

## Photoacoustics of the stressed state in solids<sup>a)</sup>

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The modern experimental and theoretical states of the problem of residual stress detection by the photoacoustic method are analyzed. Some experimental results obtained by the photoacoustic method for Vickers indentation zones in silicon nitride and  $\text{Al}_2\text{O}_3\text{-SiC-TiC}$  ceramics are presented. The effect of annealing on the photoacoustic piezoelectric signal for the  $\text{Al}_2\text{O}_3\text{-SiC-TiC}$  ceramic and the influence of the given external loading on the behavior of the photoacoustic signal near the radial crack tips are investigated. It is experimentally shown that both compressive and shear stresses contribute to the photoacoustic signal near the radial crack tips. The theoretical approach based on the nonlinear thermoelastic model of the photoacoustic effect is further developed for explanation of the photoacoustic signal behavior near the radial crack tips. It is demonstrated that this model of the photoacoustic effect agrees qualitatively with the available experimental data.

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### I. INTRODUCTION

The problem of residual and mechanical stress detection in solids by the photoacoustic (PA) method has been investigated for about 12 years. The PA detection of residual stress was reported in Refs. 1 and 2. Since then, a number of similar applications of the PA effect<sup>3-10</sup> and electron acoustic effect<sup>11,12</sup> have been performed. In spite of these efforts, the PA methods were not widely used for residual stress detection until now. This situation is essentially inconsistent with other methods such as optical,<sup>13</sup> x-ray,<sup>14</sup> and neutron<sup>15</sup> diffraction, ultrasonic,<sup>16</sup> and Raman spectroscopy,<sup>17,18</sup> stress pattern analysis by the measurement of thermal emission (SPATE),<sup>19</sup> and the hole drilling method in conjunction with holographic or speckle interferometry,<sup>20</sup> which are widely used for residual stress detection at present. This situation is due primarily to the lack of in-depth systematic studies of the PA effect in solids with residual stresses including direct confirmation of residual stress effect on the PA signal. Therefore, the main purposes of this study are to summarize the available results and to prove the dependence of the PA signal on residual stresses.

### II. PHOTOTHERMAL AND PHOTOACOUSTIC EXPERIMENTAL STUDY OF CERAMICS WITH RESIDUAL STRESSES

In the investigations of the PA phenomena in solids with residual stresses, only the PA or electron-acoustic method was used. It is known that PA or electron-acoustic signals can depend on various thermal, thermoelastic, and elastic

parameters of a sample under investigation. Therefore, in these investigations, it was impossible to independently control the thermal, thermoelastic and elastic parameters of an object, and to identify the origin of the effect observed. To overcome this restriction, we have proposed and applied in our work a multimode approach based on the simultaneous use of several photothermal (PT) and PA techniques.<sup>6-10</sup> It includes the PA gas microphone, photodeflection, photoreflexance, and PA piezoelectric measurements. The thermal properties in this approach are controlled and measured by the photodeflection, photoreflexion, and PA gas microphone methods, while the thermoelastic properties are controlled by the PA piezoelectric method.

In this work, the experimental results are presented for hot pressed silicon nitride and  $\text{Al}_2\text{O}_3\text{-SiC-TiC}$  ceramics that were obtained by us within the framework of this approach. Residual stresses were introduced in ceramics by Vickers indentation, because indentation is one of the most reliable and reproducible methods for generation of residual stresses and crack systems in solids.<sup>21</sup> Samples were indented with loads from 49 to 196 N. The average indentation side on the sample surface at the load of 98 N was about 75  $\mu\text{m}$  for hot pressed silicon nitride ceramic and about 65  $\mu\text{m}$  for  $\text{Al}_2\text{O}_3\text{-SiC-TiC}$  ceramics. Vickers indentation has a rather complicated structure which includes core, plastic and elastic zones, radial, or median cracks (see Fig. 1). However, in this work, primary focus is on the investigation of the PA and PT signal behaviors near the radial crack tips where strong residual stresses are normally concentrated.<sup>22</sup>

The images of the Vickers indented ceramics were obtained by scanning samples along two coordinates with the step of 2.5  $\mu\text{m}$ . Thermal waves and acoustic vibrations were excited in the samples by the radiation of a continuous-wave argon-ion laser modulated by an acousto-optic modulator. The radiation of the pump laser was focused on a sample surface into an approximately 2  $\mu\text{m}$  spot. In the photodeflec-

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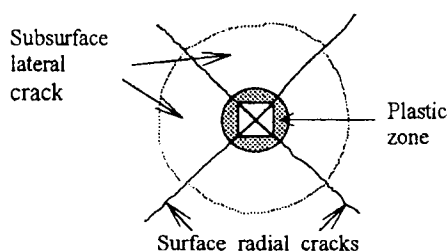


FIG. 1. Sketch of the Vickers indentation crack system for brittle solids. Plan view.

tion and photoreflectance modes, the radiation of a He-Ne laser was used for readout.

Let us consider results obtained in different operating modes of the microscope beginning with the photodeflection mode. An example of a typical photodeflection image of the Vickers indented silicon nitride ceramic is shown in Fig. 2. It should be noted that photodeflection images of  $\text{Al}_2\text{O}_3$ -SiC-TiC composite ceramic, in general, are similar to the presented image with the exception of an additional speckle structure. However, this speckle structure is not determined by thermal or thermoelastic properties of this ceramic. It appears only due to different optical properties of  $\text{Al}_2\text{O}_3$ , SiC, and TiC grains of this ceramic. In our experiments with silicon nitride and  $\text{Al}_2\text{O}_3$ -SiC-TiC ceramics, we measured the photodeflection images of various Vickers indentations. In the experiments with silicon nitride, detailed PA gas microphone and photoreflectance measurements were also made. It should be noted that the PA gas microphone, photodeflection, and photoreflectance images exhibit no particular features in the vicinity of the radial crack tips.

The PA piezoelectric images were obtained for both hot pressed silicon nitride and  $\text{Al}_2\text{O}_3$ -SiC-TiC ceramics. All these images, in general, have a similar structure, therefore we present here only the PA piezoelectric image of the  $\text{Al}_2\text{O}_3$ -SiC-TiC ceramic. The typical image of this type is shown in Fig. 3. An important peculiarity of these images is the presence of regions with large signal amplitude located near the ends of the radial cracks. Previously, analogous features have been reported for the images of Vickers indentations obtained by electron-acoustic microscopy.<sup>2</sup> We have also observed this feature during the PA piezoelectric study of a silicon nitride ceramic.<sup>6-8</sup> However, up until now, there has been a lack of direct proof that these peculiarities of the

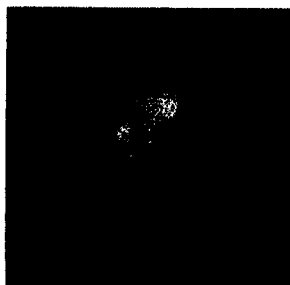


FIG. 2. The normal photodeflection image of Vickers indentation in  $\text{Si}_3\text{N}_4$  ceramic. The indentation load is 98 N, the modulation frequency is 7.6 kHz, and the area is  $320 \times 320 \mu\text{m}^2$ .

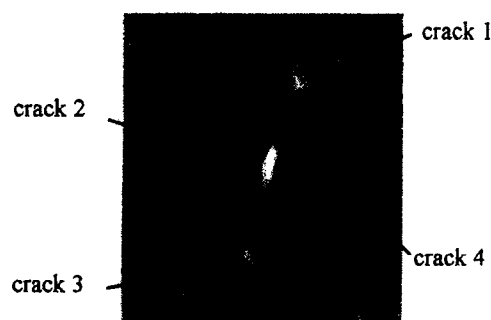


FIG. 3. The PA piezoelectric image of Vickers indentation in  $\text{Al}_2\text{O}_3$ -SiC-TiC ceramic. The indentation load is 98 N, the modulation frequency is 142 kHz, and the area is  $480 \times 500 \mu\text{m}^2$ .

PA piezoelectric signal near the radial crack tips are produced by residual stresses. Some of our results presented here can be considered as a direct confirmation of binding of the PA piezoelectric signal behavior and residual stresses.

The influence of stresses on thermophysical properties of metals was pointed out in an earlier investigation.<sup>1</sup> To control a possible contribution of this mechanism to the PA signal from stressed ceramics, we have used photodeflection and photoreflectance methods in our investigation. All of our photodeflection images (see, for example, Fig. 2) exhibit no features in the vicinity of the radial crack tips where strong stresses are concentrated. The same result has been obtained by us earlier for silicon nitride ceramic by the photoreflectance method.<sup>8</sup> Thus, our experimental results for ceramics lead to the conclusion that residual stresses do not noticeably influence their thermal properties.

In the previous studies of the PA effect in stressed materials, the PA response has not been investigated at additional external actions on objects such as temperature variation, loading, etc. The study of these effects can provide a direct demonstration of the existence of the dependence of the PA signal on residual stresses and ensure a deeper understanding of this dependence. Within the framework of this work, the main task was to investigate the PA response from regions with residual stresses in ceramics under annealing and external loading.

Let us consider first the influence of annealing on the PA piezoelectric response from regions with residual stresses. For this purpose, we have measured the PA piezoelectric images of indentation sites after the annealing of an  $\text{Al}_2\text{O}_3$ -SiC-TiC ceramic sample.<sup>23</sup> Annealing was made at  $800^\circ\text{C}$  and was produced in three stages. The duration of each stage was equal to 8 h. In the experiments with the  $\text{Al}_2\text{O}_3$ -SiC-TiC ceramic, this result was additionally confirmed by measurements of the photodeflection response after three annealing stages. These measurements provided us with images corresponding to 8, 16, and 24 h. It should be noted that after each annealing at  $800^\circ\text{C}$ , the sample temperature was decreased at a sufficiently slow rate (about  $10^\circ\text{C}/\text{min}$ ) in order to minimize the effect of thermal stresses on the crack growth. In Fig. 4, the maximum PA signal intensity normalized to the average PA response is shown within the course of annealing for two radial cracks in an  $\text{Al}_2\text{O}_3$ -SiC-TiC ceramic. Figure 4 clearly reveals a gen-

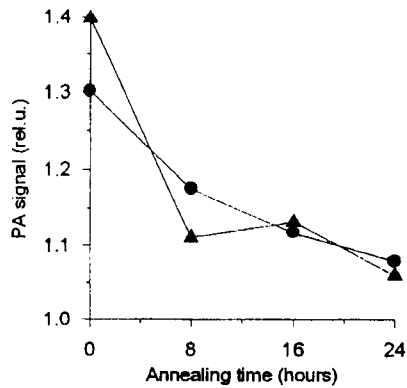


FIG. 4. The dependence of the maximal amplitude of the piezoelectric signal near the ends of two radial cracks on the annealing time.

eral tendency of the PA piezoelectric signal to decrease with increasing annealing time. For one of these cracks, some increase in the PA signal was observed after the 16 h annealing. This event probably takes place because of the regions of the material in the vicinity of the crack tips that occur in a significantly nonequilibrium thermodynamic state,<sup>24</sup> so that even weak thermal stresses can affect the crack growth. However, this event does not violate the general tendency. The presented experimental data on the PA response variation in the course of annealing of the  $\text{Al}_2\text{O}_3$ -SiC-TiC ceramic are consistent with the commonly accepted opinion that annealing decreases residual stresses.<sup>24</sup>

We have also made photodeflection imaging of an  $\text{Al}_2\text{O}_3$ -SiC-TiC ceramic sample after each stage of annealing to control its thermal properties.<sup>25</sup> These experiments did not reveal any significant influence of annealing on the photodeflection images of  $\text{Al}_2\text{O}_3$ -SiC-TiC ceramics near Vickers indentations.<sup>23</sup> Therefore, the results of photodeflection imaging both for silicon nitride and  $\text{Al}_2\text{O}_3$ -SiC-TiC ceramics show that the correlation between the PA piezoelectric response and residual stresses is not related to the effect of residual stresses on thermal properties of these materials or restoration of their thermal properties under annealing.

The second specific feature of this work is the investigation of the influence of external loading on the PA and PT responses in direct experiments with ceramics. External loading was applied in our experiments in the direction parallel to the sample surface. We have obtained the PA and PT images of Vickers indentations in unloaded and loaded  $\text{Al}_2\text{O}_3$ -SiC-TiC composite ceramic. First of all, it should be noted that the photodeflection images of Vickers indented areas in this ceramic do not demonstrate any influence of external loading. This fact correlates with the results of annealing experiments.

A typical PA piezoelectric image of the Vickers indented area in an  $\text{Al}_2\text{O}_3$ -SiC-TiC composite ceramic under external loading is presented in Fig. 5. From Figs. 3 and 5, one can see that strong changes of the PA piezoelectric image with the application of external loading take place in various regions of the Vickers indented area. However, in this work, we restrict ourselves by the investigation of the PA signal behavior near the ends of radial cracks only.

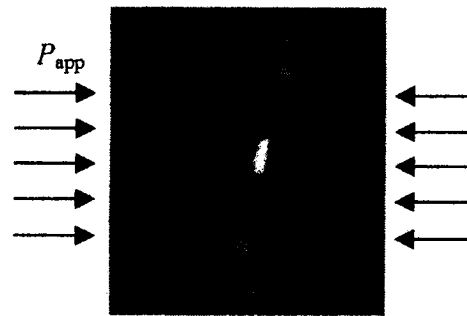


FIG. 5. The PA piezoelectric image of Vickers indentation in  $\text{Al}_2\text{O}_3$ -SiC-TiC ceramic under the external loading of 170 MPa.

### III. THEORETICAL MODEL OF THE PHOTOACOUSTIC EFFECT IN STRESSED SOLIDS

For an explanation of the obtained experimental results, we have used the theoretical model of the PA effect in solids with residual stresses developed by us earlier.<sup>7-9</sup> This theory explains the influence of residual stresses on the PA piezoelectric signal by taking into account the nonlinear thermal, thermoelastic, and elastic properties of a material. It was demonstrated<sup>7-9</sup> that the developed theoretical model agrees qualitatively with the available experimental data. Therefore, in this article, the primary focus is the application of this model to the analysis of the PA signal behavior near the radial crack tips. When applying this model to our case, we took into account the fact that in our experiments the PA signal in an  $\text{Al}_2\text{O}_3$ -SiC-TiC composite was generated in a relatively thin subsurface layer. For example, for modulation frequencies of about 100 kHz, the thickness of this layer was about 10  $\mu\text{m}$ . We took also into account that residual stresses near the tips of radial cracks are directed mainly parallel to the sample surface. Therefore, one can assume that for the strain tensor produced by residual stress  $U_{xx} \gg U_{zz}$  and  $U_{yy} \gg U_{zz}$ , where axis  $z$  is directed perpendicular to the sample surface and  $U_{xx}$ ,  $U_{yy}$ , and  $U_{zz}$  are the residual strains near the radial crack tips. For this case, the PA signal produced by residual stresses in accordance with the results of Refs. 7-9 can be expressed in the linear on residual strains approximation in the form

$$\Delta V(\omega) = A(U_{xx} + U_{yy}), \quad (1)$$

where  $A = V_0(\omega)(\beta_0 + 3/2 - 3l/\rho_0 c_\ell^2)$ ,  $V_0(\omega)$  is the PA piezoelectric signal from the undeformed body,  $\beta_0$  is the coefficient taking into account the dependence of the thermoelastic coupling on strain,<sup>8</sup>  $l$  is the third-order Murnaghan constant,  $\rho_0$  is the density of the undeformed body, and  $c_\ell$  is the longitudinal velocity of sound.

First of all, it should be noted that in accordance with Eq. (1), the dependence of the PA signal on residual strains is determined by the same combination of residual strains as in the case of the SPATE method.<sup>26</sup> However, the spatial resolution of the SPATE method lies in the millimeter range while the PA method is able to provide a micrometer resolution.

In terms of the mechanisms of cracks, Eq. (1) for the PA signal can be written as<sup>27</sup>

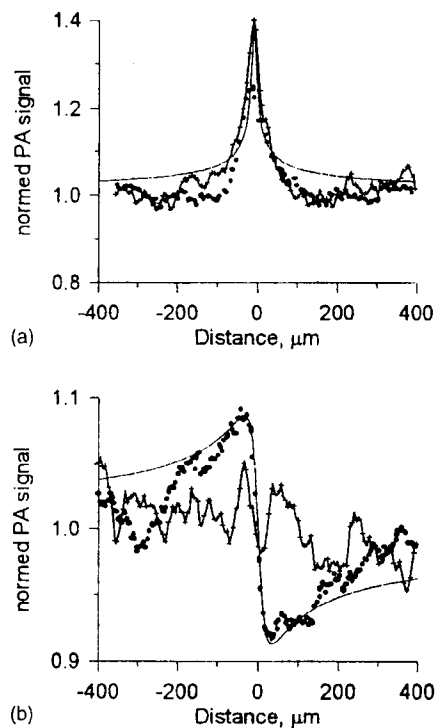


FIG. 6. The behavior of the PA piezoelectric signal across the tips of radial cracks: (a) for crack 1; (b) for crack 4. (+) experimental data for the sample without external loading, (●) experimental data for the sample under the external loading of 170 MPa; and (—) theoretical curve.

$$\Delta V(\omega) = A \frac{(1-\nu)\sqrt{2}}{E\sqrt{\pi r}} \left[ (K_I^{(0)} + K_I^{(1)} \sin^2 \phi) \cos \frac{\theta}{2} - (K_{II}^{(0)} + K_{II}^{(1)} \sin \phi \cos \phi) \sin \frac{\theta}{2} \right], \quad (2)$$

where  $\nu$  is Poisson's ratio,  $E$  is Young's modulus;  $K_I^{(0)}$  and  $K_{II}^{(0)}$  are the stress intensity factors relating to residual stresses near the crack tips;  $K_I^{(1)}$  and  $K_{II}^{(1)}$  are the stress intensity factors of the crack characterizing the crack behavior under external compressive (tensile) and shear stresses, respectively;  $r$  is the distance between the crack tip and the point of measurement;  $\phi$  is the angle between the crack and the direction of external loading;  $\theta$  is the angle between the crack and the direction to the point of measurement.

For the examination of the developed model of the PA signal formation near radial cracks, we compared the results which follow from Eq. (2) with the experimental data obtained from the PA piezoelectric images of Vickers indented areas in ceramics. The comparison was made for the behavior of the PA signal near the crack tips along a line perpendicular to the crack, because the distributions of normal and shear stresses in this direction are essentially different. The results were obtained for radial cracks oriented at different angles to the direction of the external loading. This approach provides us an opportunity to compare theoretical and experimental results at various loading conditions.

Figure 6 demonstrates the experimental data representing the behavior of the PA signal along the described direc-

tions for two radial cracks in an  $\text{Al}_2\text{O}_3$ -SiC-TiC composite ceramic. Theoretical results obtained from Eq. (2) are also presented in Fig. 6. The chosen cracks denoted as 1 and 4 in Fig. 4 correspond to the situation in which the impact of the external loading on the stress fields near crack tips has a quite different character. For crack 1, the angle  $\phi \cong 75^\circ$  and external loading is almost normal to the crack interfaces. For crack 4, the angle  $\phi \cong 17^\circ$  and external loading produces nearly pure shear stress. In the theoretical calculations, the distances between the crack tip and the line of the PA scanning were  $5 \mu\text{m}$  for crack 1 and  $20 \mu\text{m}$  for crack 4. The results presented in Fig. 6 demonstrate a good agreement of the experimental data with our theoretical model at short distances from the crack tips. Some disagreement between experimental and theoretical results at distances away from the crack tips is due to an asymptotical character of the used expressions for stress tensor components<sup>27</sup> which are valid only for short distances. It is seen from Fig. 6(a) that external compressive stress compensates partially tensile residual stress acting near the tip of crack 1.

The obtained experimental data, which are related to the PA signal behavior near the crack tips in combination with the theoretical results of the crack mechanics, enable us to make some conclusions about the stress intensity factors of the radial cracks in an  $\text{Al}_2\text{O}_3$ -SiC-TiC composite ceramic. A more detailed analysis of this problem is given by us in Ref. 27. In this article, it is shown that the proposed model gives reasonable quantitative relations between stress intensity factors of the radial cracks in an  $\text{Al}_2\text{O}_3$ -SiC-TiC composite ceramic. These relations are in good agreement with similar results obtained on the base of the crack mechanics for ceramics with  $\text{Al}_2\text{O}_3$  grains.<sup>28</sup>

#### IV. DISCUSSION

The proposed approach provides both experimental and theoretical bases for the investigation of the influence of stresses and residual stresses on the PA and PT phenomena in various materials. The obtained PT data do not show any influence of stress on the thermal properties of silicon nitride and  $\text{Al}_2\text{O}_3$ -SiC-TiC ceramics. However, there is no reason to generalize this result on other types of materials. The experimental data obtained by us under the annealing and external loading of Vickers indentations in an  $\text{Al}_2\text{O}_3$ -SiC-TiC ceramic can be considered direct confirmation of the correlation between the PA piezoelectric signal behavior and residual stresses. It is shown that our nonlinear thermoelastic theory of the PA effect in solids with residual stresses is able to provide a qualitative explanation of the obtained experimental data. It is shown also that this theory relates the PA piezoelectric signal with stresses in the form analogous to the SPATE signal. The detected behavior of the PA signal reproduces both normal and shear stresses near the ends of radial cracks in accordance with the proposed theoretical model. In combinations with the presented theoretical results, the experimental PA data can be used for extracting important information about the stress intensity factors of cracks.

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