Investigation of propagation dynamics of material deformations caused by laser pulse action

A F Banishev

Institute on Laser and Information Technologies – Branch of the Federal Scientific Research Centre “Crystallography and Photonics” of Russian Academy of Sciences, Shatura 140700, Moscow Region, Russia

E-mail: banishev@mail.ru

Abstract. The mechanoluminescent materials attract increasing attention of scientists due to their capability of visualizing the mechanical stresses and deformations experienced by them. The deformations of materials arising under the action of powerful laser pulses were studied. The composite mechanoluminescent materials based on the polymer and phosphor powder were used for visualization and registration of deformation evolution dynamics. The mechanoluminescent materials were deposited on the surface of the materials under study. It has been shown that the spatial distribution of glow intensity of the mechanoluminescent layer and the rate of its change make possible judging the value and rate of material deformation under laser pulses.

1. Introduction

The development of reliable and informative methods of measuring stresses and deformations in materials is of much interest for controlling the condition of various parts and structures exposed to the external forces (mechanical, electrical, or magnetic). To the known methods commonly employed in measurements of stresses and deformations belong strain gauges, photoelastic coatings, the digital image correlation method and the moiré interference method. Great interest has been recently expressed in the investigation of mechanoluminescent materials (mechano-phosphors) and in the development of sensors of deformations and stresses based on these materials. The interest has grown to studying mechano-piezo-phosphors and to the development of the new types of devices and mechanisms for mechano-piezo-photronics [1–15]. Mechano-phosphors are the materials transforming external mechanical actions to light emission. By now, a large number of them have been synthesized, which produce efficient mechanoluminescence in various spectral ranges [16, 17]. The mechanoluminescent coatings deposited on the surface of the component being studied are capable of visualizing the stresses and deformations in the complex-shape parts and over a large area, which cannot be done by other methods. Of special interest are the mechano-phosphors generating mechanoluminescence in the presence of elastic deformations over a wide range of loads. The mechanoluminescence intensity of the mechano-phosphors of this kind is known [18, 19] to be proportional to the amount of stresses and deformations of the surface, so they can be used in quantitative measurements of stresses and deformations in materials. The distribution of stresses and deformations in the material can be estimated by the distribution of glow intensity of the mechanoluminescent layer. In [20–22], crack formation and velocity in ceramics were studied with the use of a mechanoluminescent coating deposited on the sample surface. The formation and growth of
cracks were initiated by means of an indenter. The application of mechanoluminescent coatings in the diagnostics of stresses and crack initiation and growth in materials under mechanical action proved to be highly informative. In [23] the mechanoluminescent coatings were employed for registration of deep microcracks initiated in the volume of material under cyclic loads and tension.

This work studies the deformations of metallic plates emerging on exposure to powerful laser pulses. The visualization of deformations was realized with the use of a composite mechanoluminescent material that was deposited on the plate surfaces. The dynamics of deformation was recorded by a high-speed video camera.

2. Materials and experimental procedure
To visualize the deformations, a composite mechanoluminescent material was prepared that was based on an adhesive transparent in the visible spectrum and a powder of the mechano-phosphor SrAl$_2$O$_4$:(Eu$^{2+}$, Dy$^{3+}$). A thin layer of the suspension was deposited on the surfaces of the metallic plates (stainless steel) of 100 to 200 µm thickness and ≈30 mm diameter. Hardening of the suspension yielded a layer of the composite material ≈150-200 µm thick. Figure 1 shows the scheme of the facility for investigation of the thermal deformations emerging under the action of powerful pulses of the YAG: Nd$^{3+}$ laser ($\lambda$≈1.06µm, $\tau$=1.5 ms, $W$=1.5 J). The laser pulse was focused on the free surface of the metallic plate into a spot of d≈2-6 mm. This resulted in fast heating of the material in the area of radiation interaction with the material and caused its thermal deformation.

![Figure 1. A scheme of the experimental facility. 1. Metallic plate. 2. Mechanoluminescent layer. 3. YAG: Nd$^{3+}$ laser. 4. High-speed video camera.](image)

3. Results and discussion
Estimate now the temperature $T$ to which the backside of the plate will be heated at the end of laser pulse and the value of thermal stresses at $r=1$ mm, $d=150$ µm, $W=1.5$ J.

$$T(\tau_p) \approx \frac{AW}{\pi [r + (\chi \tau_p)^{1/2}]^2 d \rho c_m},$$

where $A$≈0.35 is steel absorptance, $\chi$=0.13 cm$^2$/s is thermal diffusivity, $\rho$=7.8 g/cm$^3$ is density, $c_m$=0.46 J/g*K is specific heat. Having substituted the numerical values, obtain $T$≈310 °C. To evaluate the thermal stresses arising by the end of the laser pulse in the irradiation area, use the expression:

$$\sigma (\tau_p) \approx \frac{\alpha G T(\tau_p)}{(1-\mu)},$$

Substituting $\alpha$=12.7*10$^{-6}$ K$^{-1}$ – thermal expansion coefficient of steel, $G$=7.3*10$^{10}$ N/m$^2$ – shear modulus, $T$≈310°C, $\mu$=0.28 – Poisson ratio, we obtain $\sigma$≈4*10$^8$ N/m$^2$.

Figure 2 presents the views of the plate surface with the deposited mechanoluminescent layer, produced with the high-speed video camera (frame rate is 500 f/s).

The bright areas in the frames illustrate the mechanoluminescent layer glow caused by the deformations of the plate. Figure 2a shows the glow of the mechanoluminescent layer just after the
end of the laser pulse. In the course of time, the luminous region rapidly increases in size, the rate of its growth far exceeding the velocity of temperature front propagation.

**Figure 2.** Visualization of deformations in the metallic plate by means of a mechanoluminescent layer: 
a) thermal deformations instantly after laser pulse action. Propagation of nonthermal deformations :b) in 15 ms, c) in 30 ms.

Figure 2b, c presents the images of the surface obtained in 15 ms and in 30 ms after laser pulse termination. This behavior demonstrates that the thermal deformations originated in the area of laser pulse action give birth to nonthermal deformations of the plate which propagate rapidly from this area. As the distance from the irradiation area increases, the glow intensity of the mechanoluminescent layer is lowered, thus pointing to a reduction in the amount of the plate deformations.

**4. Conclusion**
The investigations of material deformations arising under the action of powerful laser pulses were conducted. Visualization of the deformations was performed by using the composite mechanoluminescent materials deposited on the surface of the materials under study. It was shown that the glow distribution and intensity of the mechanoluminescent coatings give a rather comprehensive idea of the distribution rate and amount of material deformations emerging under laser pulses.

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