Study of the physical properties of materials by the photometric analysis of structure images

V A Ermishkin, S P Kulagin, A K Tomenko, N A Minina and J B Solov’eva
Federal State Institution of Science Baykov Institute of Metallurgy and Materials
Russian Academy of Sciences, Moscow, Russia
E-mail: minina1951@rambler.ru

Abstract. Several results of using the photometric analysis of structure images (PHASI) for the determination of the physical properties of materials and for the estimation of some specific features of their structural state are considered. In particular, it is shown that, using PHASI, one can construct the fatigue curve of material from standard fatigue tests by cantilever bending of 3-4 flat samples. Application of PHASI for the determination of the thermal properties of materials is shown by the example of determining the coefficient of thermal diffusivity of a copper foil subjected to the action of single laser pulse. The structure features of molybdenum single crystals oriented according to the corners of the standard stereographic triangle have been identified by PHASI and serve as example of PHASI use for the structure examination.

1. Introduction

Man gets visually more than 80% of the information necessary for productive activities. Such information not only gives a general idea about the observed object such as its shape, color, and design features, but also allows one to quantitatively estimate its size, weight, and mechanical characteristics. Therefore, it is natural to assume that the visible light flux, which is emitted by a source with known parameters, reflected from the object under study, and analyzed by objective methods, can give information about the structure and properties of material. In fact, upon the reflection from the surface of the object, the incident light is converted into the reflected light, which carries the information about the structure elements interacting with the photons of the incident light. As follows from modern physics [1, 2], the elementary act of light reflection is a photon-electron interaction. The fact that the phenomenon of light reflection is due to the photon-electron interaction is confirmed by the experimental results obtained by photometric analysis of structure images (PHASI) [3] (Figure 1). The reflection brightness spectrum is plotted in the «reflection brightness I - spectral density p(I)” coordinates. Both coordinates are measured in arbitrary dimensionless units. The zero value on the abscissa axis corresponds to the complete absorption of the incident light flux by the object surface, and the unit corresponds to the complete reflection of light from the surface. The spectral density is taken as the ratio of the number of pixels with the brightness corresponding to the predetermined brightness scale micro range to the total number of pixels of the image. The ordinate axis also ranges between 0 and 1. It is seen from Fig. 1 that, in the initial state, the reflectivity of ebonite is zero, but its electrification by friction with the help of wool fabric results in the appearance of reflection brightness spectrum from the surface areas identified by the color detection of non-zero spectral frequency range in the spectrum. The experiments conducted using PHASI have shown that
external actions cause changes in the density of electron states at the surface of the object. Such actions can increase the surface roughness (mechanical actions), change the chemical composition (corrosive actions), intensify the lattice vibrations (temperature actions), and directly change the energy states of electrons (electromagnetic actions). Since the properties of materials quantitatively measure the changes in their structural state with changing intensity of the external action, the application of PHASI opens the possibilities for measuring various physical properties corresponding to the nature of the action. Some results of such studies are presented in our work.

2. PHASI - a rapid method of fatigue tests

In particular, PHASI was the basis for the development of a rapid method of fatigue tests on flat samples subjected to alternating bending by cantilever loading scheme. The gage surface image recorded prior to the fatigue testing is fed into computer and is broken into fragments of $10 \times 10 \text{ mm}^2$ in size. After bringing the sample to failure, the sample surface is repeatedly scanned and the images in the digital code are fed into the personal computer, where they are analyzed by PHASI. Figure 2 shows the distribution of structural damage over the sample length according to the PHASI results. The structural damage ($D_s$) is understood as the expression:

$$D_s = \frac{p_i(t_f) - p_i(0)}{(p_{max}(t_f) - p_{max}(0))}$$  

where: $p_i(t_f)$ is the spectral density of the $i$-th fragment at the time of the sample failure, $p_i(0)$ is the same, but before the start of the test, $p_{max}(t_f)$ is the spectral density in the fragment, in which the sample failed, and $p_{max}(0)$ is the same, but before the start of the test. The amplitude of operating stresses in each fragment was taken as the maximum bending stress in the middle of the fragment. Such maximum stress was defined by the formula of strength of materials for the sample loaded by the distributed load $q$ determined by the deflection at its free end. The final formula for calculating the effective stress is as follows: where: $W$ is moment resistance of the cross section, $l$ is the gage length of the sample, and $z$ is the coordinate along its length from the sample head. The time to failure of the unbroken fragments, $t_{fr}$, was determined according to photometric measurements of damage by Eq. (1) and the time to failure of the sample, $t_f$. 

![Figure 1. Results of the photometric analysis of ebonite: (left) image fragment and brightness spectrum from its surface and (right) the same fragment and its spectrum after ebonite electrification by friction.](image)
Figure 2. Damage distribution in the 08KP steel sample tested for fatigue.

\[ \sigma(x) = \frac{M(x)}{W} = \sigma \left( \frac{r^2-x^2}{2W} \right) \]  

(2)

The formula for estimating the time to failure \( t_{ri} \) was obtained from the equation of structural damage, Eq. (1), and from the relationship between the times to failure of fragments and the sample as a whole:

\[ t_{ri} = t_{r} \cdot \frac{D_{5}}{D_{s1}} \]  

(3)

The fatigue curve (Figure 3) was constructed for the data sets obtained from Eqs. (2) and (3). It was found that the experimental data shown in Fig. 3 are well approximated by the dependence:

\[ \sigma = \sigma_R + \frac{B}{\sqrt{-t_r}} \]  

(4)

Note that PHASI allows one to substantially reduce the number of samples due to the possibility to use the structural damage measurement at both gage surfaces of samples and their subdivision into fragments. At a gage length of 140 mm, one sample tested becomes equivalent to 28 standard samples.

Figure 3. Fatigue curve constructed according to the PHASI data for the 08KP steel: (♦) results of PHASI measurements on the lower sample surface, (■) data obtained by standard fatigue tests, (▲) results of PHASI measurements on the upper sample surface.

3. PHASI in the study of thermo physical properties of materials
The capability of PHASI in the study of thermo physical properties of materials can be illustrated by the example of determining the thermal diffusivity coefficient of copper foil by the photometric...
analysis of the propagation of thermal field excited by a single laser pulse. The temperature field excited by laser is oscillating in character. This is shown in Figure 4 representing the time dependence of the radiation energy (in arbitrary units) measured by PHASI in the vicinity of the focus, which is not treated by the laser pulse.

**Figure 4.** Time dependence of the radiation energy of the target after laser irradiation.

The local internal energy can be estimated from Eq. (5) [4] using the radiation energy \( U \) measured by PHASI:

\[
U = A \cdot E
\]  

(5)

where: \( A \) is the coefficient, which characterizes the probability of spontaneous radiation upon oscillations of the charged particles in the body of \( E \) in internal energy. The coefficient \( A \) may be determined by measuring \( U \) at room temperature and internal energy of the target fragment with the availability of the data on the heat capacity of the target material. However, this is not necessary for the evaluation of the thermal diffusivity, since the substitution of thermal energy into the heat conduction equation, Eq. (5) cancels the constant \( A \), and only the derivatives of the variable \( U \), which is measured by PHASI, enters Eq. (5) except the thermal diffusivity. In this case, the equation is written for the two-dimensional case as:

\[
\frac{\partial U}{\partial t} = a \left( \frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} \right)
\]  

(6)

The derivatives of the variable were determined from the dependences \( U = f(x) \), \( U = f(y) \), and \( U = f(t) \) constructed from the data measured at two successive micro fragments of \( 0.254 \times 0.254 \text{ cm}^2 \) in size, diverging from the center of the ellipse in two mutually perpendicular directions. Figure 5 shows the distribution of temperature field along the 0X and 0Y axes in the center of the target 10 sec after the laser pulse action.

**Figure 5.** Temperature distribution of in the center of the ellipse 10 sec after the laser pulse action on the (◻) 0X and (◊) 0Y axes.
Note that, evaluating the energies of micro fragments, one should allow for corrections for elastic energy, which results from target bending upon oscillations of the temperature field. The thermal diffusivity coefficients estimated in a series of experiments are given in Table 1.

| No. | Characteristics determined by PHASI | $a$, m$^2$/s | $\Lambda$, W/m K |
|-----|-----------------------------------|-------------|-----------------|
| 1   | on the compressed surface          | $6.56 \times 10^{-5}$ | 212.91 |
| 2   | on the tensioned surface           | $2.243 \times 10^{-4}$ | 775.76 |
| 3   | average value                      | $1.44 \times 10^{-4}$ | 498.03 |
| 4   | according to literature data [6]   | $1.15 \times 10^{-4}$ | 397.73 |

The thermal conductivity coefficients and the data given in the fourth row of Table 1 are calculated from the tabulated data on copper from the handbook [5]. Table 1 shows fairly good agreement between the results of our experiments and the literature data.

4. The study of the structural features of single crystals by PHASI

PHASI is useful also for the study of single crystals for the determination of their structure perfection and the crystallographic orientation of the plane of observation. Figure 6 shows the structure fragments of molybdenum single crystals after their treatment by PHASI at a magnification of 250. The crystals are oriented according to the corners of the standard stereographic triangle.

![Figure 6](image)

Figure 6. Structure fragments of molybdenum single crystals and the brightness spectra of the reflected light: (a) [100]; (b) [110]; (c) [111], (d) [100]; (e) [110]; (f) [111].

Figure 6 shows that the PHASI method allows one to distinguish the single crystal orientations not only by the reflection brightness spectra, but also by color of the fragments of structure images. It is seen that the width and shape of the spectra and the spectral density of their maxima depend on the order of symmetry axes coinciding with the normal to the observation surfaces. Such differences can be quantified by the fractions of the areas of certain color. This is clearly seen (Figure 7) from the histograms of the colors of fragments shown in Figures 6 a, 6 b, and 6 c.
The parameters, which characterize the orientation of the molybdenum single crystals, were determined by PHASI method (Table 2). The reflection brightness spectra are sensible to external physical and chemical actions of any nature. This allows one to use them for the measurement of the physical properties and structural damage of construction materials.

**Table 2. PHASI data on the parameters defining the orientation of the molybdenum single crystals.**

| [hkl] | Symmetry order | Selected ranges | Number of peaks | p(I) max | Spectrum Start | Spectrum End |
|-------|----------------|-----------------|-----------------|-----------|---------------|--------------|
| [100] | 4              | 0.9361          | 0.0033          | 0.0046    | 0.3291        | 0.466        | 0.442        | 0.562        |
| [110] | 2              | 0.3291          | 0.1874          | 0.0660    | 0.1803        | 0.229        | 0.251        | 0.851        |
| [111] | 3              | 0.2691          | 0.2518          | 0.0702    | 0.1733        | 0.0168       | 0.266        | 0.854        |

The PHASI software and analytical complex is of multifunctional use, which includes the estimation of the structural state and properties of materials as well as of the crystallographic features of single crystals. Such opportunities of PHASI have been demonstrated above by several examples, which do not exhaust all possibilities of the method.

### 5. Conclusions:

1. A method for the photometric analysis of the structural imaging (PHASI), based on an assessment of changes in the reflectivity of the surface of the object being studied.
2. To implement the method Fasi photometric analyzer structural image was created on a personal computer, allowing to carry out mathematical operations on digitized data arrays corresponding to the analyzed images at certain times and under specified conditions.
3. Procedures for allowing digital information according to the brightness of the reflection spectra obtained from the surface of the objects during exposure to the physical nature of certain fields, to determine their physical characteristics.

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### References

[1] Orir J 1981 Physics [Russian translation] (Moscow: Mir) 1 335 2 622
[2] Animalu A 1981 Quantum theory of crystalline solids. [Russian translation] (Moscow: Mir) 575
[3] Ermishkin V A, Murat D P, Podbel’skii V V 2007 Information technologies of photometric analysis of materials fatigue damage. Informatsionnye Tekhnologi 11 65-70
[4] Novikov I I, Ermishkin V A, Kudryavtsev E M, Minina N A 2014 The study of thermal diffusivity by the photometric analysis of the target after laser treatment Bulletin of the Kazan Technological University 17 22 152-154
[5] Smithells C J 1980 Metals Reference Book [Russian translation] (Moscow: Metallurgiya) 415