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# OPTIMIZATION OF THE METHOD OF PULSED THERMAL DEFECTOMETRY OF EXTENDED DEFECTS

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*The authors discuss results of development and optimization of a procedure and equipment for determination of the parameters of extended defects in plates based on experimental and theoretical modeling of nonstationary heat fields.*

The temperature distribution over the surface of manufactured articles and objects exposed to a pulsed heat flux depends substantially on the shape, dimensions, location, and thermophysical properties of internal defects. Temperature gradients on the surface of a tested object are a criterion for the presence of a subsurface defect. An increase in the accuracy and sensitivity of the method and development of automated technological processes require further improvement of the methods and means of in-process thermal nondestructive testing (ITNT) and optimization of heating pulses as regards their power, number, and length. In some cases instead of thermal flow detection it is necessary to employ defectometry to measure the main parameters of a defect [1]. Use of available procedures based on the relationship between the parameters of a defect and numerical criteria for its detection do not resolve the problem since the same numerical criterion may correspond to defects differing in their parameters [2].

To resolve problems of defectometry, two related approaches are adopted in practice:

1. The first approach is experimental, in which artificial models of an object with embedded defects are used to vary input parameters (the depth of defect occurrence $h$ and its opening $d$) in order to experimentally obtain data on the output parameter (the temperature distribution over a defect surface and the dynamics of its change with time $T(h, d, t)$). Based on these data, interdependences of input and output parameters or mathematical relations between them are established. For this, the methods of analysis of variance, regression, and correlation are used.

In experiments, it is necessary to have a set of standard objects with the required range and discreteness of variation of the defect parameters. The main difficulties are associated with the necessity of providing the devices for temperature measurement that ensure high temperature space, and time resolution.

2. The second approach is based on a solving inverse problems of nonstationary heat conduction [3]. In this case, the mathematical formalization of the procedure of determination of the parameters of subsurface defects includes the creation of a set of standard "objects," henceforth called direct problems, and processing of the experimental measurement results with the aid of an algorithm of comparison of these results with theoretical data obtained in solving the direct problems. Such an approach is well-known in the literature; however it consists of individual calculations and is difficult to be generalized. In the case of mathematical modeling, the optimum parameters of heating and the maximum potentialities of the method may be found by changing the duration of radiative heating.

The present work is devoted to development of methods and equipment for determination of the parameters of extended defects in plates, experimental studies and mathematical modeling, optimization of the method, and determination of its maximum potentialities.

Thermal processes in objects with defects are complicated due to the combined effect of defect parameters and thermophysical characteristics of the material of the tested object.

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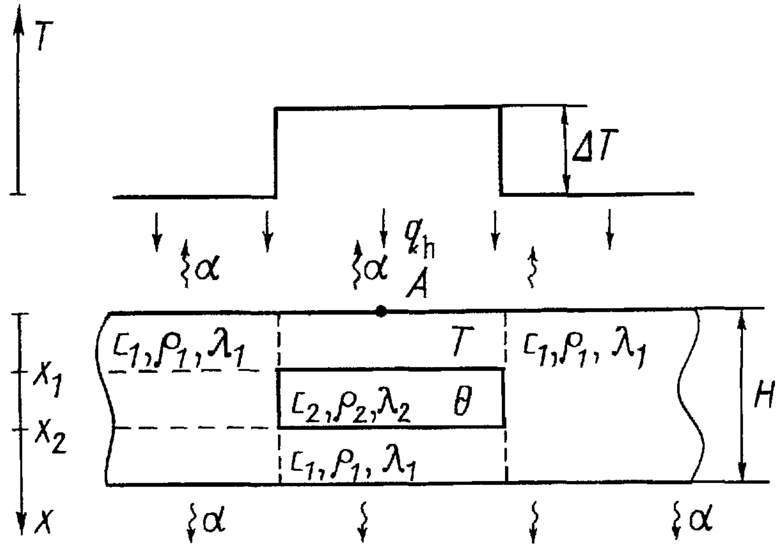



Fig. 1. Model of in-process thermal nondestructive testing.

A mathematical model of ITNT includes a system of nonlinear differential equations of nonstationary heat conduction that cannot be solved analytically because of their complexity. Therefore as the main tools of theoretical analysis of thermal testing we adopt mathematical modeling and a computational experiment that make it possible to obtain sufficiently complete information about the ITNT parameters and use it for optimization of testing.

Having common properties with a natural experiment, a computational experiment possesses some specific features:

first, it permits separate consideration of the influence of each input parameter on the temperature field; specifying changes in any parameter within certain limits, we may observe how this change influences the output parameters;

second, a computational experiment makes it possible to "conduct" ITNT in a sufficiently wide range of parameters without modifying available devices or designing new ones. This is of particular importance for determining the maximum potentialities of the method used for testing objects with defects with a very short time for establishing equilibrium between defect and defectless zones.

Until recently there was no systems approach to solving ITNT problems on the basis of mathematical modeling and a computational experiment that could cover all stages of development from evaluation of the parameters of testing to a procedure for its realization.

We shall consider a sufficiently general physical model, namely, an infinite plate (Fig. 1) of thickness $H$ that has an extended internal defect with a depth of its occurrence $h$ and an opening $d$. The thermophysical properties of the plate are $\lambda_1$, $\rho_1$, $c_1$, and of the defect $\lambda_2$, $\rho_2$, $c_2$.

The defect is extended since its transverse dimensions are much larger than the depth of its occurrence, and therefore defect and defectless regions participate in heat transfer independently of each other. In such a statement the analysis of the process of heat transfer can be performed on the basis of a mathematical model described by a one-dimensional differential equation of unsteady-state heat conduction. For the defectless region, the equation is written for an infinite plane-parallel plate, and for the defect region for an infinite three-layer plate where the intermediate layer models an air defect (Fig. 1). Defects representing an inclusion of foreign substances (e.g., slags) are modeled by specifying the appropriate $\lambda$, $\rho$, $c$ values.

In order to obtain information on the parameters of subsurface defects, the plate (Fig. 1) was preliminarily heated by pulsed radiant heat, uniformly distributed over its surface, with duration $\tau_h$ and density $q_h$. The dynamics of temperature variation in time $T_{exp}(t)$ after cessation of heating was investigated at the point $A$ ($x = 0$) on the heated surface.

The heat conduction equation and the linearized boundary conditions are as follows:

$$c\rho \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2}, \tag{1}$$

$$T|_{t=0} = T_m,$$

$$\lambda \frac{\partial T}{\partial n}\Big|_{x=0} = \begin{cases} q_h - \alpha^* (T - T_m), & t \le \tau_h, \\ -\alpha^* (T - T_m), & t > \tau_h, \end{cases}$$

$$-\lambda \frac{\partial T}{\partial n}\Big|_{x=H} = \alpha^* (T - T_m),$$

$$\lambda_1 \frac{\partial T}{\partial n}\Big|_{x=x_1} = \lambda_2 \frac{\partial \Theta}{\partial n}\Big|_{x=x_1}, \quad T|_{x=x_l} = \Theta|_{x=x_l},$$

$$\lambda_2 \frac{\partial \Theta}{\partial n}\Big|_{x=x_2} = \lambda_1 \frac{\partial T}{\partial n}\Big|_{x=x_2}, \quad \Theta|_{x=x_2} = T|_{x=x_2}.$$

The linear approximation for radiant flux is valid because of the small temperature difference $T - T_m$.

The problem was solved by a numerical method using an implicit scheme [4]. The uniqueness of the solution was proved by comparing the calculation results with those obtained by solving the same problem by a numerical method using explicit and combined schemes.

To decrease the calculation time, we performed optimization relative to space and time steps.

In order to solve Eq. (1), it is necessary to know the coefficients in the equation. The heat transfer coefficient of the plate surface was determined under the assumption that the heat transfer between the medium and the heated plate is a result of simultaneous action of convective heat transfer and thermal radiation:

$$\alpha^* = \alpha_c + \alpha_{rad},$$

where $\alpha_c$ and $\alpha_{rad}$ are the coefficients of convective and radiative heat transfer.

Based on results of [5] and a comparison of numerical solution (1) with experimental data, we assumed that the dependence of $\alpha^*$ on the temperature difference $T - T_m$ is linear.

In the region of air defects, the most common ones under actual conditions of thermal nondestructive testing, heat may be transferred by convection, conduction, and radiation. If the product of the Grashof and Prandtl numbers is smaller than 1000, convection and radiation are neglected. This condition corresponds to temperature drops less than 100°C in the defect region with a defect thickness of < 5 mm [3].

The thermophysical characteristics were measured experimentally by a nonstationary method characterized by a short measurement time and the possibility of determination of $\lambda$ and $c$ from a single experiment. A solution algorithm for the problem of determination of the thermophysical characteristics includes one-sided surface heating of a plate made of the tested material by a pulsed radiant heat flux, recording of the temperature variation in time on the side of the plate opposite the heating. The thermophysical characteristics were calculated by the method of successive approximations using multiple solutions of the direct problem of nonstationary heat conduction and comparing the experimental and calculated data. After each iteration we changed either the thermal conductivity $\lambda$ or the heat capacity $c$. The criterion for finding a solution was a minimum of the discrepancy functional. Experimental thermograms were measured with the aid of an automated computational complex described below. The memory of the computer included in the complex was filled with a databank that includes an array of calculation thermograms, which allows the thermophysical characteristics to be determined in real time.

Although the model is simple (Fig. 1, Eq. (1)), it manifests the main regularities of unsteady-state heat transfer in a plate with an extended defect. This model permits determination of the maximum potentialities in measuring the defect parameters: the depth of defect occurrence and its opening (thickness).

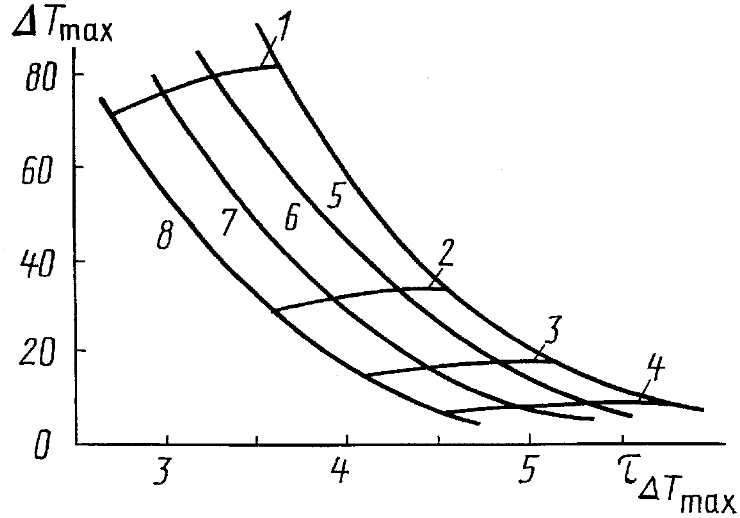



Fig. 2. Maximum temperature difference between the defect and defectless regions $\Delta T_{max}$ as a function of the time required to attain it $\tau_{\Delta T_{max}}$ for a titanium alloy plate: 1–4, calculation for $h$ = 1.0, 2.0, 3.0, 4.0 mm; 5–8, calculation for $d$ = 1.4, 0.8, 0.4, 0.2 mm. $\Delta T_{max}$, $^{o}$C; $\tau_{\Delta T_{max}}$, sec.

We now consider an algorithm for determination of the parameters of an extended defect in an infinite plate of thickness $H$. Preliminarily, we specify the ranges of variation of the depth of defect occurrence and its opening and ascertain the possibility of detection of defects with the specified parameters by the nonstationary thermal method.

As is known [6], subsurface defects may be detected by the thermal metod if they lead to a pronounced difference in the temperatures on the object surface above defect $T_d$ and defectless $T_{dl}$ zones. The criterion of detection of defects may be written in the form

$$\Delta T_d(t) = T_d(t) - T_{dl}(t) \geq m\Delta T_r ,$$

where $m$ is the signal/noise ratio; $\Delta T_r$ is the temperature resolution of the device used for measurement of surface temperatures.

In order to establish the relationships between the space-time structure of the surface temperature field and the internal structure of the tested object, we carried out a computational experiment using mathematical model (1).

Preliminarily, the optimum parameters of thermal testing, i.e., the power $q_h$ and duration $\tau_h$ of heating, were determined by solving inverse problems. For this, by solving direct thermal problems with different $q_h$ and $\tau_h$ values, we established the combination of them for which $\Delta T_d$ was at its maximum. In so doing, optimization of the heating parameters was performed for subsurface defects. For physical reasons (the lack of superheating, heater parameters, and the execution time of a manipulating robot) the following constraints on the input parameters were introduced:

$$T_{max}(1) \leq 140^{\circ}\mathrm{C}, \quad q_h \leq 150000\ \mathrm{W/m^2}, \quad \tau_h \geq 0.5\ \mathrm{sec},$$

where $T_{max}(1)$ is the temperature on the heated side of the plate at the moment of cessation of heating.

Next, by solving direct problems (1) with the depth step $\Delta h$ = 2.0 mm and the opening step $\Delta d$ = 0.2 mm in the ranges $h$ = 1.0 – 5.0 mm and $d$ = 0.2 – 1.4 mm, we found the dependences of the maximum temperature difference $\Delta T_{max}$ between defect and defectless zones and the time of attaining the maximum temperature difference $\tau_{\Delta T_{max}}$ on the depth of defect occurrence for different openings. The data obtained were used to construct nomograms $\Delta T_{max} = f(\tau_{\Delta T_{max}})$ for different $h$ and $d$ (Fig. 2). The obtained relations were employed to determine the appropriateness of conducting the in-process thermal testing and narrowing the domains of search for the defect parameters. For this, the object surface was heated by a pulsed radiant flux with the parameters $\tau_h$ and $q_h$ determined above with account for the optimization conditions required for detection of subsurface defects. Then an experimental chronological thermogram was taken for defect and defectless zones on the heating side in the cooling-off stage of the plate. From the measured thermogram the values of $\Delta T_{max}$ and $\tau_{\Delta T_{max}}$ were determined, and from the nomograms the ranges $\{h_{min} - h_{max}, d_{min} - d_{max}\}$ were found within which the defect parameters were determined. Within the limits of the chosen region of determination of the defect parameters, the latter were determined conclusively by solving inverse thermal problems. Preliminarily, a computational experiment was carried out to optimize the heating parameters for a defect with $h_{min}$ and $d_{max}$ and to choose the steps $\Delta h$ and $\Delta d$ and the time interval $t_0 - t_{max}$ within which the chronological thermograms would be analyzed.

The parameters of heating $q_h$ and $\tau_h$ were chosen from the condition

$$T(h_{min}, d_{max})|_{\tau_h} \le 140^{\circ}\text{C},$$

and the temperature difference for the optimum combination of $\tau_h$ and $q_h$

$$\Delta T(t) = T(h_{min}, d_{max}, t_k) - T(h_{max}, d_{min}, t_k) \tag{2}$$

must be maximum. Constraints for $\tau_h$ and $q_h$ were chosen as mentioned above.

To determine the steps $\Delta h$ and $\Delta d$ in the chosen region $\{h, d\}$, we may use the conditions

$$\begin{aligned} T(h_i + \Delta h_i, d_j, t_k) - T(h_i, d_j, t_k) \ge \Delta T_{meas}, \\ T(h_i, d_j + \Delta d_j, t_k) - T(h_i, d_j, t_k) \ge \Delta T_{meas}. \end{aligned} \tag{3}$$

A computational experiment aimed at a search for the steps $\Delta h$ and $\Delta d$ has shown that the temperature difference between two chronological thermograms, differing by $\Delta h_i$ at a constant opening, is at its maximum within small times (i.e., just after heating cessation), while in the case of a change in the opening by $\Delta d_j$, with the depth of defect occurrence being constant, the temperature difference is at a maximum within the region of large times approaching the relaxation time of the temperature field above the defect and defectless regions.

In connection with this, bounds of the time interval $t_0 - t_{max}$ within which chronological thermograms are calculated and measured are determined from the relations

$$\tau_h \le t_0 \le \min\left\{t_{0i}\right\},$$

where $t_{0i}$ is found from a numerical solution of the problem

$$J = \max\left\{T(h_i + \Delta h_i, d_j, t_{0i}) - T(h_i, d_j, t_{0i})\right\}, \tag{4}$$

and $t_{max}$ is determined from the condition

$$t_{max} \ge \max\left\{t_{max\,j}\right\}.$$

Here $t_{max\,j}$ is found by solving numerically the following problem:

$$J = \max\left\{T(h_i, d_j + \Delta d_j, t_{max\,j}) - T(h_i, d_j, t_{max\,j})\right\}, \tag{5}$$

where

$$i = 0, \ldots, N; \quad N = \frac{h_{max} - h_{min}}{\langle \Delta h_i \rangle},$$

$$j = 0, \ldots, M; \quad M = \frac{d_{max} - d_{min}}{\langle \Delta d_j \rangle},$$

$$k = 0, \ldots, K; \quad K = \frac{t_{max} - t_0}{\Delta t}.$$

The value of $\Delta t$ is determined by the time resolution of the measuring device.

Using the obtained parameters of testing, by solving direct thermal problems (1), we compose a bank of calculated thermograms $T_t (h_i, d_j, t_k)$. The parameters of a defect are found from a comparison of the experimental thermogram $T_{exp}(t_k)$ with the bank of calculated thermograms.

As a criterion for determination of the desired characteristics $h_0$, $d_0$ of a defect among the set of solutions, use may be made, of minimization of the discrepancy functional [7] of realizations produced by thermal testing and calculations

$$J (h_0, d_0) = \frac{1}{p - 1} \sum_{k=1}^{p} [T_t (h_i, d_j, t_k) - T_{exp} (t_k)]^2.$$

To find solutions of the given extremal problem, we used an iteration technique. The iteration process was stopped at a discrepancy within the error of temperature measurement $J \le \delta^2$, where $\delta^2$ is the mean square deviation of temperature measurement.

Since the calculation time of direct problems for a three-layer plate is small, we may solve inverse problems on determination of the parameters of extended defects without composing a bank of reference thermograms.

Chronological thermograms were measured experimentally with the aid of an automated computational complex (ACC). The ACC consisted of a device for pulsed radiant heating (PRH), a heat field recorder, and a measuring-computational unit.

The device for PRH was assembled of a block of halogen lamps (of the type KGT 220-2000), a thyristor power unit for the lamps, an insertion-withdrawal device for the block of lamps from the heating zone, based on a manipulating robot, and a control unit for a PS-09 robot.

The heat field recorder was based on the receiving chamber of an "Élektronika TV-03" IR imager. The video signal from the TV-03 chamber was converted by an A/D converter into a digital code and sent via an interface board directly to the working memory of an IBM PC/AT personal computer.

Control and synchronization of the operation of the computational complex was accomplished with the aid of a control unit at whose input pulses from the power unit for the lamps, the robot, and the interface board arrived.

In order to improve the metrological characteristics of the complex, provision was made for a reduction in instrumental errors through analog and programmed compensation as well as for periodic calibration against a model of a blackbody with a temperature stabilization block.

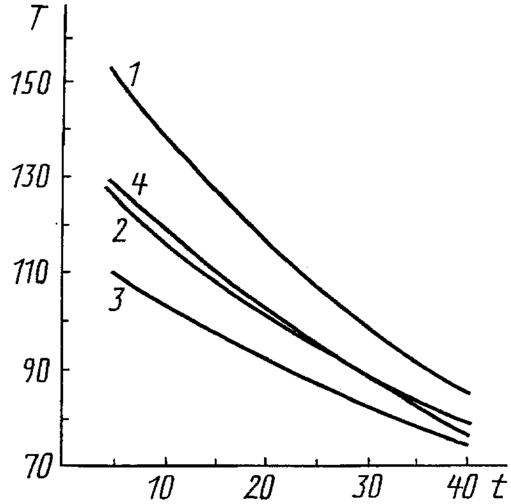
Energy parameters of the heating source were measured by a heat flux transducer designed at the Institute of Engineering Thermophysics, Ukrainian Academy of Sciences [8].

The automated computational complex provided a record of up to 1000 IR images under programmed control with a minimum time interval of 0.2 sec between the frames and temperature measurement at any point of a frame in the range 25–145 °C with an error of ±1°C.

To evaluate the method, we employed four model samples, manufactured from a titanium alloy, with subsurface defects having the following parameters:

sample 1: $h_1$ = 1.00 mm, $d_1$ = 1.05 mm;
sample 2: $h_2$ = 4.00 mm, $d_2$ = 1.05 mm;
sample 3: $h_3$ = 1.00 mm, $d_3$ = 0.20 mm;
sample 4: $h_4$ = 4.00 mm; $d_4$ = 0.20 mm.

The thickness of a plate was 6.2 mm, and the precision of manufacture was ± 0.01 mm.The thermophysical characteristics of the material of the plates were as follows: $\lambda$ = 13.0 W/(m·deg); $c$ = 490 J/(kg·deg); $\rho$ = 4450 kg/m$^3$.



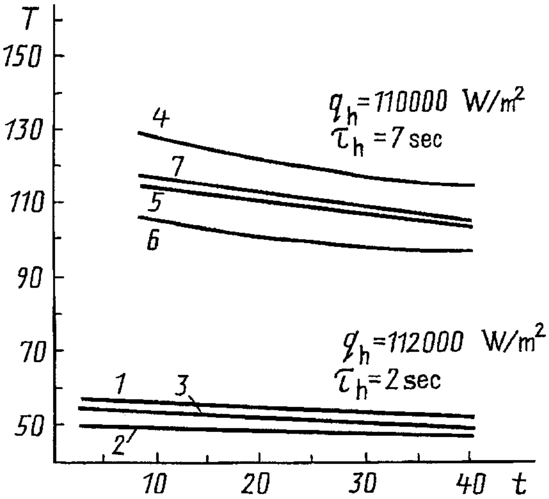




Fig. 3. Calculated and experimental thermograms for titanium alloy plates with an extended air defect (sample No. 1): calculated thermograms: $h = 0.8$ mm, $d = 1.2$ mm (1); $h = 1.0$ mm, $d = 1.1$ mm (2); $h = 1.2$ mm, $d = 1.0$ mm (3); 4) experimental thermogram, $q_h = 112{,}000$ W/m$^2$, $\tau_h = 2$ sec. $T$, °C; $t$, sec.

Fig. 4. Calculated and experimental thermograms for titanium alloy plates with an extended air defect (sample No. 2): calculated thermograms: $h = 3.5$ mm, $d = 1.2$ mm (1, 4); $h = 4.5$ mm, $d = 1.0$ mm (2, 6); $h = 4.0$ mm, $d = 1.1$ mm (5); 3, 7, experimental thermograms.

In the first stage, for samples Nos. 1 and 2 on the basis of numerical modeling the heating parameters for detecting subsurface defects ($q_h = 112{,}000$ W/m$^2$, $\tau_h = 2$ sec) were determined and a nomogram of the dependences $\Delta T_{max} = f(\tau_{\Delta T_{max}})$ was constructed (Fig. 2). Then, using the chosen heating parameters, experimental thermograms $T_{exp} = f(t)$ were taken, from which $\Delta T_{max}$ and $\tau_{\Delta T_{max}}$ were determined for each sample, and from the nomogram the domains of depths of defect occurrence and openings were determined within which the sought parameters of the defects would be calculated:

for sample No. 1: $0.8 < h_1 < 1.2$ mm, $0.6 < d_1 < 1.2$ mm;

for sample No. 2: $3.5 < h_2 < 4.5$ mm, $0.6 < d_2 < 1.2$ mm.

Next, a computational experiment with account for conditions (2)–(5) was carried out and the optimal parameters of heating as a function of the presumed depth of defect occurrence, the discreteness of variation of the parameters (the search step) $\Delta h$, $\Delta d$, and the time interval $t$ within the limits of which thermograms were calculated and measured were determined. As a result of the computational experiment, we obtained the following testing parameters:

for sample No. 1: $q_h = 112{,}000$ W/m$^2$; $\tau_h = 2$ sec; $\Delta h = 0.05$ mm; $\Delta = 0.05$ mm; $\Delta t = 40$ sec;

for sample No. 2: $q_h = 110{,}000$ W/m$^2$; $\tau_h = 7$ sec; $\Delta h = 0.2$ mm; $\Delta d = 0.05$ mm; $\Delta t = 40$ sec.

Using the data obtained, we composed a bank of calculated thermograms, measured the experimental thermograms, and determined the parameters of the defects by the method of minimization of the discrepancy functional. Figures 3 and 4 show some calculated and experimental thermograms for samples Nos. 1 and 2. As is seen in Fig. 3, the parameters of a subsurface defect are determined with good accuracy. A deeper defect (Fig. 4) required optimization of heating. The heating parameters chosen at the beginning of the experiment gave uninformative thermograms (curves 1–3). Optimization of heating yielded substantially better results (curves 4–7). Analogous studies were conducted for samples Nos. 3 and 4 with a defect opening of $d = 0.2$ mm.

The results obtained demonstrate that the suggested method ensures determination of the depth of occurrence of extended air defects with an opening of 0.25–1.0 mm with an error of at most 10% for a range of depth of occurrence of 1.0–4.5 mm in titanium alloy plates.

## NOTATION

$\lambda$, thermal conductivity; $c$, specific heat capacity; $\rho$, density of the material; $T$, calculated temperature for a defect; $t$, time; $n$, normal to the surface of the plate and the defect; $T_m$, temperature of the medium; $\Delta T_{meas}$, error of temperature measurement.

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