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Investigations of Thermal Diffusivity of Material of Compressor Blade of Turbine Jet Engine Using Modified Temperature Oscillation Method

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Abstract. The modified temperature oscillation method was applied for investigation of thermal diffusivity of the aviation turbine engine's part. The studies resulted in characterization of the applied method and experimental procedures performance. They were motivated by a need of determination of thermophysical data of the investigated material. The acquired thermal diffusivity data enabled identification of the material's type and will be applied as input data for numerical analyses on thermo-mechanical loads of the structure. The investigated specimen was a sample of material from the first stage compressor's blade of the AŁ-21F3 turbine engine. The measurements were conducted within the range of 5°C to 95°C. The thermal diffusivity was calculated from both the amplitude and phase responses to the harmonic excitation from exact analytical solution of the appropriate heat conduction problem. The appropriate transcendental equations describing the response signal amplitude attenuation and phase shift were solved applying iterative procedures. The analysis confirmed the effectiveness of the research methods and enabled to identify the material as titanium alloy.
Keywords: mechanics, thermal diffusivity, Ångström's method

1. INTRODUCTION

Implementation of new technologies and continuously developed aircraft industry as well as dynamic development of construction materials forces the need of carrying out various material investigations. In the case of materials used for production of construction elements of aircraft turbine engines, these investigations include, among others, determination of thermal properties. It should be pointed out that the knowledge about thermal properties is significantly important from the point of view of strength calculations, exploitation diagnostics, and it is necessary for numerical modelling of thermo-mechanical loads of construction elements.

One of key elements of thermophysical parameters, used for determination of thermal-mechanical loads, is thermal diffusivity. This parameter is also used for characterization of material properties and in experimental investigations, the diffusivity measurement is frequently an intermediate stage of thermal conductivity determination [5, 10, 11, 16].

As it can be expected, there are many methods of thermal diffusivity measurements, and in many cases, the measurement itself can be treated as a standard one. However, because of specific metrological requirements, in majority of cases, it is difficult to obtain high temperature resolution during thermal diffusivity or thermal conductivity investigations. Thus, precise relation between thermal diffusivity and temperature is not easy. This limitation concerns both, the Parker's method of thermal diffusivity measurement as well as the Poensgen's method of conductivity measurement [11]. As alternative, less popular methods can be used, including oscillation modified method [6, 9]. The oscillation modified method, i.e., Ångström method [1], is one of the oldest methods used for thermophysical investigations. Gradually introduced modifications, caused that this method has become one of the most efficient methods for determination of temperature relations of thermal diffusivity (compare [2, 7, 8, 12, 14, 20]). Among others, efficiency of these modifications is confirmed by the results of theoretical analyses [15, 17], numerical simulations [14] or experimental investigations [15, 20].

It has been decided, that the procedures of carrying out oscillation measurements, with high-temperature resolution for precise determination of the thermal diffusivity dependence on temperature, will be tested while properties of aviation construction material are investigated. This material is an alloy used for production of compressor blades of the aircraft turbine engine. In the face of the opportunity of application of other method for this purpose, e.g., a standard excitation method of instantaneous heat source of a surface, legitimacy of the investigations can be a subject of discussion.

However, it should be pointed out, that current measurements performed on regular in shape specimens constitute an initial stage of the development of non-destructive investigations method.

The aim of investigations, is not only determination of thermal diffusivity of the samples of material, taken from the compressor's blade of the aircraft turbine engine, but also checking metrological conditioning of the modified method of oscillation excitations.

The prismatic specimens of the material of constant cross-section along the length were investigated. The measurements of thermal diffusivity were carried out for variable temperature of oscillation base, what allows for determination of relation between the investigated parameter and temperature. The analysis of such obtained results allows for reliable estimation of efficiency of the applied procedures and the possibility of their expansion for non-destructive investigations of the whole construction elements.

2. DESCRIPTION OF THE METHOD AND THE PROCEDURE OF INVESTIGATIONS

2.1. Mathematical model

In contrast to the original Ångström method, using the model of heat exchange in a half-infinite rod with side convection losses [1, 5, 10, 19]. In this case, for description of heat transport, the heat exchange model in a plate plane was used (compare to [2]) with respect to a linearly variable base of oscillation [18]. This problem is described by the Fourier equation [6], [11]:

$$\frac{\partial\theta}{\partial\tau} = a\,\frac{\partial^2\theta}{\partial x^2}, \qquad a = \frac{\lambda}{\rho\, c_p} \tag{1}$$

where θ – is the temperature surplus (excess) T, τ – is the time, $x \in [0,l]$ – spatial variable, l – plate thickness, a – thermal diffusivity, ρ – density, c_p – specific heat at constant pressure.

The above form of the equation means that both, heat losses from side surfaces of the real object as well as relation between thermophysical parameters and temperature should be considered within the frame of error analysis. For the problem, described by Eq. (1), a solution is searched for the conditions of the structured (ordered) heat exchange [10], what means that only the boundary conditions are valid:

$$\frac{\partial\theta(0,\tau)}{\partial x} = 0; \qquad \theta(l,\tau) = T_0 + A_0 \sin(2\pi f\tau - \varepsilon) + b\tau \tag{2 a, b}$$

where A_0 is the amplitude of temperature oscillation, T_0 – the average initial temperature („oscillation level", f –oscillation frequency), ε – phase shift, b – temperature heating/cooling rate.

Solution of the problem, with using adequate solutions of oscillation excitation problem [5, 10] and linear excitation [5], takes the form [18]:

$$\theta(x,\tau) \underset{\tau\to\infty}{=} A_0 \;\psi \sin(2\pi f\tau - \varphi - \varepsilon) + b\,\frac{x^2 - l^2}{2a} + b\tau \tag{3}$$

where (compare Fig. 1.a):

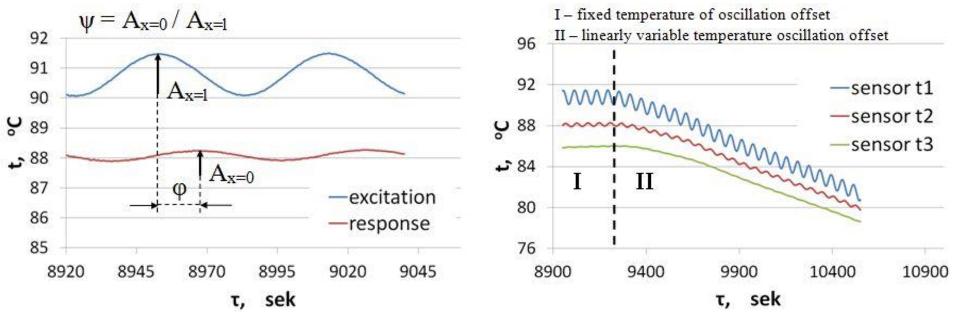
$$\psi(x) \;=\; \sqrt{\frac{\cosh 2kx + \cos 2kx}{\cosh 2kl + \cos 2kl}} \tag{4}$$

$$\varphi(x) \;=\; \arg\left[\frac{\cosh kx(1+i)}{\cosh kl(1+i)}\right] \tag{5}$$

$$k \;=\; \sqrt{\frac{\pi\; f}{a}} = \sqrt{\frac{\pi}{a\;\tau_\Omega}} \tag{6}$$

Determination of thermal diffusivity, on the basis of the results of the excitation signal ($x=l$) and the response at any point x, requires the solution of transcendental equations (4) or (5). In the case, when there are fulfilled some additional conditions, concerning the oscillation frequency, and when the response signal is registered on the adiabatic surface ($x=l$), it is possible to use approximate relations. In these relations, the diffusivity is expressed in a transparent way. The details concerning this subject are presented in works [2], [17]. In works [2], [3], [4], [8], and [16] there are discussed also other problems related to application of the described model in experimental investigations. Unfortunately, for the rod of finite length, both the application of the original Ångström model or the modified method, with the response recorded at the point corresponding to the model adiabatic surface (at the rod's end), is connected with some difficulties.

In the present case, for thermal diffusivity determination, the direct relations (4) and (5) were used. The diffusivity was determined by analysis of both, the amplitude attenuation ψ and the phase delay φ of the response signal at the point x, in relation to the excitation signal $x=l$. The thermal diffusivity occurs also in the second part of the right side of Eq. (3). Because of the higher sensitivity (vulnerability), of so-called, temperature delay b to the convective heat losses (compare Fig. 1.b), determination of thermal diffusivity with this method was not performed.



a b

Fig. 1. Comparison of real temperature changes, constituting the response and excitation signals (a) and illustration of temperature courses at two operation modes: part I – at steady offset, part II – at linearly changed temperature oscillation offset (b)

2.2. Procedure of investigations

Because of application, in the model, the Fourier equation (1), comprising the assumptions that thermophysical properties are independent of temperature, the measurements should be performed at the possibly lowest amplitudes of oscillations and adequately correlated with them rates (heating/cooling) of average temperature changes. It corresponds to the effort to obtain high temperature resolution of investigations [16]. However, the decrease in oscillation amplitude causes the increase in the error of temperature measurement, especially in the case of the response signal. There exist also limitations connected with the “input” into an area of high nonlinearity of expressions (4) and (5), for too low oscillation frequencies [15, 17].

These limitations are not so strict as the condition:

$$k\,l > 1.5 \quad \Leftrightarrow \quad f > \frac{2.25}{\pi}\,\frac{a}{l^2} \tag{7}$$

used for application of two approximate equations, instead of relations (4) and (5) [2, 3], however, they influence on selection of the parameters of oscillation excitation.

In this case, condition (9) is treated only as a criterion of an initial choice for determination of the measuring oscillation frequency. The program of temperature changes (changes of temperature of the oscillation base) consists of the sections of respectively stated and linearly changed temperature, as it is shown in Fig. 1.b. The time for each section shall be selected in such a way that the conditions of the ordered heat exchange would correspond to the most of its part.

The recorded data are subjected to approximation in the intervals corresponding to one period as a function of the form:

$$f(\tau) = A\sin\left(2\pi f\tau + B\right) + C + D\tau \;; \qquad n\,\tau_\Omega \le \tau < \left(n+1\right)\tau_\Omega \,, \quad n = 0,1,...,N \tag{8}$$

where *A*, *B*, *C*, and *D* – are the searched coefficients, *n* – index of the period (interval) of approximation, *N* – is the number of the analysed periods.

The values of right sides of equations (4) and (5) are determined as:

$$\psi = \frac{A_{x=0,\,n}}{A_{x=l,n.}} \;, \quad \varphi = B_{x=l,n.} - B_{x=o,n} \tag{9}$$

The thermal diffusivity is determined using a numerical procedure for solution of nonlinear equations (4) and (5), describing the amplitude and phase features of the response to thermal excitation, as a result of which the so-called "amplitude" or "phase" values of the thermal diffusivity are obtained. Only for model cases, these values will be the same. In reality, the determined values differ to each other. The expected values for the difference, caused by random errors, should be of zero value. Occurrence of systematic errors causes the occurrence of non-zero, in the sense of average statistical value, differences of amplitude and phase values.

To this kind of errors, it can be included an error resulting from omitting the heat losses from side surfaces of the investigated object. However, one of the features of satisfactory metrological conditioning of the Ångström method is the fact that the amplitude values constitute the lower limitation and the phase values, the upper limitation of the real value (compare [11]).

3. EXPERIMENTAL INVESTIGATIONS

3.1. Test stand

Investigations of thermal diffusivity of the prismatic specimens are performed using a measuring system, the scheme of which is shown in Fig. 2. To generate sinusoidal thermal excitation, two Peltier's elements are used. The Peltier elements are supplied from Amrel PPS 1322 DC power adapter.

The adapter operation is controlled from the computer's level, using GPIB bus system. Supply voltage is changed, in such a way to reproduce unipolar return-to-zero signal in discrete values. Stabilisation and the possibility of the programmed changes of the temperature oscillation base ensures the Laud RL6CP ultra-thermostat. For the temperature measurement, K-type thermocouples are used of a wire diameter of 0.1 mm and through-connector, market in figure as t2, t3, and t4.

In the present case, the thermocouples have been attached to the specimen surface with an adhesive tape. For measurement of thermoelectric signals, eight-channel 16-bit card of the National Instruments SCXI 1000 system was used. Optionally, it is possible thermovision recording of the temperature changes on the specimen surface using Infrared Spectroscopy (IR) and Fast Ethernet bus. Fulfilling the model adiabatic condition, during the experiment, is possible due to the use of heat insulation of side and top surfaces of the sample. Supervision of the work of the whole system, the data acquisition and elaboration of measuring data by means of virtual controllers and converters, are performed by PC computer as the system's controller.

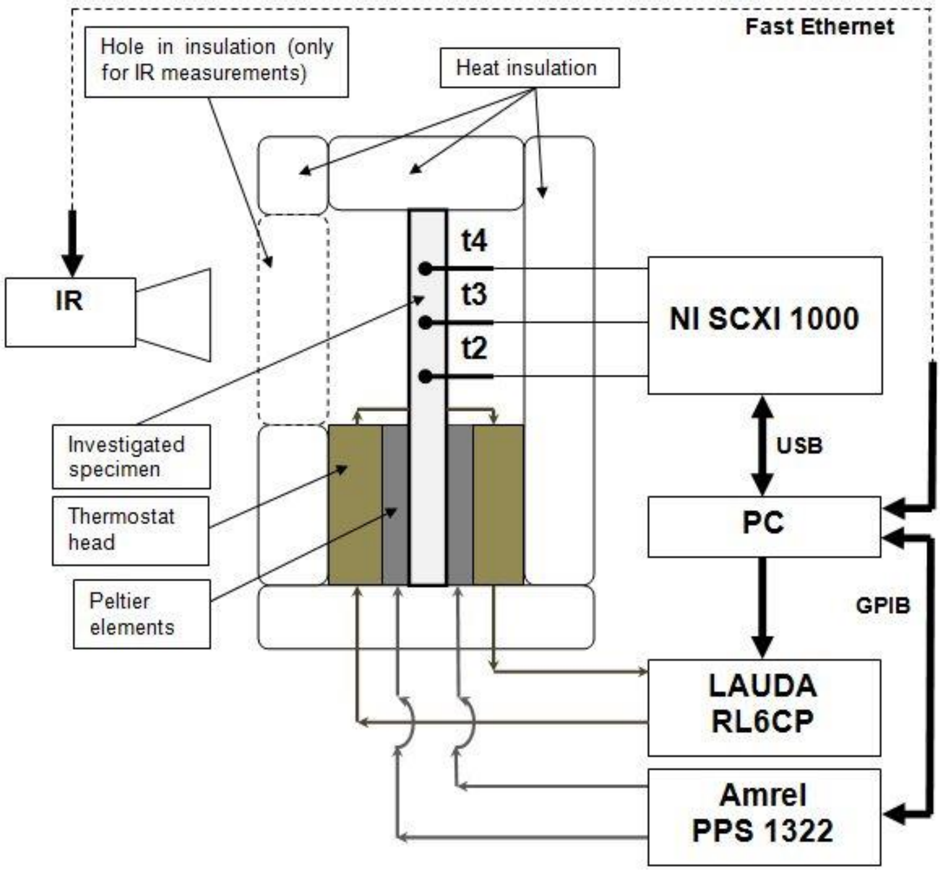


Fig. 2. Scheme of a measuring system

3.2. Description of the investigated specimen and measuring procedure presentation

The specimen for investigations of thermal diffusivity has been taken from a lock of the compressor's blade using a wire electrical discharge machine. In this way, a prismatic specimen was made in form of a prism with trapezoidal cross-section. The specimen dimensions are: height of about 30 mm, thickness about 6 mm, and mass 23.1995 g.

In the measurements of thermophysical properties of the compressor's blade material, the value of specific heat at constant pressure and density was determined.

The measurements were made according to the methodology described in [18] and [20]. For density determination, the Mettler Toledo AT260 analytical balance was used and specific heat measurements were performed with scanning micro-calorimeter Pyris 1 of the Perkin-Elmer firm [13]. The selected results, in form of values of the measured parameters at room temperature are listed in Table 1.

Investigations on thermal diffusivity were performed for the temperature range from about 5 to about 95°C. In order to check repeatability of the obtained results, a basic cycle of temperature changes was repeated (sweeping range cycle). The programs of temperature changes of the oscillation base are illustrated in Fig. 3. In the investigations, harmonic excitations were used of the oscillation period of 60 s and the amplitude from 1.4 K to 3.1 K. Variability of the amplitude results from the changes of the system's resistivity of the Peltier elements at the temperature changes of the oscillation base. The frequency of recording the signals temperature changes was 2 Hz. The measurements were performed with turned-on the option of electronic compensation of the temperature of, so-called, cold ends of thermocouples.

Table 1. Density and specific heat of blade material at 20°C

Name	Density [$kg \cdot m^{-3}$]	Specific heat [$J \cdot kg^{-1} \cdot K^{-1}$]
Material of compressor blade of turbine jet engine	4470	527.72

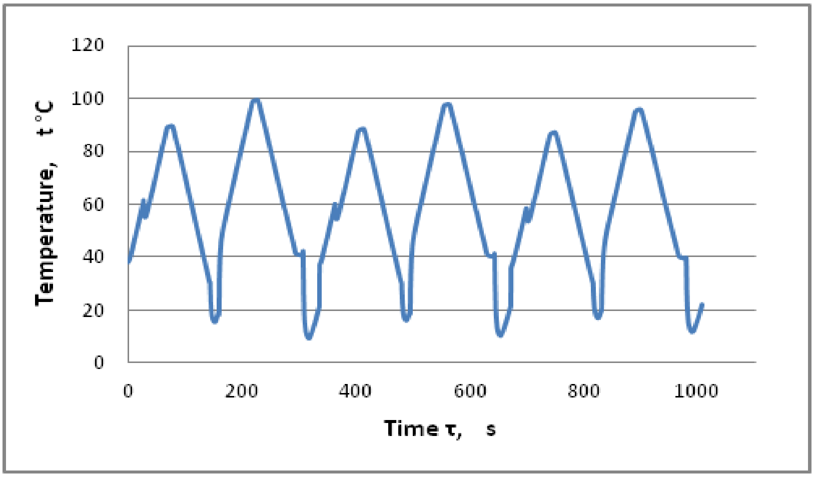


Fig. 3. Exemplary program of temperature changes of an oscillation base in time - sweeping program of the range from 5°C to about 95°C

3.3. Investigation results

The results of thermal diffusivity measurement are shown in Fig. 4.

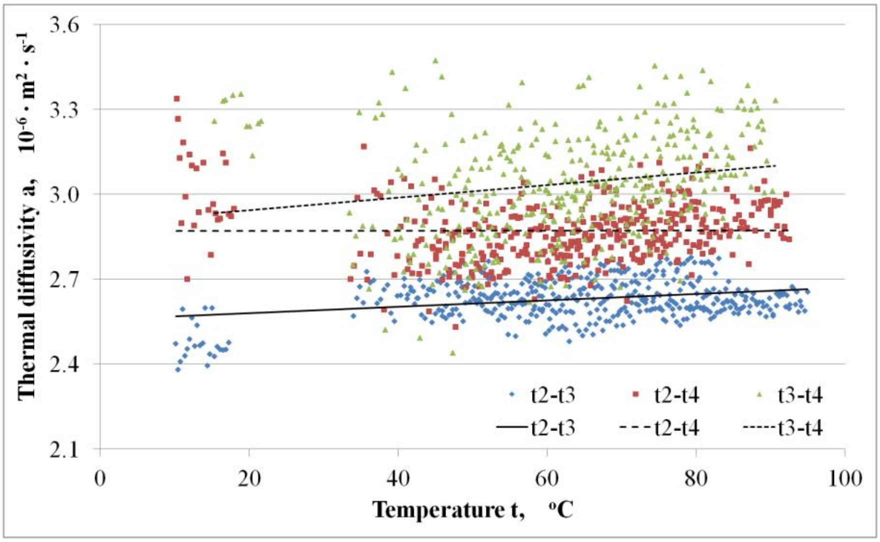


Fig. 4. Measurement results of thermal diffusivity, determined for particular pairs of signals: the calculation results are marked with the points and approximation results are marked with the lines

Only small fragments of the data, corresponding to the conditions of not-ordered heat exchange are excluded from the presentation: at the moment of the measurement's start and for each change of heating/cooling rate. In measurements, the compliance of heating and cooling data was obtained, what indicates on the lack of distinct durable effects of changes of properties of the investigated material or the effects of temperature hysteresis. It is also the basis for statement of the correctness of the obtained results. In the investigations, it was stated also that inaccuracy of keeping the given constant velocities of temperature changes and variable excitation amplitude, conditioned by variability of the resistance of the Peltier semiconductor elements, did not cause significant influence on the spread of measuring data.

The investigation results have been obtained by analysing the amplitude attenuation and the shift of quasi-sinusoidal phase of the temperature signal, so the amplitude and the phase values of thermal diffusivity have been obtained. The basis for analysis was the thermoelectric recording of the excitation signal and the thermal response at the ends of the fixed measuring sections, represented by adequate pairs of thermocouples. These sections are marked as t2-t3, t2-t4 and t3-4 (compare Fig. 2)

The presented results are average geometrical value of the diffusivity on the basis of the previously calculated amplitude and phase values, according to the original Ångström idea with the following relation

$$a_{geom} = \sqrt{a_{\varphi} \cdot a_{\psi}} \tag{10}$$

where: a_{φ} – phase results, a_{ψ}– amplitude results

The amplitude and phase results are the lower and upper limitations, respectively, for real values of thermal diffusivity. The analysis of results allows to notice that average geometrical values of the diffusivity, calculated on the basis of excitation signals and thermal responses, recorded by the thermocouples, increase with the increase in a distance between a surface of primary thermal excitation and the surface of response recording. It is caused by not fulfilled adiabatic phenomena conditions of side and upper surfaces of the specimen, what next causes increase in heat losses caused by the convection process. In relation to lateral losses, the effect is similar to the effect observed in the investigations with the applied classical Ångström method (compare [1], [11]). It is the basis for conclusion that the most reliable results are these elaborated for the pairs t2-t3 and t2-t4. Influence of heat losses has been determined on the basis of numerical analyses. Their precise presentation is not the subject of the hitherto work, but it has to be accepted that there is confirmed the hypothesis that when the heat is exchanged with environment, the real value of diffusivity is between the calculation values: amplitude values and phase ones. The results obtained after development of the measuring data for each measuring section were approximated using a linear function.

Obtained in this way, the functions of linear regression, show high quality compliance of the diffusivity results, obtained on the basis of measurements because for each pair of thermocouples, there is noticeable increase in the diffusivity values with rising temperature of the oscillation base.

The obtained results of thermal diffusivity measurement, using the data from Table 1, were calculated to the value of thermal conductivity of the blade material. The calculations were based on arithmetic average, calculated from three average geometrical values of diffusivity at 20°C. The results are listed in Table 2.

Table 2. Calculation results of thermal conductivity of the investigated material

Material	Thermal conductivity at 20°C [$W \cdot m^{-1} \cdot K^{-1}$]
Light alloy – compressor blades of aircraft turbine engine	6.71

4. SUMMARY

Interest in the temperature oscillation method for investigations on thermal diffusivity is connected with its good metrological conditioning. Its present applications are far beyond the strict area, determined in the primary Ångström idea (compare [3], [4], [7], [8], [9], [18], [20]). In the present case, the method in its modified version was used for examination of the material of compressor's blade of the turbine jet engine. Characteristic feature of the modified method of temperature oscillation is the possibility of achievement of high temperature resolution for determination of relation of temperature diffusivity when its dependence on temperature is defined. Due to application, in the calculations, precise relations of a mathematical model, the range of frequencies of the oscillation excitation, that can be used in investigations, has been expanded. All the above properties are important because they can strongly contribute to the possibility of application of the method and the procedures in non-destructive investigations of complete blades. Collective analysis of the obtained results allows for confirmation of such a possibility.

With regard to the partial results, over-estimation of the phase value and under-estimation of the amplitude value of thermal diffusivity were stated in the case when heat losses to the environment occurred.

This is consistent with the expectations and can be the basis for initial analysis of a measuring error. For three analysed cases of a combination between the excitation signal and the response signal, relatively small differences in values of thermal diffusivity were observed. These differences are transferred to the values of thermal conductivity, determined in this case only for 20°C.

They can be probably assigned to the not-fulfilled model condition on adiabatic phenomena of lateral (side) and top surfaces of the investigated specimen. In order to precisely determine influence of heat losses on the value of the being determined diffusivity, numerical calculations will be carried out, based on the analyses described in [14].

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Badania dyfuzyjności cieplnej materiału łopatki sprężarki turbinowego silnika odrzutowego metodą wymuszenia okresowego

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Streszczenie. W pracy omówiono wykorzystanie zmodyfikowanej metody wymuszeń okresowych do określenia dyfuzyjności cieplnej materiału konstrukcyjnego lotniczego silnika odrzutowego oraz przedstawiono zastosowane procedury badań. Bezpośrednią przyczyną podjęcia badań była konieczność identyfikacji i udokumentowania danych materiałowych do ich późniejszego wykorzystania w modelowaniu numerycznym obciążeń termomechanicznych konstrukcji. Długofalowo wykonane badania mają służyć opracowaniu szybkiej i skutecznej nieniszczącej metody określania właściwości cieplnofizycznych elementów konstrukcyjnych napędów lotniczych. Obiektem badań była próbka materiału pobrana z łopatki wirnikowej pierwszego stopnia sprężarki turbinowego silnika odrzutowego AŁ–21F3. Badania wykonano dla przedziału temperatury od 5 °C do 95 °C. Wartość dyfuzyjności cieplnej określono wykorzystując tzw. amplitudowe i fazowe cechy odpowiedzi na wymuszenie quasi-sinusoidalne. Analiza otrzymanych wyników potwierdziła skuteczność zastosowanej metody badań i pozwoliła na zidentyfikowanie badanego materiału, jako stopu tytanu.

Słowa kluczowe: dyfuzyjność cieplna, metoda Ångströma