International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:5, No:7, 2011

HPL-TE Method for Determination of Coatings Relative Total Emissivity Sensitivity Analysis of the Influences of Method Parameters

Z. Veselý, M. Honner

***Abstract*—**High power laser – total emissivity method (HPL-TE method) for determination of coatings relative total emissivity dependent on the temperature is introduced. Method principle, experimental and evaluation parts of the method are described. Computer model of HPL-TE method is employed to perform the sensitivity analysis of the effect of method parameters on the sample surface temperature in the positions where the surface temperature and radiation heat flux are measured.

***Keywords*—**high temperature laser testing; measurement of thermal properties; emissivity; coatings

I. INTRODUCTION

CONSIDERING the fact, that heat is propagated considerably by radiation [1] on the Earth, the knowledge of material emissivity is very important. There are efforts in many industrial and research applications to utilize surfaces (coatings) with the highest (or lowest) emissivities to increase the efficiency of physical processes. The tendencies for emissivity measuring with more accuracy [2], [3] are growing up steadily. In some specific applications, the total emissivity of the surface is more representative value than spectral emissivity values. There exists steady and transient [4] methods for total emissivity determination, the HPL-TE method can be classified to the transient ones.

II. HPL-TE METHOD PRINCIPLE

The HPL-TE measuring system for the evaluation of coatings relative total emissivity is introduced, see Fig. 1. The arbitrary heat source, for example laser beam, can be used to heat up the samples from their back side. The analyzed coating is on the front side of the sample. Using the wideband heat flux analyzer, radiation heat flux from the coating surface is measured. The reference coating is applied on the part of the measured coating surface to ensure the known and equal value of emissivity for all measured coatings. Non-contact measuring of surface temperature from the reference coating is provided utilizing infrared sensor.

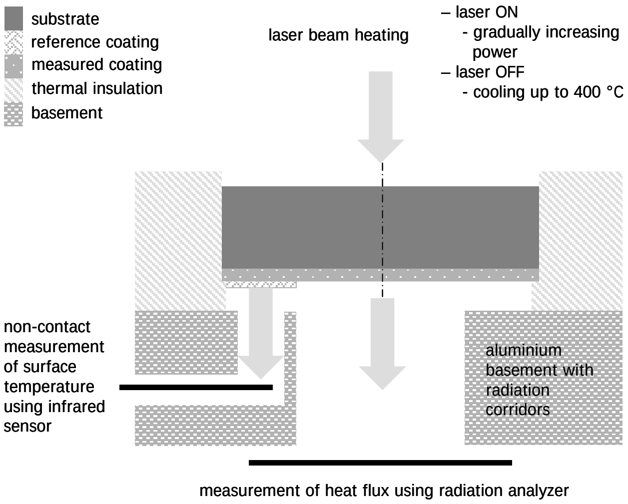

Fig. 1 HPL-TE method measuring system setup

The time behaviour of measured values of radiation heat flux and surface temperature during the cooling of the samples enable to evaluate relative values of total emissivity of the analyzed coating dependent on the temperature. HPL-TE method is based on the fact that the surface temperature in the positions, where the heat flux and surface temperature are measured, is equal. The method uncertainty is caused by the differences of sample surface temperature in these two positions. The aim of computer modeling is to determine these temperature differences for various method parameters and thus enable the HPL-TE method accuracy enhancement.

III. EXPERIMENTAL SETUP

HPL-TE measuring system is illustrated in Fig. 1, the apparatus photography is in Fig. 2a. High-power diode laser is used for heating of the upper sample surface, see Fig. 2a,c. The samples of a circular shape with 25 mm diameter and 5 mm thickness are put to the sample holder. The holder is composed from ceramic plate with two layers of thermal insulation performing side wall thermal insulation of the sample, see Fig. 2b. The sample holder is fixed to the aluminium basement with embedded infrared sensor for a non-contact measurement of surface temperature from lower sample surface. The wideband analyzer of radiation heat flux Ophir ThermalHead L30A SH-V1 (max. 30 W) with the

Z. Veselý is with the New Technologies Research Centre, University of West Bohemia, Pilsen, CO 30614 Czech Republic (phone: 420-377-634722; fax: 420-377-634702; e-mail: zvesely@ntc.zcu.cz).

M. Honner is with the New Technologies Research Centre, University of West Bohemia, Pilsen, CO 30614 Czech Republic (e-mail: honner@ntc.zcu.cz).

measuring range in wavelengths 0.19 – 20.00 μm is used, Fig. 2b. The ceramic plate has two circular holes that separate inputs for measuring surface temperature (measured coating is overlayed by reference layer) and heat flux (measured coating without overlayer), Fig. 2b.

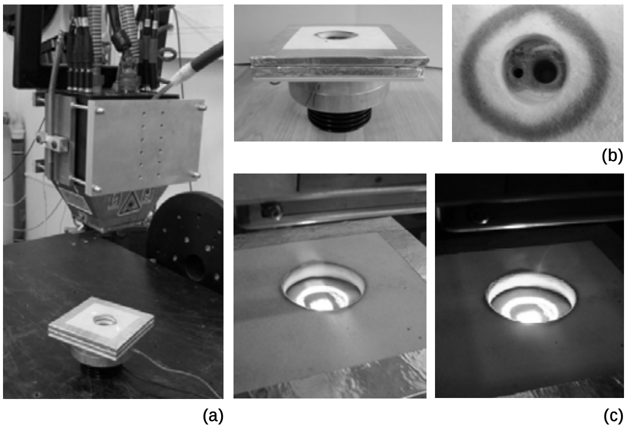

Fig. 2 HPL-TE measurement – arrangement (a), sample holder with embedded infrared sensor and analyzer of radiation heat flux (b), heated sample (c)

Laser heating is performed with gradually increasing power up to prescribed sample surface temperature. Subsequently, heating is stopped and free cooling of the sample is measured and further evaluated.

Infrared sensor records radiation from sample surface. The output signal from the sensor is the voltage that correspond to the surface emissivity and temperature. While the measured surface is overlayed using reference layer with the known emissivity, the sensor voltage output agree with measured surface temperature.

IV. EVALUATION OF THE EMISSIVITY

HPL-TE method provides relative emissivity values of measured coatings relative to the reference measured coating. Heat flux q measured by the radiation heat flux analyzer directly from the measured coating (mc) and surface temperature T_S obtained by infrared sensor from the measured coating overlayed by reference coating (rc) are inputs to the emissivity evaluation.

The emissivity value at specific temperature T_S can be obtained as the output using the relations

$$q_{mc}(T_{S,mc}) = k\,\varepsilon_{mc}(T_{S,mc})\,\varphi\,\sigma\,(T_{S,mc}^4 - T_0^4)\,S\ , \qquad (1)$$

$$q_{rmc}(T_{S,rmc}) = k\,\varepsilon_{rmc}(T_{S,rmc})\,\varphi\,\sigma\,(T_{S,rmc}^4 - T_0^4)\,S\ , \qquad (2)$$

where k is the constant representing experimental configuration, φ is angle coefficient, σ is Stefan-Boltzmann constant, S means surface and subscripts *mc*, *rmc* denote measured coating (mc) and reference measured coating (rmc). After modification, it can be written

$$\frac{\varepsilon_{mc}(T_{S,mc})}{\varepsilon_{rmc}(T_{S,rmc})} = \frac{q_{mc}(T_{S,mc})}{k\,\varphi\,\sigma\,(T_{S,mc}^4 - T_0^4)\,S}\,\frac{k\,\varphi\,\sigma\,(T_{S,rmc}^4 - T_0^4)\,S}{q_{rmc}(T_{S,rmc})} \cdot (3)$$

Using the condition $T_S = T_{S,mc} = T_{S,rmc}$, the following equation can be obtained

$$\frac{\varepsilon_{mc}}{\varepsilon_{rmc}}(T_S) = \frac{q_{mc}(T_S)}{q_{rmc}(T_S)}\ , \qquad (4)$$

that enables to evaluate the emissivity of the measured coating (mc) relative to the emissivity of reference measured coating (rmc). The temperature dependent emissivity can be evaluated using the Eq. (4) for relevant temperatures T_S.The relative value of total emissivity is determined as the ratio of measured coating emissivity and reference measured coating emissivity. In the case of known absolute value of total emissivity of reference measured coating, the absolute value of total emissivity of measured coating can be evaluated.

V. SENSITIVITY ANALYSIS

A. Sensitivity Analysis Principle

The aim of the sensitivity analysis of the HPL-TE method is to determine the effect of selected method parameters on the sample surface temperature. The results are used to improve the accuracy of total emissivity measurements.

The sensitivity analysis is performed utilizing computer model. The prescribed value of constant method parameters and selected range of values for optional method parameters are used in the model. The effect of parameters on the surface temperature in the axis of circle where the surface temperature is measured (circle A) and in the axis of circle where the radiation heat flux is measured (circle B) are evaluated, see Fig. 3.

B. Computer Model

The 3D computer model of HPL-TE method should describe the sample heating and cooling. There is used only simplified 3D model that simulate the steady state temperature distribution in the sample when the back side sample heated surface has the prescribed temperature. Real geometry of the sample contains very small thicknesses of reference, and in some cases measured, coatings. Therefore the dimensional analysis is performed to stretch the measured and reference coatings. Using the scale expressions, *object of the task* is transformed to the *model of the task* that has modified not only geometry, but also material properties and boundary conditions.

Scale expression for the quantity is the ratio of the quantity in model and quantity in object. As the sample axis is in the y axis direction, then $\mu_y = MY$ is scale expression for the distance in the y axis (where the coatings are stretched). Using the dimensional analysis, scale expressions for material properties are obtained – thermal conductivity in the x axis direction $\mu_{\lambda,x} = MY^{-1}$ and thermal conductivity in the y axis $\mu_{\lambda,y} = MY$. Scale expression for time and temperature are equal to one – $\mu_t = 1$, $\mu_T = 1$. Scale expression for heat flux in the y axis is $\mu_{q,y} = 1$, and also the scale expressions for heat transfer coefficient and emissivity in the y axis are $\mu_{\alpha,y} = 1$, $\mu_{\varepsilon,y} = 1$. Scale expression for heat flux in the x axis is obtained $\mu_{q,x} = MY^{-1}$, and also the scale expressions for heat transfer coefficient and emissivity in the x axis are $\mu_{\alpha,x} = MY^{-1}$, $\mu_{\varepsilon,x} = MY^{-1}$.

The scale expression for measured coating thickness is automatically set to such a value, that measured coating model thickness is equal to the thickness of the substrate. The scale expression for reference coating thickness is set to the value, that reference coating model thickness is 80 % of the thickness of the substrate.

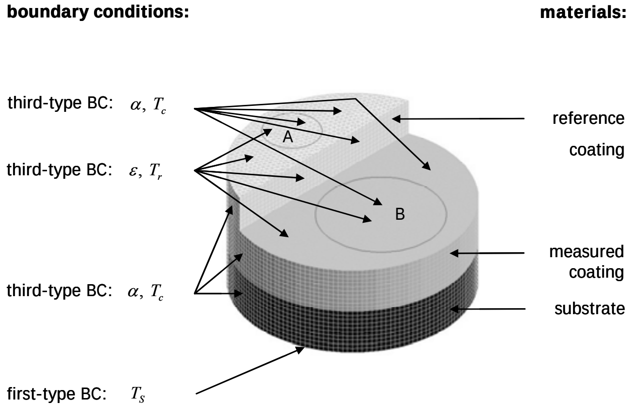

Fig. 3 The stretched geometry of the model sample with the boundary condition types

C. Model Parameters

The prescribed constant method parameters are sample radius 12.5 mm, substrate thickness 5.0 mm and thermal conductivity 25 W·m^{-1}·K^{-1}. Prescribed temperature at the heated sample surface is 1000 ºC. The side walls of the substrate, measured and reference coatings, have heat transfer coefficient equal to 1 W·m^{-2}·K^{-1}. The front parts of the measured and reference layers those lead to the sample holder have heat transfer coefficient 5 W·m^{-2}·K^{-1}, in the circles for measuring the surface temperature and heat flux there is heat transfer coefficient equal to 10 W·m^{-2}·K^{-1}. The external temperatures for convection heat transfer are 500 ºC for the circles for measuring the surface temperature and heat flux, and 900 ºC for all other sample surfaces. External temperatures for radiation are 100 ºC for circles for measuring surface temperature and heat flux, and 900 ºC for the rest surfaces at the front sample surface.

The optional method parameters are thickness of measured coating d_{mc} (50 – 300 μm), thickness of reference coating d_{rc} (20 – 100 μm), thermal conductivity of measured λ_{mc} and reference λ_{rc} coatings (0.5 – 10.0 W·m^{-1}·K^{-1}), emissivity of measured coating ε_{mc} (0.5 – 1.0) and reference coating ε_{rc} (0.6 – 1.0).

VI. RESULTS OF THE SENSITIVITY ANALYSIS

A. The effect of different boundary conditions at front side sample surface

The sample front side surface temperature is dependent on the specific boundary conditions in circles A and B. The selected method parameters are set to medium values (d_{mc} = 200 μm, d_{rc} = 60 μm, $\lambda_{mc} = \lambda_{rc}$ = 2 W·m^{-1}·K^{-1}, $\varepsilon_{mc} = \varepsilon_{rc} = 0.8$).

The same boundary condition in circle A (temperature measuring) and circle B (heat flux measuring) is used as outside the circles. The surface temperature of the reference coating (990.1 °C) is lower than the measured coating surface temperature (990.9 °C), see Fig. 4. The surface temperatures in the circles are almost constant over the surface of circles.

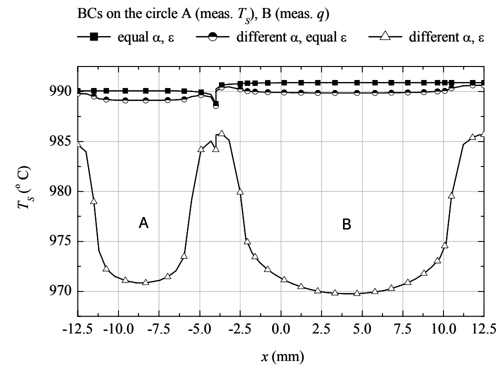

Fig. 4 The influence of different boundary conditions in circles A, B (temperature and heat flux measuring) on the surface temperature distribution at front side of the sample

In circle A (temperature measuring) and circle B (heat flux measuring) there is different convection heat transfer (α, T_c), but the same radiation (ε, T_r) as outside the circles. Minimum surface temperature of reference coating (989.1 °C) is still lower than mimimum surface temperature of measured coating (989.8 °C), because sample cooling by convection heat transfer is low. Already, it is noticeable the effect of greater sample cooling in the circles A and B.

In circle A (temperature measuring) and circle B (heat flux measuring) there is different convection heat transfer (α, T_c), and also different radiation (ε, T_r) than outside the circles. Sample radiation cooling has substantial effect. Minimum surface temperature of reference coating (970.8 °C) is higher than minimum surface temperature of measured coating (969.7 °C). This feature is caused by the larger surface of the circle B and thus due to the higher cooling rate in this circle.

B. The effect of coating thicknesses

The relations of surface temperature in the axes of circle A (temperature measuring) and circle B (heat flux measuring) on the thicknesses of measured and reference coatings are analyzed.

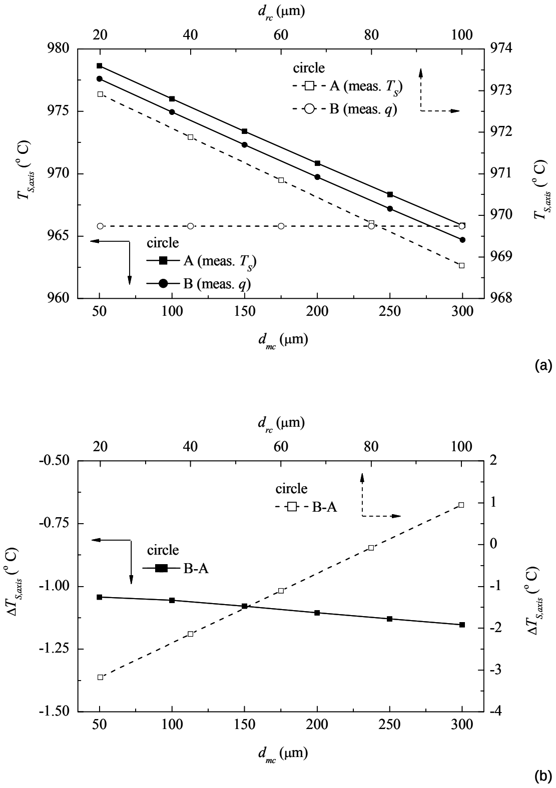

Fig. 5 The influence of measured and reference coating thicknesses on the surface temperature in the axes of circles A and B (a), and on the difference between these two temperatures (b)

Increasing the thickness of measured coating (mc), the axis surface temperature in circles A (978.7 – 965.9 ºC) and B decreases similarly, see Fig. 5a. The difference between these surface temperatures (B – A) decreases slightly with increasing thickness of measured coating (-1,04 – -1,15 °C), see Fig. 5b. The surface temperature in the axis of circle A is higher than in the axis of circle B for all thicknesses of measured layer.

Increasing the thickness of reference coating (rc), the axis surface temperature in circle A decreases (972,9 – 968,8 °C), and the axis surface temperature in circle B is constant (969,7 °C). The difference between these two surface temperatures (B – A) increases along with increasing thickness of reference coating (-3,17 – +0,95 °C). For lower thicknesses of reference coating, the surface temperature in the axis of circle A is higher than in the axis of circle B. But for highest reference coating thicknesses, the situation is opposite.

C. The effect of coating thermal conductivities

It is compared the relations of surface temperature in the axes of circle A (temperature measuring) and circle B (heat flux measuring) on the thermal conductivities of measured and reference thermocamera coatings.

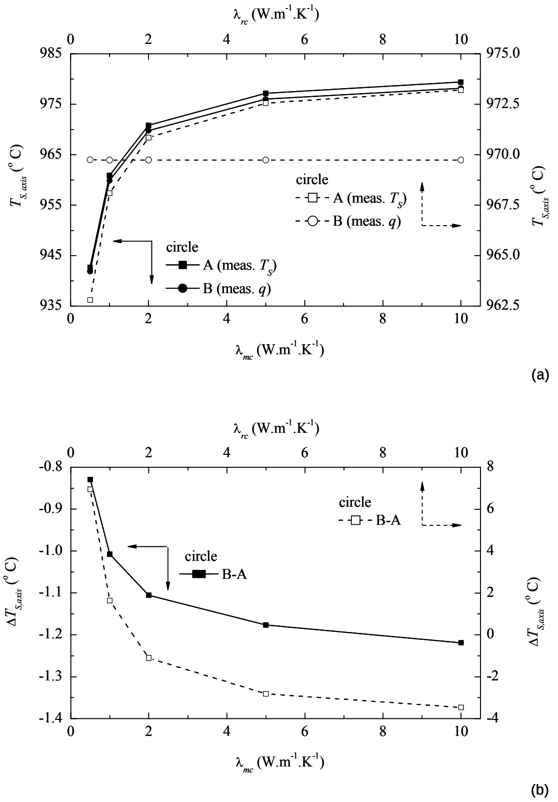

Fig. 6 The influence of measured and reference coating thermal conductivities on the surface temperature in the axes of circles A and B (a), and on the difference between these two temperatures (b)

Increasing the thermal conductivity of measured coating (mc), the axis surface temperature in circles A (942,7 – 979,4 °C) and B increases nearly identically, see Fig. 6a. The difference between these surface temperatures (B – A) decreases slowly with increasing thermal conductivity of measured coating (-0,83 – -1,22 °C), see Fig 6b. The surface temperature in the axis of circle A is higher than in the axis of circle B for all thermal conductivities of measured coating.

Increasing the thermal conductivity of reference coating (rc), the axis surface temperature in circle A increases (962,8 – 973,2 °C), while the axis surface temperature in circle B is constant (969,7 °C). The difference between these surface temperatures (B – A) decreases together with increasing thermal conductivity of reference coating (+6,94 – -3,47 °C). The axis surface temperature in circle A is lower than in circle B for lowest thermal conductivities of reference coating. Considering higher thermal conductivities of reference coating, the situation is opposite.

D. The effect of coating emissivities

The relations of surface temperature in the axes of circle A (temperature measuring) and circle B (heat flux measuring) on the emissivities of measured and reference coatings are analyzed.

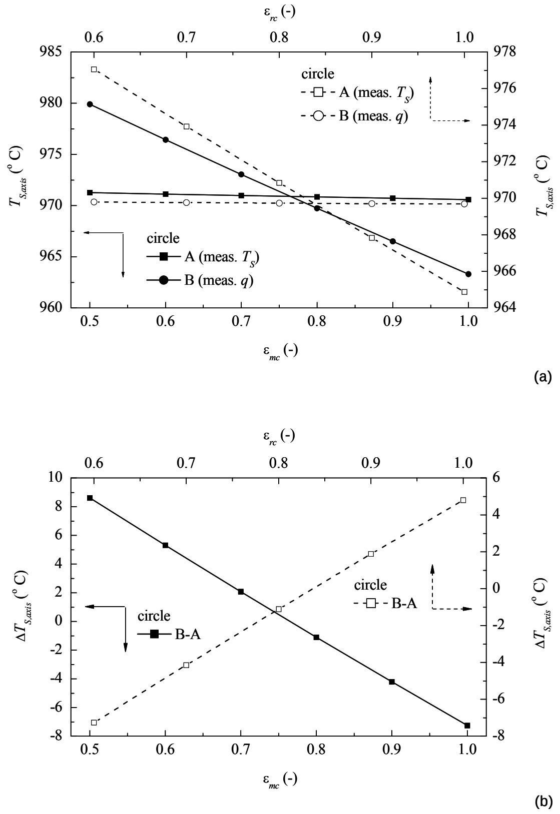

Fig. 7 The influence of measured and reference coating emissivities on the surface temperature in the axes of circles A and B (a), and on the difference between these two temperatures (b)

Increasing the emissivity of measured coating (mc), the axis surface temperature in circle A decreases very slowly (971,3 – 970,6 °C), but the axis surface temperature in circle B substantially (979,9 – 963,3 °C), see Fig. 7a. The difference between these surface temperatures (B – A) expressively decreases with increasing emissivity of measured coating (+8,62 – -7,26 °C), see Fig. 7b. The axis surface temperature in circle A is lower than in circle B for lower emissivities of measured coating. At higher measured coating emissivities, the axis surface temperature in circle A is higher than in circle B.

Increasing the emissivity of reference coating (rc), the axis surface temperature in circle A decreases (977,1 – 964,9°C), while the axis surface temperature in circle B is nearly constant (969,8 – 969,7 °C). The difference between these surface temperatures (B – A) increases (-7,26 – +4,81 °C) along with the increase of reference coating emissivity. The axis surface temperature in circle A is higher than in circle B for lower reference coating emisivities, but the situation is opposite for higher reference coating emissivities.

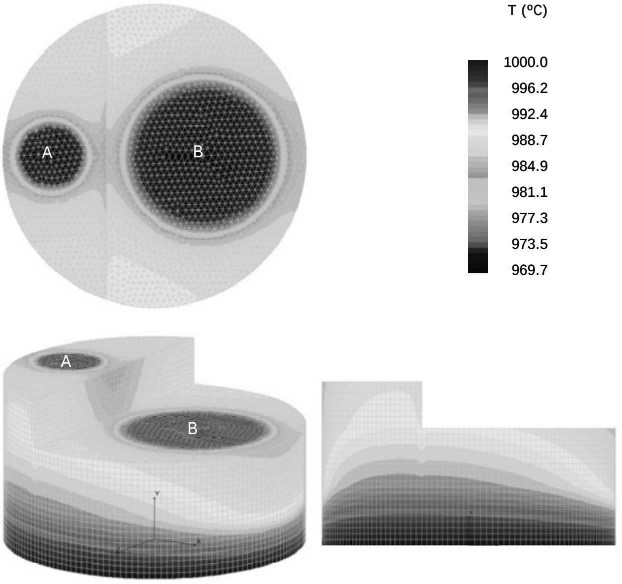

Fig. 8 Sample surface temperature distribution

E. Temperature distribution at the sample surface

Surface temperature distribution is shown in Fig. 8 for the case of medium values of optional method parameters (d_{mc} = 200 μm, d_{rc} = 60 μm, $\lambda_{mc} = \lambda_{rc}$ = 2 W·m^{-1}·K^{-1}, $\varepsilon_{mc} = \varepsilon_{rc}$ = 0.8). The temperatures are displayed at the model geometry of the sample with stretched measured and reference coatings.

The heated back side of the sample is at constant surface temperature 1000 °C with very low heat transfer at side walls of the sample. The substantial change of surface temperature distribution at the front side of the sample is caused by the combination of very high heat transfer in the circles A and B with very low heat transfer outside these circle.

VII. Conclusion

The optional HPL-TE method parameters are thicknesses, thermal conductivities and emissivities of measured and reference coatings. Considering medium values of these method parameters (d_{mc} = 200 μm, d_{rc} = 60 μm, $\lambda_{mc} = \lambda_{rc}$ = 2 W·m^{-1}·K^{-1}, $\varepsilon_{mc} = \varepsilon_{rc}$ = 0.8), the axis surface temperature in circle B (heat flux measuring) is lower than in circle A (temperature measuring).

This phenomenon is caused by the combination of two different processes – heat supply from the heated back side of the sample to the coating surfaces (determined by the thicknesses and thermal conductivities of the substrate, measured and reference coatings) and heat removal from the coatings surfaces (determined by the heat flux density at the coating surfaces that is substantially performed by the radiation, i.e. determined by the emissivity of the measured and reference coatings and also by the areas of the circles).

- High heat supply to the reference coating surface (low thickness and high thermal conductivity of reference coating) in the axis of circle A (temperature measuring).

  Equal boundary conditions in circles A, B together with small area of circle A lead to the lower heat removal in circle A. *The result is higher surface temperature of reference coating.*

- High heat supply to the surface of measured coating in circle B (heat flux measuring) and low heat supply to the surface of reference coating in circle A (temperature measuring) due to high thickness and low thermal conductivity of reference coating.

  Equal boundary conditions in circles A, B together with low heat supply to circle A inspite of higher area of circle B lead to the lower heat removal in circle B. *The result is higher surface temperature of measured coating.*

For temperatures of about 1000 ºC, it is acceptable difference 1 ºC between temperatures in the axis of circles A, B for emissivity evaluation without correction utilizing computer model. The values of method parameters for the absolute temperature difference lower than 1 ºC are put independently for reference coating and measured coating.

With medium values of measured coating parameters ($d_{mc} = 200$ μm, $\lambda_{mc} = 2$ W·m^{-1}·K^{-1}, $\varepsilon_{mc} = 0.8$), *there is absolute temperature difference between the axis of circles A, B lower than 1 ºC* for reference coating thickness in the range 60 – 100 μm with other reference coating parameters equal to medium values, or for reference coating thermal conductivity in the narrow range 1.2 – 2.0 W·m^{-1}·K^{-1} with other reference coating parameters equal to medium values, or for reference coating emissivity in the narrow range 0.8 – 0.87 with other reference coating parameters equal to medium values.

With medium values of reference coating parameters ($d_{rc} = 60$ μm, $\lambda_{rc} = 2$ W·m^{-1}·K^{-1}, $\varepsilon_{rc} = 0.8$), *there is absolute temperature difference between the axis of circles A, B greater than 1 ºC* for all tested measured coating thicknesses with other measured coating parameters equal to medium values, *there is absolute temperature difference between the axis of circles A, B lower than 1 ºC* for measured coating thermal conductivity from minimum tested value 0.5 W·m^{-1}·K^{-1} till 1.0 W·m^{-1}·K^{-1} with other measured coating parameters equal to medium values, or for measured coating emissivity in the narrow range 0.72 – 0.8 with other measured coating parameters equal to medium values.

For other cases of total emissivity measurements using HPL-TE method, it is necessary to utilize computer model for the determination of the difference between the axis surface temperatures in circles A, B for specific values of both constant and optional method parameters. These surface temperature differences should be incorporated to the emissivity evaluation process and thus the accuracy improvement of the HPL-TE method can be obtained.

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