Photoacoustic thermoelastic imaging of indented areas in metals

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Abstract

Non-destructive evaluation of metals with residual stresses was performed by the photoacoustic method. Main attention was paid to experimental investigations of areas inside Vickers and Rockwell indentations in metal samples under external loading. It is shown that external normal and shear stresses influence on the behavior of the photoacoustic signal inside indented areas in metals. The obtained results can be used for estimating sensitivity of the photoacoustic method to mechanical stress determination in metals. The theoretical model of the photoacoustic thermoelastic effect in solids is proposed for the explanation of the obtained results. It is based on the modified nonlinear model of elastic body that takes into account a possible dependence of Youngs modulus of a metal on temperature. The proposed model is applied for the explanation of the photoacoustic signal behavior in indented areas of metals and its modifications under residual and external stresses. Theoretical and experimental study of the photoacoustic signal behaviour resulted in a new method of residual stress evaluation based on thermoelastic photoacoustic effect and Vickers indentation.

1 Introduction

Recent investigation of the thermoelastic photoacoustic (TEPA) effect in solids reveals the dependence of thermal, thermoelastic and elastic properties on the internal stress [1, 2, 3, 4, 5, 6, 7, 8, 9]. These works open new possibilities for the non-destructive evaluation of objects with residual stresses at a microscopic level. It has an utmost practical as well as fundamental significance. A long history of the technique and industries shows the vitality of the residual stresses for the life expectance and reliability, whereas the mechanisms of stress effect are far from the deep consideration. Because of the universal character of The photothermoacoustic methods they can be apply for investigating the great diversity of materials.

Previously, the residual stress effect on thermal and thermoelastic properties was investigated experimentally for several ceramic composites [4, 5, 8, 9]. It was clearly demonstrated under external subjection like temperature and pressure, that the internal stress very strongly influences on the photoacoustic piezoelectric signal. Our experimental approach consisting in applying simultaneously different photothermoacoustic methods reveals main mechanisms of the TEPA signal formation in the investigated ceramics.

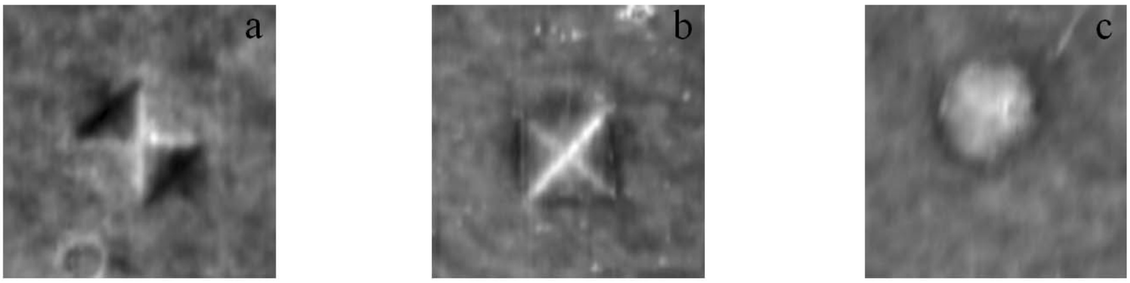

Figure 1: The photoacoustic piezoelectric images of two Vickers indented areas (a, b) and a Rockwell indented area (c) in steel smple. The size of the each image is 0.6x0.6 mm^2. The modulation frequency is 142 kHz.

To interpret the obtained results a non-linear model of the TEPA effect in solids with residual stress was developed. The model quantitatively explains the behaviour of the TEPA signal, for example, near vertical crack tips [8, 10, 11].

The photoacoustic methods provide unique opportunity for the microscopic study of the residual stress. In this case a three dimensional model for inhomogeneous objects is needed for a quantitative analysis. Here we present analytical expressions for the TEPA signal obtained in the framework of the perturbation theory.

Experimental part of the work is devoted to the photoacoustic investigation of metals with residual stresses. The objects of study were steel samples with Vickers and Rockwell indentation.

2 Experimental results and discussion

For microscopic study of the thermoelastic properties of solids we use photothermoacoustic microscope with built-in compressive mechanism that allows us to investigate samples under external load up to 2000 N parallel to the sample surface. The microscope provides scan images with minimal step 2.5 μm in two directions. Thermal waves and acoustic vibrations were excited in the sample by radiation of an argon-ion laser modulated by an acoustooptic modulator. The radiation was absorbed at the front surface of a sample. To detect the photoacoustic signal a piezoelectric detector was attached to the rear side of the sample and had an operation frequency about 140 kHz. The modulation frequency in photoacoustic microscopy is one of the pacing factors of spatial resolution. For instrumental steel U8 the corresponding thermal wave length is about 3 μm.

In this work we focused on studying steel samples. Residual stresses were produced in the sample by Vickers or Rockwell indentation. The indentation load was 98 N. In these materials there was no cracks unlike the case of ceramics [8, 10], so, the main attention was paid to the TEPA signal behaviour inside the prints and in the nearest vicinities.

Fig. 1 presents images of indented areas of a steel sample. There are two Vickers indentations made at angle 45° and Rockwell indentation. The load of indentations is 98 N. One of the features of such images is high amplitude of the TEPA signal

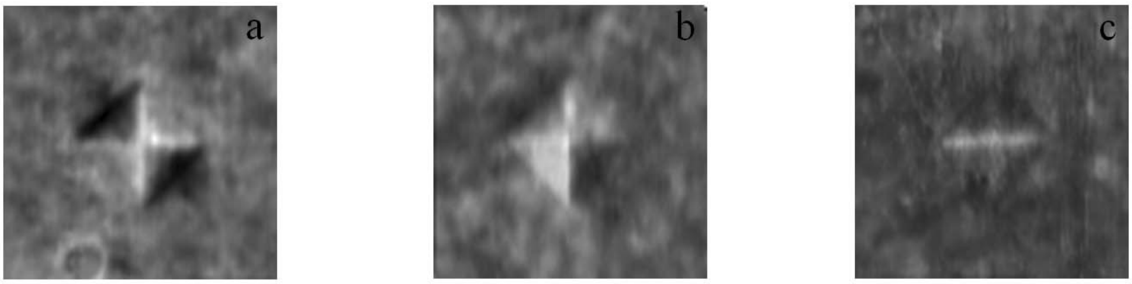

Figure 2: The photoacoustic piezoelectric images of a Vickers indented area while annealing 870°C. (A) is an image of the initial state, (b) is an image after 1h annealing and cooling in air, (c) is an image after the following 1h annealing and cooling in athe furnace. The image size is 0.6x0.6 mm^2. The modulation frequency is 142 kHz.

along the Vickers indentation diagonals which are the strong stress concentrators. The highest signal is in the indentation center. Its magnitude is about two to three times larger than the average signal outside the indentation zone. In this case a signal higher than average corresponds to the compressive stress and a lower signal corresponds to the tensile stress, which is similar to the case of ceramics [10].

To reveal the nature of photoacoustic piezoelectric response from metals with residual steress we performed experiments with thermal development of the samples. For this purpose we have made images of the indented areas after two annealing circles. The annealing was made at 870°C. The first stage was one hour heating and cooling in air. The second stage was one hour heating also but cooling in the furnace. Fig. 2 shows three images of one of the indents before and after the two annealing circles. The image after the first circle (Fig. 2b) exibits a certain decrease of the TEPA signal deviation from the average value but together with appearence of some new features corresponding to thermal stresses induced by the quick cooling in the air. The second annealing circle with the slow cooling results in a much more smooth image with a maximum signal of 160% of the average amplitude along one diagonal only (Fig. 2c). We propose that this signal feature may be due to plastic deformation. Elimination of other features implies that the main part of residual stresses disappeared during anniealing. So we confirmed once more that the TEPA signal is well attributed to stress field in objects.

Let us consider now an external load influence on indentation images and residual stress distribution. Fig. 3 presents behavior of the TEPA images of two Vickers indentation oriented at different angles to the external load axe. The indentation were made at the same sample not far from each other. The initial free state of the sample is shown in Fig. 3a and 3b. The difference of the images may be both due to initial residual stress before indentation and orientation of the prints relative to the piezoelectric detector. According to images 3c and 3d, there was a strong redistribution of the stresses inside the indentation print under moderate external pressure 24 MPa. After cancelling the load indentation image of the first indentation returned to the initial state because images 3c and 3e are similar. This means that all changes under the load were forced by elastic deformations. Signal behavior across the indent diagonal is shown in Fig. 4. The normed signal changed from 1.5 to 3.0 under the load and relaxed down to 1.7 after the load cancel. So the

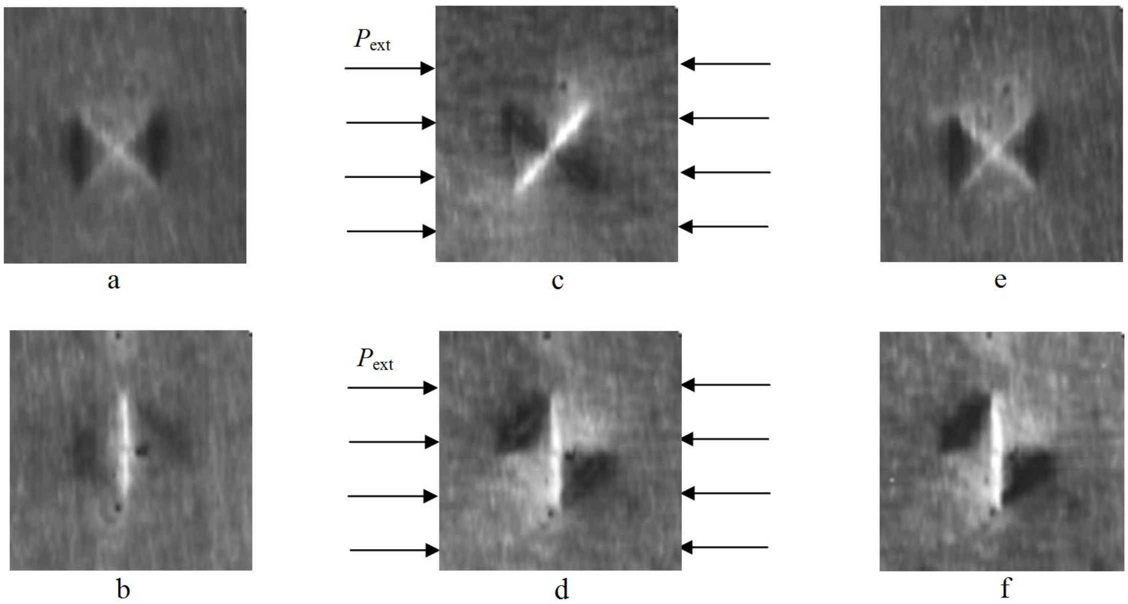

Figure 3: The photoacoustic piezoelectric images of two Vickers indented areas in the steel sample. Arrows denote external pressure direction. The image size is 0.6x0.6 mm^2. The modulation frequency is 142 kHz. (A) and (b) are the different indentations in free state, (c) and (d) are the images of the sample under external load 24 MPa, (e) and (f) are the images after the load cancel.

difference in signal between 1.7 and 1.5 corresponds to the plastic deformation and that between 3.0 and 1.7 corresponds to the elastic deformation under external pressure 24 MPa. The most interesting peculiarity of image 2c is opposite change of th signal on the two diagonals. According to our above suggestions one diagonal is subjected to compressive and the other one to tensile stress, although the both diagonals are at the angles close to 45° to the load axe. That means that the stress field is redistributed inside the indent print.

The other indent exibits a different behavior under the same external load. One can see from Fig. 3f that the load cancel does not change practically the TEPA image. This means that the all changes have the plastic character. Apparengly, the residual compressive stress concentrated along one diagonal was so high that the low external pressure was enough to produce plastic deformation. At that, irreversible changes took place not only at this diagonal but in the whole area of the indentation. In this experiments the Vickers indentation behaves itself as one system with connections between its parts.

3 Theoretical model of the thermoelastic photoacoustic effect in inhomogeneous solids

The theoretical model of the TEPA effect in solids with residual stresses was proposed in our previous works [4, 5, 6]. Here we present the further three-dimensional development of the model for a case of inhomogeneous objects with non-uniform

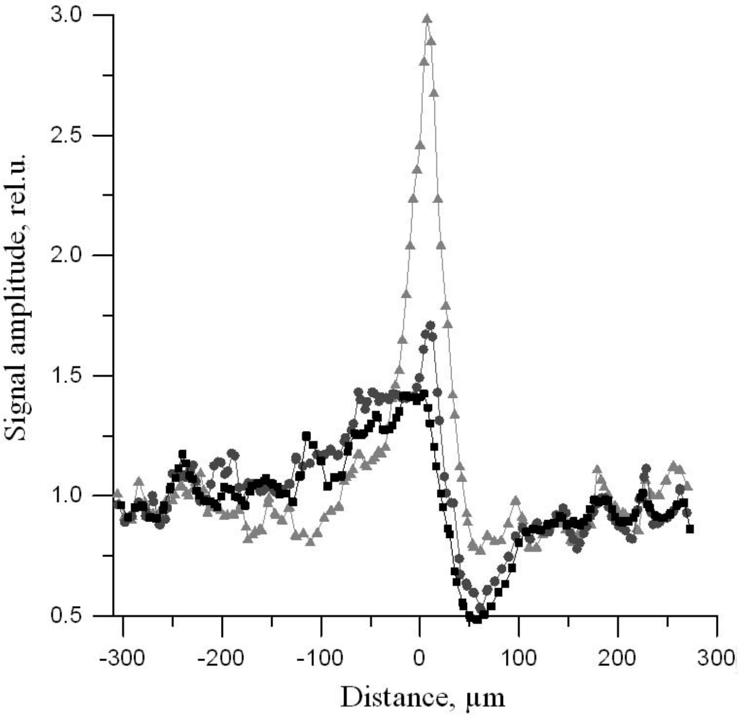

Figure 4: Distribution of the photoacoustic signal amplitude across the upper right part of diagonal of the indent shown in Figs. 3a, 3c and 3e. Black squares correspond to the initial state, grey circles correspond to the sample under the external pressure of 24 MPa, light grey triangles correspond to the sample after cancelling the load.

mechanical stress fields.

We consider the residual stress influence on the properties of a material by introducing the dependence of thermoelastic constant on elastic deformations. Previously, the photoacoustic signal variations resulted from non-uniform residual stresses was obtained for the case of fixed sample boundary [12]. Here we need an expression for TEPA signal for the case of a free sample surface. The non-stationary deformations can be defined by solving the general equation of motion for elastic solids [13]

$$\rho\frac{\partial^2 u_i}{\partial t^2} = \frac{\partial \sigma_{ij}}{\partial x_j}, \tag{1}$$

where ρ is the density of deformed body, u_i are the displacement components, σ_{ij} are the stress tensor components accounting the thermoelastic effect

$$\sigma_{ij} = 2\mu(\vec{r})u_{ij} + [\lambda(\vec{r})u_{kk} - \gamma(\vec{r})(T - T_0)]\delta_{ij}, \tag{2}$$

μ and λ are the Lame coefficients, γ is the thermoelastic coupling coefficient, u_{ij} is the tensor of the total strain of the body, T is the object temperature, and T_0 is the environmental temperature.

In line with the assumption made in [12], we will consider only the thermoelastic coupling coefficient depending on the object nonhomogeneity. Namely, $\gamma = \gamma_0 + \gamma_1(\vec{r})$, where γ_0 is the thermoelastic coupling coefficient of the homogeneous object and γ_1 corresponds to the nonhomogeneity. If the variations of the elastic deformation are small and nonhomogeneity is weak we can use the perturbation theory approximation. We believe that for weak nonhomogeneity $\gamma_0 \gg \gamma_1$. Than in the frame of the perturbation theory the temperature variation in the object resulted from the laser irradiation and the thermoelastic displacement components are $\Delta T = \Delta T^{(0)} + \Delta T^{(1)}$ and $\Delta u_i = \Delta {u_i}^{(0)} + \Delta {u_i}^{(1)}$ with $\Delta T^{(0)} \gg \Delta T^{(1)}$ and $\Delta u_i = \Delta {u_i}^{(0)} + \Delta {u_i}^{(1)}$.

For the case of a free surface the boundary conditions are

$$\sigma_{iz} n_z\big|_{z=0} = 0, \tag{3}$$

where n_i are the components of the normal to the surface, and z=0 corresponds to the illuminated surface.

To solve the problem we can follow the work [13]. The general expressions are very complex. For the case $z^2 \gg (x - x_0)^2 + (y - y_0)^2$, where (x_0, y_0) is the center of the laser beam; the TEPA signal may be expressed in a simplified form

$$\Delta V = -C\frac{(1 - 4\nu^2)(1 + \nu)}{\pi E(1 - \nu)}\frac{1}{z^2}\int dx' \int dy' \gamma_1(x', y', 0)\Delta T^{(0)}(x', y', 0), \tag{4}$$

where C is a coefficient depending on the piezoelectric detector, ν is Poisson's ratio, E is Young's modulus, z is the sample thickness.

Expression (4) can be used for definition of internal stress influence on the TEPA signal behaviour around indentation zones, where the signal magnitude is small. At this, the following circumstances must be taken into account. Firstly, according to results of works [8, 9, 10, 11] changes of the thermoelastic constant of a material due to internal stress near the sample surface may be considered proportional to $\sigma_{xx} + \sigma_{yy}$. Secondly, the residual stress distribution around the indentation may be considered as spherically symmetric [14], and then $\sigma_{xx} + \sigma_{yy}$ is proportional to σ_r, where according to Yoffe [14]

$$\sigma_r = -\frac{\sigma_r^{(0)} r_0^2}{r^2}, \tag{5}$$

where r_0 is the indentation size, $\sigma_r^{(0)}$ is an average stress at the indentation border.

The experimental average TEPA signal distribution along lines passing through the center of the Vickers print in various directions demonstrate r^{-2} dependence in accordance with the obtained expression.

Of cause, the proposed model does not take into account the residual stress existing in a sample before indentation and its application to the 2-order central symmetrical Vickers indentations would be *a priori* incorrect.

4 Conclusion

To investigate residual stress influence on the thermoelastic properties of metals we have studied theoretically and experimentally the TEPA effect in steel under subjection of thermal development and external pressure. The imaging of Vickers indented areas showed strong dependence of residual stress localization on initial stresses in the samples. Using the photoacoustic microscope combined with press machine we have demonstrated the possibility to chose external pressure for reproducing initial stress effect on the TEPA images of Vickers indentations. So, the combination of the TEPA microscopy and Vickers indentation technique may result in a simple method of the local residual stress estimation in metals. To develop the method we plan to apply and study different types of indentations.

We have continued also developing non-linear model of TEPA effect in solids with residual stresses. The paper presents an expression for TEPA signal for solids with weakly heterogeneous thermoelastic properties obtained within the framework of the perturbation theory. It was successfully applied for the description of the TEPA signal behaviour around Vickers indentations.

Acknowledgments

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