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EVALUTION METHOD OF COATING THICKNESS OF COATING THICKNESS STANDARD

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Abstract: *Modern machines and instruments are covered with different coatings (paints, ceramic coating, deposition, electro gilding, etc). Ever increasing requirements for the mechanism increase the accuracy standards for measuring of the coatings. It again presumes more accurate and easily calibrated thickness standards by reason that only with calibrated coating thickness standard can be assured the procedure of metrology control of the coating thickness measuring instruments.*
However, there does not exist any internationally accepted definition for the surface coating thickness up the present time. Considering basic principles of metrology, the surface coating thickness can be defined as the interval along the normal line of surface coating between crossing points of this line with the upper and the inner boundary surfaces of the surface coating. Above definition is valid, however, in case of perfectly plane and parallel boundary surfaces. Really, the boundary surfaces are not parallel with each other, but, depending on production technology, have deviations in geometry as well as in roughness. For that reason, in defining the surface coating thickness, terms shall be used like local thickness (in a fixed point), and maximal and minimal thickness.
Key words: coating thickness, definition of coating thickness, measurement of coating thickness, coating thickness standard, uncertainty of results of coating thickness

1. INTRODUCTION

Problem is, it's difficult to predict the coating thickness of a coating thickness standard – specific methods are used for the indirect presentation of the parallelism and the full flatness of the surface coating and of the boundary surface. The paper presents the definition for surface coating thickness between real (estimated) coating surfaces is proposed [[1]].
Therefore the contours of the boundary surfaces of the coating thickness standard before and after the coating thick so the top surface of the coating thickness standard are measured.
The definition is proved by mathematical model, based on Monte-Carlo iteration method and assumed profile of the boundary surface beneath of the coating, gives statistical distribution description for the coating surface and so for the coating itself.
With mathematical model the local thickness (in a fixed point), maximal and minimal thickness so the overall thickness can be calculated in any time. In the same way, the data collected during the first calibration process can be used on the re-calibration of the same thickness standard. Besides, on re-calibration is no need of measuring of the boundary surfaces, but only the top surface of the coating thickness standard. During the re-calibration there is possibility to estimate the condition of the coating thickness standard – for instance wear or the defect of the top surface and influence it may have to the measurement result.

With advantage of the above described method we can evaluate the profile under the coating of the coating thick. Using the developed method we can determine the coating thickness during the calibration procedure according to the definition of the coating thickness standard. It gives increase of reliability of the calibration of coating thickness standards [2].

The definition proposed for surface coating thickness is checked through practical tests, which allows to evaluate appropriateness of theoretical considerations elaborated.

The method is very suitable for thickness standards that can't be calibrated during the manufacture process, or for standards which boundary surfaces are because the cost effect not very plain.

2. THEORY

2.1 Coating thickness of a plane object of measurement

There are two random functions which determine the coating thickness of a real plane object of measurement, and which characterize the boundary surface between the coating and the surrounding environment, as well as the boundary surface between the coating and the base. The values of the above-mentioned random functions are restricted by the conditions proposed in the technical specifications, i.e. the tolerance limits of the shape deviations (usually tolerance of a plane surface) and the parameter of surface roughness $R_{max.}$ To the covered element, measuring its dimensions in the Cartesian coordinates 0*XYZ*, such that the plane 0*XY* is parallel to the mean surface (derived from the random function $Z_s = f_2(X,Y)$), the random function of the covering can, in general, be represented (according to [1]) as follows

$$h = Z_g - Z_s = f_1(X,Y) - f_2(X,Y) \tag{1}$$

Observing the coating of the element with dimensions $x \times y \times z$ in the intersection 0*YZ*, the mean thickness of coating by the intersection from y_1 to y_2 can be determined in the following relation

$$\underset{X=X_0}{h_m} = \frac{1}{y_2 - y_1} \int_{y_1}^{y_2} [f_1(X_0,Y) - f_2(X_0,Y)] \mathrm{d}y \tag{2}$$

Intersection with the plane 0*XZ*, in which the shape of the element of the object of measurement is analogous, gives the mean coating thickness of the object in the intersection from x_1 to x_2 as follows

$$\underset{Y=Y_0}{h_m} = \frac{1}{x_2 - x_1} \int_{x_1}^{x_2} [f_1(X,Y_0) - f_2(X,Y_0)] \mathrm{d}x \tag{3}$$

2.2 Coating thickness of a coating thickness standard

For determining, sustaining and reproducing a certain value of coating thickness, coating thickness standards are applied [2,3]. The latter are cuboids or bases made from a standard material, and the middle of the topmost surface of which is covered with a standard material, the thickness of which can be measured or calibrated.

Let us relate the coating thickness standard to the cross coordinate system 0*XYZ* so that the plane of the cross coordinate system 0*XY* is parallel to the foundation of the base, and the point of origin of the coordinates is in the middle of the intersectional line between the side and the foundation of the base (see Fig. 1).

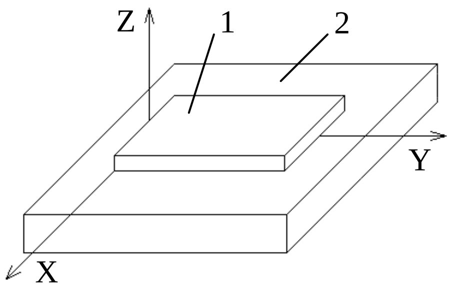

Fig. 1. Coating thickness standard
1 – coating, 2 – surface

In this case, the contours of the boundary surfaces of the coating thickness standard in intersection 0*YZ*, which are determined by random functions, take the shape provided in Fig. 2.

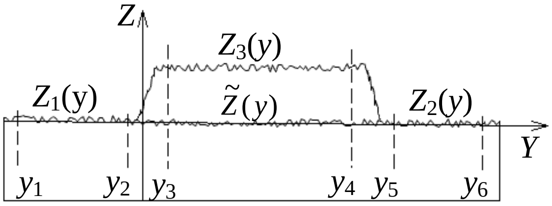

Fig. 2. Random functions characterizing the top surface

When observing this coating thickness standard in an intersection parallel to axis *X*, the obtainable shape is analogous. The problem here underlies in the fact that the two random functions characterizing the top surface of the base in the range from y_1 to y_2 and from y_5 to y_6 can be determined by groping (see Fig. 2). However, in the range from y_3 to y_4 of the random function of the boundary surface of the coating and the base, it proves impossible to determine the covering thickness through groping, since the coating is attached to the base/foundation. Therefore, within the range from y_3 to $y_{4,}$ the thickness of the coating has to be determined based on the profiles of the surface of the base, which, in its turn, are determined by two random functions in the range from y_1 to y_2 and from y_5 to $y_{6.}$ Those random functions, however, characterize the surface profile on both sides of the coating and not directly under it. The problem lies in, firstly, how to evaluate the random function $\tilde{Z}(y)$ of the boundary surface between the coating and the base in the range from y_3 to $y_{4,}$ relying on the two random functions $Z_1(y)$ and $Z_2(y)$, or their estimates, which characterize profiles in the range from y_1 to y_2 and y_5 to $y_{6.}$ Secondly, what to do to is determine the coating thickness, which has been obtained by calculating the third-degree polynomial in the intersection y_2 to y_5.

Functions $Z_1(y)$ and $Z_2(y)$ are random function, the values of which can be obtained when measuring the surface of the base of the covering thickness standard by means of groping

$$Z_1(y) = \tilde{Z}_1 + a_{11}y + a_{10}$$
$$Z_2(y) = \tilde{Z}_2 + a_{21}y + a_{20} \tag{4}$$

where $\tilde{Z}_1$ and $\tilde{Z}_2$ is have random values according to the normal distribution N(0, σ_1) and N(0, σ_2). In the given case, the functions of the mean value of functions $Z_1(y)$ and $Z_2(y)$ are the following

$$m_{Z1}(y) = a_{11}y + a_{10}, \quad y_1 \le y \le y_2$$
$$m_{Z2}(y) = a_{21}y + a_{20}, \quad y_5 \le y \le y_6 \tag{5}$$

It is clear the estimated profile under the coating can have many different shapes in our case. In Fig. 3 are two surface profiles on both sides of the coating and between them the most probably assumed profile between the coating and base.

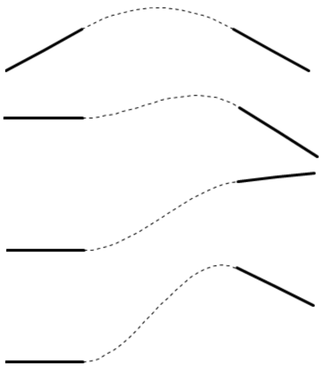

Fig. 3. Random functions characterizing the surface of the base

The most probable profile (assumed profile) under the coating in the intersection y_2 to y_5 can be described with the third-degree polynomial.

Under this assumption, we have that, the mean value of the assumed profile of the boundary surface between the coating and base (in the range from y_2 to y_5) can be expressed as follow

$$m_{\tilde{Z}}(y) = c_3y^3 + c_2y^2 + c_1y + c_0 \tag{7}$$

And the variance can be determined by the following relation

$$D_{\tilde{Z}}(y) = Dc_3 y^6 + Dc_2 y^4 + Dc_1 y^2 + Dc_0$$
$$+ 2\operatorname{cov}(c_2, c_3) y^5 + 2\operatorname{cov}(c_1, c_3) y^4 +$$
$$+ 2\operatorname{cov}(c_0, c_3) y^3 + 2\operatorname{cov}(c_1, c_2) y^3 +$$
$$+ 2\operatorname{cov}(c_0, c_2) y^2 + 2\operatorname{cov}(c_0, c_1) y \quad (8)$$

The coating thickness at a certain value of *y* can, in the case given (see Fig. 2), be calculated in the following relation

$$h(y) = Z_3(y) - \tilde{Z}(y) \quad (9)$$

in which $Z_3(y)$ is the random function of the top surface of the coating of the coating thickness standard in the range of y_3 to y_4 and can be given by the following relation

$$Z_3(y) = \tilde{Z}_3 + b_2 y^2 + b_1 y + b_0 \quad (10)$$

The mean value of the coating thickness can be represented on the basis of the equations above as follows

$$m_h(y) = m_{Z3}(y) - m_{\tilde{Z}}(y) =$$
$$= b_2 y^2 + b_1 y + b_0 -$$
$$- c_3 y^3 - c_2 y^2 - c_1 y - c_0 \quad (11)$$

If we assume, that functions $Z_1(y)$ and $Z_3(y)$, $Z_2(y)$ and $Z_3(y)$ are independent, the distribution of coating thickness (dispersion), obtainable through relation (8), can be estimated relying on the following dispersion

$$D_h(y) = D_{Z3}(y) + D_{\tilde{Z}}(y) \quad (12)$$

The equation (9) does not reflect the uncertainty of the estimates z_i and y_i of the proposed factor. To take those uncertainties components into account, we note that the total combined uncertainty $u_\Sigma(y)$ of $h(y)$ can be expressed

$$u_\Sigma(y) = \sqrt{D_h(y) + u^2(z)} \quad (13)$$

The uncertainty of the estimated *z* can expressed as follow

$$u(z) = \sqrt{u_{cal}^2 + u_{env}^2 + u_{Ra}^2} \quad (14)$$

where u_{cal} is standard uncertainty of the measurement instrument, u_{env} is standard uncertainty of the environment (noise), u_{Ra} is standard uncertainty of the surface roughness.

3. MEASUREMENT OF COATING THICKNESS AND ANALYSIS OF RESULTS

Coating thickness standards as a links of traceability chain of coating thickness measurement are calibrated [4,5]. In our case we observe, how we can use the definition of coating thickness in a procedure of calibration of coating thickness standards. To calibrate the coating thickness standard it will be placed on the working table of measuring device "Tencor P-11" [6]. The stylus of the measuring instrument will be taken to the contact with the base surface of the coating thickness standard. The *y*-directional movement will be performed and the stylus tracing the measured surface. The computer screen of measuring device gives us a true surface profile of traced length (see Fig. 4). Measurement data (y_i and z_i) well be saved on the file which will be used for furthered calculations.

It is quite similar represented in Fig. 2. According to the true surface profile we get implementations of random functions $Z_1(y)$, $Z_2(y)$ and $Z_3(y)$ in range chosen in *y* axis (y_1 to y_2, y_5 to y_6 and y_3 to y_4, see Fig. 2). On the basis of these implementations regarding to *y* values we can get according to relations (4) and (5) using a Monte-Carlo method [6] possible estimates of the random functions $Z_1(y)$ and $Z_2(y)$.

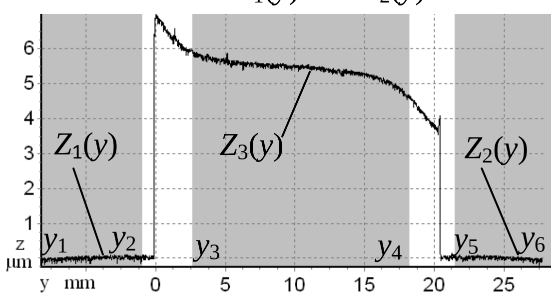

Fig. 4. Profile of the base surface and functions $Z_1(y)$, $Z_2(y)$ and $Z_3(y)$

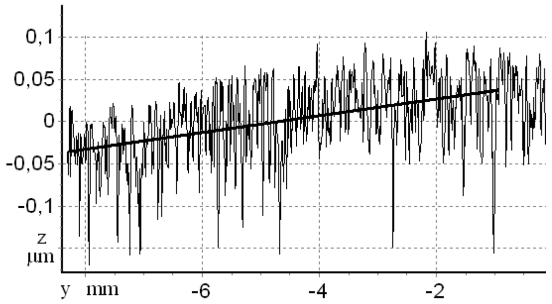

Fig. 5. Profile of the base surface and $m_{Z1}(y)$-mean value of function $Z_1(y)$ in the interval between y_1 and y_2

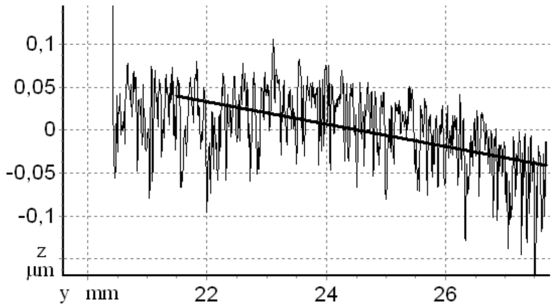

Fig. 6. Profile of the base surface and $m_{Z2}(y)$-mean value of function $Z_2(y)$ in the interval between y_5 and y_6

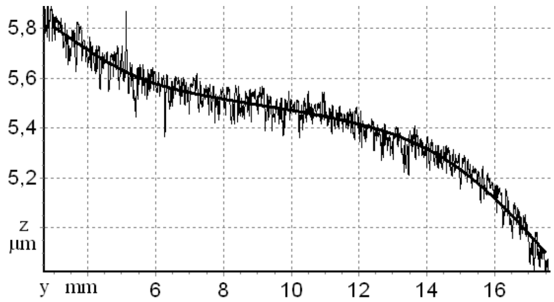

Fig. 7. Surface profile $m_{Z3}(y)$-mean value of function $Z_3(y)$ in the interval between y_3 and y_4

It means the estimates of mean values of these functions $m_{Z1}(y)$ and $m_{Z2}(y)$ and variances s_{Z1}^2 and s_{Z2}^2. According to the z values of receiving profile in intersection of tracing length the estimates are as follows (y – mm; $m_{Z1}(y)$, $m_{Z2}(y)$, u_{Z1}, u_{Z2} – µm):

$$m_{Z1}(y) = 9.737 \cdot 10^{-3} y + 0.045$$

$$s_{Z1} = u_{Z1} = 0.005$$

$$m_{Z2}(y) = -1.281 \cdot 10^{-2} y + 0.315$$

$$s_{Z2} = u_{Z2} = 0.005$$

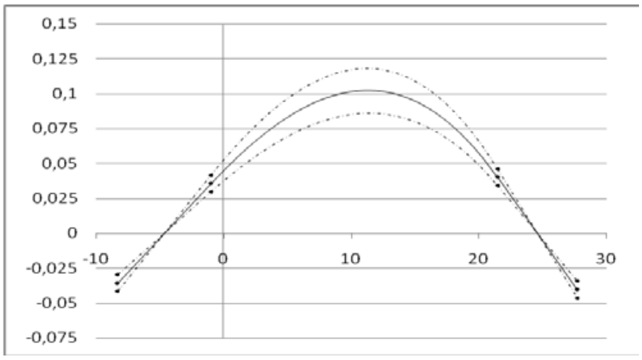

Fig. 8. Mean value of the function of assumed profile with the dispersion

Analogically we can calculate in the range from y_3 to y_4 the equation of parabola proper to relation (10) and its variance and standard uncertainty, using a Monte-Carlo method (y – mm; $m_{Z3}(y)$, u_{Z3} – µm):

$$m_{Z3}(y) = 2.201 \cdot 10^{-2} y^2 - 0.2241 y + 6.301$$

$$u_{Z3} \cong \sqrt{D_{Z3}} \cong 0.01$$

We can calculate using equations (7) and (8) the mean value function of the assumed profile of the boundary surface between the coating and base and its estimate of standard uncertainty, which are by the calibration results as follows (y – mm; $u_{m\tilde{Z}}$, $m_{\tilde{Z}}(y)$ – µm) (see Fig 8):

$$m_{\tilde{Z}}(y) = -6.846 \cdot 10^{-6} y^3 - 2.915 \cdot 10^{-4} y^2 +$$
$$+ 9.174 \cdot 10^{-3} y + 0.045$$

$$u_{m\tilde{Z}} \cong \sqrt{D_{\tilde{Z}}(y)} \cong 0.016$$

The coating thickness measurement result of coating thickness standard obtained by calibration on the basis of the tracing profile of the surface on the section from y_3 to y_4 is (y – mm, $h(y)$ – µm)):

$$h(y) = m_{Z3}(y) - m_{\tilde{Z}}(y) = -7.825 \cdot 10^{-4} y^3 +$$
$$+ 2.231 \cdot 10^{-2} y^2 - 2.332 \cdot 10^{-1} y + 6.256$$

The combined standard uncertainty of the coating thickness measurement result of coating thickness using relation (9) in point y = 10 mm $h(y_{10})$ = 5.2 µm, $u(z_{10})$ = 0.06 µm, is as follows. We assume, that estimates of the random functions $m_{Z1}(y)$

$m_{Z2}(y)$ and $m_{Z3}(y)$ are independent (y − mm; $U[h(y_{10})]$ − μm):

$$U[h(y_{10})] = k \cdot u_{\Sigma}(y) = 2 \cdot \sqrt{D_h(y) + u^2(z_{10})} =$$

$$= 2 \cdot \sqrt{(u_{Z3})^2 + (u_{m\tilde{Z}})^2 + 2 \cdot (u_{Z1,2})^2 + u^2(z_{10})} =$$

$$= 2 \cdot \sqrt{0.01^2 + 0.016^2 + 2 \cdot 0.005^2 + 0.06^2} \cong$$

$$\cong 0.16\ \mu\text{m} \cong 0.2\ \mu\text{m}$$

Base on the coating thickness of surface of the standard and its expanded measurement uncertainty by the coating thickness measured at the point y = 10 mm, we can express the final result (of the measurement) as follows

$h(y)$ = 5.4 μm ± 0.2 μm

4. CONCLUSION

As only with calibrated coating thickness standard can be assured the procedure of metrology control of the coating thickness measuring instruments, the increasing of the accuracy of coating thickness standards is very important.

On the basis of the described method we can evaluate the profile under the coating of the coating thickness standard. Using the developed method we can determine the coating thickness during the calibration procedure according to the definition of the coating thickness. It gives increase of reliability of the calibration of coating thickness standards compared with the method which consider only profiles of the upper boundary surface of the base material adjoining the coating.

5. REFERENCES

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