VARIATION OF THE STRUCTURE AND PERMEABILITY OF TENSIONED FIBER LAYERS DURING IMPREGNATION WITH A THERMOPLASTIC POLYMER MELT

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The influence of displacements of tensioned fibers on the impregnation of fibrous layers with a polymer melt and on the final composite structure is studied. Using computer simulation, it is shown that, during impregnation, the structure of tensioned fibrous layers changes considerably depending on the initial arrangement and tensioning of fibers. The consolidated regions formed under the melt front move inside the impregnated layer with the advancing melt front. Displacement of the tensioned fibers as well as the formation of "washouts" favors the impregnation of internal layers, but cause significant inhomogeneity of the polymer structure. The surface (on the side of the melt flow) regions are more saturated with the polymer than the internal ones. A difference in the melt percolation mechanisms at various impregnation regimes is revealed. The effective permeability coefficients of a tensioned fiber layer are not constant but depend on the conditions and regimes of impregnation.

Introduction. One of the most complex problems in the technology of fibrous composites with a thermoplastic matrix is the problem of effective impregnation of the filler with a highly viscous polymer melt [1-3]. The theoretical solution of the problem is complicated by the nonlinearity of the viscous properties of a polymer melt, as well as by the stochastic arrangement and mobility of fibers during impregnation. Some attempts have been made to take into account, within the framework of a linear model of melt flow, the irregularity of the actual structure [4], the scatter in the values of diameters and the stochasticity of arrangement of fibers in the transverse section [5-7], and compressibility of a fibrous system under the pressure of the melt [8]. In this case, the polymer is regarded as a linearly viscous (Newtonian) liquid, which is unacceptable for thermoplastic melts. It is shown in [9] that, during impregnation of a unidirectional layer, the stochasticity in the fiber arrangement in the cross section affects the permeability coefficient, but this influence is not so significant if the fibers remain fixed. Data of experiments on models and technical fibrous systems [9, 10] show that the structure of a fibrous layer undergoes a considerable transformation during impregnation and that the permeability coefficients and the impregnation depth depend on the viscous properties of the polymer and on the process parameters.

In this study, using a computer percolation model of the process, the changes in the structure of a unidirectional fibrous layer impregnated with a nonlinearly viscous melt of a thermoplastic polymer and the influence of the impregnation conditions on the effective permeability coefficients of the layer are investigated.

Percolation Model of the Process. A unidirectional layer (for example, glass roving) impregnated with a polymer melt, in its cross section, is regarded as a system of randomly arranged circles with a given distribution of their diameters. The arrangement of circles is specified depending on the impregnation method. Upon impregnation in a flat-slot head [11], the fibers are located chaotically in the plane of cross section at a given initial porosity $P_p = 1 - P$ ($P$ is the volume fraction of fibers). The model of the cross

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section (Fig. 1a) is constructed using an algorithm described in [12]. Upon impregnation in the devices with pins and rollers [3, 13], the fibers, modeled in the cross section by stochastically located circles, are shifted toward the surface of these elements (Fig. 1b).

The polymer melt is modeled by a nonlinearly viscous liquid with a power-type flow law,

$$\tau = \mu \dot{\gamma}^n,$$

where \( \tau \) are the tangential stresses, \( \mu \) is the coefficient of viscosity, \( \dot{\gamma} \) is the shear rate, and \( n \) is the power in the flow law.

The percolation of the melt through the gaps between the fibers (Fig. 2), according to the Kozeny—von Karman model, is regarded as a flux through a system of slots of different width. We assume here that the melt adheres ideally to the fiber surface and the capillary effects are absent. The curvilinear contour of the channel between the fibers is replaced by a system of planes parallel to the axis of the channel, and the channel itself — by a system of \( N \) sections, such that the distribution of melt rates on each section corresponds to the flux in a slot of a constant cross section. Using the known expression (see, for example, [14, 9]) for the rate distribution in a nonlinearly viscous liquid flowing in the gap between plane-parallel plates, the rate of melt flowing into the channel \( k \) formed by two fibers and consisting of \( N \) sections of length \( \Delta x \) each is given by

$$U_k = \left( \frac{p_0}{A \sum_{i=1}^{N} h_i^{-1} h_i^{-n}} \right)^n,$$

where \( p_0 \) is the pressure at the inlet of the channel (the outlet pressure is assumed zero), \( A = \mu (1 + m)^n h_0^m \Delta x \), \( h_i \) is the width of the \( i \)th section, \( h_0 \) is the width of the inlet section, \( \Delta x \) is the discretization step, and \( m = \mu / n \).

The rates of fluxes in the gaps between the fibers, when the melt flows through the model fibrous system, satisfy the continuity equations