Analysis of influence of cold plasma on stiffness properties of polymeric materials

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Abstract. A model of the polyester fabric behavior subjected to plasma treatment with a reduced pressure is proposed to evaluate its deformability in its plane. The method for identifying stiffness properties is described, and the results of processing the full-scale experiments as well as the results of the numerical studies of the problem regarding stretching samples of the fabric are presented. For the numerical analysis of the deformation process of the fabric samples the finite element method was used. The proposed finite-element model of deformation of nonlinear elastic fabric materials allows us to study the patterns of behavior of the tissue samples under various loads, given that the material is not able to support the compressive loads. The developed technique for an experimental determination of the stiffness characteristics of fabrics according to the results of testing the samples, cut at different angles to the base, under various stretching forces, made it possible to analyze the influence of treatment of the fabric with a cold plasma on its mechanical characteristics.

Keywords: polyester fabric, identification, stiffness, cold plasma, model, numerical experiment, deformation.

1 Introduction

Fabrics from such materials as polyethylene and polytetrafluoroethylene have high strength characteristics, which makes them promising for use in composite materials. But the restraining factor is a relatively low adhesive strength (adhesion) of these fibers to polymer matrices.

The use of the methods of textile material processing with a cold plasma is one of the ways to solve many economic and environmental problems in the textile industry. Modification of textile materials with a high-frequency (HF) discharge plasma of reduced pressure allows increasing their strength, stiffness and water absorption, reducing relative breaking elongation while simultaneously increasing abrasion resistance, as well as improving shape stability, capillarity, porosity and reducing shrinkage [1-4]. Using a plasma processing with a reduced pressure allows modifying a surface layer of the textile material sample in order to increase hydrophilicity, or vice versa, applying water-repellent coatings that reduce wettability and increase hydrophobicity [5, 6]. The values of hydrophobic indicators depend on duration of plasma exposure. In the article [7], a processing with the low-temperature plasma gives an ability to grey cotton fabrics to get quickly wetted by water. An increase in absorption time of the water drop has been experimentally established, and the static contact angle of wetting for the plasma-modified samples of basalt and glass fibers [8] has been calculated. In the course of the work [9, 10] it has been found that the HF plasma processing allows effectively increasing capillarity of the synthetic fabrics without losing the strength characteristics of fibers.

It has been established [10-12], that modification of synthetic yarns with the low-temperature plasma makes it possible to increase the strength characteristics of fibers. In the work, the plasma processing mode has been revealed in which the fiber strength increases. In [13] the effect of the plasma processing on a breaking load of the basalt yarn has been studied.

The processing of textile materials with membrane coatings in the HF discharge plasma of the low pressure leads to an increase in air permeability and vapor permeability, while the water-proof properties of textile materials are preserved [14]. Modification of the membrane-coated fabric with the...
plasma allows removing unwanted inclusions from the surface and increasing the strength characteristics of the material.

The processing with the HF discharge plasma of the low pressure allows collectively improving the properties of synthetic fibers. The low-temperature plasma leads to effective and stable modification of the surface properties of the sample, while not degrading the physical and mechanical characteristics. The processing is carried out at the temperatures that do not cause melting or destruction of the material [15, 16].

Being the most important in practical terms, the result of exposure of a low-temperature plasma to polymeric materials is a strong increase in their adhesive characteristics [11, 12, 17-21]. This allows us to create composites based on high strength polyethylene fabrics. However, when these types of the materials are irradiated with a cold plasma, their stiffness properties decrease.

Therefore, for a complete analysis of the changes in stiffness characteristics in the various directions of polymer composite materials (PCM), modified in a cold plasma stream, it is necessary to have their mathematical models [22-24].

2 Materials and methods
2.1 Physical relations
We introduce the concepts of stiffness. As for fabrics, the concepts of the stresses $\sigma_{11}, \sigma_{22}, \sigma_{12}$ (forces which fall on the area unit of the cross-section fabric) become improper.

Therefore, in the future we will operate only with the forces which fall on the length unit of the sample section. Let us denote them by $N_{11}$ (line force along the direction of the base which falls on 1 mm of the length of the cross section), $N_{22}$ (line force along the direction of the weft), $N_{12}$ (line shear force). In this case, the element receives relative elongations $\varepsilon_{11}$, $\varepsilon_{22}$, and initially the right angle changes by the shear angle $\gamma_{12}$. Let us introduce the vectors $\{N\}, \{\varepsilon\}$:

$$\{N\} = \{N_{11}, N_{22}, N_{12}\}^t,$$

$$\{\varepsilon\} = \{\varepsilon_{11}, \varepsilon_{22}, \gamma_{12}\}^t.$$

The index «t» means a transposition operation.

For the nonlinear case for the fabric in the axes of orthotropy $x, y$ we take an elastic potential, with which the linear forces are expressed through some deformations using the relation $N_{ij} = \partial W / \partial \varepsilon_{ij}$, in the following form:

$$W = D_{1111} \varepsilon_{11}^2 / 2 + D_{1211} \varepsilon_{11} \varepsilon_{12} / 12 + D_{1222} \varepsilon_{22}^2 / 2 + D_{2222} \varepsilon_{22}^2 / 12 + D_{3333} \gamma_{12}^2 / 2 + D_{3344} \gamma_{12}^2 / 30$$

Then the connection of the line forces increments $dN_{ij}$ through the deformations increments $d\varepsilon_{ij}$ in the axes of orthotropy according to (1) takes the form:

![Figure 1. Fabric sample, cut at an angle $\alpha$ to the base.](image-url)
The elastic law in the laboratory coordinate system \( \tilde{x}, \tilde{y} \), i.e. in the axes being parallel to the edges of the test rectangular fabric sample shown in Figure 1, takes the form:

\[
d\{\tilde{N}\} = [\tilde{D}]d\{\tilde{\varepsilon}\} = \begin{bmatrix} D_{11} & D_{12} & 0 \\ D_{21} & D_{22} & 0 \\ 0 & 0 & D_{33} \end{bmatrix} d\{\varepsilon\} 
\]

(2)

\[
D_{11} = D_{110} + D_{112}\varepsilon_{11}^2, \quad D_{12} = D_{120}, \quad D_{22} = D_{220} + D_{222}\varepsilon_{22}^2 \\
D_{23} = D_{32} = D_{13} = D_{31} = 0
\]

(3)

The elastic potential for the fabric, modified with cold plasma, is introduced in a similar way. We distinguish the relations by using the index «*»:

\[
W = D_{110}^*\varepsilon_{11}^2 / 2 + D_{112}^*\delta_{11}^2 / 12 + D_{120}^*\varepsilon_{22}^2 / 2 + D_{222}^*\varepsilon_{22}^4 / 12 + D_{330}^*\gamma_{12}^2 / 2 + D_{334}^*\gamma_{12}^6 / 30
\]

(5)

2.2 Deformation model of fabric samples

For the numerical analysis of the deformation process of the fabric samples the finite element method (FEM) was used. A six-node triangular element of the second order \([25, 26]\) was taken as a subregion.

To account for inability of the fabric to take up a compressive load, the following approach is used.

At each step of the load increment, the force field \( N_{ij} \) is analyzed. If along the base or weft the forces \( N_{11} \) or \( N_{22} \) take any negative values, then at this step, respectively, the stiffness \( D_{11} \) or \( D_{22} \) decreases by several orders of magnitude (in our case, by 500 times). After this, the equilibrium equations are again solved, and the forces are recounted. This procedure is carried out until the field of deformations and forces is stabilized.

2.3 Identification of mechanical characteristics

The problems of identification in the scientific literature are understood to be inverse (in the mathematical sense) problems, in which the parameters of the model describing behavior of the system [25] are determined from the known input and output experimental data. The model described
above was used to identify the mechanical characteristics of the fabrics based on a numerical analysis of behavior of the fabric samples, including those treated with a cold plasma. For this, the experiments on tension of the samples, cut at an angle $\alpha$ to the base, were considered (see Figures 1, 2).

The identification problem can be formulated as follows. The data of the structural tests with measuring external influences are considered known, and the mathematical model parameters of the material and structures behavior are considered desired. The direct problem of calculating the deformed state of the sample is studied, while the parameters of the model are selected in such a way that the results of the numerical calculation and experimental data turn out to be close. For example, it is possible to require a minimum of the quadratic residual between the calculated and experimental data. This residual has the following form:

$$\delta^2 = \sum_{i=1}^{n} \left[ (P^\text{calc} - P^\text{exp})^2 \right] + \sum_{i=1}^{n} \left[ \Delta a^\text{calc} - \Delta a^\text{exp} \right]^2 + \sum_{i=1}^{n} \left[ \Delta b^\text{calc} - \Delta b^\text{exp} \right]^2 + \ldots$$

(6)

here $n$ is a number of conducted experiments, $\Delta a^\text{exp}, \Delta b^\text{exp}$ are experimental values of changes in the sides of the sample in the longitudinal and transverse directions, respectively (see Figure 2), and $\Delta a^\text{calc}, \Delta b^\text{calc}$ are estimated values of the changes mentioned above. $P_1,\ldots,P_n$ are values of loads, $\alpha_1,\ldots,\alpha_n$ are angles between the base and the long side of the sample, $v_1,\ldots,v_n, m_1,\ldots,m_n, k_1,\ldots,k_n$ are weighting factors.

In this work, stiffness characteristics $D_{110}, D_{114}, D_{220}, D_{224}, D_{120}, D_{330}, D_{334}$ are considered unknown. A feature of the class of such problems is that under any deformations the following restriction must be satisfied:

$$D_{11} D_{22} - D_{12}^2 > 0$$

(7)

That is why the elastic potential must be selected in a special way. In particular, the condition (7) will be provided, if we accept $D_{110} D_{220} - D_{120}^2 > 0$.

After that, the results of the experiments on stretching the samples of polyester fabric measuring 94 mm by 50 mm were processed.

Next, the results of the stretching tests of polyester (VPE-100) fabric were processed before and after treatment with a cold plasma. At the first stage, the stiffness characteristics $D_{110}, D_{112}, D_{220}, D_{224}, D_{120}, D_{330}, D_{334}$ were determined according to the test data of the samples of polyester (VPE-100) fabric cut at the different angles ($0^\circ, 90^\circ, 45^\circ$) to the base, under various stretching conditions. The sample, cut at an angle $30^\circ$ to the base, was considered a control one. The calculations gave the following values for $D_{ijk}$:

**VPE100 (parent untreated fabric):**

$D_{110} = 1.58, \quad D_{112} = 8000, \quad D_{220} = 0.95, \quad D_{222} = 1500, \quad [\text{MPa*mm}]$

$D_{120} = 0.178, \quad D_{330} = 0.065, \quad D_{334} = 13.5$

**VPE100 (fabric, treated with a cold plasma during 180 sec.):**

$D^*_{110} = 1.2, \quad D^*_{112} = 5900, \quad D^*_{220} = 0.835, \quad D^*_{222} = 1000, \quad [\text{MPa*mm}]$

$D^*_{120} = 0.178, \quad D^*_{330} = 0.045, \quad D^*_{334} = 2$

Using the developed model, the problem about deformation of the control sample, cut at an angle $30^\circ$, was considered. Below, Figure 3 shows the dependences of the stretching forces $P$ on the longitudinal deformation $\Delta a$ for the control samples of fabric. It can be seen that the results obtained are in good agreement with the experiment for the control sample.
Figure 3. The dependence of the average force at the end face $P$, $N$ on the experimental data and the theoretical curve for the found stiffness characteristics for tissue samples VPE-100.

Further, the dependences of the mechanical characteristics on intensity of the plasma effect on the fabric were obtained. For this, the parameters $D_{ijk}$ were identified for each radiation dose.

For polyester fabric, these dependences are presented in Figure 4. It can be seen that with an increase in the dose of radiation by a cold plasma, the coefficients included in the characteristics (3) decrease, i.e. the fabric, modified in a cold plasma stream, becomes softer.

Figure 4. Dependences of nonlinear stiffness characteristics on the radiation dose gamma for fabric VPE-100.
Figure 5 shows the dependences of the stiffness characteristics $D_{ij}$ on the deformations of the sample for different durations of exposure to a cold plasma on the fabric VPE-100.

![Graphs of dependences of the stiffness characteristics $D_{11}$, $D_{22}$, $D_{33}$ on deformations for untreated and treated samples of fabric VPE-100.](image)

3 Results
A model of the polyester fabric behavior subjected to plasma treatment with a reduced pressure is proposed to evaluate its deformability in its plane.

The method for identifying stiffness properties is described, and the results of processing the full-scale experiments as well as the results of the numerical studies of the problem regarding stretching samples of the fabric are presented.

4 Discussions
For the numerical analysis of the deformation process of the fabric samples the finite element method was used.

The proposed finite-element model of deformation of nonlinear elastic fabric materials allows us to study the patterns of behavior of the tissue samples under various loads, given that the material is not able to support the compressive loads.

5 Conclusion
The developed technique for an experimental determination of the stiffness characteristics of fabrics according to the results of testing the samples, cut at different angles ($0^\circ$, $90^\circ$, $30^\circ$, $45^\circ$) to the base,
under various stretching forces, made it possible to analyze the influence of treatment of the fabric with a cold plasma on its mechanical characteristics. It was revealed that the stiffness drop is about 15% along the base, 35% - along the weft, 45% - onto the shear.

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