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Photothermoacoustic effect: applied aspects of stressed state area diagnostics in structural materials

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Specific features of photothermoacoustic (PTA) transformation process in materials under stress have been studied in experiment and theoretically. Pulse and harmonic modulation regimen of laser emission have been considered. Basing on the results so obtained, a circuit design has been proposed for the stressed area PTA diagnostics in structural materials.

Экспериментально и теоретически исследованы особенности процесса фототермоакустического (ФТА) преобразования в напряженных материалах. Рассмотрены импульсный и гармонический режимы модуляции лазерного излучения. На основании полученных результатов предложена функциональная схема ФТА диагностики напряженных областей в конструкционных материалах.

Visualization of elastic stress field distribution is among topical problems in the materials science. This is associated with that novel functional materials or compositions thereof are to be used in modern technologies. High stress levels can arise in those materials due to preparation and treatment processes as well as due to extreme operating conditions of devices made of the materials. The maximum danger is connected with the stress levels at which the material or workpiece as a whole is quite functional but in the case of insignificant variations or changes in external parameters (temperature, pressure, irradiation, etc.), irreversible processes arise there resulting in the material degradation and, what is more, in a catastrophic situation. Therefore, the control problem of stressed state and its temporal variations is critical in ensuring of the structural material working reliability. The known optical, X-ray, nuclear, and other methods for material diagnostics are rather cumbersome and mostly unsuitable for use in actual operation conditions.

Recently, photothermoacoustic (PTA) methods come into use for study and control of various materials. The essence of those methods consists in that temperature waves are generated in the specimen resulting from absorption of a non-stationary irradiation followed by formation of acoustic vibrations in the specimen or its environment due to thermal and elastic contacts. Today, PTA spectroscopy and PTA microscopy based on the PTA effect are under rapid development as powerful methods for investigation and non-destructive testing of solids [1–5].

An important criterion of practical suitability of those methods is the effective recording of the PTA response. From that standpoint, the following recording methods are among most promising ones:

(1) PTA method with piezoelectric signal recording, being the most sensitive and attractive one due to fast response, wide frequency band, absence of various limitations applied on the specimens at other recording methods.

(2) The thermal lens method making use of so-called "mirage effect" when a heated layer with optical properties differing from those of the environment arises in air or in a liquid above the surface probing point due to action of a high-power probing laser

pulse. In this case, the medium heating by the laser radiation results in a spatial deflection of the probing beam of another laser ("mirage effect"). The threshold sensitivity of the method is limited mainly by the power fluctuations of the laser radiation. At the fluctuation level not exceeding 0.5 to 1 %, the sensitivity threshold of temperature variation recording is about 10^{-4} to 10^{-6} °C.

(3) The pulse infrared radiometry method is a contactless method to record thermal radiation of a heated surface. The informative response is recorded using a fast-acting IR pyrometer. The latter makes it possible to establish in contactless manner spatial and temporal dependences of temperature in the area under probing and their correlation with the stress level therein.

At first glance, the advantages of the two latter methods, that is, the contactless excitation and receiving of the response, provide that those are unattainable for simpler methods where the contactless excitation in optical or IR range is combined with contact reception of PTA response data using sensors of acoustic waves fixed to surface of the object being investigated (piezoelectric signal recording). A more detailed consideration makes it clear, however, that the thermal lens method requires, first, higher-power excitation sources (lasers) and, second, precision optical systems to observe the mirage effect and record quantitatively the changes thereof. Moreover, it is to note that the sensitivity in the refraction methods is limited by fluctuations of the probing beam of the second laser as well as by its angular shifts due to vibrations. Therefore, that method requires an expensive apparatus and keeping of rather strict measurement conditions (absence of vibrations). That is why the application area of that method is restricted by laboratory investigations and unique scientific experiments. The pulse pyrometry method is less exigent to external conditions, so it could become the main method of the informative signal recording in the future. A progress in this field is associated, however, with development of commercially available compact portable pulse IR pyrometers that could sense a temperature difference at the level of 0.1 °C and its change rate of 0.001 deg/s or less.

In spite of numerous works aimed at investigation of PTA effect and development of various diagnostic systems based on the results obtained, the effect has not been used in essence to elaborate methodological base in diagnostics of stressed state areas in materials and constructions made thereof. In this work, the PTA effect has been studied in experiment (piezoelectric recording of the PTA signal) and theoretically in stressed areas of model specimens (bar systems) for pulse and harmonic modulation regimes of laser radiation. The purpose of the work is to elucidate the application possibility of PTA diagnostics to control the potentially dangerous areas (from the standpoint of critical stress levels therein) in some materials (Si_3N_4) and bar elements of industrial metal structures.

Pulse modulation of laser radiation. In contrast to traditional methods [2], we have considered the PTA excitation of elastic waves after the heat pulse action is over, that is, the temperature variation process occurs both in time and in space. It is just this variation process that generates the elastic pulse which is recorded in the experiment. The PTA response in the stressed area was calculated by solving the modified equation of thermoelastic medium motion under constant stresses. To that end, the temperature distribution in the medium under its irradiation by short light pulses was found. According to experimental conditions, the light was believed to be absorbed in a rather thin layer of the substance, that is, the heat flow was applied to the specimen through its surface. The light spot size being small, the temperature conductivity in transversal direction was neglected, that is, the case of planar temperature field in the direction coincident with the laser beam propagation one was considered.

Basing on the study results, we have proposed a model of PTA effect formation mechanism in a stressed medium after the action of short laser pulses is over as well as a low-frequency recording model [5]. Those models made it possible to obtain expressions for shifts (u_z) at various boundary conditions (damped and free surface) beyond the bounds of the PTA excitation.

(a) The damped surface (index "d") case:

$$u_z^d = \frac{\gamma_3^+\theta_0}{C_{33}^+} \cdot h_0 \cdot f(t). \tag{1}$$

(b) The free surface (index "f") case:

$$u_z^f = -\Pi \cdot \frac{\gamma_1^+\theta_0}{C_{33}^+} \cdot V \cdot \int_0^t f(t)dt, \tag{2}$$

where C_{33}^{+}, $\gamma_{1,3}^{+}$ are the effective elastic and thermoelastic constants, respectively; θ_0, the temperature of the h_0 thick material area; $f(t)$, a certain known time function that is slow as compared to the heat pulse front increase rate; V, thermoelastic wave propagation speed; Π, transformation coefficient of transversal stresses into exciting forces along the Z axis.

Denoting the PTA response in the absence of stationary stresses as P_0 and thermoelastic shifts in the same area as u_0, and taking into account that the PTA response (P) is in proportion to thermoelastic shifts ($P = A \cdot u$ where A is the instrument function of the whole system), we obtain for the relative change of the PTA response $\Delta P/P_0 = \Delta u/u_0$ and at end,

$$\left(\frac{\Delta P}{P}\right)_d = -\left[\left(\frac{\gamma_{12}}{\gamma}\right) - \frac{C_{112}}{C_{11}}\right]\left(\frac{\sigma_{0x}}{C_{11}}\right); \quad (3)$$
$$\left(\frac{\Delta P}{P}\right)_f = -\left[\left(\frac{\gamma_{11}}{\gamma}\right) - \frac{C_{112}}{C_{11}}\right]\left(\frac{\sigma_{0x}}{C_{11}}\right).$$

That is, the relative change of the PTA response in the stressed area of a medium is defined by linear and nonlinear elastic (C) and thermoelastic (γ) constants of the substance and depends linearly on the stationary stress magnitude. This fact is of importance in the practical use of the PTA procedure.

Harmonic modulation of laser radiation. Forced vibration of restricted solid bodies are known to be studied traditionally from two standpoints. On the one hand, the properties of vibrations themselves (e.g., elastic shifts) are considered. The dependences thereof on the frequency within the whole exciting frequency range as well as on the excitation point coordinates and the observation point ones are analyzed. The solutions of those tasks are cumbersome enough and can be obtained using numerical methods that are inconvenient in practice. On the other hand, the cases are considered where those shifts can be described analytically. Two cases, namely, a straight bar and a bent one (stressed medium) have been studied.

Solving the motion equation by eigenfunction method under account for action of a point thermoelastic force (transversal geometry), the following expressions have been derived for elastic shifts at the butt surface of a bar (observation point) in the case of longitudinal bar vibrations near the bar natural frequencies:

a) for symmetric vibrations

$$u^s_{xn}\Big|_{x=\pm l/2} = L^s_l \cdot \cos\left(\frac{\omega^s_n}{V}x_0\right); \quad (4)$$

b) for antisymmetric vibrations

$$u^a_{xn}\Big|_{x=\pm\, l/2} = L^a_l \cdot \sin\left(\frac{\omega^a_n}{V}x_0\right), \quad (5)$$

where $L^s{}_l$, $L^a{}_l$ are coordinate-independent constant factors; $\omega_n{}^{s,a}$, natural symmetric and antisymmetric circular frequencies of the bar vibrations, respectively; V, the propagation speed of longitudinal waves in the bar.

Similarly, the case of forced torsional vibrations in the bar have been studied. Taking into account the eigenfunctions near the resonance frequencies, the following expressions have been derived for the bar shifts (rotation angle of an elementary volume $\varphi_{0n}{}^{s,a}$ at the bar butt surface:

a) for symmetric torsional vibrations of a bar

$$\varphi^s_{0n}\Big|_{x=\pm l/2} = M^s_t y_0 \cos\left(\frac{\omega^s_n}{V}x_0\right), \quad (6)$$

b) for antisymmetric torsional vibrations of a bar

$$\varphi^a_{0n}\Big|_{x=\pm l/2} = M^a_t y_0 \sin\left(\frac{\omega^a_n}{V}x_0\right), \quad (7)$$

where $M^s{}_t$, $M^a{}_t$ are coordinate-independent constant factors; x_0, y_0, the laser beam incidence point coordinates.

Using the relationships obtained, values of the PTA response were calculated for longitudinal and torsional vibrations of a bar under single passing of the laser beam along the bar transversal axis. A good agreement is observed between calculated and experimental PTA response values as functions of the laser beam action coordinate. It is just the case of torsional vibration excitation and recording that has been established to provide the simplest and evident analysis of the results, in particular, when studying the effect of the material stressed state on the excitation character of those vibrations.

To illustrate the PTA method potentialities in visualization and monitoring of the stress field spatial distribution in surface layers of various materials, let the study results be presented for specimens of silicon nitride (Si_3N_4) structural ceramics. The Si_3N_4 based structural materials are used

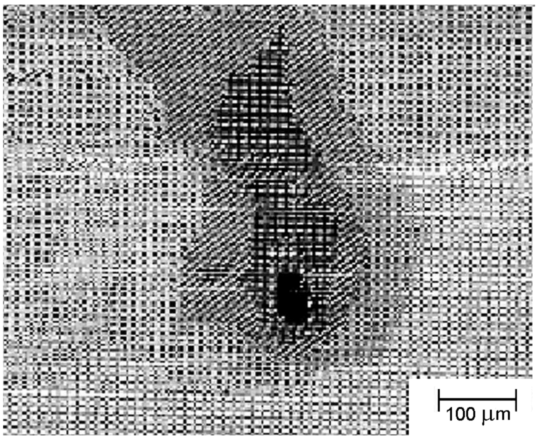

Fig. 1. PTA image of a Vickers pyramid indentation.

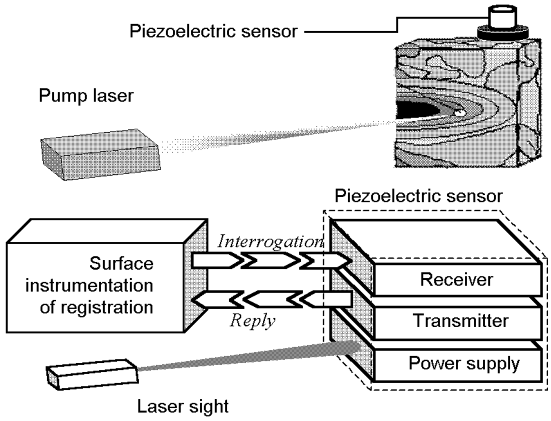

Fig. 2. Circuit design for the PTA diagnostics of stressed areas in structural materials.

widely in heat-resistant structures, in particular, in engine building, as well as to manufacture pieces and assemblies operated in aggressive media under high mechanical loading. Unfortunately, technical difficulties hinder the industrial production of ceramics exhibiting high and stable performance level within a wide temperature range. It is of importance to note that inhomogeneities and defects arising during the manufacturing of such materials result in local stress fields which, being in interaction under external loading, may cause formation of areas with critical stress levels. In this connection, in progress are investigation and technology development for manufacturing of the ceramic material itself as well as search for nondestructive methods to control its properties, in particular, of internal stresses [6].

A computerized PTA microscope with harmonic modulation of the Ar laser emission intensity was used in our experiments. The measurements were done at 80 kHz, thus providing thermowave visualization in a ceramic material in a depth of about 5 to 10 μm. Hot-sintered ceramic specimens were studied with surface marks applied using the Vickers pyramidal indenter. The indentation diagonal size was 10 to 15 μm. One of such indentations is shown in Fig. 1 as an example. The linear dimensions of the area where the PTA response is changed (about 450 μm) are seen to exceed considerably the visible size of the indentation itself (about 15 μm). This is due to that elastic stresses caused by plastic strain within the indenter action zone are extended over a considerable distance from the indention point. An attention is to be given to the anisotropic character of the PTA signal change. Perhaps this is connected with inhomogeneity of the specimen physico-mechanical characteristics.

Considering the whole set of the data obtained, it has been established that the results of experimental and theoretical studies aimed at elucidation of the PTA response formation mechanism in a medium under stress (the pulse modulation of the laser emission being used) can be considered as a methodological base to develop a circuit design for PTA diagnostics (with piezoelectric recording) of stressed state in materials and structures.

Such a circuit includes (i) a contactless optical pulse excitation channel; (ii) a PTA response recording circuit using a set of non-expensive stationary sensors fixed permanently on the structure under control; and (iii) a portable apparatus providing a contactless interrogation of the sensors and recording the PTA responses received thereby synchronously with the contactless optical excitation using a PC.

Fig. 2 shows a schematic diagram of such a circuit. The "smart" sensor is a piezoelectric plate being in a reliable acoustic contact with the structure and converting the acoustic PTA response signal into the electric one. The latter is amplified and transmitted to the portable apparatus within the time interval between the synchronizing pulses. The signal transmission from the sensor to the receiver occurs in various frequency ranges, but, in our opinion, it is just the VHF-FM ranges (sensors out of the direct vision zone) or an optical channel connecting the sensor light diode and the receiving photodiode (when there is a free path for the informative light beam). The power supply for the sensor could be provided either by built-in photo-cell with accumulating element (high-capacity condenser) or (when there is a short distance between the sensor and receiver) using the interrogating pulse energy. In the latter case, a stationary power supply for the sensor is unnecessary.

The photo-cells could convert into electric current either the daylight or those could be charged by an optical pumping source (e.g., a low-power laser) that is an obligatory member of the portable apparatus as a pointing system element (laser sight). A similar compromise between fully contactless data transmitting systems from various sensors and contact ones was proposed by Russian specialists at the "Complex Communication Systems" company when developing the Page Up complex using two-way pager communication to receive and transmit the telemetric data from sensors of a city engineering infrastructure [7].

Thus, the studies make it possible to conceive the nature of physical processes occurring under absorption of modulated electromagnetic radiation in a stressed material medium and suggest that the proposed circuit design is optimal and sufficient to use thereof as a base for the PTA diagnostics of materials and potentially dangerous areas of various industrial structures from the standpoint of critical stress levels therein.

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Фототермоакустичний ефект: прикладні аспекти діагностики областей напруженого стану в конструкціийних матеріалах

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Проведено експериментальні та теоретичні дослідження особливостей процесу фототермоакустичного (ФТА) перетворення у напруженому середовищі у випадку імпульсного та гармонічного режимів модуляції лазерного випромінювання. На основі отриманих результатів запропоновано функціональну схему ФТА діагностики областей напруженого стану в конструкційних матеріалах.