors, especially when high accuracy is required. The thermal effects can be improved by a suitable combination of materials with different thermal expansion coefficients. In [1], a system consisting of steel wire wound on an inwar rod, was used. The rise in temperature has reduced the circumferential stress induced by the steel on the invasion and consequently reduced the length of the rod (within the specified range, of course).

Conclusions

Although many different methods of measuring surface unevenness are currently being used in science and industry, the most common instruments used for such measurements are contact profilometry based on profiled analysis methods. Their place in the industrial practice is well-established many years of experiments and standardization procedures, which until recently only refer to this measurement technique. The addition of contact profilometers for surfaces where contact with the measuring tip is unacceptable, are optical heads, e.g. profilometric confocal heads. When measuring 3D imbalances, however, one should be aware of sources of measurement errors and their magnitudes to avoid situations where distortion will become an important part of the measurement signal.

It is not always possible to refer to statistical methods when estimating the uncertainty of measurement. It is necessary to isolate the source of the error and determine what size interference is not introduced into the measurement result. This is particularly important in the measurement of surface topography at the micro level, where the measurement is often so time-consuming that its repetition is not an option, and have difficulty making relocation, which is a measurement over time in the same place. Examples of such error sources and their effect on the measurement result are described in the article. It is also worth noting that what is visible in the measurement signal is not always related to the surface measured - it may reflect the outside world or the limited capabilities of the measuring device. A software filtering such interference may be partially eliminated, but in most cases will modify the measured signal.

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