INFORMATION SIMULATION AND PROCESSING AT INSPECTION OF PRODUCTS WITH INTERNAL INHOMOGENEITIES USING ACTIVE THERMAL METHOD

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Abstract: Ways of making the active thermal NDT method more informative and reliable are being considered. It is suggested to perform thermophysical modeling of the object with inner heterogeneities before testing. The model analysis allows not only to optimize the control regime to increase signal caused by defect, but also to chose the best detection criterion.
The approach suggested was implemented at detachment detection in thermoprotective coatings applied on aircraft engine components and detection of cooling passages plugging in turbine blades of jet engines.

Introduction: While solving industrial tasks of active thermal NDT, a number of problems arise to increase the testing results reliability:

- to find the optimal regime of control, i.e. the values of the object heating time τ_H to the maximum permissible temperature and of the dead time τ_r (the point of the temperature field registration)
- to pickup the useful signal (a temperature contrast caused by a defect) against a noise background caused by heterogeneity of surface emissivity and other causes.

To resolve the problems mentioned an approach based on construction and analyzing of a thermophysical model of the control object (with defects) seems to be the most effective, the analysis lying in resolving of the direct problem of unsteady thermal conductivity in heterogeneous structures.

The objective of the model construction and analyzing is not only to calculate the optimal regime of control (by criterion of maximum temperature contrast), but also to choose another, more informative sign of the defect presence. Such a sign may comprise the time to peak temperature on various parts of a surface and derivative of the temperature time dependences.

At the approach development the following specific tasks were examined:

- Detachments detection in thermoprotective coatings applied on aircraft engine components.
- Detection of cooling passages plugging in turbine blades of jet engines.

Results: A two-bands plate is used as a model of thermoprotective coating in aircraft engine components, one layer corresponding to the thermoprotective coating by its thermophysical properties and the other corresponding to the substrate [1]. Air detachments over 0.1mm width were considered as a defect.

Boundary conditions on outer surfaces correspond to two-sided control scheme, namely: local heating of the object with thermal flux of a determined density **q** during a determined time τ_H and following registration of the temperature field on reverse surface (fig. 1).

Heat transfer through the defect and heat emission from outer surfaces are taken into account.

On the base of resolving of the direct problem of transient heat conduction the time dependence of the surface temperature was calculated, i.e. $T(\tau)$ for the faulty and unfaulty parts.

Evaluation of heat resistance respectively for metal layer of the substrate, thermoprotective coating layer and the air defect showed that the heat resistance of air layer is determinative at detachments widths under examination.

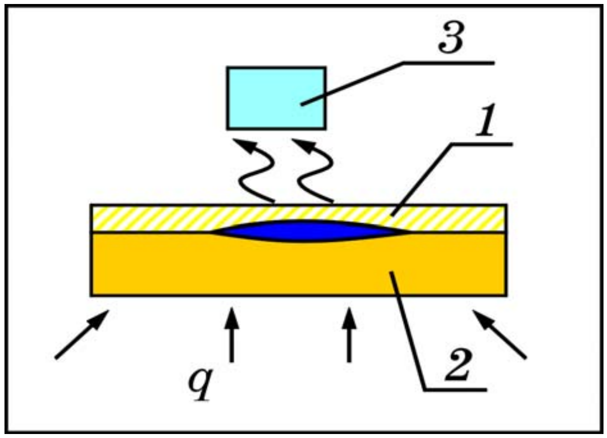

Fig. 1. Detachments in a thermoprotective coating: 1- coating, 2- substrate, 3-IRl imager.

The following expression [2] is obtained for temperature contrast above the defect (detachment of minor width):

$$\Delta T \approx \frac{q_o (c\rho h)_1 (c\rho h)_2}{[(c\rho h)_1 + (c\rho h)_2]^2} \cdot \frac{\delta}{\lambda_o},$$

where q_o is density of the heating power flux;

$(c\rho h)$ is product of thermophysical properties and thickness for substrate (1) and coating (2) respectively;

δ is air layer thickness;

λ_o is air heat conductivity.

Figure 2 shows the qualitative layout of the dependences $T(\tau)$ obtained.

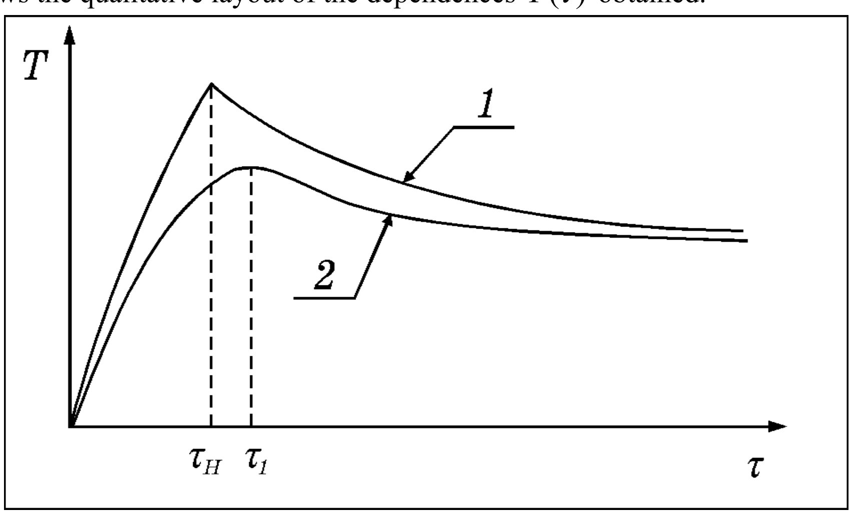

Fig.2. Surface temperature dependences on time for unfaulty (1) and faulty (2) parts of the structure.

It can be seen on the graphs that the coating temperature in the defect area keeps growing for some time τ_1 after heat stopping, while it decreases immediately in the unfaulty area; the coating temperature above the detachments always remaining lower than that at defects absence.
This gives grounds to introduce temporal informative parameter (instead of temperature contrast ΔT), namely:

$$\Delta\tau = \tau_1 - \tau_H \, .$$

Moreover, the difference between the graphs in angle of inclination (i.e. derivative $\partial T / \partial \tau$) close to the point τ_H also can be used as the complementary informative parameter. The proportion for the derivative obtained by the analysis is:

$$\frac{\partial T}{\partial \tau} \approx \Delta T \frac{\lambda_0}{\delta} \cdot \frac{1}{(c\rho h)_2} \approx \frac{q_0 (c\rho h)_1}{[(c\rho h)_1 + (c\rho h)_2]^2}$$

It should be mentioned that the value of the derivative to a first approximation does not depend on the detachment thickness. This is connected with the fact that, although heat resistance of a thin detachment is lower, but the temperature drop between the coating and the substrate which has formed by the end of heating is less to the same extent.
Experimental check of the results obtained was conducted with a specially elaborated test bench which included a halogen emitter as the heater, a rotary mechanism (for cylindrical samples) and IR imager IRTIS. It was determined that the temperature drop caused by real coating detachment from the substrate was 3-6 K and its value was comparable with those of noises caused by heterogeneity of the surface emissivity.
This is illustrated with the thermogram of an article with thermoprotective coating (see fig. 3). The noises nature does not allow identifying the defect with sufficient reliability.

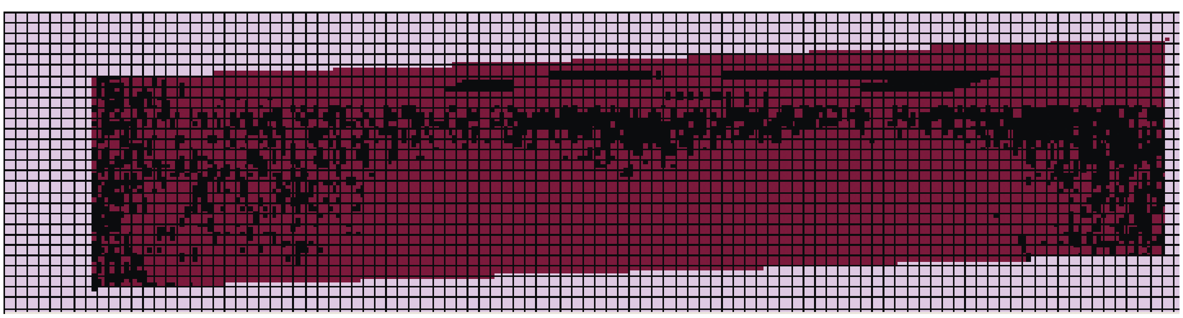

Fig.3. Thermogram of the thermoprotective coating with a defect (in the center) and noise caused by surface emissivity.

The experiment confirmed that the difference in dependences mode $T(\tau)$ for the faulty and unfaulty parts (fig.2) was indeed significant. Time lag $\Delta\tau$ to peak temperature was 2-4 sec, this allowing usage of the $\Delta\tau$ parameter as the criterion of the defect presence which is protected from the noises impact.
According to the second temporal informative parameter $\partial T / \partial \tau$ the difference between the faulty and unfaulty parts was 10 to 50 %.

The second sample object to be used for development of the authors' approach was turbine blades of aircraft engines with inner cooling passages. The task of active thermal NDT was to detect plugging of one or several of the mentioned passages.
Thermophysical model of this object presented in fig. 4 is simplified variant for one passage, the blade shape is not taken into account. Heat emission owing to air blow-through α_1, heat emission to the ambient medium α_2, heat flux **q** from the passage cooled to the blade body are taken into consideration in the model.

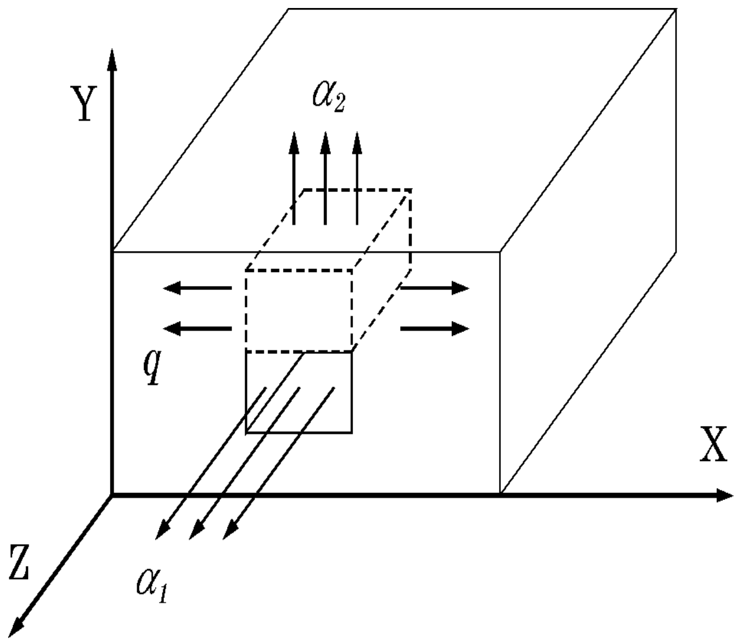

Fig. 4. Thermophysical model of the cooling passage in a turbine blade.

At the model analyzing the "rate of cooling" known by references data [3] is taken as the criterion of the defect presence. It was fixed that the rate of cooling (or their ratio taken for the unfaulty and faulty parts) is less informative than criterion μ determined by the ratio [4]:

$$\mu = \frac{h}{l} \cdot \frac{Nu}{Bi},$$

where Nu – Nusselt number, $Nu = \frac{\alpha_1 \cdot l}{\lambda}$;
l - effective length of the cooling passage; λ - coefficient of heat conductivity; Bi - Biot criterion, $Bi = \frac{\alpha_2 H}{\lambda}$; H – effective thickness of the plate (blade); h - depth of the cooling passage location.
It was showed that the μ criterion can be determined by cooling rate dependence on time for each pixel of the blade surface by processing of thermograms obtained at control (thermo-film). Processing algorithm was implemented by the FIRST software which was approved at blow-though control of a number of blades. Sample of control results is shown in fig. 5 as a generalized thermogram of a blade, areas of cooling passages plugging being marked.

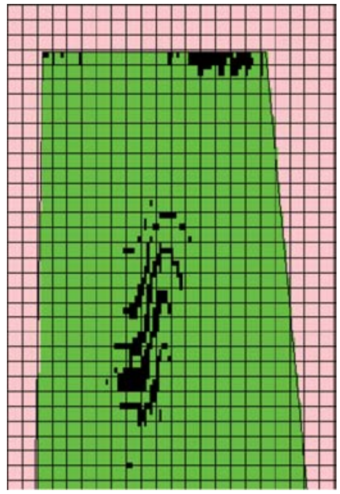

Fig. 5. The result of blow-though control of a serviceable blade.

We suggest usage of sum square of areas with passages plugging as the quality criterion for blades sorting. For the blade thermogram in fig. 5 this square makes 4% of overall square, thus presuming the blade to be serviceable.

Discussion: The results obtained are evidence of sufficient efficacy of the suggested approach to practical tasks of active thermal NDT. Preliminary thermophysical analysis of the control object (with a defect) gives possibility to determine an optimal control regime before actual experiments and evaluate the signal expected (temperature contrast) caused by the defect [5].

However the modeling does not allow taking into account the influence of the noises on the defects detection, first of all those caused by heterogeneity of the emissivity coefficient. Yet, as the abovementioned experimental data showed, this interference may be rather significant. Like the temperature drop equivalent to the noise was of the same value as the useful signal for thermoprotective coatings. The same situation was with turbine blades. But also in such cases it proved to be very useful to have a thermophysical model of the object. It gives possibility to seek for a defect criterion other than conventional amplitude criterion (temperature contrast). In particular, to detect a detachment in thermoprotective coating, it was possible to suggest time lag to peak temperature $\Delta\tau$ as such a criterion, and also the value of the derivative from $T(\tau)$ function which was calculated close to the end of heating.

A new criterion μ is suggested for detection of cooling passages plugging in turbine blades, which is in fact also a temporal criterion as it is based on thermogram each pixel cooling rate dependence on time.

Usage of the informatives parameter suggested undoubtedly complicates the thermograms processing and prolongs the control procedure. However these spending proved to be justified as it was possible almost completely to escape the noises impact and thus to increase the control results reliability.

Conclusions: To solve practical tasks of active thermal NDT it is worthwhile to use a complex approach including the stages:

- construction and analysis of the control object thermophysycal model;
- experimental check of the analysis results with a limited quantity of the control object articles;
- choosing of the most effective informative feature of the defect detection (criterion for the defect);
- algorithm development for the data processing and its software implementation;

– building of a controlling system with devices to add to the IR imager (heater, control object relocating mechanism, etc.).

The efficacy of the complex approach suggested was confirmed with solving of active thermal NDT tasks for detection of detachments of thermoprotective coatings in aircraft engines components and for detection of cooling passages plugging in turbine blades.

References: 1. Storozhenko V. A., Melnik S. I., Meshkov S. N., *Thermal defectometry of thermoprotective coatings of aircraft components*. Materials of the 4th National Exhibition “Non-destructive Control and Technical Diagnostics”, Kiev (2003): 344-349.

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5. Storozhenko V. A., Vavilov V. P., Volchek A. D., *Non-destructive quality control of industry products with active thermal method*. Kiev, Tehnika (1998): 127.