Contact stresses modeling at the Panda-type fiber single-layer winding and evaluation of their impact on the fiber optic properties

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Abstract. The impact of contact transverse forces on the birefringence of the single-mode polarization-maintaining Panda-type fiber is numerically modeled. It has been established that with a single-row power winding on a cylindrical mandrel, the fiber tension at winding is the principal factor that influences birefringence. When coiling the fiber based on the local defect microbending, the birefringence at the microbending point differs from that of the free fiber by 1.3%.

1. Introduction
Polarization-maintaining optical fibers are widely used for the production of interferometric sensors, fiber-optic gyroscope sensors and in the monitoring systems as distributed sensors of thermomechanic stresses [1-3]. Performance parameters of these fibers are, first of all, provided by the internal residual stress fields that are formed in the manufacturing process [4], and secondly, by the level and type of fibers mutual effects and interaction with the mandrel during power wiring under technological tests and sensing circuit coil manufacturing. As a result, the stress state of the polarization-maintaining fiber and its optical properties are determined by a combination of factors which are connected with the properties of silica fiber materials and polymer protective and strengthening coatings (PSC), manufacturing conditions, and external stresses of contact nature [5]. Papers [6, 7] consider the effect of power winding on the optical fiber characteristics disregarding PSC and contact fiber – mandrel interaction is not considered for simplicity. The present paper is focused on numerical mathematical models that enable description of technological stresses development regularities considering all the above factors.

The paper sets the boundary problems of quartz heterogeneous fiber system interaction in the two-layer linear viscoelastic polymer protective-strengthening coating with the elastic cylindrical mandrel and with neighboring fibers along the lateral surfaces under single-layer power winding. Contact boundary conditions are formulated without friction. Finite element procedure for the numerical solution of linear viscoelasticity contact problems for the fiber power winding on the mandrel has been developed and implemented. Basing on the numerical polyvariant studies, the contact stress state evolution regularities in the optic fiber have been investigated considering the residual technological stresses, tensile force at wiring, the mandrel diameter, and fiber orientation in relation to the mandrel. Residual stresses were predicted as described in [4].
2. Dependence of optomechanical characteristics of the Panda-type fiber with the protective-strengthening coating on the power effects at a single-layer winding on the aluminum coil

The finite element three-dimensional analog of the investigated structure is presented in Figure 1. The calculation was made for two fiber section orientations in relation to the radial direction of the coil – parallel (α =0°) and normal (α =90°) ones, as well as for two coil diameters – 44 and 100 mm. Fiber tension $F_n$ changed from 0.2 to 1 H.

![Figure 1](image1.png)

**Figure 1.** The finite-element model of contact fiber - coil interaction under power winding for α = 90° and $D_k$ =44mm.

Figure 2 illustrates first principal stress fields in the structure for two tension values $F_n$=0 H and $F_n$=0.2 H. The maximum first principal stress rises from 173 to 202 MPa. The figures also clearly demonstrate the kink effect on the fiber stress-strain state. It should also be noted that the stress level in PSC is considerably lower than in silica fiber, which results from Young's modulus of the protective coating inner cladding material, which is lower by several digits.

![Figure 2](image2.png)

**Figure 2.** First principal stress $\sigma_1$, Pa: a – $F_n$=0, α =0°, b – $F_n$=0.2, α =0°

The transverse contact forces change the principal stress difference fields distribution pattern in the optical fiber (Figure 3), which eventually leads to the modal birefringence change. The effect of viscoelastic properties of the protective-strengthening coating is manifested in some evolution of stresses, and, as a result, of birefringence (Figure 4), however, it is clear that the effect is negligible and the birefringence value stabilizes rapidly enough (within some minutes after winding).
Figure 3. $F_n = 0.2$ H. Difference of principal stresses in the optic fiber core.

Figure 4. $F_n = 0.2$ H. Modal birefringence time evolution.

Figure 5. Birefringence - fiber tension dependence, H.
Figure 5 shows summarized data on the optical fiber modal birefringence $B$ dependence on tension for two coil diameters and two orientations. The graph analysis demonstrates that the principal factor that affects the $B$ value is the fiber tension during winding which forms contact stresses along the fiber – coil surface interaction boundary. As in [6], obtained dependence $B(F_n)$ is linear, moreover, birefringence does not practically depend on the coil diameter and fiber section orientation. For the maximum force studied $F_n=1$ Н, birefringence increases by 38%. The effect of other factors (orientation and coil diameter) varies within 0.8% of average values.

3. Effect of 167 micron fiber microbending
To study the microbending effect on the fiber opto-mechanical properties, the mandrel-fiber system stress-strained state problem was solved with tension-coiled fiber and transverse kink through the 167 micron fiber lengthwise stuck to the mandrel. Such local imperfection leads to additional transverse contact forces which influence stress-strain state in the fiber core and, as a result, optical characteristics.

Isoline and stress intensity patterns (Figure 6.) show the effect of external forces on the stress pattern: fields are vertically weakly asymmetrical, which is induced by the transverse contact forces and kinking. The defined impact does not extend to the optical fiber core area. Significant redistribution of localized contact forces is provided by the protective inner shell from the highly elastic low mode incompressible material.

![Figure 6. Stress tensor intensity in the cross-sectional plane of the PSC fiber](image)

The numerical investigation ascertained that the birefringence value in the optic fiber core immediately above the microbending point differs from that of the free fiber (equally strained) no more than by 1.3%. The farther from the defect, the more birefringence values approach those of the free (not kinked) fiber (Figure 7).
Figure 7. Relative change of modal birefringence along the fiber for three cross-section orientations \((\alpha = 0^\circ, \alpha = 90^\circ, \alpha = 45^\circ)\).

4. Conclusion
As a result of the research, a mathematical model has been constructed and its numerical realization procedure has been developed. The obtained birefringence dependence on fiber tension during its winding on the mandrel \(B(F_n)\) is linear, which correlates with the results published earlier [6]. It has been determined that birefringence does not practically depend on the coil diameter and fiber section orientation. It has been established that there is modal birefringence in the section above; the microbending point differs from that of the free fiber by no more than 1.3% (at winding tension \(F_n = 0.2\) H). The farther from the defect, the closer birefringence values are to those of the free fiber (Figure 6).

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