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Modeling of Coating Optical Fibers with Polymer-Magnetic Powder Composite Coating

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Abstract: *A mathematical model of forming a composite coating on optical fiber was established. The model is based on existing mathematical models for coating optical fibers with polymer coating and experimentally defined rheological behavior of the investigated dispersed system. The model was developed for a dispersed system consisting of poly(ethylene-co-vinyl acetate) - EVA in a form of toluene solution and powders of magnetic materials ($BaFe_{12}O_{19}$ and $SmCo_5$). The influence of the die diameter, diameter of the original optical fiber, concentration of EVA and magnetic powders on the thickness of composite coating was investigated. The model shows good agreement with experimental data.*

Keywords: *Modeling; Composite coating; Optical fiber; Magnetic powder; Coating condition.*

Резюме: *В данной работе установлена математическая модель образования композитного покрытия на оптическом волокне. Модель базирована на существующей математической модели покрытия волокон полимерным покрытием и экспериментально определена реологическим поведением исследуемой дисперсной системы. Модель сформулирована для дисперсной системы, образованной из раствора поли(этилен-ковинил ацетат) – ЭВА в тоулоле и порошков постоянных магнитных материалов ($BaFe_{12}O_{19}$ и $SmCo_5$). Исследовано влияние диаметра основного волокна, концентрации ЭВА и магнитных порошков на толщину композитного покрытия. Модель хорошо согласуется с экспериментальными данными.*

Ключевые слова: *Моделирование; композитное покрытие; оптическое волокно; магнитный порошок; условия покрытия.*

Садржај: *Поставњен је математички модел формирања композитне превлаке на оптичком влакну. Модел је заснован на постојећим математичким моделима превлачења влакана полимерном превлаком и експериментално утврђеном реолошком понашању испитиваног диспезног система. Модел је развијен за дисперзни систем који чине раствор поли(етилен-ко-винил ацетат) – EVA у толуену и прахови перманентних магнетних материјала ($BaFe_{12}O_{19}$ и $SmCo_5$). Испитиван је утицај пречника дизне, пречника основног влакна, концентарције EVA и магнетних прахова на дебљину композитне превлаке. Модел показује добро слагање са експерименталним подацима.*

Кључне речи: *Моделовање; композитна превлака; оптичко влакно; магнетни прах; услови превлачења.*

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1. Introduction

Coating optical fiber with composite ferromagnetic coating gives the so obtained fiber new fields for applications. For instance, it is possible to use optical fibers, modified in this manner, as optical sensors of a magnetic field or for magnetically detectable telecommunication optical fibers, etc. [1-3]. The composite coating can be made by adapting the existing process of manufacturing optical fibers in the stage in which the polymer coating is applied to drawn fiber [4-5]. Instead of a solely polymer coating a coating with particles of magnetic powder dispersed in polymer melt or solution can be applied.

An adequate mathematical model of the coating process enables investigation of a great number of process parameters including those that are particularly time consuming and expensive.

The existing mathematical models for coating optical fibers with polymer coating were analyzed and modified the process of coating optical fibers with a composite coating consisting of polymer and magnetic powder [4, 6-7]. The rheological behavior of a system that enables formation of a composite coating polymer-magnetic powder was investigated. The model was developed for a dispersed system consisting of poly(ethylene-co-vinyl acetate) in the form of a toluene solution and powders of magnetic materials ($BaFe_{12}O_{19}$ and $SmCo_5$) [4, 7].

2. Experimental

The commercial single-mode optical fiber produced by Alcatel [8] was coated with composite coating. The diameter of the original optical fiber given by the producer is 245 ± 10 μm. The polymer component of the composite coating was poly(ethylene-co-vinyl acetate) – EVA with 28 mass% of vinyl acetate, produced by DuPont, (ELVAX 265) [9]. Two types of the magnetic component of the composite coating were investigated [4, 10]:

- milled $SmCo_5$ powder (particle size 1.0 - 10.0 μm with an average size of 5.4 μm);
- Ba-ferrite, $BaFe_{12}O_{19}$ (particle size 0.6 - 2.5 μm with an average size of 1.0 μm).

The optical fibers were coated with various concentrations of Ba-ferrite and $SmCo_5$ dispersed in a 17.5 mass% solution of EVA in toluene. The composite coating was obtained by drawing the optical fiber through a reservoir containing a defined dispersion with a die ($\phi = 0.5$ mm) at the bottom. The temperature in the reservoir was controlled and constant (38 ± 0.5°C) [4].

The viscosities of EVA solutions in toluene as well as Ba-ferrite and $SmCo_5$ dispersions in these solutions were investigated using a Rheotest 2 rotational viscometer. The viscosity of EVA solutions in toluene was investigated for various temperatures (30 - 60°), concentrations (15 - 25 mass% EVA in toluene) and shear rates (3 - 1390 s^{-1}). It was proved that polymer solutions behave according to the "power law" [11] (eq. 1), while the rheological behavior of dispersions can be described with the modified Einstein equation (eq. 2) [4, 12]:

$$\eta = \eta_0 \dot{\gamma}^{n-1}, \tag{1}$$

$$\eta_{dis}(T,c,\dot{\gamma}) = \eta_{sol}(T,c,\dot{\gamma}) \cdot (1 + k_E \cdot \varphi), \tag{2}$$

where: η_0 – viscosity at the zero sheer rate, $\dot{\gamma}$ - sheer rate, n – exponent of the "power law"; $\eta_{sol}(T,c,\dot{\gamma})$ - viscosity of the solution of concentration c, at temperature T and for sheer rate $\dot{\gamma}$; $\eta_{dis}(T,c,\dot{\gamma})$ - viscosity of the dispersion of concentration c, at temperature T and for sheer rate $\dot{\gamma}$; T - temperature, c – concentration of EVA in toluene, φ -volume fraction of the magnetic powder in dispersion, k_E – Einstein constant, estimated to be k_E = 4.5 for Ba-ferrite and k_E = 7.5 for $SmCo_5$ [4, 7].

3. Overview of the model

The model is based on Miller's model [6] for coating optical fibers with a polymer coating and experimentally defined rheological behavior of the investigated dispersed system. Miller's model was developed for a cylindrical coating die, with an unpressurized applicator. A schematic of the coating applicator with a cylindrical die together with some parameters of the model are given in Fig. 1.

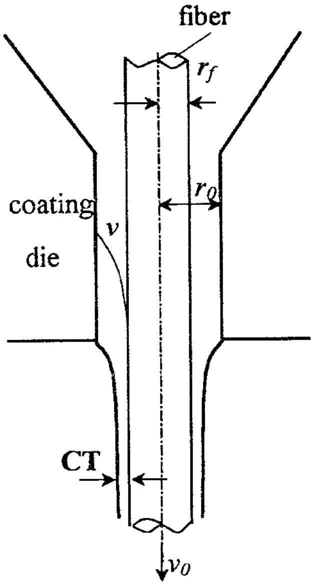

Fig. 1 A schematic of a coating applicator with a cylindrical die (r_0 – die radius; r_f – radius of the original optical fiber; v_0 – coating rate; CT – coating thickness; v – axial velocity profile).

Uncoated fiber moves with a rate of v_0 in z-direction. Neglecting gravitational, inertial and surface tension forces the equation of motion can be reduced to [4, 6, 13-14]:

$$\frac{d}{dr}\left(r\eta\frac{dv_z(r)}{dr}\right)=0, \tag{3}$$

where: η - viscosity of the coating fluid and $v_z(r)$ – axial velocity profile of the coating fluid.

The coating dispersion was proved to be Non-Newtonian obeying a power law (eq. 1) therefore eqs. 3 and 1 for boundary conditions:

$v_z(r) = v_0$ for $r = r_f$,

$v_z(r) = 0$ for $r = r_0$

after integrating became:

$$v = v_o\left[1-\left(\frac{r}{r_o}\right)^{\frac{n+1}{n}}\right]. \tag{4}$$

The coating thickness can be calculated using mass balance (eqs. 5 and 6). The mass of the solid substance passing through the die is given by [4, 6]:

$$Q = 2 \cdot \pi \cdot \omega \cdot \rho \cdot \int_{r_f}^{r_o} r \cdot v \cdot dr, \tag{5}$$

while the mass of the solid substance forming on the fiber is [4, 6]:

$$Q = \pi \cdot \rho' \cdot \left[(r_f + CT)^2 - r_f^2 \right] \cdot v_o, \tag{6}$$

where: Q - material consumption rate; ρ - density of the coating dispersion; ρ'- density of the composite coating; ω - mass percent of the solid component in dispersion; *CT* – coating thickness.

According to eqs. 4-6 the coating thickness (*CT*) can be calculated as:

$$CT = \sqrt{\frac{Q}{\pi \cdot \rho' \cdot v_o} + r_f^2} - r_f. \tag{7}$$

According to previous investigations [15-17] it was confirmed that uniform coating thickness could be achieved when coating is performed with appropriate viscosity. It was established that viscosity of the dispersion should lie in the interval 0.8 – 1.4 Pas. If the viscosity is smaller than 0.8 Pas, then inhomogeneous composite coating with a form similar to pearls is formed. If the viscosity is greater than 1.4 Pas inhomogeneous and too thick coatings are formed [15-17].

Therefore, the first step in using the model is calculating the viscosity of the coating dispersion according to input data: type of magnetic powder, concentration of EVA in toluene, concentration of the magnetic powder, coating rate using eqs. 1 and 2. If the viscosity is within the range where uniform coatings can be obtained (0.8 – 1.4 Pas) then the coating thickness (CT) is calculated according to eq. 7, otherwise with the given input process parameters it is impossible to obtain uniform coating and therefore CT is not calculated.

The main algorithm for calculating the thickness of the composite coating is given in Fig. 2.

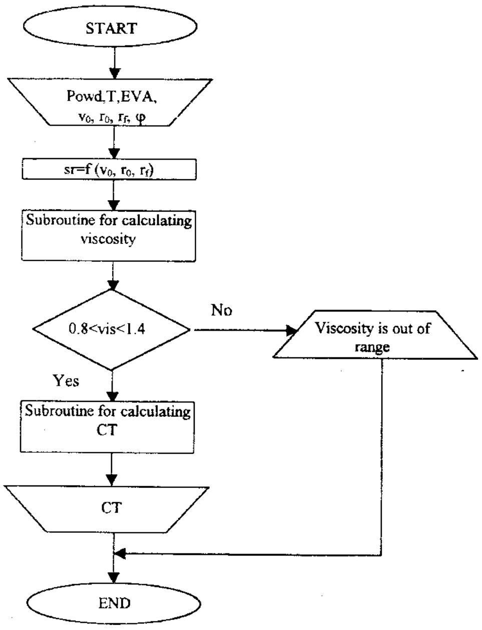

Fig. 2 Algorithm of main program (CT – coating thickness, μm; Powd – type of powder ($BaFe_{12}O_{19}$ or $SmCo_5$); T – temperature, °C; EVA – concentration of EVA in toluene, mass%; r_0 – radius of die, mm; r_f – radius of the original optical fiber, μm; v_0 – coating rate, m/s; sr – shear rate, s^{-1}; z - fraction of the magnetic powder in the formed composite coating, vol.%; vis –viscosity of dispersion, Pas).

4. Results and discussion

The influences of the die diameter, diameter of the original optical fiber, concentration of EVA in toluene and Ba-ferrite or $SmCo_5$ in dispersion on the thickness of the composite coating were investigated.

As an illustration of results obtained using the presented model, in Fig. 3 the influence of volume fraction of $SmCo_5$ in composite coating on the coating thickness for different die diameters is given.

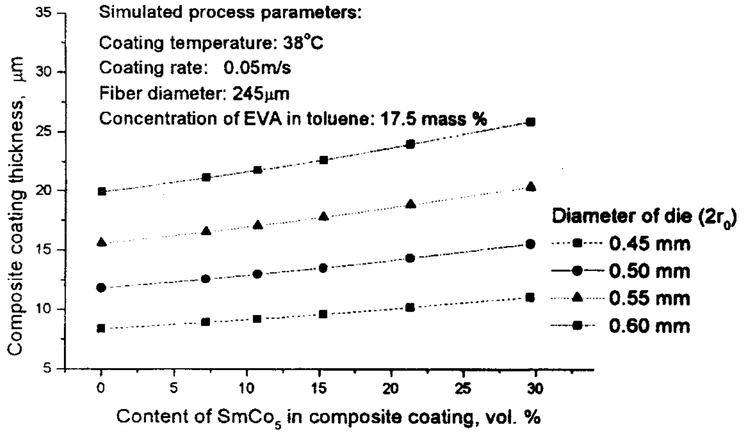

Fig. 3 Dependence of composite coating thickness on $SmSo_5$ content in composite coating for different die diameters.

In the same manner the influence of all investigated process parameters has been analyzed. The coating thickness is most sensitive to die diameter variations and then to the diameter of the original optical fiber. Among the investigated process parameters the importance of EVA concentration in toluene on the composite coating thickness is next, while the influence of the concentration of magnetic powder in dispersion is even less significant. The influence of the type of magnetic powder used ($SmCo_5$ or Ba-ferrite) is negligible.

Validity of the model was confirmed by comparing results obtained using the presented model with experimental results. The experimentally obtained mean value of the diameter of the optical fiber with composite coating was used for the comparison. Results of numerical simulation are given for three diameters of the original optical fiber: 235, 245 and 255 μm, since the optical fiber used had a diameter of 245 ± 10 μm [8]. Fig. 4. shows a comparison of experimental results obtained for various concentrations of $SmCo_5$ dispersed in the 17.5 mass% solution of EVA in toluene with results of numerical simulation for the same process conditions ($v = 0.05$ m/s, $T = 38$°C).

The model shows good agreement with the mean value of experimental data. The obtained deviations of experimental results from results obtained using the presented model are smaller than experimentally established standard deviation of the mean value.

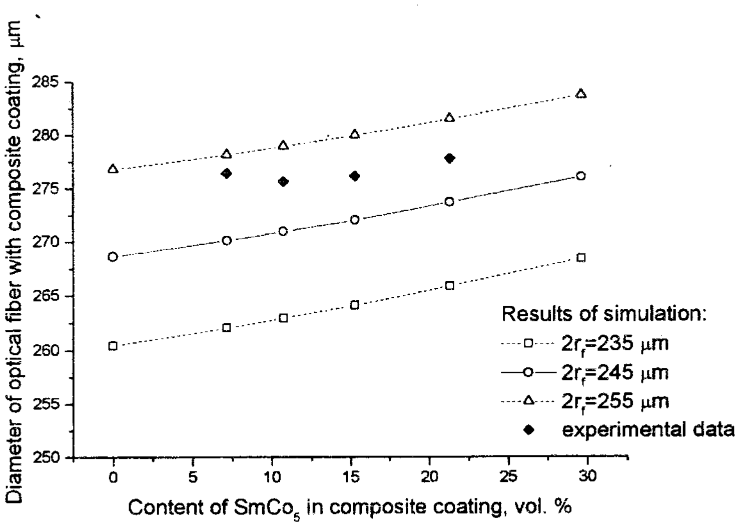

Fig. 4 Comparison of experimental results with results of numerical simulation.

5. Conclusion

A mathematical model of forming composite coating on optical fiber was established. The model is based on an existing mathematical model for coating optical fibers with polymer coating and experimentally defined rheological behavior of the investigated dispersed system (powders of $BaFe_{12}O_{19}$ and $SmCo_5$ dispersed in EVA solution in toluene). Using the developed model the influence of the die diameter, diameter of the original optical fiber, concentration of EVA and magnetic powders on the thickness of the composite coating was investigated. It was established that the coating thickness mostly depends on geometrical properties of the coating system. The model shows good agreement with experimental data, therefore it can be used for defining the process and equipment parameters (die diameter, coating rate, temperature...) that produce the desired uniform composite coating thickness with a defined magnetic powder content.

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