6th International DAAAM Baltic Conference
INDUSTRIAL ENGINEERING
24-26 April 2008, Tallinn, Estonia

THE COATING THICKNESS AND ITS DEFINITION

Indrek Abiline, Rein Laaneots, Alar Leibak and Jürgen Riim

Abstract: *Coating on the certain object will be formed between the boundary surface of surrounding environment and coating and between the boundary surface of object base and coating.*
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: local thickness (in a fixed point), and maximal and minimal thickness.
The paper presents the definition for surface coating thickness between real coating surfaces is proposed. The definition is proved by mathematical model, which using Monte-Carlo iteration method, gives statistical distribution description for the coating surface. The definition proposed for surface coating thickness is checked through practical tests, which allows to evaluate appropriateness of theoretical considerations elaborated.
Keywords: coating thickness, definition of coating thickness, measurement of coating thickness, coating thickness standard, uncertainty of results of coating thickness

1. INTRODUCTION

For the surface coating the thickness is one of the most important characteristics. 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. The boundary surfaces are determined as surfaces between coating and surrounding gas or liquid environment, and between coating and base material, correspondingly [1]. 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: local thickness (in a fixed point), and maximal and minimal thickness [2].

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 $R_{max.}$ Relating the covered element, measuring $x \times y \times z$ of a plane object of measurement, to the cross coordinate system $0XYZ$ in a way where the surface of the cross coordinate system $0XY$ is parallel to the mean plane surface (derived from random function $Z_s = f_2(X, Y)$, the boundary surface of the covering and base, c.f. Fig. 1), the random function of the covering can, in general, be represented (according to [3]) as follows:

$$h = Z_g - Z_s = f_1(X,Y) - f_2(X,Y), \quad (1)$$

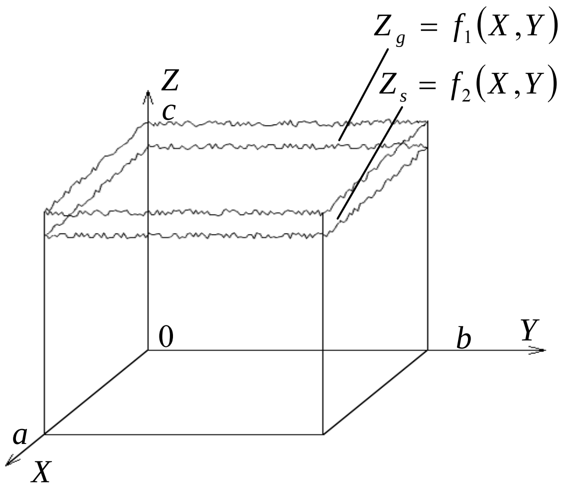

Fig. 1. Covered element

Observing the coating of the element of the object of measurement with dimensions $x \times y \times z$ in the intersection 0*YZ* (presented in Fig. 2), the mean thickness of coating in the intersection from y_1 to y_2 can be determined in the following relation

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

(2)

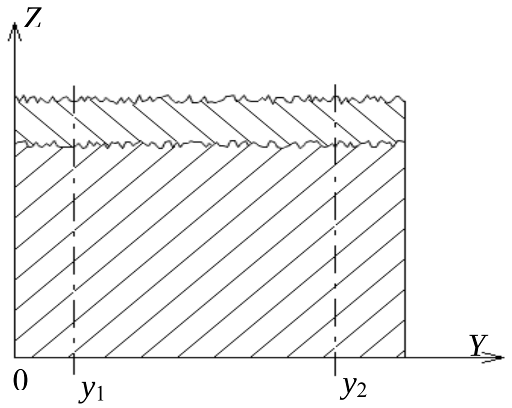

Fig. 2. Element of the object

In intersection 0*XZ*, in which the shape of the element of the object of measurement is analogous to the one presented in Fig. 2, the mean coating thickness of the object in the intersection from a_1 to a_2 can be determined similarly:

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

(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 [4, 5]. 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. 3).

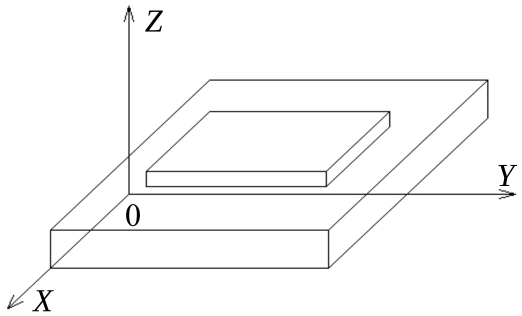

Fig. 3. Coating thickness standard

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. 4.

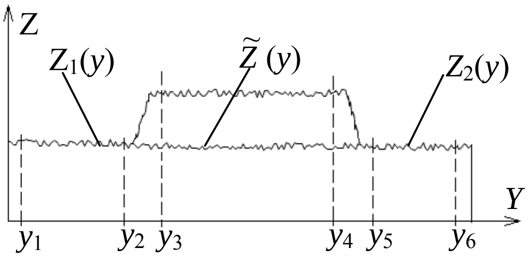

Fig. 4. Random functions characterizing the top surface

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. 4). 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 $\widetilde{Z}(y)$ 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, and, secondly, what to do to determine the coating thickness,

$$\widetilde{Z}(y)=\frac{y_4-y}{y_4-y_3}\cdot Z_1\left(\frac{y_2-y_1}{y_4-y_3}(y-y_3)+y_1\right)+ +\frac{y-y_3}{y_4-y_3}\cdot Z_2\left(\frac{y_6-y_5}{y_4-y_3}(y-y_3)+y_5\right) \qquad (4)$$

which has been obtained by shifting the functions $Z_1(y)$ and $Z_2(y)$ into the intersection y_3 to y_4. Initially, moving from y_3 to y_4, function $Z_1(y)$ dominates, and, afterwards, $Z_2(y)$, i.e. a linear change takes place.

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.

$$Z_1(y)=\widetilde{Z}_1+a_1y+b_1$$
$$Z_2(y)=\widetilde{Z}_2+a_2y+b_2 \qquad (5)$$

in which $\widetilde{Z}_1$ and $\widetilde{Z}_2$ 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:

$$m_{Z_1}(y)=a_1y+b_1,\quad y_1\le y\le y_2$$
$$m_{Z_2}(y)=a_2y+b_2,\quad y_5\le y\le y_6 \qquad (6)$$

Based on the functions of mean value represented in formula (6), the function of the mean value of the assumed profile of the boundary surface between the coating and base (in the range from y_3 to y_4) can be expressed as follows

$$m_{\widetilde{Z}}(y)=\frac{y_4-y}{y_4-y_3}\cdot\left\{a_1\left(\frac{y_2-y_1}{y_4-y_3}(y-y_3)+y_1\right)+b_1\right\}+ +\frac{y-y_3}{y_4-y_3}\cdot\left\{a_2\left(\frac{y_6-y_5}{y_4-y_3}(y-y_3)+y_5\right)+b_2\right\} \qquad (7)$$

The dispersion of the function of the mean value represented in formula (7), however, can be determined in the following relation

$$D_{\tilde{Z}}(y)=\left(\frac{y_4-y}{y_4-y_3}\right)^2\sigma_1^2+\left(\frac{y-y_3}{y_4-y_3}\right)^2\sigma_2^2+$$
$$+2\frac{y_4-y}{y_4-y_3}\cdot\frac{y-y_3}{y_4-y_3}\operatorname{cov}(\tilde{Z}_1,\tilde{Z}_2) \quad (8)$$

The coating thickness at a certain value of y can, in the case given (see Fig. 4), 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

$$Z_3(y)=\tilde{Z}_3+a_3y^2+b_3y+c_3 \quad (10)$$

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

$$m_h(y)=m_{Z_3}(y)-m_{\tilde{Z}}(y)=$$
$$=a_3y^2+b_3y+c_3-m_{\tilde{Z}}(y) \quad (11)$$

Distribution of coating thickness (dispersion), obtainable through relation (9), can be estimated relying on the following dispersion:

$$D_h(y)=\sigma_3^2+\left(\frac{y_4-y}{y_4-y_3}\right)^2\sigma_1^2+\left(\frac{y-y_3}{y_4-y_3}\right)^2\sigma_2^2-$$
$$-2\frac{y_4-y}{y_4-y_3}\operatorname{cov}(\tilde{Z}_1,\tilde{Z}_3)-2\frac{y-y_3}{y_4-y_3}\operatorname{cov}(\tilde{Z}_2,\tilde{Z}_3)+$$
$$+2\frac{y_4-y}{y_4-y_3}\cdot\frac{y-y_3}{y_4-y_3}\operatorname{cov}(\tilde{Z}_1,\tilde{Z}_2) \quad (12)$$

3. MEASUREMENT OF COATING THICKNESS AND ANALYSIS OF RESULTS

Coating thickness standards as a links of traceability chain of coating thickness measurement are calibrated [6, 7]. 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 "Perthometer Concept" [8]. 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. 5). It is quite similar represented in Fig. 4. 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. 4).

On the basis of these implementations regarding to y values we can get according to relations (5) and (6) using a Monte-Carlo method [9] possible estimates of the random functions $Z_1(y)$ and $Z_2(y)$. It means the estimates of mean values of these functions $z_1(y)$ and $z_2(y)$ and experimental 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; $z_1(y)$, $z_2(y)$, u_{z1}, u_{z2} − μm):

$$z_1(y)=-0{,}02y+0{,}09; \qquad s_{z1}=u_{z1}=0{,}07$$
$$z_2(y)=0{,}036y-0{,}569; \qquad s_{z2}=u_{z2}=0{,}08$$

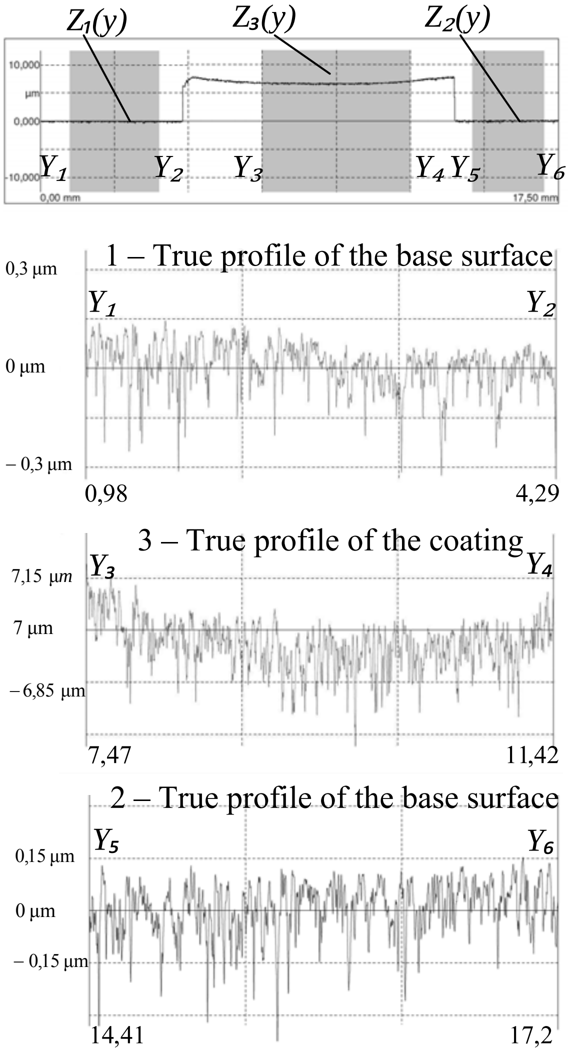

Fig 5. True surface profiles

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; $z_3(y)$, u_{z3} – µm)

$$z_3(y) = 0{,}0385y^2 - 0{,}7517y + 10{,}57$$

$$s_{z3} = u_{z3} = 0{,}05$$

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; $u_{m\tilde{Z}}$ – µm) (see Fig 6):

$$m_{\tilde{z}}(y) = \frac{y_4 - y}{y_4 - y_3} \cdot \left\{ a_1 \left(\frac{y_2 - y_1}{y_4 - y_3}(y - y_3) + y_1 \right) + b_1 \right\} +$$

$$+ \frac{y - y_3}{y_4 - y_3} \cdot \left\{ a_2 \left(\frac{y_6 - y_5}{y_4 - y_3}(y - y_3) + y_5 \right) + b_2 \right\} =$$

$$= 0{,}0015y^2 - 0{,}0346y + 0{,}1274$$

$$u_{m\tilde{Z}} \cong \sqrt{D_{\tilde{Z}}(y)} \cong \sqrt{u_{z1}^2 + u_{z2}^2} =$$

$$= \sqrt{0{,}07^2 + 0{,}08^2} \cong 0{,}11$$

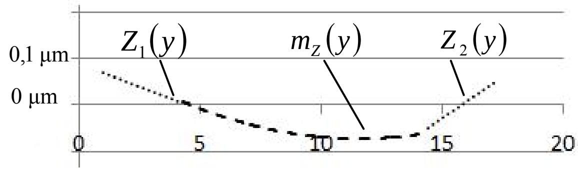

Fig. 6. Function of the assumed profile

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):

$$h(y) = z_3(y) - m_{\tilde{z}}(y) =$$

$$= 0{,}04y^2 - 1{,}097y + 10{,}697$$

The combined standard uncertainty of the coating thickness measurement result of coating thickness using relation (12) is as follows. We assume, that estimates of the random functions $z_1(y)$ $z_2(y)$ and $z_3(y)$ are independent.

$$u[h(y)] \cong \sqrt{D_h(y)} \cong$$

$$\cong \sqrt{u_{z3}^2 + u_{z1}^2 + u_{z2}^2} \cong 0{,}12 \text{ µm}$$

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

1. Herrmann, D.: Schichtdickenmessung. München-Wien: R.Oldenbourg Verlag, 1993, 354 S.
2. Laaneots, R.: Schicht und ihre Dicke. IX. Internationales berflächenkolloquium. Poster. Chemnitz: Technische Universität Chemnitz-Zwickau, 1996, S. 147−155
3. Laaneots, R. and Vyal'yas, M.: The term film thickness and its definition. Mesurement techniques, 1990, vol 33, No 4, pp 313−315
4. Abiline, I., Laaneots, R. and Nanits, M.: Research results of the coating thickness standards. OST-2005 Symposium on Machine Design. Stockholm: KTH, 2005, 6p
5. Hoffmann, K.-P., Ahbe, T. and Thomson-Schmidt. P.: Rückführung von Schichtdickenmessungen. Galvanotechnik, 2006, No 11, pp 2654−2660
6. Hoffmann, K.-P. and Laaneots, R.: Calibration of goating thickness standards (in Estonian). EVS Teataja, 1999, No 7,8, pp 1 3−17
7. Hoffmann, K.-P.: Schichtdickenbestimmung durch profilometrischen Messen in Verbindung mit örtlich begrenzter Schichtablösung. Galvanotechnik, 2000, No 1, pp 82−87
8. Perthometer Concept. Operating Instructions. MAHR GmbH, Göttingen. Germany, 2001
9. Gmurman, V.,E.: Rukovodstvo k rešeniju zadatš po teorii verojatnostei i matematitšeskoi statistike (in Russian). Moskva: Vjušeje obrazovanije, 2007

6. ACKNOWLEDGEMENTS

This work was supported by Estonian Ministry of Education targeted financing grant No. 0140113B and Estonian Science Foundation grant No. 7475.

7. ADDITIONAL DATA ABOUT AUTHORS

Tallinn University of Technology, Institute of Mechatronics, Ehitajate tee 5, 19086 Tallinn, Estonia. E-mail: jyrgen@qvalda.com; indrek@prenar.ee