Ultrasonic and optical stimulation in IR thermographic NDT of impact damage in carbon composites

by V. Vavilov*, W. Świderski** and D. Derusova*

* National Research Tomsk Polytechnic University, Russia 634028, Tomsk, Savinykh St., 7, vavilov@tpu.ru
** Military Institute of Armament Technology, 05-220 Zielonka, Poland, waldemar.swiderski@wp.pl

Abstract

A thermo mechanical problem of internal friction in zero-thickness cracks is numerically solved, and the theoretical predictions are qualitatively compared with experimental data. Some examples of the characterization of impact damage by applying both ultrasonic and optical material stimulation are presented.

1. Introduction

This study is devoted to thermal nondestructive testing (NDT) of impact damage in carbon composites by the thickness of few millimeters, mainly, by applying ultrasonic stimulation, while the classical optical heating has been used as an alternative inspection technique. The term «carbon composite» specifies here both carbon fiber reinforced plastic (CFRP) and carbon/carbon composites. In these two types of composites, impact damage with energy from 5 to 400 J represents a serious structural defect which appears during exploitation, thus worsening component strength. In CFRP, typical impact damage includes two similar areas symmetrically located around a hit point. In carbon/carbon composite, a pattern of impact damage is more uniform due to a tissue-like fiber layout.

When applying ultrasonic stimulation, the main research emphasis has been made on the development of a thermo mechanical model which allows the analysis of such test parameters as composite mechanical properties (Young's modulus, Poisson's coefficient and friction coefficient), stimulation energy, type of a sample support and distance between a defect and a stimulation point. In the experimental section, some results obtained on impact damages of the same but low energy (5-20 J) are reported to illustrate the above-mentioned dependencies between the parameters involved.

2. Optical stimulation: elements of theory

The modeling of optical heating in thermal NDT is based on solving 1D, 2D or 3D equations of heat conduction. Peculiarities of available solutions, whether they are analytical, numerical or combined, are well known and discussed elsewhere [1]. Analytical 1D solutions explain some important features of signal build-up, but in practice trust-worthy results appear when using 2D and 3D models. Such solutions allow the calculation of «classical» dependencies between differential temperature signals $\Delta T(\tau)$ evolving in time and material/defect thermal properties, as well as defect size and depth. In this case, the heating energy is supposed to be released on material surface, and its temporal function is typically represented by a Dirac or square pulse (pulsed procedure), or a harmonic function (thermal wave procedure). In advanced cases, one may take into account partial optical transparency of a tested material, arbitrary variation of heating energy in time and some other phenomena [1]. The corresponding mathematical formulations are trivial and omitted here.

3. Ultrasonic stimulation: elements of theory

Studies of thermo mechanical coupling in solids that involve the use of infrared (IR) thermography have been known for several years (see the works by Reifsnider et al. [2], Mignogna et al. [3] and Pye et al. [4] in the 1980s) . As mentioned in [5], these studies are being conducted in three areas: 1) the visualization of mechanical stresses in materials through the analysis of thermo plasticity and mechanical hysteresis, 2) the analysis of material failure under cyclic (fatigue) loading, and 3) the detection of structural defects (cracks) under ultrasonic stimulation.

Until present, the modeling in ultrasonic IR thermography has been mostly done on 1D models by involving basic physical laws, or experimental results have been used to derive features of this technique. There is an ongoing project at Tomsk Polytechnic University on the development of a 3D modeling software to solve a thermal NDT thermo mechanical problem. In details, the underlying equations will be discussed in the coming paper.

The proposed algorithm includes two stages: 1) solving a 3D problem of ultrasound propagation in a plate and calculating heat power generated by a crack of zero thickness because of internal friction, 2) solving a 3D problem of heat conduction in a material with a heat source of whose power was determined previously.

In each elementary volume of a solid body, there are mechanical stresses acting on each parallelepiped plane, namely, one normal and two tangent stresses (figure 1). For example, on the plane perpendicular to the x coordinate there, are σ_x, τ_{xy} and τ_{xz} stresses. The balance of forces by x is:

$$(\sigma_{x+0} - \sigma_{x-0})\Delta y \Delta z + (\tau_{y+0,x} - \tau_{y-0,x})\Delta x \Delta z + (\tau_{z+0,x} - \tau_{z-0,x})\Delta x \Delta y + X \Delta x \Delta y \Delta z = 0 , \quad (1)$$

where $\Delta x, \Delta y, \Delta z$ are the parallelepiped dimensions, X is the projection of volumic forces (if they are present) on the x axis. The subscripts $x+0$ and $x-0$ correspond to the maximum and minimum x coordinate.

In a differential form, equation (1) can be reduced to:

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + X = 0 , \quad (2)$$

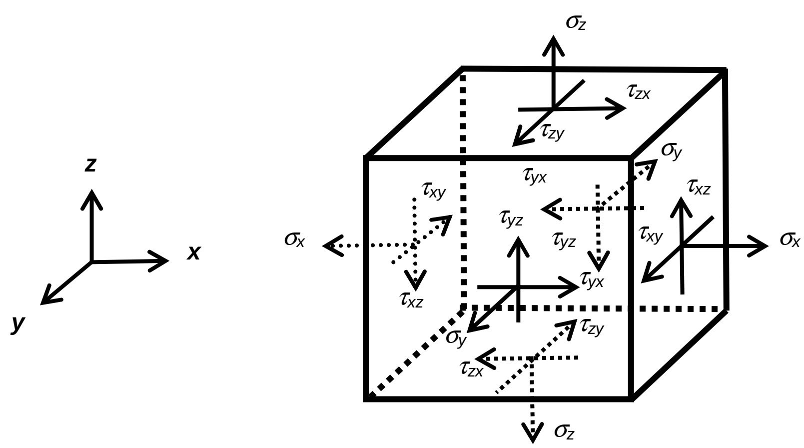


Fig. 1. *Stresses acting in a material elementary volume*

By skipping the mathematics, we give a set of basic equations that has been solved numerically by using ThermoSon software (Tomsk Polytechnic University):

$$(\lambda + 2G)\frac{\partial^2 U}{\partial x^2} + G(\frac{\partial^2 U}{\partial y^2} + \frac{\partial^2 U}{\partial z^2}) + (\lambda + G)\frac{\partial^2 V}{\partial x \partial y} + (\lambda + G)\frac{\partial^2 W}{\partial x \partial z} , \quad (3)$$

where λ is the Lamė constant, G is the shear elasticity modulus, and U, V, W are the displacement projections on the x, y, z coordinates.

Since we consider elastic waves in a solid, the right member in the Lamė equation (3) should be replaced by the corresponding components of inertia forces in a chosen elementary volume, for instance, by the x direction:

$$F_{in,x} = \rho \frac{\partial^2 U}{\partial \tau^2} , \quad (4)$$

where ρ is the material density.

The boundary conditions accepted in the model above assume: 1) the absence of normal and tangent stresses on the top and side plate surfaces, and 2) zero vertical displacements on the bottom surface and forced harmonic vibrations in a stimulation point. Internal crack surface is characterized by non-linear boundary conditions. At the stage of crack compression, one assumes no tangent stresses, and at the stage of crack strain, the condition of zero normal stresses is added. These conditions can be easily achieved by assuming the corresponding members in Esq. (3) equal to zero. As the initial condition, displacements are assumed zero at $\tau = 0$. Then, a displacement by x at each next time step can be calculated by solving equation (3), same by coordinates y and z. The surface vertical displacement W in a stimulation point is described as follows:

$$W = A[1-\cos(2\pi f \tau)]/2, \tag{4}$$

where A and f are the vibration amplitude and frequency.

The heating power in a crack perpendicular to the x direction is calculated by:

$$P = \frac{\mu \sigma_x S_{fr}}{\tau^*} \int_0^{\tau^*} \left| \frac{\partial U}{\partial \tau} \right| d\tau \tag{5}$$

where μ is the crack wall friction coefficient, S_{fr} is crack surface, σ_x is the stress normal to the crack surface.

At the second step, a 3D heat conduction equation is numerically solved to calculate the temperature distribution in a sample (the implicit calculation scheme, such as in the ThermoCalc-6L software, has been used).

4. Ultrasonic stimulation: calculation results

Figures 2 and 3 show some results calculated by the algorithm above. Temperature patterns in defective areas are significantly affected by orientation of a stimulated point in respect to cracks: the maximum temperature increase appears at the crack tips that are closest to the stimulation point (figure 2, left), while the differential temperature signal strongly depends on frequency (figure 2, right). The corresponding graphical presentation of the latter dependence was called «acousto thermal» spectrum [6].

Evolution of temperature in time over surface cracks, both experimental and theoretical, is close to linear if stimulation lasts up to 5 s (see figure 3a), however, comparison in true temperature units seems to be difficult because of many parameters involved. Trust-worthy standard specimens with reproducible defects are still to be developed to enable a decent comparison between experiments and the theory.

In the work [7], the so-called «energy index» was introduced as

$$EI = \sum_n \frac{f_n}{f_0} \varepsilon_n^2, \tag{6}$$

where f_n / f_0 represents a 'weight' of the *n*-th frequency in regard to the reference frequency f_0, and ε_n is the vibration amplitude. In this way, a quadratic dependence of temperature signals on vibration amplitude was predicted. The corresponding results obtained within the proposed 3D model prove this conclusion (f3b).

5. Defect characterization

A 400x400x3.4 mm carbon/carbon sample was subjected to multiple impact damages with the energy from 5 to 20 Joules and tested by using both ultrasonic and optical methods of excitation. An example of a «good»IR thermogram is shown in figure 4a. Here the qualitative term «good» means that the image reveals a good correlation between the impact energies and the temperature signal amplitudes. However, in general, our experimental results show that the possibility of defect characterization by applying ultrasonic stimulation is questionable due to the fact that both amplitude and shape of temperature patterns strongly depend on a distance between a stimulation point and defects. Fiber layout may also play a significant role in signal build-up; for example, maximum temperature elevations used to appear when ultrasound propagated along fibers directly to a defect area (in the case of a carbon/carbon composite with a tissue-like fiber layout).

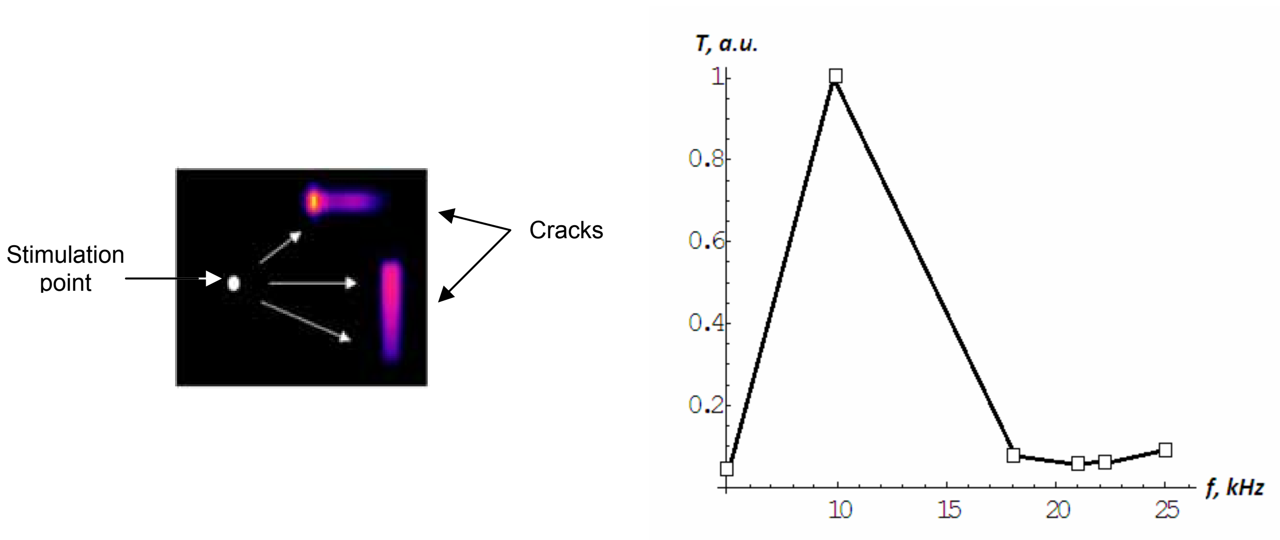
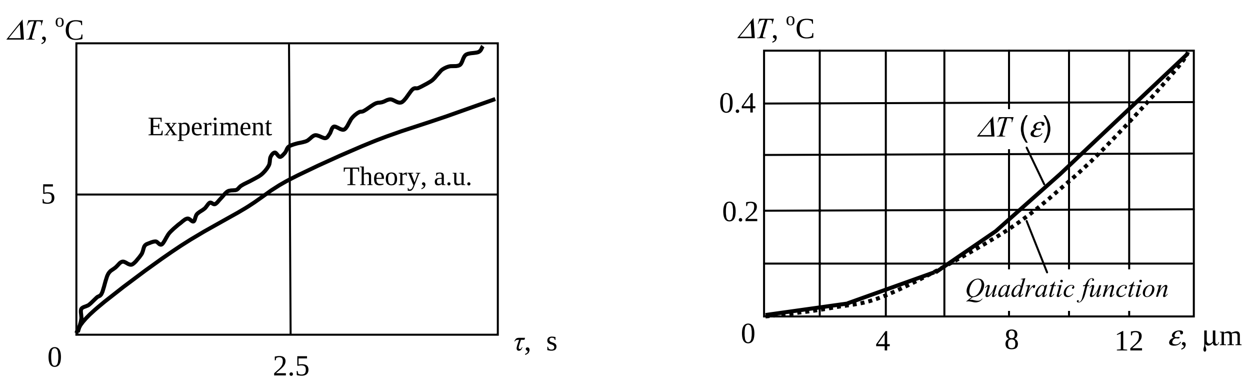


Fig. 2. *Temperature signal vs. ultrasound frequency (1 mm-thick CFRP, two zero-thickness perpendicular defects by the length of 5 mm; thermal conductivities;* K_x *=0.33 W/(m·°C),* K_y *=0.48 W/(m·°C),* K_z *=0.55 W/(m·°C), density* ρ *=1570 kg/m³, specific heat* C *=780 J/(kg·°C), Young modulus* $6.8 \cdot 10^{10}$ *N/m², Poisson coefficient 0.36, friction coefficient 1, vibration amplitude ±7 μm)*



a) *b)*

Fig. 3. *Temperature signal vs. stimulation time (a) and vibration amplitude (b)*

When applying optical stimulation, a simple and reliable defect characterization algorithm involves the conversion of raw temperature images into a distribution of material thermal properties. Best of all, it can be done in a two-sided procedure allowing the determination of thermal diffusivity by applying a Parker-like algorithm. An 18 cm-diameter area of the above-mentioned carbon/carbon sample was heated with a single flash Xenon lamp to reveal a very strong circle-like non-uniformity of heating (figure 4b). After the rear-surface temperature evolution was transformed into the image of diffusivity, it was found that the diffusivity α correlates well with the impact energy, while the non-defect area is characterized by a constant diffusivity.

It is known that, in CFRP, ultrasonic and optical stimulations produce different temperature patterns on sample surfaces that can be explained by different mechanisms of temperature build-up. Ultrasonic thermographic signals appear as a result of the energy release which, in its turn, is conditioned by internal friction of defect surfaces. In this way, even rather deep defects may produce considerable temperature signals. In the case of optical heating, the thermal energy which propagates in-depth is being stored over thermally-resistive defects, and this phenomenon strongly decays with growing defect depth in a one-sided procedure. However, in the case of carbon/carbon composite, temperature patterns looked similarly in both cases, as shown in figure 4 for the same sample. This can be probably explained by a relatively uniform structure of the composite.

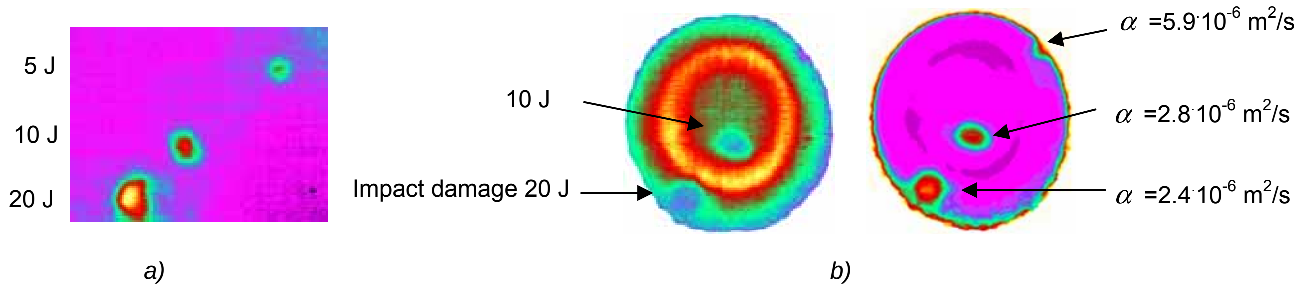


Fig. 4. *Comparing ultrasonic (a) and optical (b) stimulation of a 3.4 mm-thick carbon/carbon composite sample*

6. Conclusions

A 3D thermo mechanical problem has been numerically solved by combining solutions for heat conduction and mechanical wave propagation in solids with zero-thickness cracks which, under external ultrasonic stimulation, generate thermal energy because of crack wall friction. The numerical solution has been realized as original ThermoSon software allowing to analyze dependencies of temperature signals on material physical properties, ultrasonic excitation parameters, size of defects and their distance in regard to a point of ultrasonic stimulation.

The experimental research has confirmed theoretical predictions qualitatively while quantitative comparison requires development of a standard sample with specific defects. The usefulness of ultrasonic IR thermography for defect characterization purposes has not been confirmed, while classical optical stimulation has proven to be promising in the identification of impact damage energy by analyzing thermal diffusivity maps.

REFERENCES

[1] Vavilov V.P., "Modeling Thermal NDT problems", International J. of Heat and Mass Transfer, Vol. 72, p.75-86, 2014.

[2] Reifsnider K.L., Henneke E.G. II, and Stinchcomb W.W., "The mechanics of vibrothermography", Mechanics of Nondestructive Testing, Stinchcomb W.W. ed, Plenum Press, New York (USA), p. 249–276,1980.

[3] Mignona R.B., Green R.E. Jr., Duke J.C. Jr. et al., "Thermographic investigation of high-power ultrasonic heating in materials", Ultrasonics, p. 159-163, July 1981.

[4] Pye C.J.,and Adams R.D., "Heat emission from damaged materials and its use in nondestructive testing", J. Phys. D, Vol. 14, p. 927-933, 1981.

[5] Guo X. and Vavilov V. P. "Crack detection in aluminium parts by using ultrasound-excited infrared thermography". Infrared Physics & Technology, Vol. 61, p. 149-156, 2013.

[6] Gleiter A., Spießberger C. and Busse G., "Improved ultrasound activated thermography using frequency analysis", Intern. J. Quant. IR Thermography, Vol. 4, No. 2, p. 155-164, 2007.

[7] Morbidini M. and Cawley P., "A calibration procedure for sonic infrared nondestructive evaluation", J. of Appl. Physics, Vol. 106, p. 023504-1–023504-7, 2009.