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Analysis of the residual life of an aluminum 2024 alloy by photometric analysis of structural images

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ABSTRACT

The light reflection by the surface of condensed matter is a problem that has not yet been explained enough in modern physics. Analyzing the spectra of the reflected light is possible to estimate the energy of free electrons evaluating the variation of the reflection spectra under the influence of an external power effect. The physical requirements for photometric analysis of the images were carried out during the development of a multifunctional complex program. This allowed to establish a correlation between the structural damage and photometric parameters in 2024 aluminum alloys, which is presented in this study. Photometric Analysis of Structural Images (PHASI) to obtain the local damage of the material was used. It was performed measuring the amount of visible light reflected by the fragments of the material, before and after fatigue tests. The damage that the material supports under known stress amplitudes was evaluated by fatigue curves, doing a data relation as function of the stress amplitude applied. Results shown a polyharmonic regime between the spectral brightness reflected by the coated aluminum surface and the stress concentration. Thus, the degree of fatigue damage was determined by the material and the actual structural elements.

1. Introduction

The continuum mechanics of deformable bodies and theory of elasticity, are the theoretical basis for the resistance calculations of metallic structures [1,2]. Besides, the atomic and crystalline structure obtained by X-rays and electron microscopy, offers incontrovertible arguments against the hypothesis of the continuity and isotropy of its structures [3–5]. The use of methods to measure residual stresses in metals exposed to different treatments demonstrated the unsustainable hypothesis of an original stress-free state of a material under load [6]. Random presence of defects in the crystalline structure of the material contradicts the hypothesis of its perfect homogeneity [5], and the breach of direct proportionality between deformation and stress under considerable plastic deformations, demonstrates the limitations of Hooke's law [1,2]. Although

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the relationship between the structure and mechanical properties of materials is well known, the structural parameters of the materials are not reflected in the calculations of resistance [7], And the influence of the structural state is carried out indirectly by introducing constraints on the values of the stresses applied to its allowable stress σ, which we determine it as:

$$\sigma = \frac{\sigma_{0,2}}{n} \tag{1}$$

Where $\sigma_{0,2}$ – is the conventional material creep limit, n is a safety factor. Eq. (1) for $n > 1$ must ensure the material service under elastic conditions, so any break circumstance must be considered as an extraordinary event. However, these events are very usual. This means that during the manipulation of the material, its structure varies so the condition of the Eq. (1) is breached, but in normal calculations of resistance, it is not taken into consideration. From our point of view, it is necessary to introduce the structural state information in the resistance calculations, and particularly in the calculations to determine the remaining life of the structure. The aim of this study is the implementation of a practical method that allows analysis of images of the structural condition, in order to determine the residual life of a material under fatigue conditions.

2. Problem statement

In this paper the analysis has been oriented mainly to explain the laws governing the phenomenon in optically homogeneous media, free of localized centers of reflection and is carried out in the approach of weak dispersion. In particular, the plastic deformation of a material alters its surface due to dislocations escaping to the surface. The output of a dislocation generates only one monatomic step, while the escape of multiple dislocations sources generates a noticeable volumetric alteration in the roughness surface of the material, and then this type of distortion in the surface structure becomes dominant. Thus, the light reflected by the surface of the metal can be considered as an indication of the energy state of the free electrons, that is, they are involved in the formation of their physical and chemical properties. According to the approach proposed by Miner-Palmgren [8], Fatigue damage D_f can be estimated quantitatively by the Eq. (2):

$$D_f = \frac{N}{N_r} \tag{2}$$

Where N – is the present value of the load cycles applied on the samples under a stress with amplitude σ, N_r – is the number of cycles to fracture for a given stress amplitude value. Multiplying the numerator and denominator of Eq. (2), by the period of oscillation T, the formula can be written as:

$$\mathrm{D_f} = \frac{\mathrm{t}}{\mathrm{t_r}} \tag{2'}$$

Where t – is the current test time, and t_r – is the time until the rupture of the sample.

In the present study, to evaluate the fatigue damage of the specimens, we used Photometric Analysis of the Structural Images (PHASI), based on measurements of the visible light reflectivity from the material's surface, before and after the fatigue tests. In Eq. (3), the indicator of structural damage D_s – is expressed considering the initial and final conditions:

$$\mathrm{D_s} = \begin{pmatrix} to\, t = 0, = 0 \\ to\, t = \mathrm{t_{r,}} \; = 1 \end{pmatrix} \tag{3}$$

According to the data obtained with the PHASI method, Eq. (3) can be expressed as:

$$\mathrm{D_s} = \frac{\mathrm{S_i}(\mathrm{t_r}) - \mathrm{S_i}(0)}{\mathrm{S_{max}}(\mathrm{t_r}) - \mathrm{S_{max}}(0)} \tag{4}$$

Where $S_i(0)$ – is the area under the spectral curve of a specimen fragment i before the test, $S_i(t_r)$ – is the area under the spectral curve of a specimen fragment i after its fracture, Smax(0) – is the area under the spectral curve of a specimen fragment i after its fracture that occurs before the start of the test, Smax(t_r) – is the area under the spectral curve of a specimen fragment i after its fracture.

3. Experimental method

To evaluate the distribution of the local fatigue damage, 2024 aluminum alloy specimens was pre-scanned in high resolution. Besides after the fatigue tests, each sample is scanned again. Then the specimens were repeatedly scanned after the completion of its test. The images obtained were processed with a program for image analysis using the PHASI method, which was previously developed in the IMET RAS [4–6]. For the analysis of these images, the working surface of the samples was divided into fragments as shown in Fig. 1.

The split lines are produced on both sides of the specimen. On one side the sample has a coating and the other does not. The images of each fragment on both sides of the specimens, and the brightness of the visible light spectra reflected by the samples are compared to each other. Through cyclic algebraic operations were detected intervals where there are qualitative and quantitative changes. These areas were highlighted using color staining that is transferred to image of the fragment. Thus, is possible to visualize the regions of sample that contribute to have the appropriate color of the spectral intervals.