The effect of contact influence on the opticomechanical properties of Panda-type fiber under thermocycling conditions

Y I Lesnikova and A N Trufanov
Department of Computational Mathematics and Mechanics, Perm National Research Polytechnic University, 29 Komsomolsky prospekt, Perm 614990, Russia
E-mail: ulesig@gmail.com, ant@pstu.ru

Abstract. The mathematical model of the stress strain state evolution in polarization-maintaining Panda-type fiber in conditions of contact thermopower loading is developed. The influence of the position of the light-conducting core on the birefringence of the fiber is investigated. It is found that the temperature change in the thermal cycle has a minor effect on the stress strain state of the fiber. The impact of temperature change on the fiber optical characteristics is shown to increase with the deviation of its geometry from the design values.

1. Introduction
The special types of optical fibers made of doped quartz glasses are used as sensitive elements of some modern sensors of physical quantities [1]. Polymeric coatings protect the optical fiber from the external environment and mechanical influences. In one embodiment of such a protective coating (PC), two layers of UV-cured polymer are attached to fiber (figure 1). The primary coating is in a highly elastic relaxation state at room temperature, its task is to reduce the influence of force effects (bending, lateral force, etc.) on optical fibers. To protect the relatively soft primary coating from mechanical influences and the influence of the external environment, a secondary coating layer is applied. The second layer is in a vitrified state at room temperature.

Figure 1. Cross-sectional scheme of the polarization-maintaining (PM) optical Panda-type fiber: 1 – stress applying rod, 2 – core, 3 – cladding, 4 – primary coating, 5 – secondary coating.

The use of special optical fibers in the composition of various measuring systems, navigation systems based on fiber-optic gyroscopes, systems for monitoring the state of building structures, etc. imposes strict requirements on the correct operation of the products in a given operating temperature
range. A change in temperature due to the heterogeneity of the PM fiber design and a significant difference in the coefficient of linear thermal expansion of protective coatings and silica glass entail the formation of deformation fields, which, due to the photoelastic effects, affect the optical characteristics of the fiber. In addition, heating or cooling significantly affects the rheological properties of protective coatings. Temperature fluctuations in the operational range can lead to relaxation transitions in PC polymers, which are accompanied by a change in the compliance of the material by several orders of magnitude, which also affects the optical characteristics of the fiber.

The process of manufacturing a polarization-maintaining fiber consists of several stages. It is known [2] that imperfection of technological processes leads to deviations of geometric parameters of structural elements from design values. It was shown in [3,4] that such imperfections in geometry affect the stress state in the core and, as a consequence, the optical characteristics of optical fiber. In this connection, at some technological stages of production the conformity of fiber parameters to project values is checked. In one such test, the tensed fiber is wound onto the coil and subjected to thermal cycling, during which the optical characteristics are controlled. The effect of the force winding of the fiber on the coil without taking into account the protective coating and contact with the coil was considered in [5,6]. In [7], the analysis was carried out with regard to the contact effect on the fiber with protective coating at room temperature and with no consideration for the imperfections of the PM fiber geometry.

2. Problem statement

In this paper, the methods of mathematical modeling are used to investigate the effect of thermopower action on the stress-strain state in PM fiber and on its optical characteristics, with a single-layer force winding on an aluminum coil, taking into account the factors listed in the introduction, including the relaxation processes taking place in polymeric protective coatings with a cyclic temperature change according to a given law in the range from -60 to 60 °C (figure 2) and deviations of the center of the light conducting core from the center of the fiber.

![Figure 2. A cycle of the temperature change.](image)

The computational scheme of the contact interaction of the coil with the fiber is shown in figure 3. The approach described in [8,9] was used to account for the residual stresses in polarization-maintaining Panda-type fiber formed after high-temperature drawing. Thus, in the first stage, residual strain fields were obtained, which were used in the second stage as initial conditions.

The mathematical formulation of the described problem includes the equilibrium equations

\[
\text{div} \mathbf{\sigma} = 0, \quad \mathbf{x} \in V
\]  

(1)
where \( \hat{\sigma} \) is the stress tensor, \( V \) is the considered domain, and \( \bar{x} \) is the radius-vector. The geometric relations, taking into account the smallness of deformations, are

\[
\dot{\varepsilon} = \frac{1}{2} \left( \nabla \bar{u} + (\nabla \bar{u})^T \right), \quad \bar{x} \in V
\]

where \( \dot{\varepsilon} \) is the strain tensor, and \( \bar{u} \) is the displacement vector.

The generalized Hooke's law was used as the physical relations for the fiber structural elements consisting of doped quartz glasses. Taking into account that the elastic characteristics of quartz glass are varied insignificantly in the range of operating temperatures under consideration [10], the hypothesis that they do not depend on temperature was assumed

\[
\hat{\sigma} = \lambda I_1(\dot{\varepsilon}) \dot{I} + 2G\dot{\varepsilon}, \quad \bar{x} \in V
\]

where \( \lambda \) is the Lame's parameter, \( G \) is the shear strain modulus, \( I_1(\dot{\varepsilon}) \) is the first invariant of the strain tensor, and \( \dot{I} \) is the unit tensor.

For PC polymers, physical relationships were used that correspond to a linear viscoelastic model [11] with the approximation of the relaxation modulus by the sum of exponentials

\[
\hat{\sigma} = K \Delta \hat{I} + 2 \int_0^\infty G(t-\tau)d\left(\dot{\varepsilon}(\tau) - 1/3 \Delta(\tau) \dot{I}\right)
\]

\[
G(t) = G_0 \left[ C_0^d + \sum_{i=1}^{n_G} C_i^d \exp\left(\frac{-t}{\tau_i^d}\right) \right]
\]

where \( \Delta \) is the bulk deformation, \( K \) is the bulk compression module, \( G(t) \) is the shear relaxation function, \( G_0 \) is the instant module, \( C_i^d \) are the experimental coefficients, \( n_G \) is the number of terms of the exponential series, and \( \tau_i^d \) are the relaxation times. The temperature-time analogy is used when considering the influence of temperature on material properties. For the reduced times calculation, the temperature-time shift coefficient obtained by the Williams-Landell-Ferry equation is used

\[
\lg a_r = \frac{C_1(T - T_i)}{C_2 + (T - T_i)}
\]

where \( C_1 \), \( C_2 \), \( T_i \) are the experimental coefficients.

Displacement boundary conditions are \( \bar{u} = U, \bar{x} \in S_u \) and stress boundary conditions are \( \hat{\sigma} \cdot \bar{n} = P, \bar{x} \in S_p \), where \( S_u \) and \( S_p \) are the parts of the boundary with the specified displacements and loads respectively, and \( \bar{n} \) is the surface normal.

The contact interaction of two surfaces without friction was modeled by the relations recorded in a coordinate system associated with the general normal to the first surface at the point of contact:

\[
x_{01} + u_1(t) = x_{02} + u_2(t) - \text{with a contact}, \quad x_{01} + u_1(t) < x_{02} + u_2(t) - \text{without a contact}
\]

where indices 1 and 2 refer to the corresponding contacting surfaces, and \( x_{0i} \) and \( u_i \) are the initial coordinate and the displacement of the \( i \)-th contact point, respectively.

The numerical implementation was performed by the finite element method. Preliminary, the residual stress fields formed in the fiber during the high-temperature drawing were defined by the method described in [8,9].

3. The results

In the first stage of multivariate numerical experiments, the residual stress fields in the fiber after the high-temperature drawing were obtained. The characteristic diagrams of fields are shown in figure 4.
Figure 4. Profiles of residual stresses after high-temperature drawing along the line connecting the centers of stress applying rods: (a) $\Delta h_z = -4\mu m$, (b) $\Delta h_y = 4\mu m$.

Figure 5. Evolution of the stress tensor components in the centre of the optic-fiber core: (a) $\sigma_x$, (b) $\sigma_z$, (c) $\sigma_y$. 
In the second stage, the dependences of the stress tensor components on time under the conditions of temperature variation according to the thermocycle shown in figure 2 were obtained. The characteristic dependences of the evolution of the stress tensor components for three different deviations of the fiber geometry are shown in figure 5.

The dependences of the contact pressure on the temperature for two variants of the fiber tension force when winding the coil are shown in figure 6. Analysis of the results suggests that the contact pressure becomes equal to 0 at negative temperatures. It indicates that a "gap" in the contact occurs. The characteristic nonlinear regions in the range 6800-8600 sec correspond to the active relaxation processes in the primary coating, which begins to soften upon heating.

![Figure 6. Evolution of the contact pressure.](image)

Using the known relationships [12] connecting the stressed state with optical characteristics, the dependence of the mode birefringence on the deviations of the fiber geometry and temperature was obtained (figure 7). As a result of the data analysis, it was found that the deflection of the light conductor along the OY axis is more sensitive to the temperature change, as evidenced by the larger scatter of the curves in figure 7, which increases with increasing deflection $\Delta h_y$. It also suggests that the greater the deviation of the fiber geometry, the more its optical characteristics are affected by the temperature change.

![Figure 7. Dependence of the deviations of mode birefringence on temperature $T$ and geometry imperfection and free ideal fiber $\Delta B = B_{\text{geom imp}} - B_{\text{fib}}$ on deflection of the light-conducting core center from the fiber center $\Delta h$.](image)
4. Conclusions
A numerical model of the coil contact interaction with PM optical fiber in protective-strengthening coating with a single-layer force winding under thermal cycle conditions is constructed. As a result of the multivariate numerical experiments, the dependences describing the evolution of the stress fields in the fiber, as well as the associated optical characteristics were obtained. It has been found that:
- the position of the light-conducting core significantly affects the birefringence;
- the change in temperature under thermal cycling conditions has an insignificant effect on the stress-strain state in the fiber wound on coils of 40 and 100 mm in diameter;
- the fibers with a deflection of the light conductor along the OY axis are more sensitive to temperature changes;
- a greater deviation of the fiber geometry from the design values results in a greater influence of the temperature change on the optical characteristics of the fiber.

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