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EFFECT OF THE SURFACE STRUCTURE OF A COMPOSITE MATERIAL ON SPATIO-POLARIZATION CHARACTERISTICS OF REFLECTED RADIATION

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The polarization degree, rotation of the polarization plane, and strength indicatrix of radiation with a wavelength of 0.63 μm reflected from the surface of a unidirectional superhigh-modular organic plastic are investigated.

High-modular organic fiber-based composite materials are characterized by a lower (compared to glass-reinforced plastics) density and improved strength, electric, and thermal insulation parameters. In thermal stability, they rank only below composite materials with carbon and boron fillers [1]. These properties of high-modular organic plastics make them an important group of heat-shielding coatings.

Very little information on the radiation properties of composite materials, in particular organic plastics, for solving problems of heat transfer in high-temperature constructions is available. In this case information on both the reflection coefficients and the parameters of the material that determine the spatio-polarization properties of the reflected radiation is required.

We investigated the effect of fiber disposition in a unidirectional superhigh-modular organic plastic on the spatio-polarization properties of the reflected radiation of a He-Ne laser with a wavelength of 0.63 μm for various orientations of the polarization plane of the incident flux. We measured the strength indicatrices of the radiation reflected by an organic plastic with an epoxy binder and the degree of polarization and rotation of the polarization plane of the reflected flux.

As a result of the partial transparency of the composites [2], component formed upon scattering of the incident flux by optical inhomogeneities in the material is present in the reflected radiation. In this case the smooth surface layer of the polymerized binding resin plays the role of an amplitude-anisotropic element by polarizing additionally the radiation emerging through this layer, which is depolarized within the material [3]. In order to exclude the effect of the binding resin film on the spatio-polarization characteristics of the radiation reflected by the sample under investigation, we sheared off its surface layer and uncovered organic filler filaments coiled unidirectionally.

Measurements were carried out on a goniophotometric setup [3, 4] that included a He-Ne laser (LG-126) whose linearly polarized radiation was directed normally to the sample surface, and the reflected flux was investigated in a single plane (the observation plane) at various angles α with respect to the incident beam. The plane of polarization of the probing radiation was oriented by polarimetric plates at angles of 0, 45, and 90 deg with respect to the observation plane. Samples under investigation were fixed in three different positions so that the filler fibers were oriented at angles of 0, 45, and 90 deg with respect to the observation plane, i.e., measurements were carried out when the plane of polarization of the incident radiation coincided with the orientation of fibers on the sample surface, made an angle of 45 deg with, or was perpendicular to them. By linking a Cartesian coordinate system with the sample under investigation so the fibers on its surface were directed along the z-axis, and with the beam propagated in the negative direction along the x-axis, we investigated the following three cases: in the first case we investigated the characteristics of the radiation scattered in the xz-plane; in the second case, in the plane passing through the x-axis and making an angle of 45 deg with the xy-plane; and in the third case, in the xy-plane.

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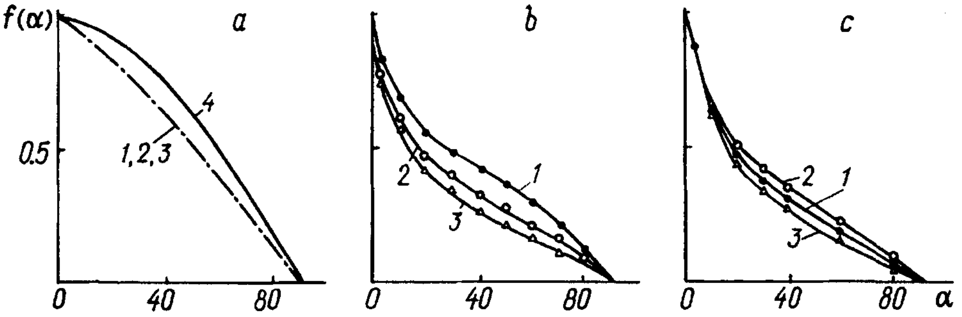

Fig. 1. Strength indicatrices of radiation scattered by organic plastic in plane perpendicular to (a), parallel to (b), and making an angle of 45 deg (c) with the fiber direction for a polarization azimuth of the probing flux with respect to the observation plane equal to 90 (1), 45 (2), and 0 deg (3), and the strength indicatrix of radiation of a Lambertian reflector (4). α, deg.

A more detailed description of the setup along with estimates of errors of measurement of rotation of the plane of polarization, polarization degree, and strength indicatrices of the reflected radiation can be found elsewhere [2-4].

We found that the organic plastic scatters the incident radiation in the xy-plane, which is perpendicular to the direction of fiber orientation. In this case the shape of the strength indicatrices of the reflected radiation approaches that of the indicatrix of a Lambertian scatterer and does not depend on the polarization azimuth of the incident flux (Fig. 1a). With an increase in observation angle α of from 0 to 40 deg, the ratio of the measured and Lambertian indicatrices $f(\alpha)/\cos\alpha$ decreases from 1.0 to 0.75. A further increase in α to 75 deg does not lead to changes in the $f(\alpha)/\cos\alpha$ ratio, which equals 0.75. In the observation plane coincident with the fiber direction the radiation is scattered in a more specular manner (Fig. 1b). In this case the scattering indicatrix of probing radiation polarized perpendicular to the observation plane and correspondingly to the fiber direction (curve 1) is higher than that for radiation polarized in the observation plane (curve 3) or at an angle of 45 deg with respect to it. In an observation plane oriented at an angle of 45 deg with respect to the fiber direction, the scattering differs little from scattering by the sample in the plane parallel to fibers (Fig. 1c). In this case the dependence of the shape of the indicatrix of the scattered radiation on the polarization azimuth of the probing flux is less pronounced.

Polarization measurements have shown that the polarization degree of the reflected radiation in the plane perpendicular to the direction of the fibers of the organic plastic is close to unity and is virtually constant for various observation angles when the radiating flux is polarized in the observation plane ($P_{\perp}^{\parallel}$) or normally to the plane ($P_{\perp}^{\perp}$) (Fig. 2a, curves 1, 3). In this notation, the subscript characterizes the fiber disposition and the superscript denotes the orientation of the vector E in the incident flux with respect to the observation plane. When the sample under investigation is irradiated by a flux making an angle of 45 deg with the observation plane, the polarization degree of the reflected radiation ($P_{\perp}^{45}$) also depends only slightly on the scattering angle, although the reflected radiation itself is substantially depolarized (Fig. 2a, curve 2). When the observation plane coincides with the fiber orientation, a substantial angular dependence of the polarization degree of the reflected flux is revealed for all polarization azimuths of the probing flux (Fig. 2b).

It is known that, due to differences in Fresnel reflection coefficients for polarized components of radiation, the plane of polarization of linearly polarized light reflected in a specular direction by a smooth surface (except for radiation with azimuth $\gamma = 0$ or 90 deg) rotates towards the normal to the incidence plane, and that of the transmitted radiation rotates in the opposite direction [5]. Similar behavior is characteristic of changes in the polarization azimuth of radiation reflected by a rough surface of nontransparent materials [6] and by isotropic partially transparent composites [3]. In this case an increase in the multiplicity of scattering of radiation leads to an increase in the angle of rotation of the plane of polarization. As regards the effect of the fiber orientation on the rotation of the plane of polarization, it has not been studied so far.

We measured the rotation of the plane of polarization of the radiation reflected by an organic plastic at a polarization azimuth of 45 deg in the incident flux with respect to the observation plane. The angle of rotation of the polarization plane $\Delta\gamma$ of the reflected radiation was considered to be positive when the rotation towards an

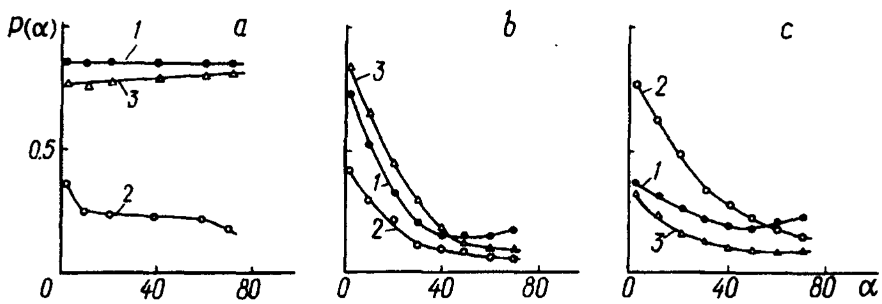

Fig. 2. Relationship between the polarization angle and the observation angle of radiation reflected by organic plastic when the observation plane is perpendicular to (a), parallel to (b), and makes an angle of 45 deg (c) with the fibers; the polarization azimuth of the probing flux with respect to the observation angle equals 90 (1), 45 (2), and 0 deg (3).

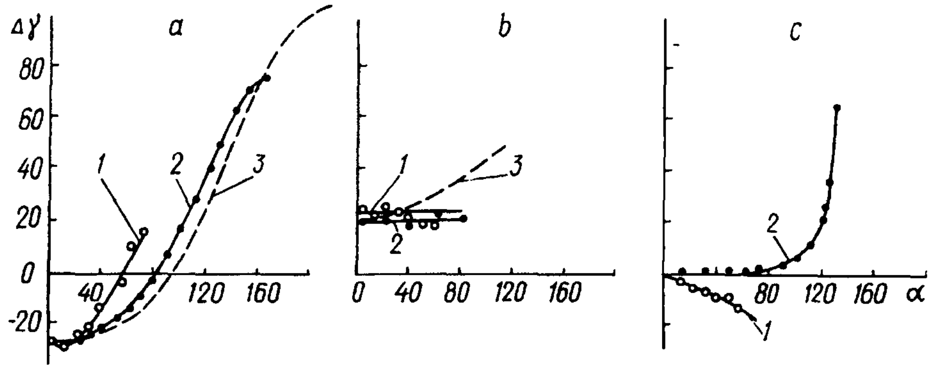

Fig. 3. Rotation of polarization plane of radiation scattered (1) and reflected specularly (2) by organic plastic whose surface fibers are oriented parallel (a) and perpendicular (b) to the observation plane and at an angle of 45 deg with respect to the plane (c) for a polarization azimuth of the probing flux equal to 45 deg. Curves a, 3 and b, 3 were calculated by formulas (3) and (4), respectively. $\Delta\gamma$, grad.

increasing azimuth angle with respect to the polarization azimuth of the incident flux took place. Measurements were carried out both at normal incidence and at various observation angles, and in the direction of specular reflection with the incidence angle varying from 5 to 85 deg.

The measurements have shown that the plane of polarization of the polarized component of the reflected radiation is rotated through 20–25 deg by the plane of polarization of the incident flux towards the fiber direction even for normal incidence of the probing radiation. Earlier [3], no rotation of the plane of polarization of the specularly reflected flux was observed in the case of normal incidence (i.e., at $\alpha = 0$ deg) on the surface of isotropic composite materials. The polarization azimuth of the radiation reflected specularly from the plane coinciding with the fiber direction increases with the incidence angle. While at normal incidence the polarization azimuth of the reflected radiation is less than the polarization azimuth in the incident flux by 24 deg, already at incidence angle $\alpha/2 = 40$ deg the azimuths are equal, and at $\alpha/2 = 80$ deg the azimuth of the reflected radiation exceeds that of the reflected radiation by 75 deg (Fig. 3a, curve 2). The rotation is even more pronounced in the scattered radiation at normal incidence and corresponding observation angles (Fig. 3a, curve 1). The increase in the polarization azimuth by 90 deg when the observation angle is changed by 180 deg in the coordinate system tied to the reflected beam is in keeping withthe fact that the planes of polarization coincide in the incident and reflected fluxes.

In the plane perpendicular to the fiber orientation the polarization azimuth of both the scattered and specularly reflected radiation is virtually independent of the observation angle and constantly exceeds the polarization azimuth of the probing flux by 20 deg (Fig. 3b, curves 1 and 2). If the observation plane is oriented at an angle of 45 deg with respect to the fiber direction, then with normal incidence, the plane of polarization of the backscattered radiation coincides with that of the incident flux (Fig. 3c). The plane of polarization rotates in a different manner in the scattered and specularly reflected radiation with an increasing observation angle. The polarization azimuth of the polarized component of the scattered flux changes in the opposite direction. Therefore, this component is formed by the radiation emerging from the interior of the material, and, therefore, it was likely polarized upon passing through fibers of the surface layer, as has been observed earlier in isotropic composites with passage through the lacquer layer on their surface [3]. As regards the polarization azimuth of the specularly reflected radiation, it coincides, up to incidence angles $\alpha/2 = 40$ deg, with that of the incident flux, and only at large incident angles starts to grow rapidly (Fig. 3e, curves 1 and 2).

Let us try to present the physical pattern of radiation scattering by unidirectional composites. It is known [1] that these materials have anisotropic mechanical, thermal, and optical properties. For example, the Kevlar-49 organic fiber produced by Du Pont Corp., USA, has a refractive index in the visible region of the spectrum equal to 2.0 in the direction along the axis and 1.6 in the perpendicular direction [1]. The anisotropy of the refractive index must lead to a rotation of the plane of polarization of the reflected radiation even with normal illumination [5]. We have observed a similar pattern experimentally (Figs. 3a and 3b). If the fibers are perpendicular to the observation plane, then, according to [5], the rotation of the plane of polarization of the reflected radiation in this case will be described by the expression

$$\Delta\gamma_\perp = \arctan\left[\left(\frac{n_\parallel - 1}{n_\parallel + 1}\right) \Big/ \left(\frac{n_\perp - 1}{n_\perp + 1}\right)\right] - 45^\circ, \tag{1}$$

and if the fibers are parallel, by the expression

$$\Delta\gamma_\parallel = \arctan\left[\left(\frac{n_\perp - 1}{n_\perp + 1}\right) \Big/ \left(\frac{n_\parallel - 1}{n_\parallel + 1}\right)\right] - 45^\circ, \tag{2}$$

where $n_\parallel$ and $n_\perp$ are the refractive indices for a wave polarized along and across the fiber, respectively. According to [5], the refractive index $n_\parallel$ will be equal to the tangent of the Brewster angle when the sample is situated such that the fibers on its surface are perpendicular to the incidence plane and E in the incident flux makes an angle of 45 deg with the plane. In this case the plane of polarization in the specularly reflected flux will rotate by 45 deg with respect to the plane of polarization of the incident radiation. In the case under consideration $n_\parallel = 2.1 \pm 0.1$, i.e., is close to the reference data on Kevlar-49. With $n_\parallel$ known, one can determine by formula (1) or (2) the value of $n_\perp$, which was found to be equal to 1.5 ± 0.1.

By using the data on $n_\parallel$ and $n_\perp$ it is possible [5] to find the angular dependences of the components of the amplitude of the reflected wave perpendicular ($R_\perp^{1/2}(\alpha)$) and parallel ($R_\parallel^{1/2}(\alpha)$) to the fiber axis:

$$\Delta\gamma_\parallel(\alpha) = \arctan\,[R_\perp(\alpha)/R_\parallel(\alpha)]^{1/2} - 45^\circ, \tag{3}$$

$$\Delta\gamma_\perp(\alpha) = \arctan\,[R_\parallel(\alpha)/R_\perp(\alpha)]^{1/2} - 45^\circ. \tag{4}$$

Calculations have shown that $\Delta\gamma_\perp(\alpha)$ coincides fairly well with the exprimental results (Fig. 3a, curves 2 and 3). At the same time, $\Delta\gamma_\parallel(\alpha)$ differs substantially from the measured dependence (Fig. 3b, curves 2 and 3). The difference is connected with the fact that formulas (3) and (4) are applicable only to smooth surfaces of anisotropic nonabsorbing materials. A unidirectional organic plastic is better modeled by a set of close-packed infinite cylinders. Such a representation of a unidirectional organic plastic reveals the nature of its optical anisotropy and makes it possible to explain a number of observed features of scattering of laser radiation.

It is known that the problem of diffraction of a plane electromagnetic wave by infinite round cylinders is one of the few exactly solvable problems in electromagnetic diffraction theory. Therefore, it is used as a reference when solving more complicated problems [7].

Let us consider the incidence of laser radiation propagating along the x-axis in the form of a Gaussian beam

$$u = u_0 \exp(-(z^2 + y^2)/\sigma^2) \exp(-ikx), \tag{5}$$

on an organic plastic oriented in such a manner that its reflecting surface coincides with the coordinate plane $x = 0$, and the fibers (cylinder axes) are oriented along the z-axis. The wave u (5) is related to the vector of the electric field strength as $u = E_z$, i.e., $\mathbf{E} = (0, 0, E_z)$, when the incident radiation is polarized along the fibers and $u = E_y$, i.e., $\mathbf{E} = (0, E_y, 0)$, when the field is polarized in the plane orthogonal to the fibers. The constant σ in expression (5) characterizes the rate of decrease in the radiation intensity across the laser beam, and k is the wavenumber of the incident electromagnetic wave.

Inasmuch as in the case under consideration the fiber diameter ($d = 0.1$ mm) is small compared to the constant $\sigma = 2.4$ mm, which represents the radius of the Gaussian beam, the amplitude remains virtually constant within the limits of a single fiber. Therefore, we can assume that a plane wave is incident on each of cylinder fibers, and the scattered field is a superposition of fields scattered by individual cylinders. This approach is approximate. It does not take into account the reciprocal influence of the cylinders. The existence of a reciprocal influence follows, e.g., from the exact solution of the problem of scattering of a plane electromagnetic wave by two parallel elliptic cylinders [7]. Nevertheless, this approximation provides an explanation for the high polarization degree of the scattered radiation in cases when the incident wave is polarized either along the fibers or in the orthogonal direction. It follows from the exactly solvable problem of scattering of a plane electromagnetic wave by cylinders that in both of these cases the initial hundred per cent polarization of the wave must be preserved. The presence of an unpolarized component in the scattered radiation is explained, in our opinion, by the roughness of fibers forming the organic plastic, i.e., by the deviation of the shape of these fibers from ideal cylinders. This is substantiated by additional experiments on scattering of radiation by cylindric objects with smoother side surfaces, approaching the surfaces of ideal cylinders. Fishing line and copper wire 0.2 mm in diameter were chosen as such objects. In both cases the polarization degree of the reflected flux was substantially higher than that for the radiation scattered by the organic plastic. Thus, while with incidence of radiation polarized parallel to the fibers of the organic plastic the polarization degree of the scattered radiation is 85%, it equals 96% for the fishing line and 98% for the wire. When the incident radiation was polarized orthogonal to the cylinder axes, the corresponding values were 75, 81, and 98%.

The pattern of wave scattering by an infinite cylinder provides a good basis for explanation of the comparably sharp drop in the scattering indicatrix as a function of the observation angle when the observation plane is parallel to the fibers of the organic plastic and the angle is measured from the plane orthogonal to the fibers. As is known, the indicatrix of the scattered field is determined by the asymptotics of the field. An asymptotic representation of the field scattered by an infinite round cylinder is given by the expression [8]

$$u \to v(r, \theta) = \Phi(\theta) \frac{\exp(ikr)}{kr}, \tag{6}$$

where $\Phi(\theta) \sim F(k \cos\theta) = F(\theta)$; r and θ are spherical coordinates, F are coefficients of the expansion of the scattered field into an integral in solutions of the scalar wave equation. Due to separation of variables in the cylindrical coordinate system for the given problem, a common factor

$$\exp(-\sigma^2 p_z^2) = \exp(-\sigma^2 k^2 \sin^2\theta), \tag{7}$$

emerges in the coefficient $F(\theta)$, which is a Fourier transform of the multiplier $\exp(-z^2/\sigma^2)$ in the expression for the incident wave (5). In expression (7) p_z is a projection of the wave-vector of the wave, which is a solution of the above-mentioned scalar equation.

Factor (7) is governing for explanation of the sharp drop in the intensity of the scattered radiation as a function of the observation angle. However, the actually observed drop in the intensity of the scattered radiation as a function of α is not as sharp as would follow from theory. This, in our opinion, can again be explained by scattering of the incident radiation by the roughnesses of the fibers comprising the organic plastic. As in the case of measurement of the polarization degree, we carried out additional experimental investigations on scattering of laser radiation by cylindrical objects with the surface approaching move closely an ideal one. Results of the investigation substantiated the assumption. The slope of the scattering indicatrix appeared to be steeper for the fishing line and wire than for the organic plastic. At the same time, the fishing line produced a broader scattering indicatrix when processed by emery cloth. Finally, the smooth drop in the scattering indicatrix of the laser radiation as a function of the observation angle in the plane orthogonal to fibers (Fig. 1a) is explained by scattering of the radiation by the side surfaces of the fiber cylinders with subsequent interference. Scattering by a single cylinder produces a φ angle-independent indicatrix determined by expression (6). About 50 fibers fit into the spot of laser radiation. Interference of the light scattered by these fibers and the exponential drop in the intensity toward the edges of the spot do lead to the observed indicatrix.

Thus, the measurements and estimates have shown that, to a first approximation, the spatial and polarization characteristics of radiation reflected by a unidirectional organic plastic with an epoxy binder are explained by diffraction of electromagnetic waves by an infinite ideal cylinder. However, roughness of filler fibers complicates the exact theoretical description of radiation scattering and leads to broadening of the indicatrices of the scattered radiation and reduction of its polarization degree.

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NOTATION

x, y, z, Cartesian coordinates; r, θ, φ, spherical coordinates; ρ, z, φ, cylindrical coordinates; E, vector of the electric field strength of the electromagnetic wave; E_y, E_z, components of the vector of the electric field strength of the electromagnetic wave along y- and z-axes; u, scalar potential coincident with Cartesian components of the vector of the electric field strength of the incident electromagnetic wave usually used in diffraction theory; u_0, amplitude of the incident electromagnetic wave in a scalar description; k, wavenumber of the incident electromagnetic wave; $\sigma/2$, distance from the center of the laser beam at which its intensity decreases by a factor of e; v, asymptotic expression of the strength of the electric field of the reflected electromagnetic wave; p, wave vector; p_z, projection of the wave vector onto the z-axis of the wave, i.e., solution of the scalar wave equation in the cylindrical coordinate system; $F(\theta)$, coefficients of expansion of the scattered field into an integral in solutions of the same equation; ε, dielectric constant of composite fibers; α, observation angle with respect to the incident angle at which measurements of rotation of the plane of polarization, polarization degree, and strength of the reflected radiation were carried out; γ, polarization azimuth of the incident radiation; $\Delta\gamma$, angle of rotation of the plane of polarization of the incident radiation with respect to the polarization azimuth of the incident flux; P, polarization degree of reflected radiation; $f(\alpha)$, normalized strength indicatrix of reflected radiation.

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