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Analysis of Temperature-rise of the Material Surface over Hidden Defect Thermally Stimulated in Active Thermography

Abstract. *The paper presents the simulation results of heat transfer in a homogeneous material with an invisible defect located at some depth. The tested material is subjected to thermal excitation and defect detection is based on analysis of temperature-rise of the material surface. Temperature field can be observed by IR camera. The influence of chosen factors on the shape of temperature-rise curves is analyzed. The processed thermogram with a new thermal contrast, called filtered contrast, gives more information on the thermal nature of the arrangement of tested and defect materials than the analysis of the raw temperature-rise that is valuable for quantitative characterization of defects.*

Streszczenie. *W artykule przedstawiono wyniki symulacji wymiany ciepła w jednorodnym materiale z defektem położonym na pewnej głębokości. Badany materiał jest poddawany pobudzeniu cieplnemu, a wykrycie defektu jest oparte na analizie przyrostów w czasie temperatury powierzchni materiału, rejestrowanych np. za pomocą kamery termowizyjnej. Zbadano wpływ wybranych czynników na kształt krzywej przyrostów temperatury. Zastosowanie nowej formuły kontrastu termicznego, zwanego kontrastem filtrowanym, do analizy termogramu dostarcza dodatkowej informacji o naturze układu materiał badany - materiał defektu w porównaniu z analizą przyrostów temperatury, co jest pożądane w ocenie defektu. (**Analiza przyrostów temperatury powierzchni materiału nad ukrytym defektem pobudzanym termicznie metodą aktywnej termografii**).*

Keywords: nondestructive testing, subsurface defect detection, analytical model of heat transfer, thermal contrast
Słowa kluczowe: badania nieniszczące, detekcja wad podpowierzchniowych, model analityczny wymiany ciepła, kontrast termiczny

Introduction

Active thermography visualizes subsurface defects through analysis of temperature differences in the transient heating or cooling phase while the object is thermally stimulated. Typically, an external stimulation is applied by means of heat sources, i.e. incandescent lamps or flashes. Two approaches are commonly used: transmission and reflection modes. In the transmission mode the tested material is heated or cooled from one side while the infrared camera views the rear surface. In the reflection mode instead both the heating or cooling source and the camera are positioned on the same side of specimen [1]. The change in temperature of material can be also obtained by conversion of mechanical energy to internal, realized by mechanical vibrations. This kind of active thermography is called vibrothermography [2]. It seems that, in practical realization, the easiest stimulation is a step heating by using the incandescent lamps e.g. bulbs. However, two conditions must be fulfilled: warming time of the lamp should be as short as possible to be negligible, and power dissipated to the specimen should be constant during data collecting performed by IR camera. Another kinds of shapes are impulse (impulse thermography - TSR) [3] or sinusoid (lock-in thermography) [4].

The size of appeared defects can be estimated either directly from the analysis of a single thermogram by exactly known spatial resolution of the employed optics or by reference to known size of specimen. It is the standard ability of computer software integrated with IR camera. Quantitative information about depth and nature of defects can be acquired by post-processing of sequence of thermograms. Furthermore, a thermal diffusion can be carried out as shown for example in [5] with thermography as an alternative to the other techniques [6]. To realize these objectives, sophisticated software packages implementing validated results of research or extra functionality of existing programs are required.

Background

In [7] the experimental setup to study the metrological properties of algorithms of thermogram processing was presented. In addition, the proposed mathematical formula called the filtered contrast, as a way to compensate the nonuniformity of heat disposal to the material surface was also described. In fact, it is an alternative to other methods of approximation of thermal background, e.g. using polynomials [8]. In [9] the attempts of estimation of the uncertainty of determining the depth at which the defect is located are presented. The method of propagation of probability distributions using Monte Carlo techniques was applied. In [10] authors' achievement were summarized and an algorithm of automatic defect detection and localization, counting the detected defects and estimating the coordinates of characteristic points of defects (local maxima) are presented.

This paper discusses the simulation results of heat transfer in a homogeneous material with a defect located at some depth. The tested material was subjected to thermal excitation and then a temperature-rise of the surface was analyzed to detect the flaw. Because the considerations are limited to one-dimensional analytical model, the temperature-rise is determined only in one point. Furthermore, the material is treated as a semi-infinite body. The modelling was carried out for various value of thermal mismatch factor of the arrangement consisting of tested and defect materials and various ratio of defect depth to thickness of tested material. The temperature-rise in time for area with subsurface defect was compared with processed data according to the idea of filtered contrast.

Principle of flaw detection by IR active thermography

Fig.1 presents a section of the inspected material (*mat*) with inclusion of another material classified as defect (*def*). It is assumed that material is infinitely widespread in the directions perpendicular to the radiation of heat source and the thickness of material equals L along the direction parallel to radiation. The front-face surface of defect is flat and is located at depth L_{def}. Thermal properties of tested material and defect are described by effusivity, which is constant throughout the whole volume of each material, and is defined as:

$$e = \sqrt{\lambda \cdot \rho \cdot c_p} \tag{1}$$

where: λ – heat conductivity, W/(m·K), ρ - density, kg/m^3, c_p – specific heat, J/(kg·K). If $e_{mat} \neq e_{def}$ then temperature over defect-free area T_1 in Fig. 1 differs from temperature T_2 over defect.

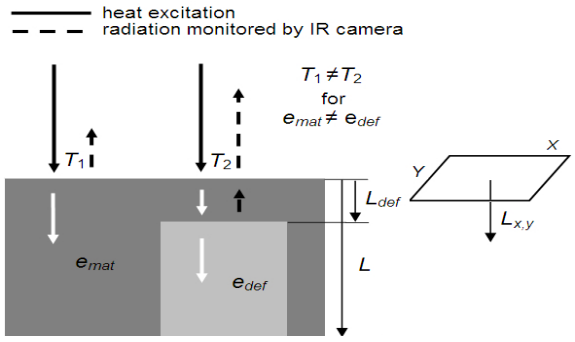

Fig. 1. Heat transfer in homogenous and inhomogeneous body, where *mat* - tested material, *def* – defect

An infrared thermographic camera can be applied to register a 2D temperature distribution of specimen surface and hidden defects can be easily detected. To characterize thermally the set of two materials a thermal mismatch factor Γ (in some papers called "reflection ratio") is used, and defined as follows:

$$\Gamma = \frac{e_{def} - e_{mat}}{e_{def} + e_{mat}} \tag{2}$$

It is dimensionless and varies from constant range of -1 up to 1. Its value gives information how much two materials differ in thermal sense. If thermal mismatch factor is close to 1 it indicates a good ability to draw a distinction between a defect and defect-free areas by analysing the temperature gradient on the surface of inspected material. Additionally, if $\Gamma \neq 0$ then sign of Γ indicates which material is a thermal insulator in relation to the second. Table 1 explains the meaning of thermal mismatch factor in thermographic nondestructive testing - TNDT.

Table 1. Thermal mismatch factor Γ and its meaning in TNDT

Γ	Thermal mismatch factor	Defect is … in relation to tested material	Temperature-rise of the surface…*	Detectability of defect by active IR thermography
-1	high	good thermo insulator	faster	high
-0,1	low	weak thermo insulator	slightly faster	low
0	lack	the same	the same	impossible
0,1	low	weak thermo conductor	slightly slower	low
1	high	good thermo conductor	slower	high

* temperature-rise of the surface of material with defect related to defect-free material

For defect detection purpose the temperature field of the material surface has to be observed during heating phase. According to [11], temperature-rise in time above the initial temperature T_o, of the hypothetical point of surface with coordinate x, is given by 1D analytical model expressed by equation (3), where: a_{mat} is diffusivity of material, L_x is thickness of material for point of surface with coordinate x. Parameter C_x depends on many factors, i.e: surface emissivity, surface reflectivity and radiation intensity of heat source. It was assumed, that C_x was constant for every point along x axis, hence $C_x=C_{def}=C_{mat}$, furthermore $C_x=1$ K/s$^{1/2}$. The next simplification is caused by *infinity* symbol (∞) in (3):

$$\Delta T(\tau) = C_x\sqrt{\tau}\left\{1+1+\sum_{n=1}^{\infty}2(-\Gamma)^n\left[exp\left(-\frac{n^2L_x^{\,2}}{a_{mat}\cdot\tau}\right)-\right.\right.$$
$$\left.\left.-\frac{nL_x\sqrt{\pi}}{\sqrt{a_{mat}\cdot\tau}}erfc\left(\frac{nL_x}{\sqrt{a_{mat}\cdot\tau}}\right)\right]\right\} = C_x\sqrt{\tau}\left[1+f(L_x,\Gamma,\tau,a_{mat})\right] \tag{3}$$

In practical calculations the finite number of terms of sum must be taken. For more than 10 terms the differences in shapes of temperature-rise curves are negligible.

In [7], a new kind of contrast was proposed, so-called „filtered contrast". For better text clarity its definition will be re-called. Filtered contrast is calculated as a subtraction of raw thermogram and smoothed thermogram. Smoothing can be carried out by 2D Gaussian filtering [7, 9] or polynomial approximation [8] for example. It hides potentially occurring defects; hence the temperature of surface over defect is the same as temperature for defect-free areas. If L is the total thickness of specimen and L_x (Fig. 1) is thickness of layer over point with coordinate x then inserting (3) into definition of the filtered contrast it can be modelled as follows:

$$\begin{aligned} KF_m(\tau) &= T(\tau) - filter(T(\tau)) = \\ &= \Delta T(\tau) - [filter((T(\tau) - T_0)] = \\ &= C\sqrt{\tau}\left[f(L_x,\Gamma,\tau,a_{mat}) - f(L,\Gamma,\tau,a_{mat})\right] \end{aligned} \tag{4}$$

Relative filtered contrast, also proposed in [7] can be modelled as follows:

$$KFWP_m(\tau) = \frac{\Delta T(\tau) - [filter(T(\tau) - T_o)]}{filter(T_{x,y}) - T_o} =$$
$$= \frac{f(L_x,\Gamma,\tau,a_{mat}) - f(L,\Gamma,\tau,a_{mat})}{1+f(L,\Gamma,\tau,a_{mat})} \tag{5}$$

The benefit of using it instead of filtered contrast *KF* is that *KFWP* is dimensionless and does not depend on scale of temperature. The disadvantage of it is its higher noise sensitivity.

Results and discussion

The simulation was carried out assuming that the specimen is made of Plexiglas with a_{mat}=0,11·10^{-6} and thickness L=11,1 mm. Fig. 2 presents a temperature-rise in time according to (3) as a function of Γ and L_{def}/L, where $L_x=L_{def}$ for defective one area. Calculations were performed for ratio of L_{def}/L varying from 0,1 up to 1 and the value of thermal mismatch factor from full range, i.e. -1 to 1.

For example, if Γ=-1 it means that a defect is an insulating material (e.g. air gap) in relation to the sample material (Plexiglas) and if Γ=1 it means that a defect is good conductor (e.g. metallic-inclusion).

From Fig. 2 the following conclusions can be drawn:

- for $\Gamma \approx 0$ or $L_{def} \rightarrow L$ a temperature range of ΔT is small; hypothetically, a considerable error of determination of defect depth can occur.
- for Γ =-1 ΔT is greater than in case of Γ=1; for Γ=-1 the second layer (defect) is thermo insulator and heat-losses to the material of defect are small.
- for Γ =1 and L_{def}/L=0,1 the ΔT is about 2K; the second layer draws in the heat, hence the temperature-rise in time of first layer is low.
- for Γ =-1 and L_{def}/L=0,1 the ΔT is about 50K; the second layer (defect) is a thermo insulator and the first layer

(tested material) has a small heat capacity due to small thickness.

- no matter what sign of Γ is, the ΔT is greater than 0 and estimation of sign of Γ is not possible.

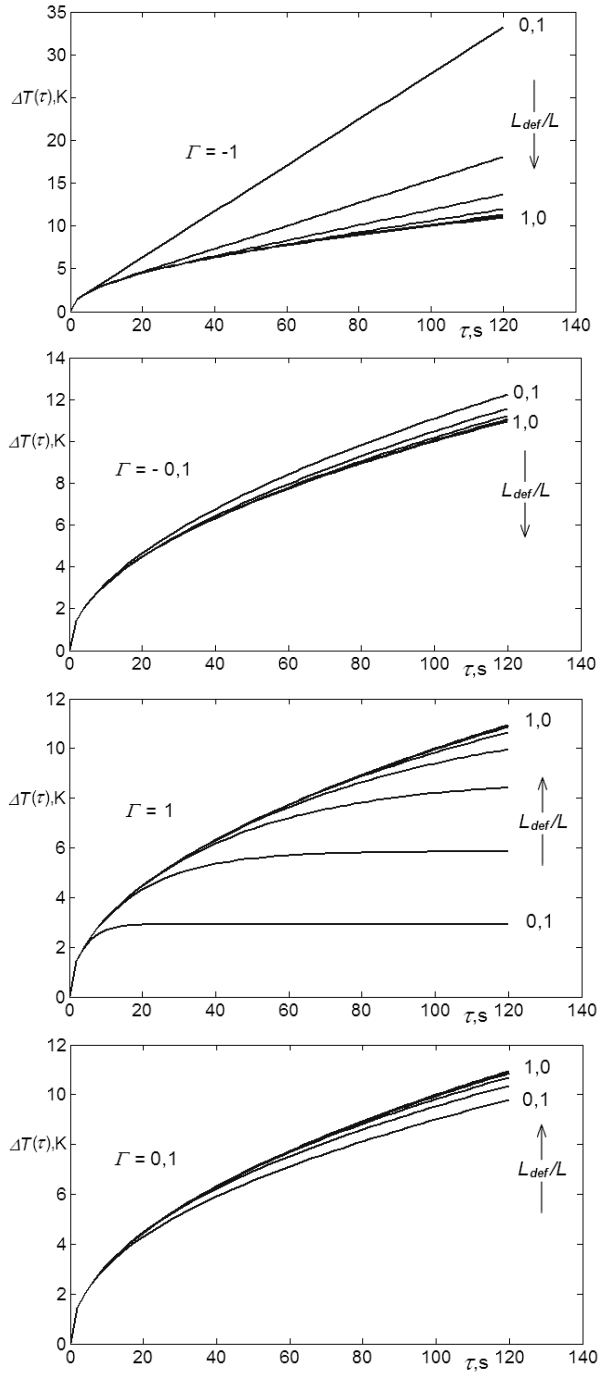

Fig. 2. Temperature-rise in time according to (3) as a function of Γ and L_{def}/L.

Fig. 3 presents increment of a KF_m in time as a function of Γ and L_{def}/L. In Fig. 4 increment of a $KFWP_m$ in time as a function of Γ and L_{def}/L is shown. Comparing the curves from Fig. 2 with corresponding curves from Fig. 3 and 4 the following conclusions can be drawn:

- if $L_{def} \rightarrow L$ then span of KF_m or $KFWP_m$ is small; hypothetically, a considerable error of determination of defect depth can occur.
- for $\Gamma \approx 0$ the better selectivity of curves KF_m or $KFWP_m$ comparing with ΔT is achieved; hypothetically a less error of determination of defect depth.
- for $L_{def}=L$ is $KF_m=0$ and $KFWP_m=0$; a background level with associated zero value is obtained for defect-free area.
- for $\Gamma>0$ is $KF_m<0$ and $KFWP_m<0$ and furthermore for $\Gamma<0$ is $KF_m>0$ and $KFWP_m>0$; estimation of sign of Γ is possible based on sign of KF_m or $KFWP_m$,
- absolute value of KF_m or $KFWP_m$ is zero for defect-free area and greater than zero for defect and global segmentation into two classes is possible.

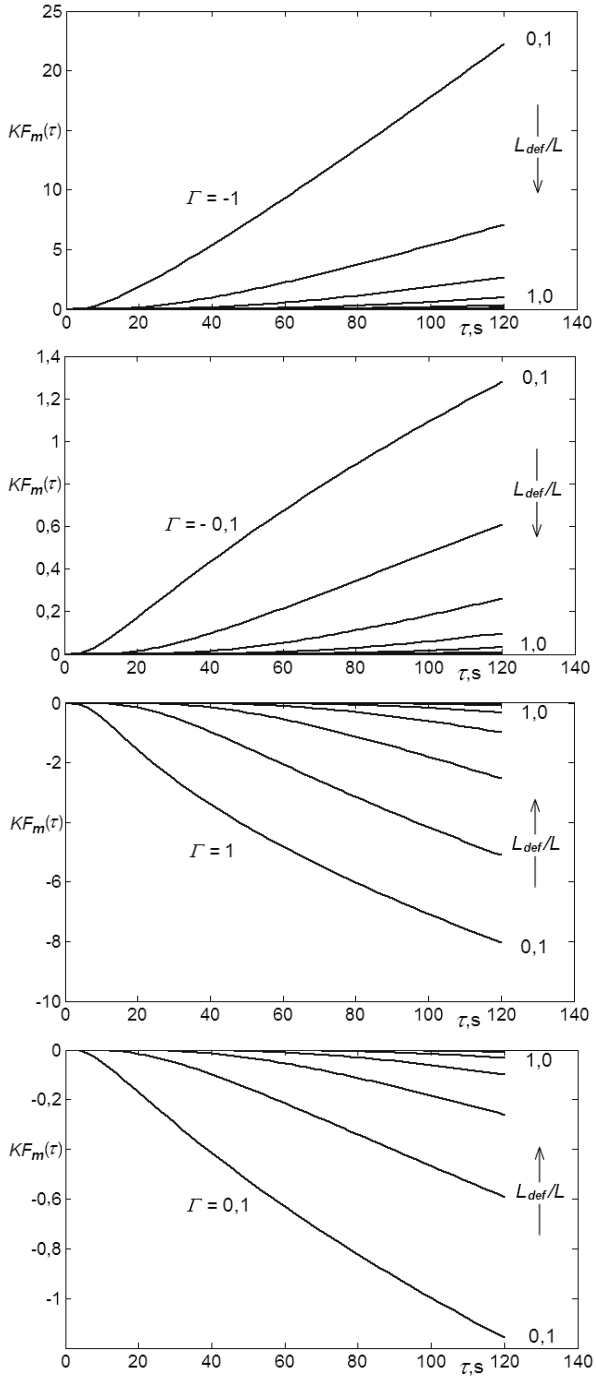

Fig. 3. Increment of a KF_m in time as a function of Γ and L_{def}/L

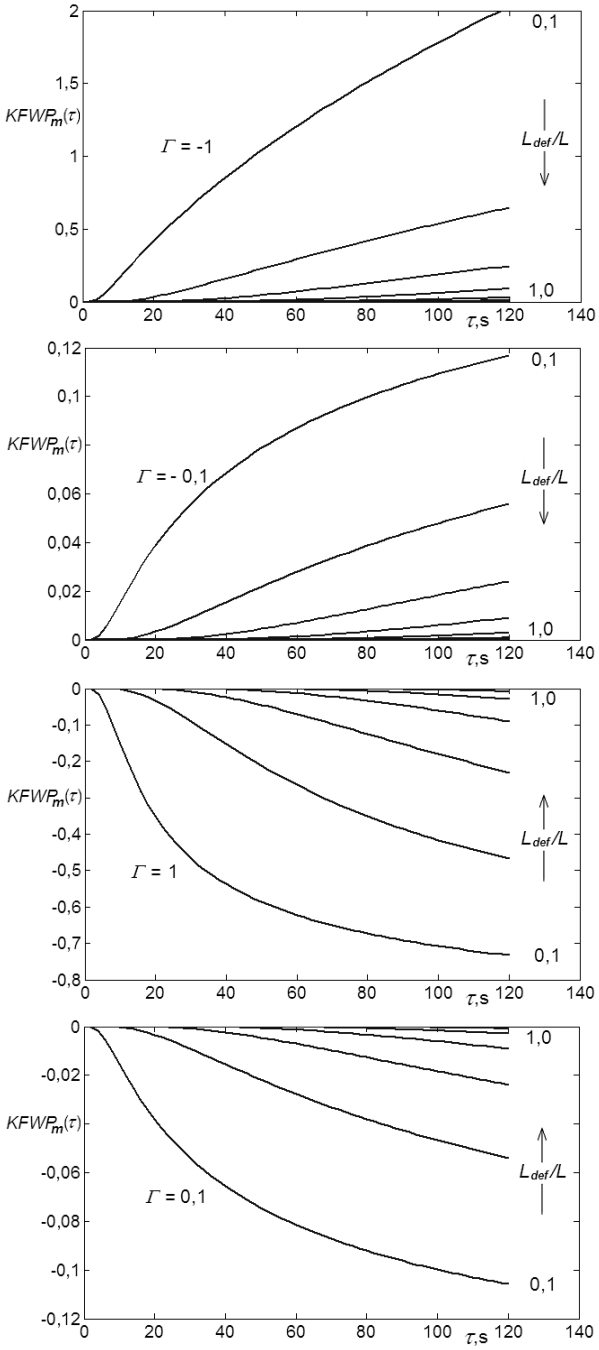

Fig. 4. Increment of a $KFWP_m$ as a function of Γ and L_{def}/L

An example of segmentation using global threshold found with Otsu method is shown in Fig. 5. Data were obtained from 3D numerical model of sample of Plexiglas with thickness as above. Defect was modelled as bottom open cylinder located at 1 mm below the material surface - Fig. 6.

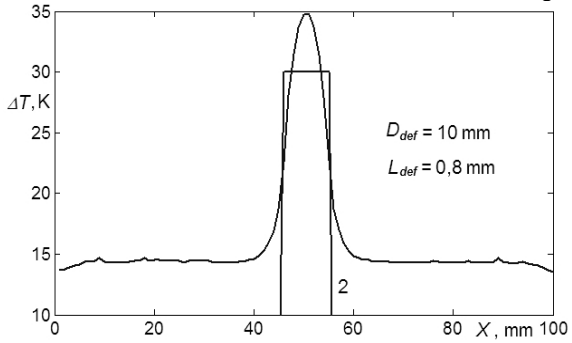

Fig. 5. An example of global segmentation with Otsu method

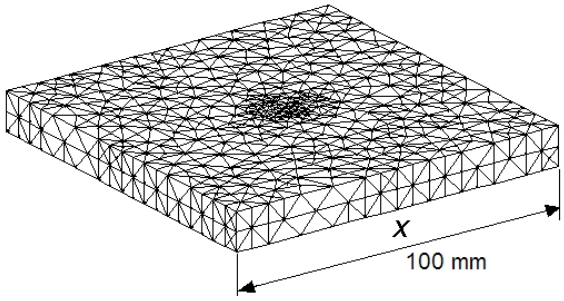

Fig. 6. Mesh for modelled sample of Plexiglas plate with defect

Summary

The use of filtered contrast *KF* or relative filtered contrast *KFWP* increases sensitivity of estimation of defect depth in case of small value of thermal mismatch factor of tested material and defect. By taking into consideration the sign of *KFWP* or *KF* it is possible to estimate the sign of thermal mismatch factor. The positive sign of *KFWP* or *KF* means that the thermal mismatch factor is also negative. Moreover, if absolute value of *KFWP* or *KF* is applied then a global threshold can be evaluated for segmentation of thermogram into two classes: defects and defect-free area.

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