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PHOTOELASTIC METHOD FOR ANALYZING RESIDUAL STRESSES IN COMPACT DISKS

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The issues of size and shape stability are especially important in modern high technologies, in particular, in the compact disk technology. Stability in this case is substantially affected by residual stresses that occur in disks because of the imperfection of their production process. The objective of the present study was to develop a simple optical method to estimate the stress state of compact disks.

Key words: *residual stresses, relaxation, photoelasticity.*

Introduction. Residual stresses have a substantial effect on the long-term serviceability of modern compact disks (CDs). Sometimes, redistribution of residual stresses is responsible for crack initiation in disks at one of the production stages or such a redistribution increases the stresses to a critical value for which even insignificant external loading results in fracture of CDs. Relaxation is one of the main reasons for residual-stress redistribution, and this process can occur without external loading or heating. Residual stress relaxation can lead to size and shape changes, and this is unacceptable in modern high technologies, in particular, in the production and use of CDs for information storage.

Modern CDs are made of polycarbonate, which exhibits a birefringence effect. This allows stresses in CDs to be estimated by a photoelastic method. A metallized coating applied to one of the CD surfaces ensures ideal conditions for recording a reflected-light interference pattern. In studies of stresses in CDs using a V-shaped reflective polariscope, the resulting equations become similar to those employed in the photoelastic coating method. The present papers discusses the results of investigation of residual stresses in CDs with various service lives produced by various manufacturers using various technologies (molding, laser recording).

1. Experimental Method. Photoelasticity is an experimental method for stress and strain analysis that is especially useful in studies of objects of complex geometry under complex loading conditions. In some cases where theoretical methods are laborious or inapplicable, an experimental analysis is preferred in studies of dimensional problems, problems of dynamic loading, residual stresses, and inelastic behavior of materials [1].

Light propagates in air at a velocity $C = 3 \cdot 10^8$ m/sec. In transparent bodies, the velocity V is lower and the ratio C/V is called the index of refraction. In homogeneous media, this index is constant and does not depend on the propagation direction or the orientation of the plane of vibrations of the electric intensity vector of the light wave. Some materials, especially plastics, are isotropic in the absence of loading but become anisotropic under loading. The variation in the index of refraction under loading is similar to the resistance variation in strain gauges [2].

When a polarized light beam with amplitude a propagates through a CD made of polycarbonate with thickness t, it is separated into two polarized beams propagating in the planes X and Y coinciding wit the directions of the principal stresses at the point considered (Fig. 1). If the stresses along the X and Y axes are equal to σ_1 and σ_2 and the velocity of light in these directions is V_x and V_y, respectively, the relative delay δ between these two beams is given by

$$\delta = C(t/V_x - t/V_y) = t(n_x - n_y), \tag{1}$$

where n is the refraction coefficient.

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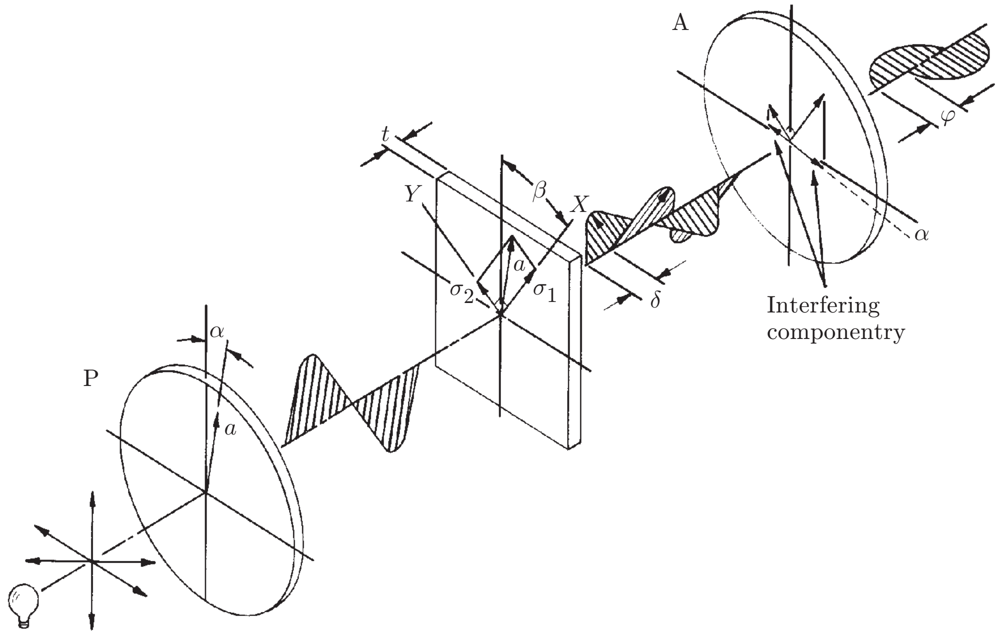

Fig. 1. Flat polariscope: polarizer (P), analyzer (A), delay (δ), phase shift (φ).

According to Brewster's law,

$$n_x - n_y = K(\sigma_1 - \sigma_2). \tag{2}$$

The constant K is called the optical activity coefficient and characterizes the physical properties of a material. This constant is usually determined by calibration and is similar to the sensitivity of resistance strain gauges. From Eqs. (1) and (2), we have $\delta = tK(\sigma_1 - \sigma_2)$ for transmission and $\delta = 2tK(\sigma_1 - \sigma_2)$ for reflection (light passes twice through the sample).

Hence, in the photoelastic method, the main relation for stresses is given by

$$\sigma_1 - \sigma_2 = \delta/(2tK) = N\lambda/(2tK). \tag{3}$$

Because of the relative delay δ, these two light waves are not cophased when they pass through a flat sample. Analyzer A allows only one component (parallel to the analyzer axis) of these two waves to pass, as shown in Fig. 1. These waves interfere, and the resultant intensity is a function of the delay δ and the angle between the analyzer axis and the direction of the principal stresses $\beta - \alpha$.

In the case of a flat polariscope, the light intensity I is

$$I = a^2 \sin^2 2(\beta - \alpha) \sin^2 (\pi\delta/\lambda).$$

The light intensity is equal to zero for $\beta - \alpha = 0$ or when the crossed analyzer/polarizer is parallel to the principal stress direction. Thus, a flat polariscope is used to measure the principal stress direction [3].

2. Analysis of Fringe Patterns. The photoelastic method allows one to interpret fringe patterns over the entire field, to estimate nominal the stresses and gradients, and to perform quantitative measurements. In particular, it is possible to determine the principal stress directions at all points of the photoelastic model, the value and sign of tangential stresses along the free boundaries and in all regions where the stressed state is uniaxial; for plane stresses, it is possible to determine the value and sign of the difference of principal stresses at selected points of the object being studied.

The photoelastic method can used to identify overloaded and underloaded regions. Success in using the method depends only on the accuracy in determining the fringe color (isochrome) and the relation between the fringe order and the stress value [4].

Under sequential loading of a sample, isochromes first appear at the most loaded points. As the load increases, new fringes appear on the sample surface and are shifted toward the lowest stresses. The fringes can be assigned ordinal numbers (the first, second, third, etc.) in accordance with their appearance, and they retain their individual numbers with load variation. Isochromes appear sequentially, do not intersect and merge with each other, and always occupy their positions in strict order.

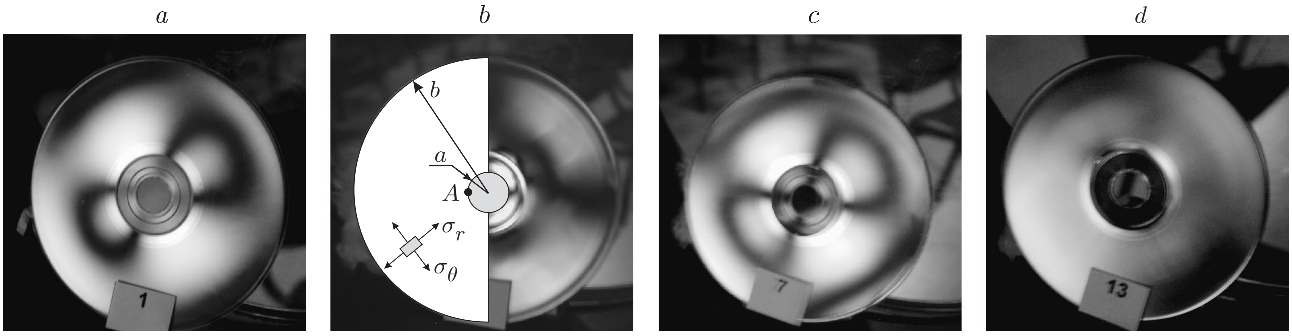

Fig. 2. Fringe patterns in different types of CDs.

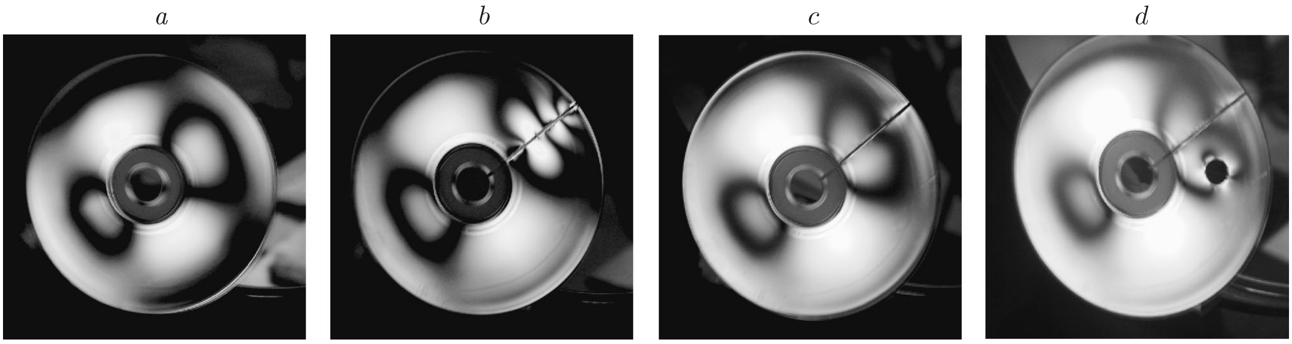

Fig. 3. Fringe pattern for fracture of a CD.

3. Experimental Results. Different types of CDs — musical and digital — were studied. Information on the CDs was recorded by an industrial method or using a CD writer in the process of investigation. During examination of CDs with a reflective polariscope, isochromes appeared as sequential color fringes, in which each point corresponded to different degrees of birefringence and, hence, to different stresses of the segment studied. Because the color fringes appeared in a constant sequence, the photoelastic fringe pattern can be read as a topographic map, which allows a visualization of the surface stress distribution on the examined parts of the CDs.

Figure 2a and b shows typical fringe patterns for musical compact disks produced by different corporations in Russia and abroad in 1993–1997. Information on the CDs is packed with a very high density. The size of each pit (unit cell) is rather small — about 0.6 μm, and the spiral track pitch on the disk surface is only 1.6 μm. In the industrial manufacture of CDs, molten polycarbonate is applied to the matrix under a high pressure. The pressure is required to form pits of high quality. The time of manufacture of one disk is approximately 4 sec, which inevitably leads to the occurrence of an inhomogeneous stress field and a corresponding fringe pattern.

On the free contour of the CDs, the principal stresses σ_1 or σ_2 normal to the contour are equal to zero. Then, Eq. (3) implies that the fringe order N on such a contour is proportional to the normal stress σ_θ acting along the contour. In Fig. 2b, $N \approx 1$ at the point A on the inner free contour. Assuming that the optical sensitivity coefficient of a polycarbonate CD is 7 kN/m [5] and its thickness is $t = 1.2$ mm, we find that at this point, $\sigma_\theta = 2.9$ MPa. Therefore, the stress σ_θ cannot be neglected because the proportionality limit for polycarbonate is $\sigma_B = 3.5$ MPa [5].

The same method was used to obtain photoelastic patterns in a stress analysis of digital CDs. The fringe patterns obtained are presented in Fig. 2c and d. It is easy to see that the fringe pattern in Fig. 2c is similar to that shown in Fig. 2d. The lack of a noticeable fringe pattern in Fig. 2d suggests the higher quality of this CD sample.

Performing sequential milling of a radial groove on an intact disk with an initial fringe pattern (Fig. 3a), we observed the occurrence of fringes at points with the maximum stress level (Fig. 3b). Figure 3c shows a photoelastic pattern after through cutting of a CD. The pattern in Fig. 3d is obtained by drilling a hole in a CD. This expedient is standard in determining residual stresses using the hole method. The presence of a hole on the CD led to residual stress redistribution.

The process of recording–reading information on a CD gives rise to additional operation stresses due to the rotation of the disk. The problem of stress distribution in a round rotating disk of small thickness is considered in detail in [6]. Using the notation of Fig. 2b, we have

$$\sigma_r = \frac{3+\nu}{8}\,\rho\omega^2\Big(b^2 + a^2 - \frac{a^2b^2}{r^2} - r^2\Big), \qquad \sigma_\theta = \frac{3+\nu}{8}\,\rho\omega^2\Big(b^2 + a^2 + \frac{a^2b^2}{r^2} - \frac{1+3\nu}{3+\nu}r^2\Big),$$

where ν is Poisson's coefficient, ρ is the mass per unit volume of the disk material, ω is the angular velocity, a and b are the inner and outer radii, respectively, and r is the current radius of a point on the disk. On the inner free contour of the disk, $\sigma_r = 0$ and the circumferential stress σ_θ reaches the maximum:

$$\sigma_{\theta\,\max} = \frac{3+\nu}{4}\,\rho\omega^2\Big(b^2 + \frac{1-\nu}{3+\nu}\,a^2\Big).$$

In our case, $a = 1.5$ mm, $b = 120$ mm, $\rho = 1.2$ g/cm^3, $\nu = 0.38$, $\omega = 1000$ rpm, and $\sigma_\theta = 0.16$ MPa. The existing trends toward increasing the rotation velocity of CDs make the problem of analyzing residual technological stresses rather urgent because summation of these stresses with operation stresses can lead to violation of the strength condition.

Conclusions. It is shown that residual stresses in compact disks can be estimated using a simple optical method. A nonuniform distribution of technological residual stresses in disks and their relaxation with time can cause a loss of information stored on the disk. The results of the present study show that CDs from different producers differ in the nature of fringe patterns. Only in a few of the samples studied, the residual stress level was lower than the interferometer sensitivity threshold. The results of the experiments can be useful for effective optical damage control of production processes at CD manufacturing plants.

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