EFFECT OF A CRACK ORIENTATION IN A METAL STRUCTURE ON ITS DETECTABILITY BY THE USE OF NUMERICAL MODELLING AND THE INFRARED THERMOGRAPHY

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ABSTRACT

Infrared thermography has emerged as a powerful tool to reveal eventual presence of internal or external disturbance in the process of heat transfer or temperature discontinuities in these structures. These disturbances usually generated by a sudden or progressive in the change of thermophysical properties, are at the origin of the appearance of colour contrast of the surface temperature of the structure in question representing different levels of temperatures. This technique of non-destructive testing is quick, easy to implement and is of a large use in various areas of auscultation. In this work we are interested in the nondestructive testing study, by the use of infrared thermography principle and the numerical modeling, of the effect of a crack presence in the studied structure. The main work is related to the effect of the position and the orientation of the crack, in form of an air layer, in the considered metal. The modeling, in three-dimensions, carried out in this paper concerns the effect of the crack orientation angle by report to the input surface of the metallic structure. For various configurations of simulations, the obtained thermographical images and the spatial evolution of the entry face temperature are presented and analyzed.

Key words: metal, crack, finite elements, infrared thermography, finite element.

1. Introduction

The thermal non-destructive control by infrared thermography allows the study of the surface temperature variation in materials, which permit the detection of a possible presence of anomalies in the studied structure without damaging it. This technique is often used in several areas of the industry (automotive, petroleum, shipbuilding, aerospace, etc.)… Indeed the presence of an inhomogeneous region in a material affects the heat propagation process and causes a local temperature variation. The only precondition for detection of such defects is that defects presence in the object under examination lead to a sufficient variation of thermal properties compared to the healthy material [1].
It is known that infrared thermography has some limitations when dealing with deep and low thermal resistance defects, but it has proved to be still useful in conjunction with high-depth techniques [2]. The aim of this study is to show the temperature variation on the surface of a metal plate, on which a heat pulse is applied, by a numerical modeling method for the thermal non-destructive testing and the analysis of results by infrared thermography using a commercial software “comsol” based on the finite element method.

2. Description of the structure

2.1 Geometrical characteristics
The non-destructive testing study involve a metal plate (figure 1.a), having a length $l_1=24\text{cm}$, width $l_2=15\text{cm}$ and a height $h=2.7\text{cm}$. In this plate are inserted cracks of parallelepiped form (Fig. 1.b), having a square form as basic surface of sides $l_1=10\text{mm}$, $l_2=10\text{mm}$ and taking successively (along the z axis increasing) the thicknesses $h_{1}=10\text{mm}$, $h_{2}=5\text{mm}$, $h_{3}=3\text{mm}$ and $h_{4}=1\text{mm}$, forming successively (along the x axis increasing) angles $\alpha_1=90^\circ$, $\alpha_2=60^\circ$, $\alpha_3=30^\circ$, $\alpha_4=0^\circ$, $\alpha_5=-30^\circ$, $\alpha_6=-60^\circ$ and $\alpha_7=-90^\circ$ with respect to an inner surface of the plate and parallel to its entry surface.

![Fig. 1: a) 3D geometry of the studied structure, b) Structure of the crack.](image)

The highest edge of a crack remote from the entrance surface of $(11-10\sin\alpha)\text{mm}$ for $0^\circ \leq \alpha \leq 90^\circ$ and $11\text{mm}$ for $-90^\circ \leq \alpha \leq 0^\circ$. With $\alpha=\{\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6, \alpha_7\}$ and $h_{\tau}=\{h_{1}, h_{2}, h_{3}, h_{4}\}$.

2.2 Thermophysical characteristics
The following table (Table 1) shows the thermophysical parameters used in the study.

<table>
<thead>
<tr>
<th></th>
<th>$\lambda$ [W/m.K]</th>
<th>$\rho$ [Kg/m$^3$]</th>
<th>$C_p$ [J/Kg.K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>160</td>
<td>2700</td>
<td>900</td>
</tr>
<tr>
<td>Steel</td>
<td>44.5</td>
<td>7850</td>
<td>475</td>
</tr>
<tr>
<td>Copper</td>
<td>400</td>
<td>8700</td>
<td>385</td>
</tr>
<tr>
<td>Air</td>
<td>0.0272</td>
<td>1,1845</td>
<td>1005</td>
</tr>
</tbody>
</table>

With:  
$\lambda$ [W/m.K] : thermal conductivity  
$\rho$ [Kg/m$^3$] : density of the material  
$C_p$ [J/Kg.K] : heat capacity at constant pressure
3. Numerical modelling

To solve the following thermal equation:

\[ \alpha \nabla^2 T = \frac{\partial T}{\partial t} \]  

(1)

The report \( \alpha = \frac{1}{\rho c_p} \) is called thermal diffusivity.

We call upon the numerical method of the finite elements [3, 4]. The analytical resolution is indeed impossible being given the geometry of the problem. The method consists in using an approximation by finite elements of the unknown functions \( T \) to discretize the variational form of the equation (1) and to transform it into a system of algebraic equations of the form:

\[ [A] \, T = F \]  

(2)

With

- \( A \) square matrix of dimension \([ N_h, N_h ]\)
- \( F \) a vector of \( N_h \) components
- \( T \) the vector of the temperatures to be calculated

We start by building the variation form of the equation (1). We carry out a spatial discretization which consists in calculating the elementary integrals by using the finite element and a temporal discretization.

There are many specialized software which make it possible to implement the method of resolution of problems by finite elements in a more or less simple and convivial way. They take care in particular of the grid of the studied object, of the automatic numbering of the elements and the nodes, of the calculation of a solution then of the chart of the results.

In this study, we used commercial software “comsol” based on the finite element method which makes it possible to calculate the evolution of temperature at any moment and in any point of material. The material is considered isotropic.

With the boundary conditions (Fig. 2):
- A heat pulse is applied to the upper face of the plate, with a flux density \( Q=600 \text{W/m}^2 \).
- The underside of the plate is maintained at a constant temperature \( T_a=25^\circ\text{C} \).
- The other faces are assumed thermally insulated.

The initial temperature of the subdomains is 25°C.

![Fig. 2: Boundary conditions](image)

4. Simulation results

Using the commercial software "comsol" based on the finite element method, we can illustrate the thermal image of the input face of the studied metal plate (Fig. 3), the metal plate is uniformly excited by a stream of heat, and then the steady-state surface temperature is constant and is the same everywhere. But when there is any defect in the structure it will appear on the
metal surface region or regions warmer than others. The hotter thermal tasks translate the existence of potentially problematic areas inside the plate. The simulation results are given in the form of thermal images representing the distribution of the apparent temperature, in degree Celsius on the surface. The chosen scale of temperature to describe the surface temperature variation is a color scale which associates to the highest temperatures of surface the red color and to the lowest temperatures the blue one and between two limits the intermediate colors.

Fig. 3: Thermal image of the entrance face of the aluminum plate

4.1 Effect of the orientation of the crack

The (Fig. 4) represents the spatial variation of the temperature as a function of the inclination angle for each thickness of a crack, on the input face of the aluminum plate. For a fixed thickness, it follows that:

- For an orientation angle of $0^\circ \leq \alpha \leq 90^\circ$: more than the angle increases more than a part of the crack approaches the face of entrance, more than it becomes simpler to be detected.
- For an orientation angle of $-90^\circ \leq \alpha \leq 0^\circ$: the crack is still far from the entrance face of 11mm, the variations in temperature between the healthy areas and that of those potentially problematic are very small compared with those obtained for $0^\circ \leq \alpha \leq 90^\circ$.

We can say that the crack which has the highest level of detectability is that which has the greatest thickness and at a position closer to the entry face of the plate (inclination angle $\alpha=90^\circ$).
4.2 **Effect of the crack thickness**

4.2.1 *For an orientation angle of $90^\circ \leq \alpha \leq 0^\circ$*

The (Fig. 5) represents the spatial variation of temperature as a function of the thickness for each orientation of a crack of $0^\circ \leq \alpha \leq 90^\circ$, on the input face of the aluminum plate.

For a fixed orientation angle, it follows that: more than the thickness of the crack increases, more than it can be detected in good.

![Fig. 5](image)

Fig. 5 : a) Distribution of defects in the metal structure, b) Effect of the crack thickness on the input surface temperature profile of the aluminum plate along the lines (A1-A2, $\alpha_1=90^\circ$), (A3-A4, $\alpha_2=60^\circ$), (A5-A6, $\alpha_3=30^\circ$) and (A7-A8, $\alpha_4=0^\circ$)

4.2.2 *For an orientation angle of $-90^\circ \leq \alpha \leq 0^\circ$*

The (Fig. 6) represents the spatial variation of the temperature as a function of the thickness for each orientation of a crack of $-90^\circ \leq \alpha \leq 0^\circ$, on the input face of the aluminum plate.

For a fixed orientation angle, it follows that: the more the thickness of crack increases, the more it can be easily detected and vice versa.

The crack which is more detectable is the one which has a greater volume and is closest to the input surface of the aluminum plate.

![Fig. 6](image)

Fig. 6 : a) Distribution of defects in the metal structure, b) Effect of the crack thickness on the input surface temperature profile of the aluminum plate along the lines lines (A7-A8, $\alpha_4=0^\circ$) (A9-A10, $\alpha_5=-30^\circ$), (A11-A12, $\alpha_6=-60^\circ$) and (A13-A14, $\alpha_7=-90^\circ$)
4.3 **Comparison of three different materials**

In this section we will focus on the effect of crack orientation on the input surface of the metal plate for three different materials (steel, aluminum and copper).

The temperature difference between the region with defect and the one without defect shows that for the three metals the orientation angle of 90°, 60° and 30° of defect are the inclinations that provide the maximum contrast on the metal surface and thus are easier to detect than other orientations. But comparatively, it is easier to detect the presence of various defects in the steel metal, than the aluminum or copper.

![Fig. 7](image)

**Fig. 7**: Effect of the crack orientation on the input surface temperature profile of the metal plate along the lines (B1-B2, \(h_1=1\) mm), (B3-B4, \(h_3=3\) mm), (B5-B6, \(h_5=5\) mm) and (B7-B8, \(h_7=10\) mm)

5. **Conclusion**

In this work we studied cracks of different thicknesses inclined with respect to an inner surface and parallel to the input surface of a metal plate. It can be concluded that the volume of the crack, closest to the entrance surface plays a very important role in its detectability.

- More than a volume of the crack (part of the crack) increases, more than it can be detected in good.
- More than the volume of the crack is greater more than it can be detected in good.
- The crack which is more detectable is that which has a greater part of volume closest to the inlet surface of the metal plate.

The comparison between steel, aluminum and copper for the temperature distribution showed that the cracks in the steel plate are more detectable than the aluminum and copper plate, shown by the difference temperature between the healthy areas and that potentially problematic.

6. **References**


