Investigating of the Residual Stresses During the Extraction of a Polymer Product from an Extruder

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Abstract. The accumulation of residual stresses during the manufacturing process of a product can affect its performance in the future. Under the action of an inhomogeneous temperature field, polymeric materials can acquire indirect inhomogeneity, which is a change in physical and mechanical parameters (elastic and rheological), which are a strong function of temperature. The article provides information about definition of the stress–strain state of a polymer cylinder removed from an extruder. The heat exchange with the environment is taken into account, the temperature field is determined, and the change in stresses in the polymer body is studied, taking into account the development of creep deformations. It is shown that as a result of the development of stresses only from the inhomogeneity of the material caused by an uneven temperature field, the values of residual stresses in the body are very small and can be neglected.

Keywords: Residual stresses · Indirect inhomogeneity · Polymer creep · Temperature inhomogeneity

1 Introduction

One of the main tasks in mechanics is the problem of determining the residual stresses that arise in the manufactured polymer product during its cooling. Similar problems have already been considered in the works [1–3], however, in them, the boundary conditions were set as a certain function, without taking into account the heat exchange with the environment. In the process of solving the problem, it becomes necessary to take into account many individual processes: determination of the temperature field; determination of indirect inhomogeneity caused by uneven distribution of the temperature field and, accordingly, different distribution of physical and mechanical parameters of the product at each moment of time in its thickness; determination of the stress–strain state at each moment of time; determination of rheological processes occurring in the product.

A special limitation is imposed by the fact that stresses and deformations can be reversible in time, which does not allow taking into account such common complexes as ANSYS, Abaqus, SolidWorks and others.

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Works [4, 5] are devoted to the calculation of polymer cylindrical bodies, taking into account the pressure on the internal and external surfaces. The work [6] considers the study of a polymer cylinder during its rotation.

In [7], a multilayer polymer pipe is studied under the action of internal pressure.

In Russia, academician Andreev [8–11] studied the study of the heterogeneity of polymer cylinders, which occurs due to the gradient of the temperature field along the polymer body. The work [12] shows how the induced inhomogeneity can be used to control the stress–strain state of the body.

An attempt to determine the change in the stress–strain state is shown in [13]. The authors consider a rotating body subjected to an alternating temperature field and inertial forces. At the second stage, the rotation of the body stops and the body cools down. Thus, the development of reversible deformations is observed, which, without special techniques, cannot be studied in the widespread FEM complexes listed earlier. Most of the earlier works considered models of a polymer body either under conditions of a plane stress state or under conditions of a plane deformed state.

The study of the stress–strain state of a polymer cylinder removed from an extruder requires the creation of a higher-dimensional model: a two-dimensional axisymmetric problem.

2 Methods and Materials

The main purpose of this article is a comprehensive study of residual stresses in a polymer cylindrical body removed from an extruder over time. In this case, uneven cooling of the cylinder along its length and thickness leads to material inhomogeneity, expressed in the variation of its physical and mechanical parameters. In general, the general deformation of the material consists of several components: elastic, temperature and creep:

$$\varepsilon = \varepsilon_{el} + \varepsilon_{T} + \varepsilon_{cr}; \tag{1}$$

where ε is the total strain; ε_{el} is the elastic deformation; ε_{T} is the temperature component of deformation; ε_{cr} is the creep strain.

The process of extracting a polymer cylinder from a dryer is considered. The material of the product is EDT-10 thermal curing epoxy resin; the thermal and physical–mechanical parameters of the material are given below. The calculation model is shown in Fig. 1. Three stages are considered:

1. The initial moment of time (Fig. 1a). The sample is in the extruder and it is assumed that its entire temperature is equal to the temperature of the extruder itself.
2. Extracting of the cylinder (Figs. 1b and 2). The sample is partially withdrawn from the cylinder, on the lower face and the outer face, which is located in the extruder, the temperature is equal to the temperature of the extruder. On the inner face, the heat exchange in the air layer is considered, the temperature of which is also assumed to be equal to the temperature of the extruder. On the upper face and the outer face that came out of the extruder, heat exchange with the external environment is considered.
3. Cooling (Fig. 1c). The sample was removed from the extruder during t = 1.2 h; heat exchange with air is considered on all four faces.

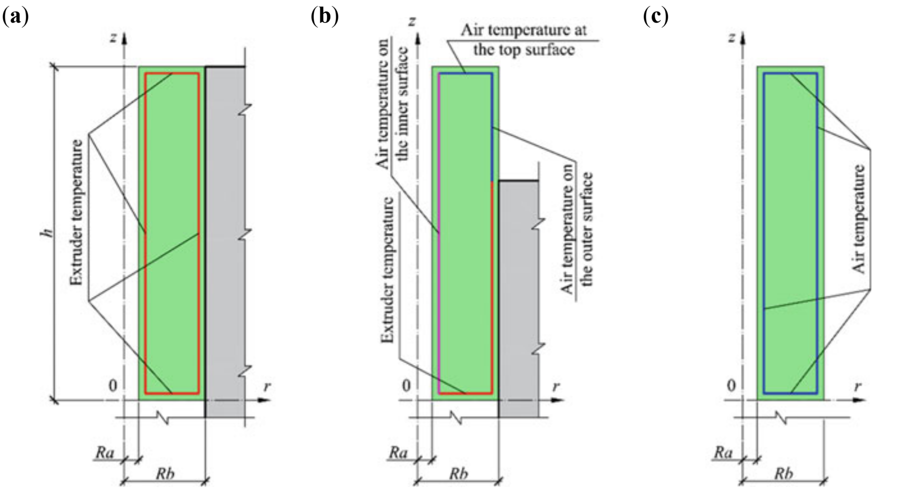

Fig. 1 Calculation model of polymer cylinder drawing (green color) from the extruder (gray color): **a** is the initial moment of time; **b** is the time point within the cylinder drawing time; **c** the hood is completed, full contact with the environment

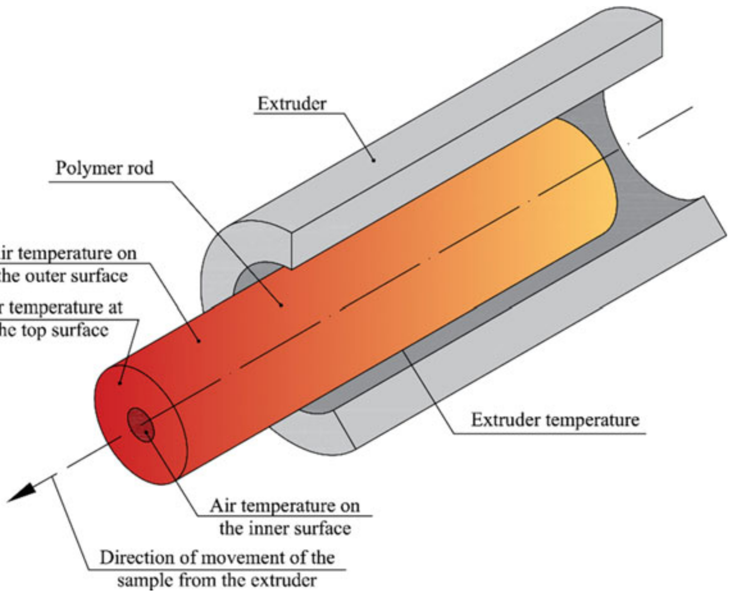

Fig. 2 The visual diagram of the calculation model, which shown in Fig. 1b

The temperature of the extruder and the temperature of the air inside the extruder is 100 °C. This is because the curing process of epoxy resin should be carried out at temperatures of 100–130 °C, however, since mechanical calculation is carried out, the temperature should not exceed the glass transition temperature of EDT-10, equal to about 102 °C. The temperature of the external air is 20 °C.

The dimensions of the polymer cylinder are $Ra = 0.008$ m; $Rb = 0.028$ m; $h = 0.5$ m. There are no mechanical loads at all ends.

The full settlement period was 3.6 h. The total number of time intervals was $h_t = 100$ pcs; the number of rectangular finite elements approximating the polymer cylinder was the same in the vertical and radial directions and amounted to $h_r = h_z = 51$ pcs.

The calculations performed taking into account the dependence of all physical and mechanical parameters of the cylinder material on temperature in a non-linearized formulation.

The problem was solved using the finite element method. A rectangular area was considered, the diagonal corners of which had the coordinates $[Z_i, R_i]$ and $[Z_k, R_k]$.

The determination of the variable temperature field in time was carried out by minimizing the temperature field functional [14]:

$$\mathrm{Im}(T) = \int_V \left[\lambda(\mathrm{grad}\, T)^2 + \frac{\rho c}{h_t} T^2\right] dV + \int_{\Gamma 3} \alpha T^2 d\Gamma - 2\int_{\Gamma 3} \alpha T_0 T\, d\Gamma - 2\int_V fT\, dV, \tag{2}$$

where T is the product temperature; λ is the thermal conductivity coefficient; c is the isobaric heat capacity; ρ is the density of the material; $\Gamma 3$ is the boundary of the region.

Minimization of expression (2) and further solution led to the system of equations of the finite element method

$$\left[K^{(T)}\right] \cdot \left\{T^{(T)}\right\} = \left\{f^{(T)}\right\}.$$

The coefficients of the resulting system of equations are not given in detail in this article.

To determine the stress–strain state, a system of equations of the finite element method was obtained, which has the form:

$$[K] \cdot \{U\} = \{F\},$$

where $[K]$ is the global stiffness matrix; $\{U\}$ is the global load vector.

$$[K] = \sum_{e=1}^{E} \int_{Z_i}^{Z_k} \int_{R_i}^{R_k} r[B]^T [D][B]\, dr\, dz;$$

$$[F] = \sum_{e=1}^{E} \int_{Z_i}^{Z_k} \int_{R_i}^{R_k} r[B]^T [D]\{\varepsilon_T\}\, dr\, dz + \sum_{e=1}^{E} \int_{Z_i}^{Z_k} \int_{R_i}^{R_k} r[B]^T [D]\{\varepsilon_{cr}\}\, dr\, dz.$$

The coefficients of the resulting system of equations are also not given in detail in this article.

Creep deformations are described using the nonlinear Maxwell-Gurevich constraint equation:

$$\frac{\partial \varepsilon_{cr,ij}}{\partial t} = \frac{f_{ij}^*}{\eta^*}, \tag{3}$$

where $\partial\varepsilon_{cr,ij}/\partial t$ is the creep strain rate along the directions of the *ij* axes; f_{ij}^{*} is the stress function; η* is the coefficient of relaxation viscosity.

$$f_{ij}^{*} = \sigma_{ij} - E_{\infty}\varepsilon_{cr,ij};\ \frac{1}{\eta^{*}} = \frac{1}{\eta_{0}^{*}}\exp\left\{\frac{|f_{rr}^{*}|_{\max}}{m^{*}}\right\}, \quad (4)$$

where E_{∞} is the modulus of high elasticity of the polymer; η_0^* is the coefficient of initial relaxation viscosity; m^* is the speed modulus.

The methods for determining the elastic and rheological parameters of polymers are detailed in [15–17].

Thus, the coefficient of relaxation viscosity η* directly depends on the maximum value of the stress function f_{rr}^{*} for the principal directions.

Physical and mechanical (rheological and thermophysical) characteristics used are as follows: λ = 0.17 W/(m × deg); ρ = 1250 kg/m^3; c = 0.35 J/(kg × deg); ν = 0.3; E = – 17.5 T + 3525 MPa; E_{∞} = – 30 T + 3150 MPa; m^{*} = – 0.011 T + 4.75 MPa; η^{*} = η_0^* exp(–0.0275 T) MPa × h.

3 Results and Discussion

The calculation was implemented in the MATLAB environment. The calculation results are shown in Figs. 3, 4, 5 and 6.

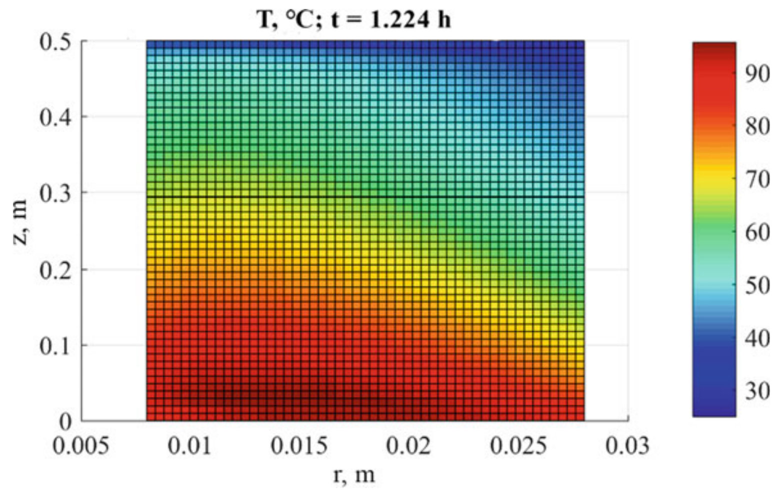

Fig. 3 The temperature field for the moment when the cylinder is completely removed from the extruder, t = 1.2 h

Figure 3 shows the temperature field for the moment when the cylinder is completely removed from the extruder, t = 1.2 h. As a result of the existing temperature field gradient, the material of the polymer cylinder acquires a pronounced induced indirect

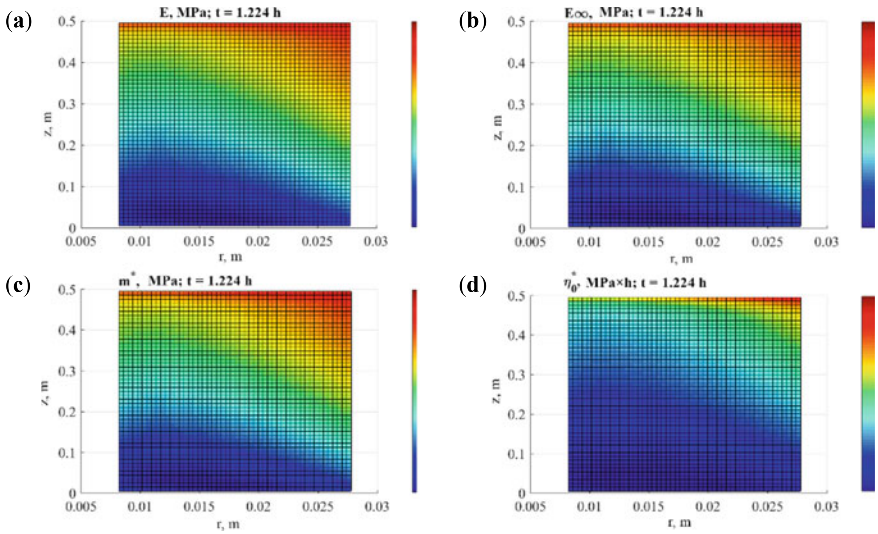

Fig. 4 Changing in the physical and mechanical parameters of the material depending on the temperature field at the moment of complete extraction of the polymer cylinder from the extruder, t = 1.2 h

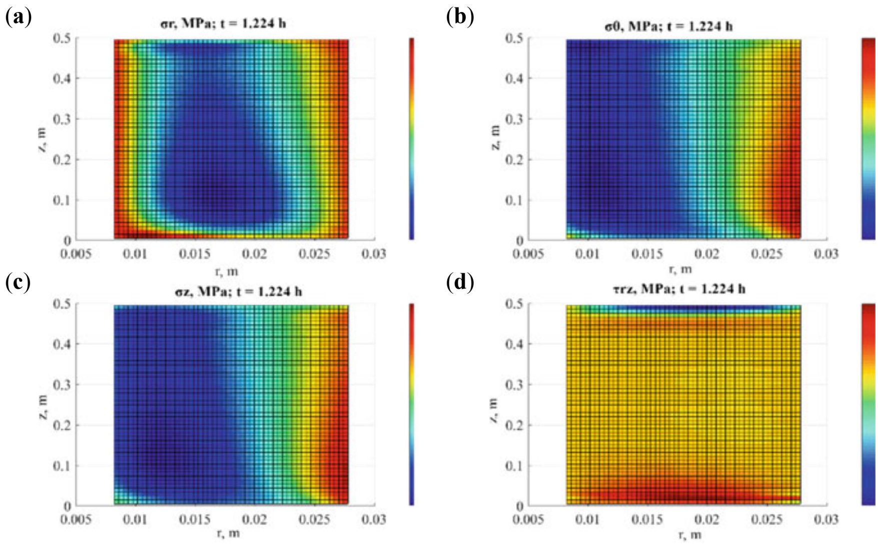

Fig. 5 Distributing of the axial and shear stresses in the polymer cylinder at the moment of its complete extraction from the extruder, t = 1.2 h

inhomogeneity in the form of a difference in physical and mechanical parameters (elastic and highly elastic) in the thickness of the body (Fig. 4).

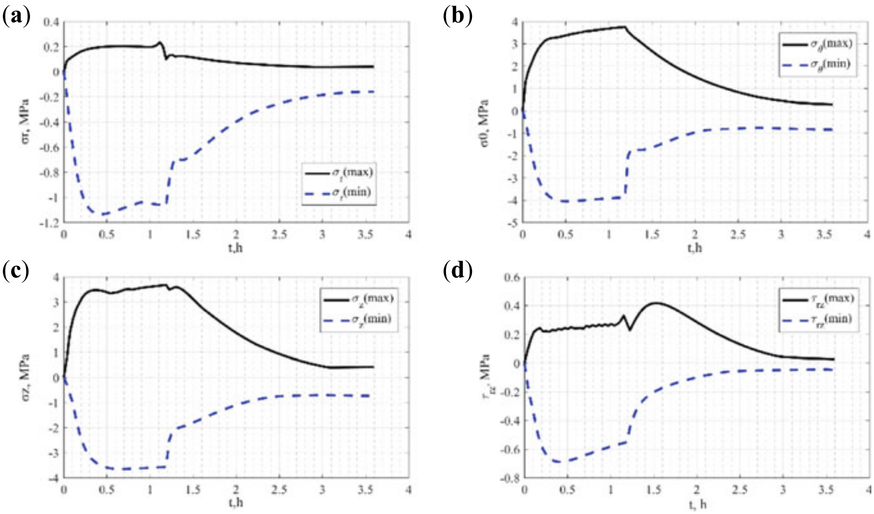

Fig. 6 Changing in the maximum and minimum stresses in the thickness of the polymer cylinder at the moment of removing the body from the extruder, t = 1.2 h

In the process of extracting material from the extruder, stresses arise in the body due to the occurrence of induced inhomogeneity of the material (Fig. 5). An analysis of the stress fields shows that they have a somewhat different nature of their distribution in the thickness of the body, but the same order of magnitude. For the convenience of analyzing the change in values over time, at each calculation step, the maximum and minimum values of stresses in the body were determined, after which graphs of their change were plotted, which are shown in Figs. 6. The maximum tensile and maximum compressive axial stresses over the entire calculation period have a level of about 4 MPa.

An analysis of the data obtained shows that a stress state of a sufficiently high level may occur in the body, which can adversely affect the subsequent processing of the product without the possibility of cooling and holding it under normal conditions. During cooling of the body and its settling under normal conditions, due to the development of highly elastic deformations in the polymer several hours after the cylinder is drawn from the extruder, the stresses take on a value that can be neglected in the subsequent operation of the sample.

4 Conclusion

The task of determining the residual stresses in the body remains very relevant, since there can be an infinite number of different combinations of loadings: temperature and force.

It is interesting to study a different class of materials that can be used in construction, taking into account changes in their properties [18–21].

In the future, it is possible to study the stress–strain state of such products, but at different times of their extraction from the extruder, as well as when considering linear and nonlinear creep laws.

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