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Evolution of Technological Stress Fields in Cylindrical Stress Applying Rods for the Panda-Type Optical Fiber During Annealing

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Abstract: In this paper, we study the evolution laws of the technological stress fields in the stress applying rod for a preform of the Panda type optical fiber under annealing conditions. It is shown that the main reason of reducing the levels of the stress state is the relaxation of stresses due to viscous deformation of silica glass in the temperature range of glass transition. Numerical implementation of the mathematical model, which is based on the linear relations of thermo-visco-elasticity, allows us to investigate the formation of technological stresses in the stress applying rod within the temperature range corresponding to annealing conditions. Numerical analysis was performed using the finite element method (FEM). The quantitative characteristics of stress relaxation have been obtained for different annealing regimes. Based on the conducted numerical experiments we have determined the annealing modes which provide the maximum possible reduction of dangerous tensile normal stress and intensity of the stress tensor. It has been found that for rods with uniform doping the annealing process has much stronger effect on the residual stresses than for rods doped according to the parabolic law.

Key words: Technological stresses · Residual stresses · Polarization maintaining fiber · Relaxation transition · Annealing

INTRODUCTION

One of the important areas of fiber optic system designing is towards the development of optical fibers capable of maintaining the linear polarization state of light throughout the fiber, the so called polarization-maintaining optical fiber (PMF), which are widely used in fiber optic sensors for measuring various physical parameters [1]. Polarization-maintaining optical fibers are manufactured using high temperature drawing technique, in which fibers are down drawn from silica glass preforms and then rapidly cooled [2].

A distinguishing feature of such fibers is the embedded anisotropy of the internal stress fields, which is provided intentionally by embedding in the fiber structure special stress applying elements, whose thermal expansion coefficient differs from that of the cladding material. As a result of the stress anisotropy and known photoelastic effect, such fibers have high optical birefringence. Some types of polarization-maintaining optical fibers are described in [3-5]. Today, one of the most processible and effective are the Panda-type PM optical fibers, in which the SAP is realized by two cylindrical silica glass rods with inhomogeneous doping along the radius. The technological residual stresses formed during manufacturing of such rods are rather high, which can lead to their fracture already at the production stage [6-8]. The level of residual stresses can be essentially reduced through the application of high temperature annealing technique [9].

EFFECT OF ANNEALING ON THE STRESS STATE

Method of Analysis: In this study, based on mathematical modelling we investigate the influence of high temperature annealing on the evolution of the stress state in the stress applying rod during its manufacture. It is suggested that the basic mechanism responsible for reducing the level of stresses generated in the process of annealing is the mechanism of stress relaxation due to viscous deformation of silica glass in the range of glass transition temperatures. The substantiation of the

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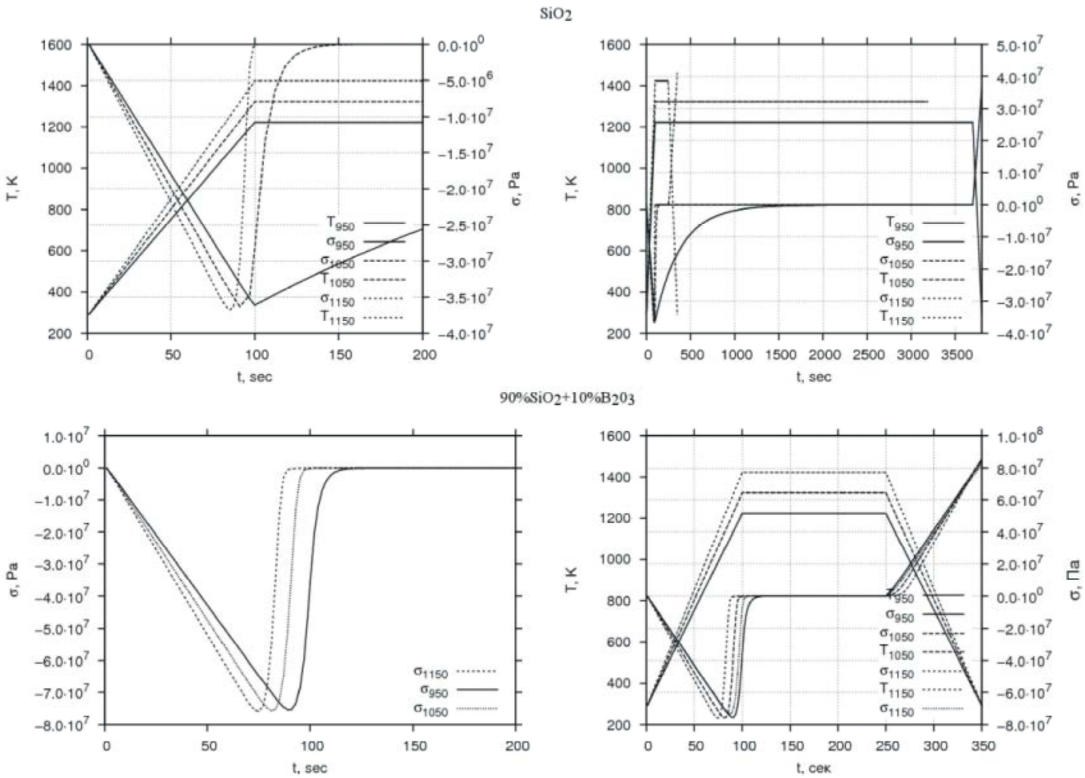

Fig. 1: Evolution of stresses and temperature in clamped rods made of SiO_2 and 90%SiO_2+10%B_2O_3 in the following mode: heating – holding at fixed temperatures –cooling to room temperature.

mathematical model, which has been selected for describing the behaviour of doped silica glass structures over a wide temperature range including the relaxation transition is given in [10]. A investigation of the laws governing thermomechanical processes in the material under high temperature annealing conditions was carried out for the problem of evolution of the uniaxial stress state in a clamped rod made of pure silica glass. The constitutive relations of the problem and the method of its solution are discussed in [6-8,10]. Figure 1 shows variation of stresses in the clamped rods made of pure silica glass and silica glass doped with 10% boron oxide subject to heating at a constant rate up to a certain temperature (950°, 1050°, 1150°C) holding it at these temperatures and subsequent cooling to ambient temperature, which corresponds to the annealing regime. The stress-time curves presented in the figure allows us to estimate holding time required for complete relaxation of stresses in the rod at the prescribed annealing temperature. Adding of boron oxide to silica glass leads to a decrease in the melt viscosity and glass transition temperature and increase in the linear thermal expansion coefficient [11]. It is seen that complete relaxation of the residual stresses in doped silica glass at given temperatures and prescribed heating rate (the specimens were heated up to the exposure temperature for 100 seconds) occurs already during heating, so that actually there is no necessity for long annealing.

Numerical implementation of the thermomechanical problem was accomplished by a stepwise method described in detail in [6-8,10].

Analysis of the Stress State in a SAP under Annealing Conditions: We have analyzed the evolution of stresses in the stress rod at the manufacturing and annealing stages. The stress rod is a cylinder of infinite length and radius $b = 5.10^{-3}$ m, which in the zone extended up to $r=r_0<b$ is doped with boron oxide B_2O_3 non-unifromly distributed along the radius, $r_0 = 3.10^{-3}$ m is the boundary between the doped silica glass and pure silica glass zones. The distribution of the dopant content along the radius is modeled using the relations of the following form:

$$\mu(r) = \mu_{\max}\left(1-\left(\frac{r}{r_0}\right)^n\right), r \in [o, r_0], \quad (1)$$

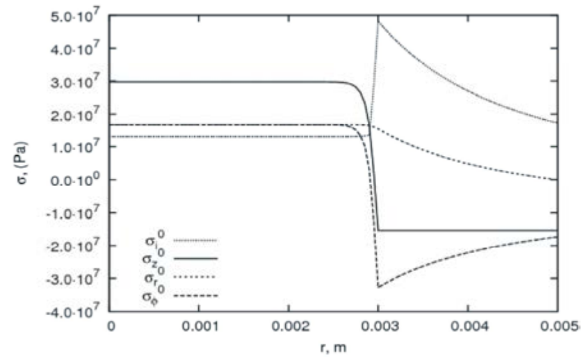

Fig. 2: Post-manufacturing residual stresses in the stress rod at n=40

We consider two cases of rod doping according to law (1): with value of the index degree n=40 (the distribution is nearly uniform) and n=2. The statement of the thermomechanical axisymmetric boundary-value problem dealing with vitrifying non-uniformly doped silica glass and the procedure of its solution by the finite element method have been detailed in [6,7].

Figure 2 presents the diagrams of post-manufacturing residual stresses in the stress rod with n=40. The numerical experiment has demonstrated that at a decreasing stress level the residual stress diagrams obtained for the same rod after completion of annealing performed at 850°C, 950°C, 1050°C, 1150°C are qualitatively of the same character. Figure 3 shows the evolution of tensile stress $\sigma_z(0)$ in the center of the SAP and stress intensity $\sigma_z(r_0)$ at the boundary between the doped and pure silica glass zones (the most critical stresses for the rod strength) during annealing at 950°C at n=40 and n=2 (solid line shows variation of temperature at the annealing stage). It should be noted that annealing at 850°C leads to a 10% decrease in the normal stresses $\sigma_z(0)$ and practically has no effect on the stress intensity $\sigma_z(r_0)$. Annealing at 950°C reduces the normal stresses $\sigma_z(0)$ by 17% and stress intensity $\sigma_z(r_0)$- almost by 20%. Further increase of annealing temperature up to 1050°C and 1150°C has no essential effect on the stresses.

A comparison between the evolution diagrams of stress $\sigma_z(0)$ and stress intensity $\sigma_i(r_0)$ during annealing at 950°C for n=40 and n=2 (Fig.3) allows us to conclude that in rods, in which doping is governed by the uniform law, annealing has a stronger effect than in rods, in which doping law is close to the parabolic one. Thus, in the selected annealing regime, stress relaxation occurs after 5-hour holding at 950°C for n =40, whereas for n=2 such regime does not so strong effect on stress state, so that there is no sense in implementing this procedure at a given temperature.

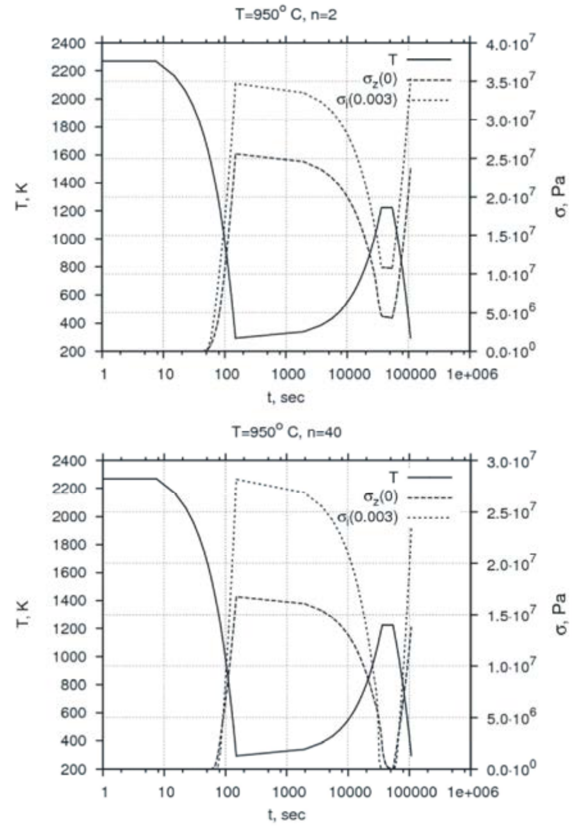

Fig. 3: Evolution of the normal stress $\sigma_z(0)$ in the central zone of the stress applying rod and stress intensity $\sigma_i(r_0)$ at the boundary between doped silica glass and pure silica glass zones during annealing at 950°C for n=40 and n=2

CONCLUSIONS

A mathematical model based on the relations of thermoviscoelasticity has been applied to describe the evolution of technological stress fields in the temperature regimes corresponding to the process of stress rod annealing. The quantitative characteristics of stress relaxation under different annealing conditions have been obtained. The annealing modes providing a maximum reduction of most dangerous stresses have been determined. It has been found that for rods doped according to the uniform law, annealing has a stronger impact on the residual stresses than for rods doped according to the parabolic law.

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