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A three-dimensional reconstruction algorithm for pulsed thermography

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Abstract
This paper presents a new algorithm for three-dimensional reconstruction of defect shape using pulsed thermography data. The aim is to detect and reconstruct the shape of defect located on the inaccessible rear face of a homogeneous material. The proposed method is based on the analysis of the object thermal response to a heat pulse. Digital processing of the evolution of the temperature versus time allows the determination of a time value as a characteristic of the distance between the defect and the heated surface. The evaluation of the distance at each heated surface point allows the three-dimensional reconstruction of defect shape. The algorithm initial values are taken at the non defect area. The application of this algorithm to reconstruct the elliptic and triangular shape of a geometry defect located on the inaccessible face of steel and aluminum samples, confirmed the proposed algorithm.

Keywords: Pulsed Thermography, Three-dimensional reconstruction, Defect detection, Absolute peak slope time.

1. Introduction
Thermographic techniques are based on the propagation of thermal waves within an object and the consequent analysis of the waveforms. This is the thermal response of the sample to time-dependent radiation. The presence of voids, incrustations, delaminations, density changes, or boundary discontinuities perturbs the propagation of the thermal waves, affecting the temperature distribution of the object as a function of time**[1]**.
Pulsed thermography is a nondestructive evaluation method, which has been qualitatively and quantitatively applied for different classes of materials to detect variety of defects, such as corrosions and delaminations in composite and metal **[2]**. For many applications, pulsed thermography compares favorably to conventional inspection technologies in terms of its sensitivity and speed, while offering some advantages in terms of curvature tolerance and non-contact inspection **[3]**. In pulsed thermography, we use an IR camera to acquire a sequence of thermograms during the cooling process of an object, after it has been irradiated with a heat pulse **[4]**. The surface temperature profiles contained in the thermographic video may be analyzed with a variety of techniques for detecting internal defects **[5]**. By means of these techniques, we may retrieve the thermal diffusivity, conductivity, specific heat capacity, size, depth, and thickness of internal defects **[6]**.
By using the pulsed thermography, the reconstruction of defects has been the subject of several researches **[1, 7, 8, 9]**. At the present time, the performed reconstructions require a prior knowledge of the thermal properties of the material. Here, we present a PT data-analysis algorithm that overcomes this limitation. This algorithm is capable of reconstructing subsurface defects inside homogeneous objects in three dimensions.
In this paper, we propose the theoretical concept of our algorithm and we apply it to reconstruct the shape of a defect located on the inaccessible surface of an steel and aluminum samples.

2. Theoretical concept
The principle of pulsed thermography consists in heating the front surface of the examined sample by a flash with short duration, the generated heat on this surface propagates inside the sample by conduction, and leads to a continuous reduction

of the surface temperature **[2]**. An infrared camera, controlled by computer, captures the thermal excitation response and allows to have the temperature distribution on the sample surface as a function of time.
The heat transfer equation by conduction through the material is written as follows:

$$\nabla.[k\nabla T(r,t)] - \rho c_v \frac{\partial T(r,t)}{\partial t} = -w(r,t) \qquad (1)$$

For an isotropic semi-infinite material, contains a defect located at the depth L, heated by a source heat which delivers on its input face energy Q as a Dirac impulse, the temperature evolution above the defect is written as follows [**10**]:

$$\Delta T(t) = \frac{Q}{e\sqrt{\pi t}}\left[1 + 2\sum_{n=1}^{\infty}\exp(\frac{-n^2L^2}{\alpha t})\right] \qquad (2)$$

To find the defect depths from the temperature variation on the heated surface, Zhi et al [**11**] have proposed to multiply both sides of equation (2) by $\sqrt{t}$, and a new time-dependent function f(t) is obtained:

$$f(t) = \Delta T(t).\sqrt{t} = \frac{Q}{e\sqrt{\pi}}\left[1 + 2\sum_{n=1}^{\infty}\exp(\frac{-n^2L^2}{\alpha t})\right] \qquad (3)$$

From equation (3), Zhi et al [**11**] define the time t_{APST} (Absolute peak slope time) by the following relationship**[11]**:

$$t_{APST} = \frac{L^2}{2\alpha} \qquad (4)$$

Where:

- α : the material thermal diffusivity,
- L: the material thickness.

The relation (4) shows that the thickness variation of homogeneous material results in a variation of t_{APST} value. We take arbitrary two points Pi and Pj from the sample surface, the sample thickness at these two points can be written from equation (4) as:

$$L_i = \sqrt{2\alpha t_{APST_i}} \qquad (5)$$

$$L_j = \sqrt{2\alpha t_{APST_j}} \qquad (6)$$

The division of the two terms of relations (5) and (6) eliminates the material thermal diffusivity α, and we get the equation (7):

$$\frac{L_i}{L_j} = \sqrt{\frac{t_{APST_i}}{t_{APST_j}}} \qquad (7)$$

The proposed algorithm in relation (7) allows the estimation of the sample thickness at any point Pi of the front surface from a reference point Pj without consideration of material thermal properties such as thermal diffusivity α. The initial values as the reference point Pj can be choose from non defect area where the sample thickness is known.

3. 3D reconstruction of a geometry defect located on the inaccessible surface

a. Considered models

To verify the algorithm, we apply the relation (7) to do a 3D reconstruction of a defect located on the inaccessible face of two samples of 0.1m in length, 0.1m in width and 0.005m in thickness. The inaccessible face of the first sample contains an elliptical defect (Figures 1-a and 1-b), whereas the second sample contains a triangular defect (Figures 2-a and 2-b). The elliptical defect has as a dimensions: the length of the semi-major axis is 0.0174 m and that of the semi-minor axis is 0.004 m.

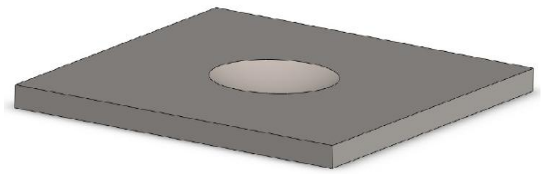

Fig. 1-a : Sample with an elliptical defect - Isometric view

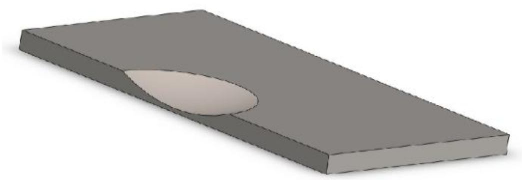

Fig. 1-b : Sample with an elliptical defect - Cutaway view

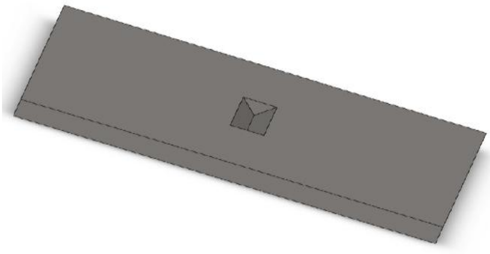

Fig. 2-a: Sample with triangular defect, Opening angle 90 °- Isometric view

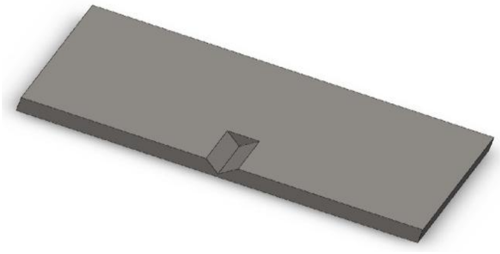

Fig. 2-b: Sample with triangular defect, Opening angle 90 °- Cutaway view

The initial temperature is T_0=25°C (Figure 3). The side faces of the samples are isolated and the inaccessible face is maintained at a constant temperature T_0=25°C.

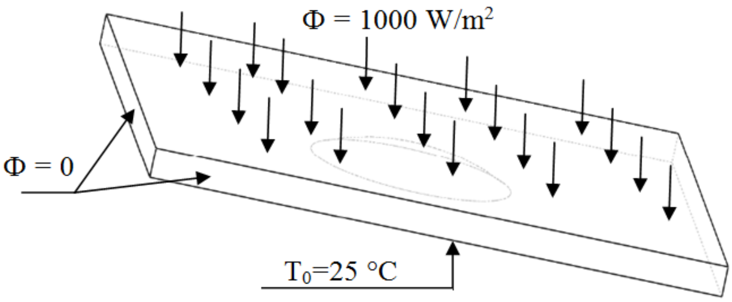

Fig. 3: Sample with boundary conditions

b. Application of the proposed algorithm for the 3D reconstruction of an elliptical defect

At first, we simulate the heat conduction in the case of two samples with an elliptical defect (Fig. 1-a), by a commercial software finite elements calculation. The material of the first sample is steel with thermal diffusivity α= 1.1934 10^{-5} m^2/s while the material of the second sample is aluminum with thermal diffusivity α= 6.6 10^{-5} m^2/s. On the steel sample front face, we applied a pulse heating with a flux density equal to 1000 W/m^2, and a variable length as shown in the following table:

Table 1: Variation of the pulse duration

Simulation N°	1	2	3
Pulse duration	5ms	10ms	15ms

To make the 3D defects reconstruction from the temperature distribution on the heated surface, we chose 10^6 equidistant points on this surface. The analysis by a Matlab program of the temporal evolution of temperature multiplied by the square root of time allows the determination of the absolute peak slope time t_{APST} at each point on the heated surface. The reference point is selected on the defect-free zone where the sample thickness is equal to 0.005m.

To quantify the overall accuracy of the reconstructed geometry, the average error was expressed by the arithmetic mean:

$$error = \frac{\sum_{i=1}^{N} \left| z_{real}{}^{i} - z^{i} \right|}{N} \qquad (8)$$

Where

- $z_{real}{}^{i}$ is the thickness of the actual geometry at the i^{th} point Pi of the front surface,
- z^i is the calculated thickness by relation (7) at the same point Pi.
- N is the front face points number.

Let's consider P1the plane defined by the points (0, 0.05, 0), (0.1, 0.05, 0) and (0.1, 0.05, 0.005). Figures 4-a, 4-b and 4-c show the 3D reconstruction of the elliptical defect for the steel sample, a section of this reconstruction following the plane P1 and the reconstruction error for each pulse duration value.

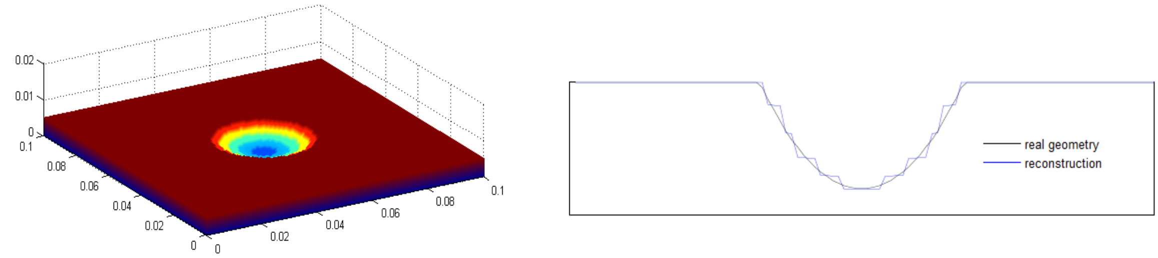

Fig. 4-a : 3D reconstruction of the elliptical defect (left) and the corresponding section along the plane P1 (right).
Case of a steel sample.
Pulse duration = 5ms
Error = 2.0702 10^{-5}m

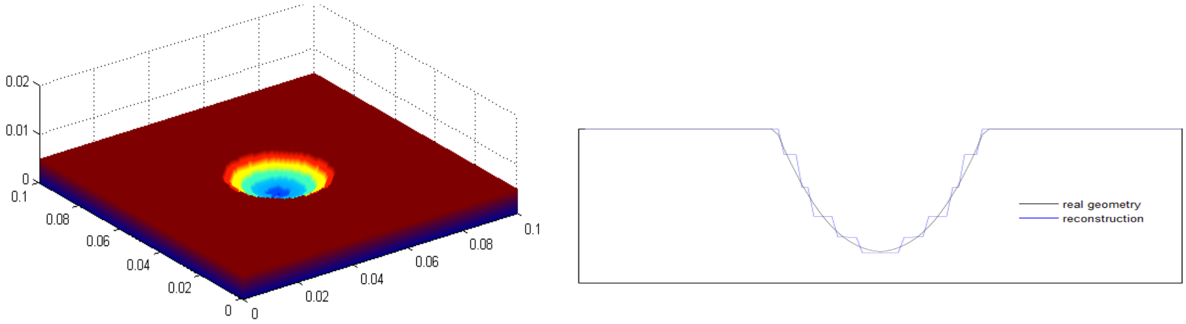

Fig. 4-b : 3D reconstruction of the elliptical defect (left) and the corresponding section along the plane P1 (right).
Case of a steel sample.
Pulse duration = 10ms
Error = 1.9732 10^{-5}m

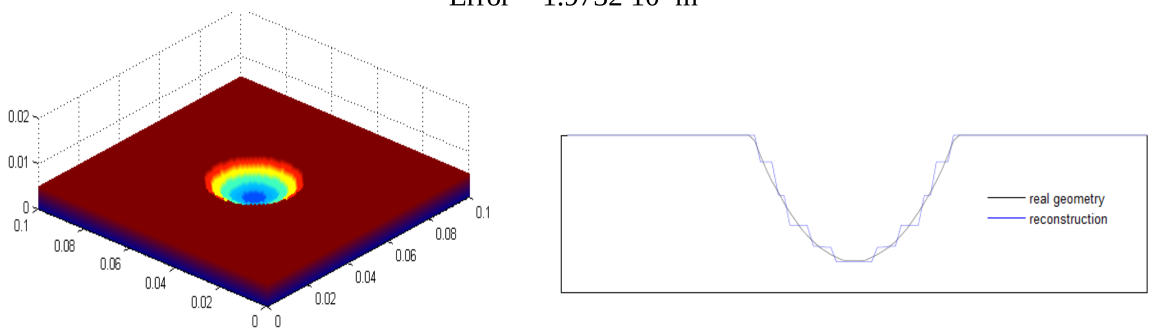

Fig. 4-c : 3D reconstruction of the elliptical defect (left) and the corresponding section along the plane P1 (right).
Case of a steel sample; Pulse duration = 15ms; Error = 2.0367 10^{-5}m

The results show the ability of the proposed algorithm to reconstruct the shape of the elliptical defect in the case of a steel sample. Obtained reconstructions Error are very close, then we can neglect the effect of the variation of pulse width in the application of this algorithm. We repeated the simulation in the case of an aluminum sample and a heating time equal to 10ms. Figure 5 shows the obtained reconstruction.

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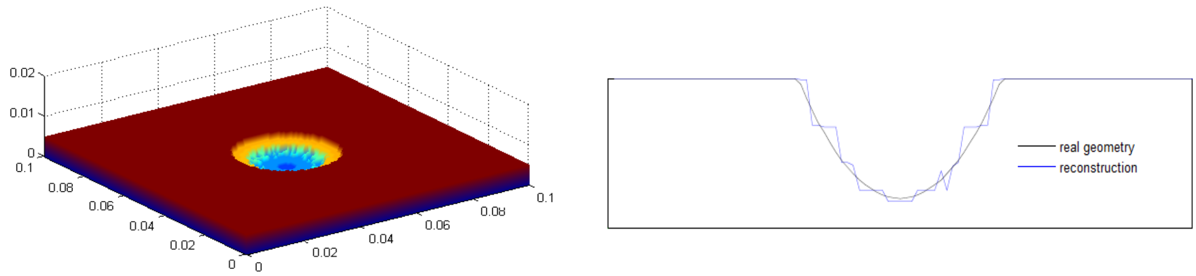

Fig. 5 : 3D reconstruction of the elliptical defect (left) and the corresponding section along the plane P1 (right).
Case of an aluminum sample.
Pulse duration = 10ms
Error = 3.3397 10^{-5}m

We find that the proposed algorithm allows the 3D reconstruction of an elliptical defect for aluminum sample and the reconstruction error remains minimal. It can be concluded that the variation of the material thermal properties has no influence on the 3D reconstruction of an elliptical defect by the proposed algorithm in this manuscript.

c. Application of the proposed algorithm for the 3D reconstruction of a triangular defect

We simulated two samples of steel and aluminum with a triangular defect located on the inaccessible face. On the front of the two samples, we applied a pulse heating as a flux density equal to 1000 W/m^2, and a pulse duration equal to 10ms.
The obtained reconstructions are shown in Figures 6-a and 6-b.

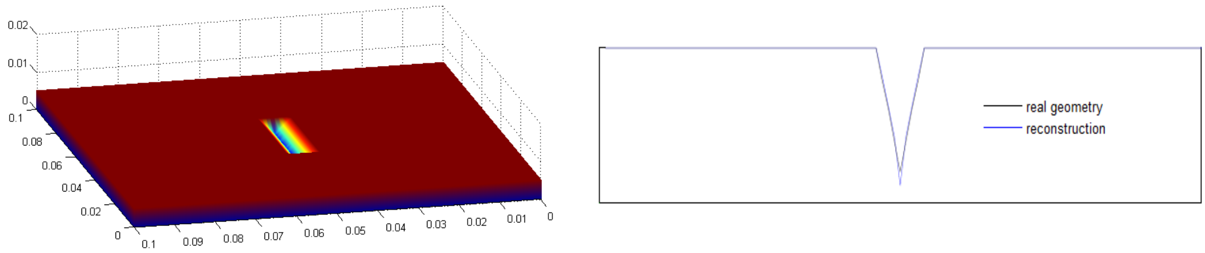

Fig. 6-a : 3D reconstruction of the triangular defect (left) and the corresponding section along the plane P1 (right).
Case of a steel sample; Pulse duration = 10ms; Error = 3.0605 10^{-6}m

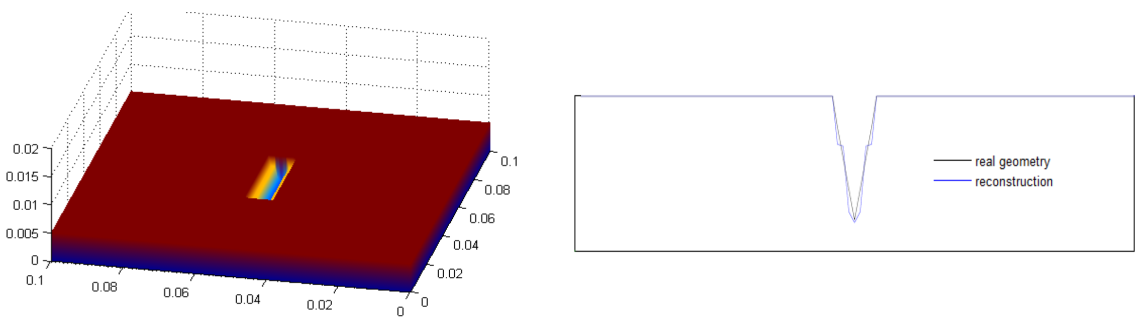

Fig. 6-b : 3D reconstruction of the triangular defect (left) and the corresponding section along the plane P1 (right).
Case of an aluminum sample; Pulse duration = 10ms; Error = 9.7074 10^{-6}m

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We note that the 3D reconstruction of the triangular defect was successfully performed for both samples. The reconstruction error is negligible compared to the dimensions of the considered samples. This shows the effectiveness of the used 3D reconstruction algorithm.

Conclusion

We proposed a new algorithm to enhance the capacity of pulsed thermography in nondestructive testing of homogeneous objects. This algorithm allows the detection and the 3D reconstruction of inaccessible defects without taking into account the thermal properties of the auscultated material. The application of this algorithm to the 3D reconstruction of elliptical and triangular defects, located on the inaccessible face of a steel sample and an aluminum specimen, showed that the proposed algorithm is a valuable tool in objects non-destructive testing because it provides a 3D description of defect shape close to the real with minimal error.

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