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INFLUENCE OF THE POLARIZATION AZIMUTH OF INCIDENT RADIATION ON SPACE-POLARIZATION CHARACTERISTICS OF THE FLUX REFLECTED BY COMPOSITE MATERIALS

V. A. Dlugunovich, E. A. Kruplevich, and V. N. Snopko

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At the wavelength 0.63 μm the degree of polarization, the angle of rotation of the polarization plane, and the indicatrix of the intensity of radiation reflected by the surface of composite materials before and after their heating by radiation of a CO_2 laser were measured.

Composites consisting of a heat-resistant filler and a binding organic resin are being widely used as structural materials and heat-protection coatings. To model radiative heat transfer processes and to solve the thermophysical problem of heating of materials or high-temperature structures by concentrated energy fluxes, it is necessary to know not only the energy but also the space-polarization characteristics of the reflected radiation.

Earlier [1] we measured the degree of polarization and the indicatrix of the intensity of radiation at wavelengths of 0.63 and 1.15 μm reflected by composites illuminated by a laser beam with a fixed polarization plane. The present work is devoted to the influence of the orientation of the polarization plane of the incident radiation on the degree of polarization, the rotation of the polarization plane, and the form of the indicatrix of the intensity of radiation (λ = 0.63 μm) reflected by STK glass cloth-based laminate, PTK cloth-based laminate, and paper-based laminate before and after their heating by CO_2-laser radiation. We investigated samples both with initial and with rough surfaces as well as after heating in air by a CO_2 laser until charring of the surface layer. Moreover, the glass cloth-based laminate was also studied after heating to the state where the charred layer burned up and the glass fibers of the filler were exposed [2].

Measurements were made on a goniophotometric setup [3] with a solid angle of the recording system of $1.5 \cdot 10^{-4}$ sr (in recording the indicatrix) and $3.7 \cdot 10^{-3}$ sr (in determining the azimuth and the degree of radiation polarization). The angular resolution was 0.25 and 5°, respectively. The sounding radiation of an He-Ne laser (model LG-126) was directed perpendicular to the surface of the sample, and the reflected flux was investigated in the same observation plane at different angles ϑ to the direction of the incident flux. When it was necessary to know the parameters of specular reflection of radiation, we made measurements at angles of incidence of $5-85^{\circ}$. The polarization plane of the sounding radiation was oriented by polarimetric plates at angles of 0, 45, and 90° to the observation plane. With this procedure of measurements in the reflected flux, the total (polarized and depolarized) radiation (indicatrix measurements), the contribution of the polarization component to the total reflected flux (measurements of the degree of polarization), and the polarization component itself (rotation of the polarization plane) were analyzed.

The effective degree of polarization [4] was found from the relationship of the difference and the sum of the extremal intensities of the light passed through a polaroid rotatable about the axis of the recorded radiation. The azimuth of the polarization was determined by the position of the polaroid at which the intensity of the light passed was at its maximum. The main error of the measured quantities depended on the degree of polarization and the random error of measurement of the extremal intensities. The absolute error of a mean result was $\Delta P = 0.01-0.05$ and $\delta\varphi = 1-6^{\circ}$ at a confidence coefficient of 0.95.

B. I. Stepanov Institute of Physics, Belarussian Academy of Sciences, Minsk, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 66, No. 4, pp. 442-447, April, 1994. Original article submitted July 8, 1992.

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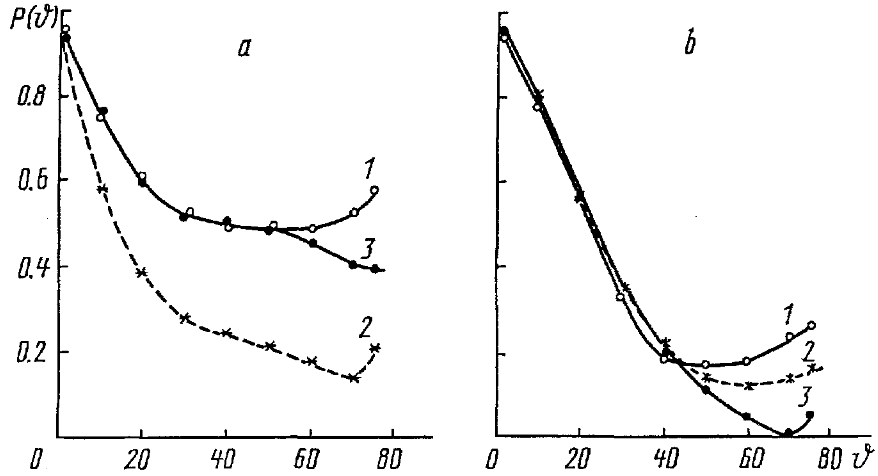

Fig. 1. Polarization ($P(\vartheta)$) versus the angle of recording of the radiation reflected by the glass cloth-based laminate (a) and the paper-based laminate (b) with their surfaces being in the initial state for different azimuths of polarization of the sounding flux: 0 (1), 45 (2), and 90° (3). ϑ, deg.

It was established that the indicatrices of the intensity of the radiation reflected by the investigated composites with the initial state of their surface are not sensitive to the polarization of the incident flux and correspond closely to specular reflection. Removal of a smooth layer of polimerized resin from the surface by abrasive paper results in broadening of the indicatrices [1]. In this case, the indicatrix corresponding to sounding radiation polarized perpendicular to the plane of incidence $f_{\perp}(\vartheta)$ lies systematically somewhat higher than for the radiation polarized in the plane of incidence $f_{\parallel}(\vartheta)$. After laser annealing of the samples, the indicatrices of the intensity of the reflected radiation, depending on the state of the charred surface, lie between the indicatrices of the composites with the smooth and rough initial surfaces [1]. Here the influence of the polarization azimuth of the incident flux becomes more pronounced, especially for observation angles $\vartheta > 20°$. If the polarization plane in the incident flux is at 45° to the plane of incidence, then the indicatrix of the intensity of the radiation reflected by the rough and charred surfaces of the composites in the direction ϑ is equal to the half-sum of $f_{\perp}(\vartheta)$ and $f_{\parallel}(\vartheta)$. Fot the glass cloth-based laminate, longer intense heating leads to burnup of the charred surface layer and exposure of the glass cloth [9]. The indicatrix of the intensity of the radiation reflected by the glass cloth-base laminate with this a state of its surface is broader than the indicatrix corresponding to the charred surface [1] and independent of the orientation of the polarization plane of an incident flux.

The measured degrees of polarization P of the radiation reflected by the composites with the initial state of their surface show that only scattered radiation undergoes strong depolarization, whereas the degree of polarization of the specularly reflected radiation remains close to unity (Fig. 1). Moreover, there is some difference in the angular dependence of the degree of polarization of the radiation reflected by the glass cloth-based laminate (Fig. 1a) and the cloth-based and paper-based laminates (Fig. 1b). Independently of the polarization azimuth of the incident flux, the paper-based and cloth-based laminates depolarize scattered radiation more strongly than the glass cloth-based laminate, especially for $\vartheta = 0-50°$ (Fig. 1b). At the same time, radiation whose polarization plane is at 45° to the plane of incidence is depolarized by the glass cloth-based laminate more strongly than radiation polarized perpendicular or parallel to this plane (Fig. 1a).

Treatment of the samples surfaces by a abrasive paper, i.e., an increase in surface roughness, enhances the depolarization of scattered radiation in all directions (Fig. 2a). Surface charring of the composites due to laser heating again decreases the depolarization of reflected radiation both in the specular reflection direction and at different angles to it (Fig. 2b). It is pertinent to note that when the charred composite is sounded by a flux polarized perpendicular to the plane of incidence, the degree of polarization of the scattered radiation changes insignificantly with deviation from the specular reflection direction and, for example, for $\vartheta = 80°$ is 0.9. But when the charred composite is sounded by a flux polarized in the plane of incidence or at an angle of 45° to it, the degree of

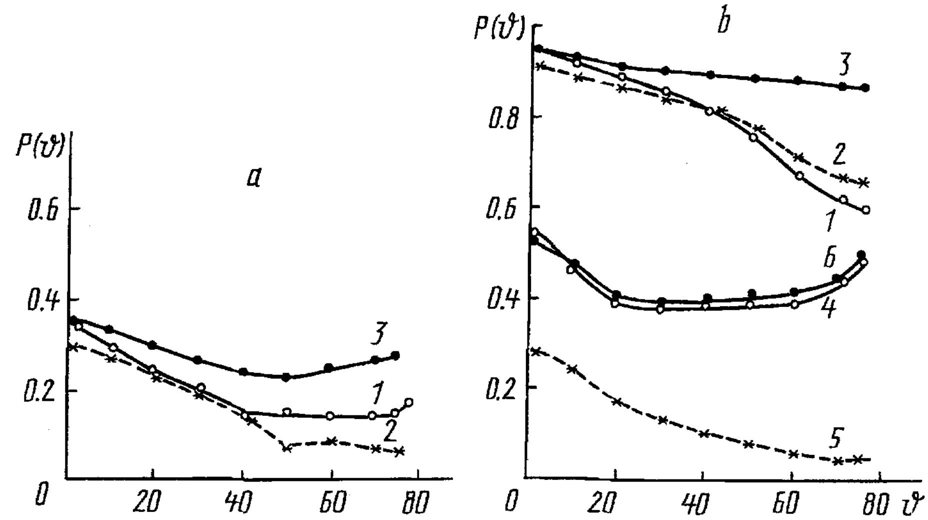

Fig. 2. Relationship between the degree of polarization and the angle of recording of the radiation reflected by STK glass cloth-based laminate with rough (a) and carbonized (b, curves 1-3) surfaces as well as with a burnt-up charred layer (b, curves 4-6) for different azimuths of polarization of the sounding flux: 0 (1, 4); 45 (2, 5), and 90° (3, 6).

polarization of thereflected radiation decreases more strongly with increase in the observation angle, and for $\vartheta = 80^{\circ}$ it is 0.6–0.7. Further heating of the glass cloth-based laminate, causing burnup of the charred layer and exposure of the glass cloth, results in stronger depolarization of the reflected flux (Fig. 2b). Here, as in the case of the glass cloth-based laminate with a smooth surface not subjected to laser heating, radiation with an azimuthal angle of 45° is depolarized more strongly than radiation polarized perpendicular or parallel to the observation plane.

The results obtained may be explained in terms of the notions of singly and multiply scattered components of the reflected flux [5]. The materials investigated are partially transparent in the initial state [1], and therefore these components are formed not only on the surface but also inside the material, which must affect the degree of polarization and the indicatrices of reflected radiation.

The initial smooth surface of the composites formed by a polymerized resin provides a narrow indicatrix and a high degree of polarization of the specularly reflected radiation. The radiation scattered to the side is formed as a result of multiple reflections from internal inhomogeneities, which explains the flux depolarization and the correspondingly weak sensitivity of the indicatrices to the polarization azimuth of the incident light.

Removal of the upper layer leads to an increase in the surface roughness of the composites. This causes an increase in the portion of the radiation multiply scattered by the microrelief of the surface, which leads to depolarization of the specularly reflected flux and broadening of the indicatrices. Carbonization of the surface layer of the composites due to heating entails an increase in absorption and, consequently, a decrease in the portion of the radiation emitted from within the material in the reflected flux. As a consequence, the indicatrix of the reflection is narrowed and the degree of polarization of the radiation becomes close to unity, i.e., to the degree of polarization of the sounding flux. In the latter case, the depolarized part of the reflected flux is associated only with multiple scattering and diffraction of radiation by the surface microrelief [5] and contributes little to the total reflected flux.

Burnup of the charred layer of the glass-reinforced plastic surface and exposure of glass fibers of the filler causes a decrease in the absorption coefficient of the surface layer, with the surface roughness remaining substantial. This leads to an increase in the share of the radiation multiply scattered on the surface and inside the glass-reinforced plastic in the reflected flux and causes broadening of the indicatrix of the reflection as well as substantial depolarization of the reflected flux.

The cloth-based and paper-based laminates in the initial state have a lower absorption coefficient than the glass cloth-based laminate [1], which permits radiation to penetrate deep into the composites and increases the multiplicity of scattering by internal optical inhomogeneities. As a result, depolarization of the radiation reflected

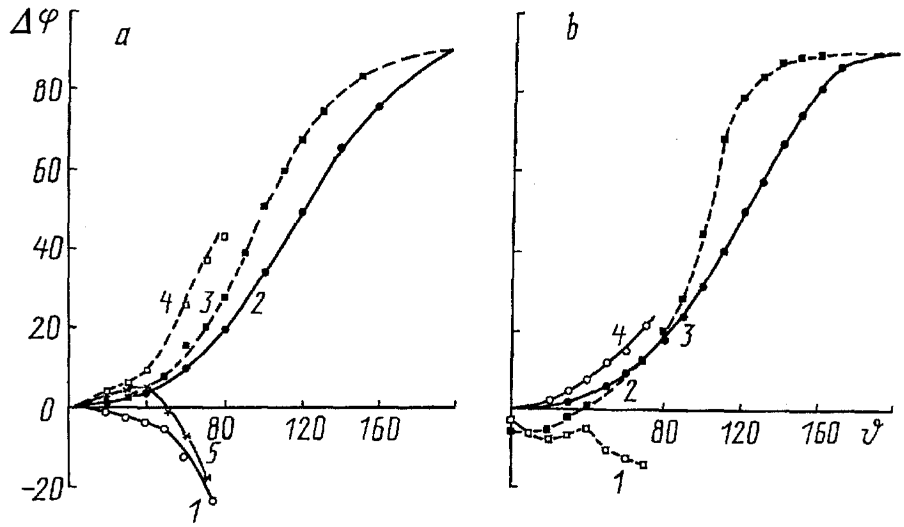

Fig. 3. Rotation of the polarization plane of radiation scattered (1, 4, 5) and specularly reflected (2, 3) by the paper-based laminate (a, curves 2, 5) and the glass cloth-based laminate with the initial (a, curves 1, 2), rough (a, curves 3, 4), and charred (b, curves 3, 4) surfaces as well as by the glass cloth-based laminate with a burnt-up charred layer (b, curves 1, 2) versus the angle of recording. $\Delta\varphi$, deg.

at angles differing from those of the specular reflection (see Fig. 1) becomes stronger than for the glass cloth-based laminate. In the general case, a smooth boundary between air and a partially transparent composite serves as a polarizer and influences the polarization characteristics of the reflected radiation observed at an oblique angle to the surface. The reasonings above are confirmed by measurements of the rotation of the polarization plane of the reflected radiation.

It is known that due to a difference in the Fresnel reflection coefficients for the polarized components of radiation the polarization plane of linearly polarized light (with the exception of $\varphi = 0$ or 90^0) reflected by a smooth surface turns toward the normal to the plane of incidence, whereas on passing from an optically denser to a less dense medium the polarization plane turns in the opposite direction [6]. The polarization azimuth of radiation reflected by a rough surface behaves identically [5]. In this case, an increase in the multiplicity of radiation scattering entails an increase in the angle of rotation of the polarization plane.

We measured the angle of rotation of the polarization plane of the radiation reflected by the above samples for an azimuthal angle of polarization of 45^0 in an incident flux. The angle of rotation of the polarization plane $\Delta\varphi$ of the reflected radiation was considered positive when the rotation proceeded toward an increase in the azimuthal angle relative to the azimuthal angle of polarization of the specularly reflected flux. The angles of observation ϑ at which the reflected radiation was recorded were counted from the direction of the incident beam. Measurements were made both for normal incidence and different angles of observation and along the direction of specular reflection with the angle of incidence being changed from 5 to 85^0.

The component of polarized radiation specularly reflected by the investigated composites, with their surfaces being in the initial state, pertains to surface radiation, as evidenced by the positive direction of rotation of the polarization plane of the reflected flux (Fig. 3a). At the same time, the polarized component of radiation scattered by the paper-based, cloth-based, and glass cloth-based laminates with smooth surfaces at angles ϑ exceeding, respectively, 50, 30, and 0^0 is a result of radiation inside the material (Fig. 3a); i.e., a smooth surface of the composites acts as an amplitude-anisotropic element that partially polarizes the radiation depolarized inside the material and passing through the surface. Thus, the basic flux of radiation scattered by the glass cloth-based laminate with a smooth surface is formed inside the material, while the flux scattered by the paper-based and cloth-based laminates is initiated inside the material only for the observation angles higher than 50 and 30^0, respectively. The observation angle starting at which rotation of the polarization plane of the radiation scattered in the negative direction occurs is larger, the smaller the absorption coefficient of the composite is.

Removal of the smooth layer increases the roughness, thus causing an increase in the multiplicity of scattering of radiation by microinhomogeneities and, as a consequence, an increase in the rotation of the polarization plane of the reflected flux, especially of its scattered part (Fig. 3a). In this case, the polarized component of the scattered radiation is formed by the surface, as indicated by the positive direction of rotation of the polarization plane (Fig. 3a, curve 4).

For carbonized surfaces of the composites, the polarized component of the specularly reflected radiation is most probably due to single scattering by surface microinhomogeneities. This is evidenced by the coincidence of the measured angles of rotation of the polarization plane of the specularly reflected radiation and those calculated by the formula $\Delta\varphi = \arctan\,[P_{\perp}f_{\perp}(\vartheta)/P_{\parallel}f_{\parallel}(\vartheta)]^{1/2} - 45^{\circ}$, derived from the assumption of single scattering. The polarized component of the radiation scattered by the charred composites at angles differing from specular reflection is of surface origin and is formed by multiple scattering by surface microfacets (Fig. 3b).

The reflection of radiation by the glass cloth-based laminate with the burnt-up charred layer is dependent not only on its partial transparency but also on the shape of the exposed fibers of the glass cloth. Both factors exert an influence on the dependence of the rotation of the polarization plane of radiation on the observation angle (Fig. 3b). As is seen, both the scattered radiation and the specularly reflected radiation $\vartheta = 0-40^{\circ}$ are mainly formed inside the material, with the exception of the radiation specularly reflected by the glass cloth-based laminate for angles of incidence exceeding 20°, which is mainly formed on the surface.

Thus, the partial transparency of the composites gives rise to the component in the reflected radiation that is caused by scattering by microhomogeneities inside the material. This radiation, passing through the material–air interface, becomes partially polarized and causes the primary polarization plane to rotate in the direction opposite to the reflection corresponding to the surface. Laser heating of the composites changes their absorption coefficients, thus influencing the ratio of fluxes scattered inside the material and on its surface, and, as a consequence, affects the space-polarization characteristics of the reflected radiation.

NOTATION

λ, wavelength at which measurements are made; P, degree of polarization of the reflected radiation; ΔP, absolute error in measurements of the degree of polarization of the reflected radiation; φ, azimuth of the polarization of the incident flux; $\Delta\varphi$, angle of rotation of the polarization plane of the reflected radiation with respect to the polarization azimuth of the incident flux; $\delta\varphi$, absolute error in measurements of the rotation angle of the polarization plane of the reflected radiation; $f_{\parallel}(\vartheta)$, $f_{45}(\vartheta)$, $f_{\perp}(\vartheta)$, normalized indicatrix of the intensity of the reflected radiation at polarization azimuths of the incident flux of 0, 45, and 90°, respectively; ϑ, angle at which measurements of the degree of polarization, the angle of rotation of the polarization plane, and the intensity of the reflected radiation are made.

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