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# ХИМИЧЕСКИЕ ТЕХНОЛОГИИ, НАУКИ О МАТЕРИАЛАХ, МЕТАЛЛУРГИЯ

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Original article

## Engineering-Physical Method for Determining the Thermal Conductivity of Objects with Micrometric Thickness and a Complex Structure

**Oleg V Kudryakov, Valeriy N Varavka ✉, Lyudmila P Arefeva**
Don State Technical University, 1, Gagarin sq., Rostov-on-Don, Russian Federation
✉ varavkavn@gmail.com

**Abstract**

***Introduction.*** The application of functional coatings on products, the performance properties of which are localized in the surface layer is a trend in modern mechanical engineering and materials science. The issues considered in this regard are relevant, in particular, for thermal-barrier coatings of turbine blades of steam and gas turbine engines. It is worth mentioning the materials that experience significant thermal loads during operation. In this case, the lack of reliable methods for predicting the thermophysical properties of the coating seems to be a problem. The work objective is to create a computational and analytical methodology for determining the thermal conductivity of coatings. This approach is based on experimental data and takes into account structural parameters of the material.

***Materials and Methods.*** The experiments were carried out with the blades of a high-speed gas turbine of a locomotive engine made of heat-resistant chromium-nickel alloy Inconel 713LC. An experimental multiphase coating of the Nb-Ti-Al intermetallic system with a thickness of about 80 microns was applied using vacuum ion-plasma technology. The two-beam scanning electron microscope Zeiss CrossBeam 340 was used in the work. The thermal conductivity of the coatings was determined by an experimental technique based on the measurement of the contact potential difference (CPD). Numerical values of this difference were obtained using a mirror galvanometer with high voltage sensitivity. A special signal amplifier and a USB oscilloscope were used to record the readings.

***Results.*** The calculation apparatus of the thermal conductivity determination technique is based on the experimental values of Δφ CPD:

– for the base metal (Inconel 713LC) +846 mkV;

– for the coating Nb-Ti-Al — 90 mkV.

The solution to the problem of the distribution of particles in a force field with a potential difference Δφ is described by the Boltzmann distribution. Starting from the obtained result, we get:

– CPD at the boundary of the contacting metals;

– energy and thermal conductivity of the Fermi level;

– electron relaxation time.

The multidirectional influence that the dimensional differences of the particles of the second phase have on the effective thermal conductivity is considered. For this case, a dimensionless value of the effective thermal conductivity in the direction of each axis and the effective thermal conductivity of the composite are found. Porosity is taken into account according to the Maxwell—Aiken dependence and introduced into the general calculation system. The thermal conductivity of Nb-Ti-Al is established: $\lambda_{NbTiAl}$ = 4,76 W/m·K. Thus, the thermal barrier coating Nb-Ti-Al fully meets its functional purpose.

***Discussion and Conclusion.*** The method of determining thermal conductivity described in the article is applicable only to conductive consolidated materials or composites with a continuous conductive matrix. The presented work completes the initial stage of creating a computational and analytical model for predicting the thermal conductivity of materials and coatings. The results of testing the model for materials with a complex structure showed its satisfactory accuracy. This indicates the expediency of using the two considered elements of the model. The first one is the instrumental measurement of the CPD. The second one is taking into account the features of the structural and phase state of the material. With the development of the model, it is expected to overcome its weaknesses:

– the impossibility of using non-conductive objects to determine the thermal conductivity;

– a significant decrease in the accuracy of determining thermal conductivity for materials and coatings with a gradient structure.

**Keywords:** thermal barrier coatings of turbine blades, prediction of thermal properties of the coating, Inconel 713LC, Nb-Ti-Al, determination of thermal conductivity, Boltzmann distribution, contact potential difference, Fermi level, Maxwell—Aiken porosity, thermal conductivity of non-conductive objects, thermal conductivity of coatings with gradient structure.

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*Научная статья*

## Инженерно-физический метод определения теплопроводности объектов микрометрической толщины со сложной структурой

**О.В. Кудряков, В.Н. Варавка ✉, Л.П. Арефьева**

Донской государственный технический университет, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1

✉ varavkavn@gmail.com

***Аннотация***

***Введение.*** Нанесение функциональных покрытий на изделия, у которых эксплуатационные свойства локализованы в поверхностном слое, — это тренд в современном машиностроении и науке о материалах. Рассматриваемые в этой связи вопросы актуальны, в частности, для термобарьерных покрытий лопаток турбин паровых и газотурбинных двигателей. Стоит отдельно упомянуть материалы, которые при эксплуатации испытывают значительные тепловые нагрузки. В таком случае представляется проблемой отсутствие надежных методов прогнозирования теплофизических свойств покрытия. Основной целью работы было создание расчетно-аналитической методики для определения теплопроводности покрытий. Данный подход базируется на экспериментальных данных и учитывает структурные параметры материала.

***Материалы и методы.*** Эксперименты проводили с лопатками высокоскоростного газотурбинного локомотивного двигателя из жаростойкого хромоникелевого сплава Inconel 713LC. С помощью вакуумной ионно-плазменной технологии наносили экспериментальное многофазное покрытие интерметаллидной системы Nb-Ti-Al толщиной около 80 мкм. В работе использовали двулучевой сканирующий электронный микроскоп Zeiss CrossBeam 340. Теплопроводность покрытий определяли по экспериментальной методике, основанной на измерении контактной разности потенциалов (КРП). Численные значения этой разности получили с помощью зеркального гальванометра с высокой чувствительностью по напряжению. Для фиксирования показаний задействовали специальный усилитель сигнала и USB-осциллограф.

***Результаты исследования.*** Расчетный аппарат методики определения теплопроводности базируется на экспериментальных значениях Δφ КРП:

– для основного металла (Inconel 713LC) +846 мкВ;

– для покрытия Nb-Ti-Al — 90 мкВ.

Решение задачи о распределении частиц в силовом поле с разностью потенциалов Δφ описывается распределением Больцмана. Отталкиваясь от полученного таким образом результата, узнали:

– КРП на границе соприкасающихся металлов;

– энергию и теплопроводность уровня Ферми;

– время релаксации электрона.

Рассмотрено разнонаправленное влияние, которое размерные различия частиц второй фазы оказывают на эффективную теплопроводность. Для этого случая найдено безразмерное значение эффективной теплопроводности в направлении каждой оси и эффективная теплопроводность композита. Пористость учтена по зависимости Максвелла — Эйкена и введена в общую систему расчетов. Установлена теплопроводность Nb-Ti-Al: $\lambda_{NbTiAl}$ = 4,76 Вт/м·К. Таким образом, термобарьерное покрытие Nb-Ti-Al полностью отвечает своему функциональному назначению.

***Обсуждение и заключения.*** Описанная в статье методика определения теплопроводности применима только к проводящим консолидированным материалам или композитам с непрерывной проводящей матрицей. Представленная работа завершает начальную стадию создания расчетно-аналитической модели прогнозирования теплопроводности материалов и покрытий. Итоги тестирования модели для материалов со сложной структурой показали ее удовлетворительную точность. Это свидетельствует о целесообразности использования двух рассмотренных элементов модели. Первый — инструментальное измерение КРП. Второй — учет особенностей структурно-фазового состояния материала. С развитием модели предполагается преодолеть ее слабые места:

– невозможность использования для определения теплопроводности непроводящих объектов;

– значительное снижение точности определения теплопроводности для материалов и покрытий с градиентной структурой.

**Ключевые слова:** термобарьерные покрытия лопаток турбин, прогнозирование теплофизических свойств покрытия, Inconel 713LC, Nb-Ti-Al, определение теплопроводности, распределение Больцмана, контактная разность потенциалов, уровень Ферми, пористость по Максвеллу — Эйкену, теплопроводность непроводящих объектов, теплопроводность покрытий с градиентной структурой.

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**Introduction.** The results obtained in a number of leading universities and research centers of the world on ion-plasma technology of surface modification and coating indicate the great possibilities of this method for the formation of physical, mechanical, corrosion and functional properties of materials. One of the most promising areas of research in this area is the application of protective coatings to the blades of steam turbines and gas turbine engine turbines (GTE). Such coatings are classified as wear-resistant, but in fact they are multifunctional. Thermal protection should be considered as their main function. There is also a differentiation within the thermal protection function. So, for example, the subgroup of thermal barrier coatings (TBC) includes coatings with low thermal conductivity designed to relax the thermal load on the GTE turbine blades. The characteristic features of such TBC coatings are their chemical composition based on refractory elements and a sufficiently large thickness for vacuum ion-plasma coatings — within 100 microns [1, 2].

Currently, ion-plasma technology is a well-managed process. However, the prediction and control of many physical properties remains a serious problem, since, for example, the thermal conductivity of heterophase coatings depends on many non-technological parameters: the microstructure of the matrix phase, the number and configuration of secondary phases, porosity morphology, etc. [3, 4]. That is, the issue is that the problem of forming the necessary coating structure is solved at the technological level, but the problem of determining the thermal conductivity of the formed coating has not been solved to date. The lack of solutions is due to the complexity of instrumental measurement of the properties of thin films and coatings and the lack of a calculation apparatus that takes into account the influence of structural characteristics on the thermal conductivity of coatings. In this regard, the work objective is to develop a computational and analytical methodology for determining the thermal conductivity of vacuum ion-plasma coatings based on readily available measurement methods and reference data.

**Materials and Methods.** The coating of Nb-Ti-Al system was applied using a vacuum ion-plasma installation "PLATITπ80" in an arc three-cathode mode with deposition on cast GTE blades made of heat-resistant Incone 713LC superalloy. In addition to the task of creating a computational and analytical methodology and using it to determine the thermal conductivity of the coating, the task was to verify the validity of the calculated values obtained. For this purpose, the developed technique was used not only to determine the thermal conductivity of the coating, which is currently not found in the scientific literature, but also to determine the thermal conductivity of the Inconel 713LC alloy substrate, which, according to reference data[1], is 11.2–4.5 W/m·K in the temperature range of 25–800 °C. Inconel family alloys, as a rule, are solid solutions with refractory elements W, Co, Mo, etc. dissolved in nickel. They are resistant to thermal fatigue and oxidation, heat resistant to temperatures of 950–1000 °C. However, during long-term operation of the gas turbine engine in the range of higher temperatures, they experience softening, for protection from which thermal barrier coatings are used. Among the requirements for TBC coatings, the main ones are the conditions that allow the thermal barrier effect to be realized — low thermal conductivity and a sufficiently large thickness [5–9]. There are no requirements for the structure and phase composition. Therefore, the experimental intermetallic coating Nb-Ti-Al include refractory components Nb and Ti with additives Al, have a multiphase composition, complex layered morphology and a total thickness of ~80 microns

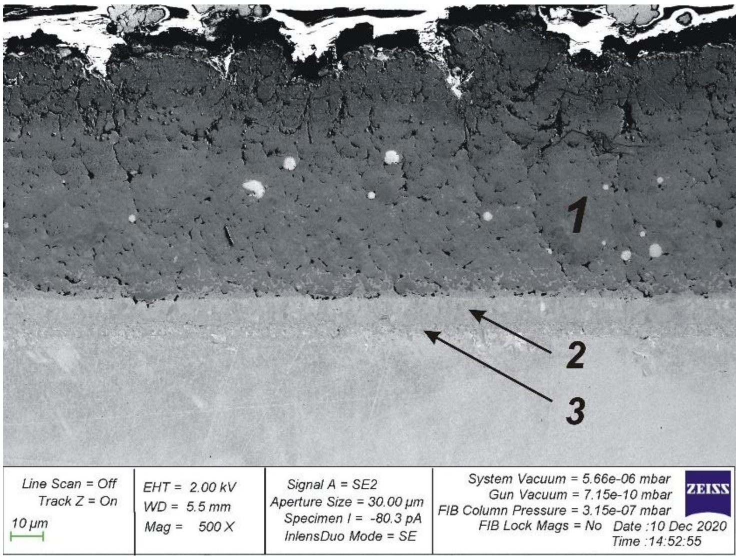
The magnitude of the contact potential difference (CPD), required to calculate the thermal conductivity by the computational and analytical method, is determined using an experimental laboratory technique using an electrocontact measurement method, in which one of the copper electrodes is heated to a temperature of +60 °C. From the point of view of the theory of physical measurements, this method is aimed at determining the extent of the potential barrier at the point of contact of the heated electrode and the object under study, on the basis of which the problem of electron equilibrium in two touching dissimilar metals is solved. The instrumental implementation of the method is carried out using a highly sensitive mirror galvanometer measuring the CPD on a microvolt scale. The measuring system also uses a USB oscilloscope and a signal amplifier to output the measured values of the CPD to print on a given time scale.

Since the developed method for calculating thermal conductivity includes characteristics of the structural-phase state of the measured object, microstructural studies are performed using a Zeiss CrossBeam 340 double-beam scanning

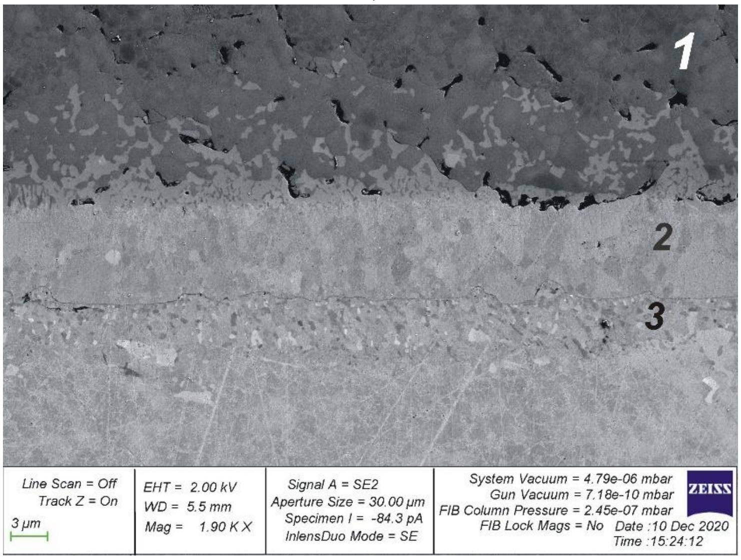
[1] *Engineering Properties of ALLOY* 713C. Brussels: Nickel Institute. URL: https://nickelinstitute.org/media/2487/alloys-713c_337.pdf (accessed 10.04.2023).

electron microscope (SEM). The elemental composition of the coating and substrate is studied on cross-sections using X-ray energy dispersion analysis (EDAX) by point sensing and scanning over the area of an arbitrary contour. Based on SEM and EDAX data, the phase composition of the coating is reconstructed.

**Results.** One of the distinctive features and signs of the novelty of the calculation and analytical methodology being created is taking into account the structural and phase characteristics of the object when calculating its thermal conductivity. Therefore, a coating with a complex structure consisting of several phases located along the depth of the coating with different distribution densities is purposefully chosen as the object of research. There are pores in the coating that have an uneven distribution in depth. In Fig. 1, in the NbTiAl coating structure, three layers are distinguished by section, indicated by numbers. It is clearly seen that they differ from each other in thickness, phase composition and porosity. Moreover, it should be noted that the uppermost layer of the coating (the outer one, which does not have a digital designation in Fig. 1 *a*) has a very branched porosity, openly in contact with the atmosphere. Therefore, its thermal conductivity is actually equal to atmospheric. Due to this circumstance, the outer porous layer is excluded from consideration of the thermal conductivity of the coating.




*a*)




*b*)

Fig. 1. Microstructure of NbTiAl thermal barrier coating in cross section, SEM:
*a* — general view of the layered architecture of the coating; *b* — fragment of the coating area adjacent to the substrate. The numerical designations refer to layers with different structural and phase composition

The main function of thermal barrier protection is performed by layer 1. The results of detection by the EDAX method show that its elemental composition includes: 49–54 at. % Ti, 34.7–41.2 at. % Al, 6–8 at. % Nb. Moreover, according to the thickness of layer 1, the elements have a gradient distribution: Al increases to the surface by 15–20 at. % due to the facilitated diffusion of the fusible element with prolonged coating application and a temperature of 400–500 °C; Ti decreases by 5–10 at. % from the substrate to the surface, and Nb decreases by 2–6 at. %.

The reconstruction of the phase composition of layer 1 in Fig. 1, carried out on the basis of the obtained results of the elemental distribution of EDAX analysis, as well as based on the data of a few literary sources [10-15], gives reason to believe that the phase with the darkest shade in Fig. 1 is the $Ti_3Al$ intermetallic compound – phase 2 doped with niobium. It consists of 49–54 at. % Ti, 34.7–41.2 at. % Al and 6–8 at. % Nb. The phase with the lightest shade in Fig. 1 also represents phase 2, in addition to niobium (up to 8 at. % Nb), nickel-doped (9 at. % Ni). As it can be seen from Fig. 1 *a*, the light phase — $Ti_3Al$ (Nb,Ni) intermetallic compound — occupies a small volume fraction in layer 1 (no more than 5–7 %), which is why it does not significantly affect the thermal conductivity of the layer. Nickel is not part of the sprayed ion-plasma coating. It is detected in the lower part of the coating as a result of diffusion from the substrate during a long sputtering process, which lasted about 20 hours (taking into account the 4-hour diffusion annealing). During this time, nickel penetrates into the coating to a thickness of about 10-15 microns, displacing aluminum into the upper part of the coating.

The thermal barrier coating is operated at high temperatures (>1000 °C) and in an aggressive atmosphere, which is why it must be resistant to high-temperature gas corrosion. For this purpose, during vacuum ion-plasma spraying of TBC coatings, a dense nonporous NbTiAl sublayer (boat coat) of relatively small thickness is formed on the substrate, the main function of which is protection against the penetration of oxidants to the surface of the base metal. During the subsequent spraying of the outer thermal barrier layer, the anticorrosive sublayer is saturated with the elements of the substrate, so in Fig. 1 b in its place between the substrate and main layer 1 of the coating, two thin layers are found — 2 and 3. Layer 2 is almost entirely $Ti_3Al$ (Nb,Ni) intermetallic. It makes a small contribution (corresponding to its small thickness) to the overall thermal conductivity of the coating, which takes into account the developed computational and analytical methodology. Layer 3 has a more complex heterophase composition, which includes, in addition to the main intermetallic phase 2 $\alpha_2$, also titanium and aluminum nickelides, which complicates the calculations of thermal conductivity.

Due to the large thickness of the coating, a forced spraying mode with disabled magnetic separation was used to reduce the time of its application. This leads to the formation of a significant number of droplets in the vacuum chamber. The droplet phase in the ion flow leads to the formation of porosity in the coating. From the point of view of the thermal barrier effect, porosity does not impair the properties of the coating, since the air filling the pores is a good thermal insulator. If we talk about the thickness of the coating, then porosity is a limiting factor. If there are a lot of pores and they open, then they greatly branch the surface relief. The coating becomes unstable even to weak external influences. When assessing and calculating thermal conductivity, the volume fraction of pores and their morphology are taken into account as one of the phase components of the coating with known thermophysical characteristics inherent in the air atmosphere.

According to the depth of the coating, porosity P has a gradient distribution, since the drip phase partially heals the pores of the underlying layers during the coating process. Porosity was estimated from multimodal microstructural images of the coating with correlation settings set using the Zeiss Atlas 5 software integrated into the Zeiss CrossBeam 340 SEM. After statistical processing of the data, the following values were obtained, which were later used in calculating the integral thermal conductivity of the coating of Nb-Ti-Al system: in the upper half of the coating, the porosity P was 26 %, in the lower half — 4 %, the average value of P for the coating as a whole was at the level of 10 %.

*Physical basis and thermal conductivity calculation method*. As an initial stage, the method of determining thermal conductivity includes instrumental measurement of contact potential difference $\Delta\varphi$. At the same time, the temperature difference between the electrodes is fixed and is $\Delta T$ = 40 K. The measurements showed the following values:

- $\Delta\varphi_{Inconel}$ = +846 mkV — for the base metal of the blades of the Inconel 713LC alloy (substrate);
- $\Delta\varphi_{NbTiAl}$ = –90 mkV — for thermal barrier coating of the three-component Nb-Ti-Al system.

Physical significance of using the CPD value (at a fixed value of $\Delta T$) in the process of calculating thermal conductivity is that $\Delta\varphi$ determines the electromagnetic force field in which the distribution of electrons at the boundary of two metals (in our case, this is a copper electrode with an electron concentration $n_0$ and the measured metal with an electron concentration $n_1$) is given by Boltzmann distribution (1), from which the energy value of the Fermi level $E_F$ can be obtained [16]:

$$n_0 = n_1 \cdot \exp\left(-\frac{q_e \cdot \Delta\varphi}{kT}\right), \quad (1)$$

$$\Delta\varphi = \frac{kT}{q_e} \cdot \ln\frac{n_1}{n_0}, \quad (2)$$

$$E_F = \frac{h^2}{8m_e} \cdot \left(\frac{3n_0}{\pi}\right)^{2/3} \cdot \exp\left(\frac{2q_e}{3k} \cdot \frac{\Delta\varphi}{\Delta T}\right), \quad (3)$$

where $m_e$, $q_e$ — electron mass and charge; $k$, $h$ — the Boltzmann and Planck constants.

Thermal conductivity of metals and metal alloys is determined by their electronic conductivity. Therefore, in the process of calculations, the methodical transition from the energy of the Fermi level $E_F$ to the thermal conductivity of metal systems $\lambda$ is carried out indirectly — through the calculation of the electron relaxation time $\tau$, which is determined by the expression [17]

$$\tau = \frac{2\sqrt{2}}{\pi^3} \cdot \frac{a^3 \cdot M \cdot \sqrt{m^*} \cdot k \cdot T_D}{h^2 \cdot C^2} \cdot \left(\frac{T_D}{T}\right) \cdot E_F^{3/2}, \quad (4)$$

where $a$ — the lattice constant; $m^*$ — effective mass of the electron, equal to $10^{-27}$ g; $M$ — mass of an oscillating atom; $T_D$ — the Debye temperature; $C = h^2 / (2m \cdot a^2)$ — the intensity constant of the interaction of an electron with lattice vibrations.

Then, according to the classical theory of thermal conductivity [17]:

$$\lambda = \frac{1}{3m} \cdot n_1 \cdot k^2 \cdot T \cdot \tau. \quad (5)$$

The calculation model consisting of expressions (1)–(5) is applicable to determine thermal conductivity of any single-phase metal alloy with a homogeneous structure, including for the Inconel 713LC nickel superalloy used by the authors as a substrate for NbTiAl thermal barrier coating. However, it is not sufficient for the coating itself. The calculation model of the thermal conductivity of a multiphase system [18, 19], in addition to the thermal conductivity of isotropic matrix $\lambda_m$, should take into account the number of phases, their shape, the dispersion of the distribution and the thermal conductivity $\lambda_0$. With respect to these parameters for such two-phase systems, to which the NbTiAl coating belongs, the following approximations can be taken [19]:

– NbTiAl coating in each of its layers (see layers 1, 2, 3 in Fig. 1) is two-phase and can be considered as a two-phase composite, for which it is customary to determine effective thermal conductivity $\lambda$, averaged over three spatial axes, that is, by values $\tilde{\lambda}_\alpha$, where $\alpha$ = 1, 2, 3;

– inclusions of the second phase are approximated by the shape of an ellipsoid with the ratio of semi-axes $\bar{d} = d/l$;

– the orientation of the ellipsoids is arbitrary and equally probable, which corresponds to the real structure of NbTiAl coating shown in Fig. 1, and makes it possible to exclude the influence of dimensional differences of inclusions of the second phase in different spatial directions on the effective thermal conductivity of the coating;

– porosity can also be considered as the second phase in a homogeneous isotropic metal matrix, which makes it possible to apply the approximations of sub-s 2 and 3 to it; however, unlike many intermetallic phases, porosity always reduces thermal conductivity of metals and metal alloys; in accordance with classical theory [20] for thermal conductivity of a solid with a continuous matrix and isolated pores, the universal Maxwell–Aiken equation is applicable, in which porosity P appears as a fraction of the total volume of a solid, which is taken as one:

$$\lambda_\Pi = \lambda \cdot (1 - \Pi) \cdot (1 + 0{,}5 \cdot \Pi), \quad (6)$$

Then the calculation model of thermal conductivity of a multiphase system, which includes NbTiAl ion-plasma thermal barrier coating, along with expressions (1)–(5), will be supplemented with an expression for the dimensionless effective thermal conductivity in the direction of each spatial axis:

$$\tilde{\lambda}_\alpha = \frac{1 - (\bar{\lambda} - 1) \cdot (D_\alpha + (1 + D_\alpha) \cdot C_V)}{1 + (\bar{\lambda} - 1) \cdot D_\alpha \cdot (1 - C_V)}, \quad (7)$$

where $\widetilde{\lambda}_\alpha = \lambda_\alpha / \lambda_m$, $\overline{\lambda} = \lambda_0 / \lambda_m$, $D_1 = D_2 = \frac{1}{2}\left(1 - \overline{d}^2 \ln \frac{2}{\overline{d}}\right)$, $D_3 = \overline{d}^2 \left(\ln\left(\frac{2}{\overline{d}}\right) - 1\right)$, $C_V$ — volume fraction of inclusions, as well as an expression for the effective thermal conductivity of the composite:

$$\lambda = \frac{2\widetilde{\lambda}_1 + \widetilde{\lambda}_3}{3} \cdot \lambda_m . \tag{8}$$

The method of determining the thermal conductivity of multiphase metal systems, based on the measurement of CPD and expressions (1)–(8), allows us to calculate the effective thermal conductivity of both the base metal of the blades —the Inconel 713LC alloy, and the thermal barrier coating of Nb-Ti-Al system, taking into account their structural-phase state. Omitting the details of the calculations performed, due to the limited volume of the publication, we present only the final results obtained using the MathCAD application software package.

According to X-ray energy dispersion analysis (EDAX), the base metal of the substrate, Inconel 713LC alloy, had an elemental composition of Ni = 69.6 at. %, Al = 13 at. %, Mo = 2.8 at. %, Cr = 14.6 at. % and homogeneous structure of a solid solution of Cr, Al and Mo in nickel. In accordance with the calculation using expressions (1)–(8), including the above value of the CPD (($\Delta\varphi$ = + 846 mkV), the value of its thermal conductivity is $\lambda_{Inconel}$ = 14.34 W/m·K. The obtained value corresponds with satisfactory accuracy to the reference data given earlier, which makes up an interval of 11.2–14.5 W/m·K.for the Inconel 713LC alloy.

Compared with a single-phase base metal, the presence of multilayered and multiphase coating of Nb-Ti-Al complicates the computational part of the developed technique associated with the influence of the material structure. The coating included 4 layers. Their main phase is $Ti_3Al$ (Nb) intermetallic compound with a different volume fraction in each layer and some variation in the composition of the components. Porosity was considered as the second phase. Only in the thinnest layer adjacent to the base metal, the second phase with a volume fraction of about 20 % was a solid solution based on $Ti_3Al$ (Nb, Ni) intermetallic compound containing up to 9 at. % Ni. The porosity in this layer had zero value, so each layer was considered two-phase in the calculations. The influence of the structural-phase state of the coating on its thermal conductivity was taken into account using expressions (6)–(8), based on the measured value of the CPD for the coating as a whole ($\Delta\varphi$ = – 90 mkV).

The calculation of the thermal conductivity of NbTiAl coating showed that $\lambda_{NbTiAl}$ = 4.76 W/m·K. The obtained value is significantly lower than the thermal conductivity of the base metal Inconel 713LC and corresponds to the level of heat-resistant ceramics. Thus, an experimental heterophase coating formed by vacuum ion-plasma technology based on refractory metals Nb and Ti with the presence of Al can be used as a thermal barrier coating.

**Conclusion.** The developed computational and analytical technique allows us to predict and simulate the thermophysical properties of heterophase materials with a complex structure. Its approbation in relation to coatings of micrometric thickness opens up new opportunities in a fairly narrow field for the diagnosis of the properties of coatings and thin films.

The features of the proposed method for determining thermal conductivity through the measurement of CPR, calculation of the Fermi energy level and some other factors allow it to be applied only to conductive consolidated materials or composites with a continuous conductive matrix. The number of phases in the alloy or composite being measured is not limited, and the phases can be of a non-metallic and intermetallic nature (as in the coating of Nb-Ti-Al system). To determine the thermal conductivity of a material or coating using the developed technique, the composition, volume fraction and spatial morphology of phases are important. This makes it possible to determine the contribution of each phase to the thermal conductivity of the material, as well as to apply the technique to porous materials (subject to the continuity of their conductive matrix), identifying the pores as one of the phases of a non-metallic nature.

This work represents the completion of the initial stage of creating a computational and analytical model for predicting the thermal conductivity of materials and coatings. The above model testing results obtained for materials with a complex structure demonstrate a satisfactory level of accuracy. Thus, it is possible to assert the validity of the use of the described physical principles and algorithms in the model. First of all, this is a method of CPD instrumental measurement and consideration of the peculiarities of the structural and phase state of the material, on the basis of which the computational part of the model is constructed. The results of scientific research suggest that the model should develop, overcoming limitations and weaknesses:

– impossibility of using it to determine thermal conductivity of non-conductive objects,

– significant decrease in the accuracy of determining thermal conductivity for materials and coatings with a gradient structure.

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*About the Authors:*

**Oleg V Kudryakov**, professor of the Materials Science and Metal Technology Department, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, RF), Dr. Sci. (Eng.), professor, ResearcherID, ScopusID, ORCID, kudryakov@mail.ru

**Valeriy N Varavka**, professor of the Materials Science and Metal Technology Department, Director of REC "Materials", Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, RF), Dr. Sci. (Eng.), ResearcherID, ScopusID, ORCID, varavkavn@gmail.com

**Lyudmila P Arefeva**, associate professor of the Materials Science and Metal Technology Department, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, RF), Dr. Sci. (Phys.-Math.), associate professor, ResearcherID, ScopusID, ORCID, ludmilochka529@mail.ru

*Claimed contributorship:*

OV Kudryakov: academic advising, formulation of the basic concept, goals and objectives of the study, obtaining experimental data on determining the CP of materials and coatings, discussion of the results, preparation of the text, formulation of the conclusion. VN Varavka: planning and organization of experiments, conducting metallophysical studies, analysis of the results, correction of the conclusion. LP Arefieva: the idea and development of a computational and analytical model for determining thermal conductivity, calculations, analysis and discussion of the results, participation in experimental studies.

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*Об авторах:*

**Кудряков Олег Вячеславович,** профессор кафедры «Материаловедение и технологии металлов» Донского государственного технического университета (344003, РФ, г. Ростов-на-Дону, пл. Гагарина, 1), доктор технических наук, профессор, ResearcherID, ScopusID, ORCID, kudryakov@mail.ru

**Варавка Валерий Николаевич,** профессор кафедры «Материаловедение и технологии металлов», директор НОЦ «Материалы» Донского государственного технического университета (344003, РФ, г. Ростов-на-Дону, пл. Гагарина, 1), доктор технических наук, ResearcherID, ScopusID, ORCID, varavkavn@gmail.com

**Арефьева Людмила Павловна,** доцент кафедры «Материаловедение и технологии металлов» Донского государственного технического университета (344003, РФ, г. Ростов-на-Дону, пл. Гагарина, 1), доктор физико-математических наук, доцент, ResearcherID, ScopusID, ORCID, ludmilochka529@mail.ru

*Заявленный вклад соавторов*

О.В. Кудряков — научное руководство, формирование основной концепции, цели и задачи исследования, получение экспериментальных данных по определению КРП материалов и покрытий, обсуждение результатов, подготовка текста, формулирование заключения. В.Н. Варавка — планирование и организация экспериментов, проведение металлофизических исследований, анализ результатов, корректировка заключения. Л.П. Арефьева — идея и разработка расчетно-аналитической модели определения теплопроводности, выполнение расчетов, анализ и обсуждение результатов, участие в проведении экспериментальных исследований.

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