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CERTAIN PROBLEMS OF HEAT AND MASS TRANSFER IN ROTATIONAL MOLDING

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The basic steps of rotational molding are described. Emphasis is on the heat- and mass-transfer processes occurring during the heating stage. The basic regularities of variation in the temperature during the cycle of rotational molding are given. Models of motion of a material in the mold in the above stage are considered. The kinetics of heating of an individual spherical particle is described.

Keywords: *rotational molding, heating, heat transfer, powder, mold, thermal conductivity, temperature, circulation, collapse, sliding.*

Introduction. Rotational molding is one of the most promising methods of obtaining large-scale hollow products from thermoplastics. There are several variants of the process that use different forms of polymer raw material (powder, microgranules, plastics); however, all of them share a number of common stages, primarily heating and cooling.

The process of rotational molding begins with charging a measured-out portion of material into a hollow metallic mold which is hermetically scaled and is set in rotation about two mutually perpendicular axes. In one variant of the method, the rotating rig is moved to a sintering chamber (furnace) in which it is heated. The polymer material is heated together with the mold. Sintering is accounted for by the heat transferred from the hot flue gases first to the surface of the metallic mold and next to the polymer particles. After a prescribed period of time, the rig begins to be cooled by air blowing or water spraying. Combined air–water cooling is possible, too. The product cooled down to a sufficient extent is withdrawn from the mold and the cycle of rotational molding is repeated.

Formulation of the Problem. The stages of heating and cooling involve transfer of heat first from the hot medium to the polymer material and next from it to the cooling environment. In both cases, the process of heat transfer occurs in an unsteady regime; therefore, its kinetics attracts the greatest interest in considering these steps.

In the heating stage, the heat taken from the hot gas is absorbed both by the mold and the polymer material. The rig for rotational molding usually has a relatively small wall thickness and is manufactured from metals with a high thermal conductivity (aluminum, steel). As a rule, the mold transfers much more heat than plastic can absorb; therefore, the mold temperature must vary linearly. Mathematically this is described by the following equation [1, 2]:

$$\rho C_p L \frac{\partial T}{\partial \tau} = \alpha \left(T_{\text{air}} - T_{\text{r}}\right) . \tag{1}$$

We assume that the temperature across the thickness of the mold wall is constant and the heat-transfer coefficient is equal on both sides of the mold wall. In actual practice, the transfer of heat from the exterior surface (from the furnace) to the interior surface of the mold is delayed. The time after which the temperature inside the mold's cavity begins to increase is approximately computed from the formula [3]

$$\tau_{\text{int}} \approx 0.0156 \frac{L^2}{a} . \tag{2}$$

In all cases, the interior surface of the mold takes the energy of its exterior surface in less than 1 sec. As soon as the interior surface of the mold begins to heat up, its temperature T_{int} lies behind the temperature of the exterior mold surface T_{ext} by a certain value. We can approximately compute T_{int} from the dependence [3]

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$$T_{\text{int}} \approx T_{\text{ext}} - \alpha \frac{(T_{\text{air}} - T_{\text{ext}})\, L^2}{2\lambda} . \tag{3}$$

The rate of heating of both surfaces of the mold becomes equal after a lapse of time [3]:

$$\tau_{\text{eq}} \approx 0.45 \frac{L^2}{a} . \tag{4}$$

The maximum temperature difference along the cross section of the mold wall may attain only a few degrees in most cases. The polymer heats up along with the mold. Increase in the materials's temperature is often considered as applied to an individual particle.

In the process of heating, the heat transferred to the material from the hot furnace air is consumed by the phase transformation of the polymer (transition to a viscous-flow state). On melting of the material's particle it adheres to other particles; a new particle of larger size is formed. Gradually this enlargement gives rise to a thin polymer film on the entire interior surface of the mold, and a wall of the product with a prescribed thickness is formed subsequently in the process.

For the process of adhesion of polymer particles to be realized, the latter must be heated to a certain temperature which is dependent on the nature of the material. In this connection, of great interest is variation in the temperature of an individual powder particle during the stage of heating. This process has been studied in detail for the dynamic heat conduction of a spherical or cubic body. The corresponding equation for a sphere has the form [3]

$$\frac{\partial T_{\text{r}}}{\partial \tau} = a \left(\frac{\partial^2 T_{\text{r}}}{\partial r^2} + \frac{2}{r} \frac{\partial T_{\text{r}}}{\partial r} \right). \tag{5}$$

Although the particle may adhere to the hot mold wall or to other particles, the area of its contact remains smaller than its total surface. As a result, the transfer of energy to the particle surface is probably best described by the equation of convection from the ambient air [3]:

$$-\lambda \frac{\partial T_{\text{r}}}{\partial r} = \alpha \left(T_{\text{air}} - T_{\text{r}}\right) . \tag{6}$$

Experience has shown that more acceptable is the approach to the transfer of energy to a powder particle based on a simpler model [3]:

$$\rho C_p V dT_{\text{r}} = \alpha F \left(T_{\text{air}} - T_{\text{r}}\right) d\tau . \tag{7}$$

If the air temperature is assumed to be constant, the solution of this equation will take the form [3]

$$\frac{T_{\text{air}} - T_{\text{r}}}{T_{\text{air}} - T_0} = \exp\left(- \alpha \frac{aF\tau}{V\lambda} \right), \tag{8}$$

where T_0 is the initial temperature of the polymer material.

Investigation Results. When the surface temperature of the rig for rotational molding is measured with the unit of the public corporation "Borisov Plant of Plastic Products," its correspondence to the theoretical values is noted (Fig. 1). The movement of the material (mass transfer) occurs in parallel with heat-transfer processes during the cycle of rotational molding.

The rotational velocity in rotational molding is rather low (4 to 20 rpm). As a result, in the first stages of the heating cycle, the charged material remains as a powder layer at the bottom of the mold. In rotational molding, one uses powders with Coulomb motion and viscous-flow powders. The former are characterized by the fact that particles are in any event in continuous contact with each other. In the case of the latter, binding forces are hindered by the

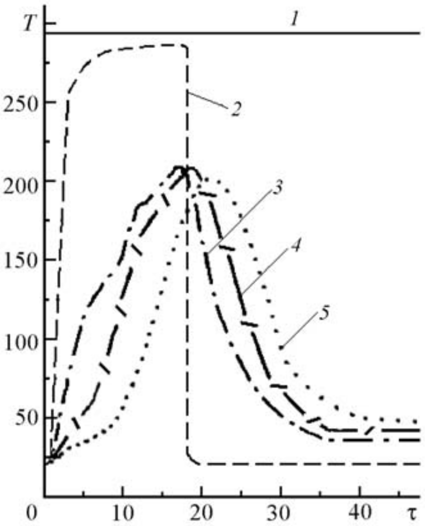

Fig. 1. Variation in the temperature during the cycle of rotational molding: 1) of the furnace (prescribed), 2) of the furnace (measured), 3) of the exterior mold surface (measured), 4) of the interior mold surface (calculated), and 5) of the polymer (hypothetical). T, ^{o}C; τ, min.

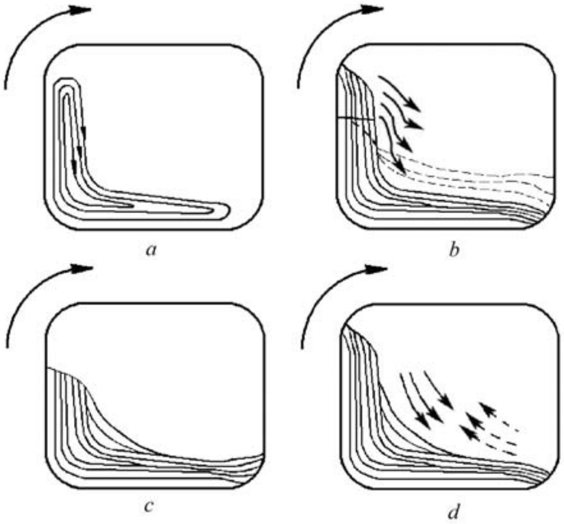

Fig. 2. Types of motion of the powder layer: a) steady-state circulation; b) collapse; c) stable sliding, and d) cyclic sliding-adhesive motion.

momentum transfer between particles which move relative to each other. These two groups of motion can also be observed in rotational molding. We recognize three types of motion of the material layer (Fig. 2) [4].

Steady-state circulation (Fig. 2a) manifests itself with a fairly large particle size, a rather rough mold surface, and a medium powder volume compared to the rig volume. Powders of this type of motion belong to viscous-flow ones. In this mode of motion, individual particles of the material on the mold surface move together with the mold until they exceed the dynamic angle of natural slope (25–50^{o} of the horizon). At this point, the material's particles fall off the mold wall and move in a cascade manner along the static surface of the powder layer.

Collapse (Fig. 2b) occurs in the case of a needle-shaped or two-dimensional structure of the powder and when the material possesses adhesiveness. In this motion resembling a snow avalanche, the originally stationary powder layer is raised in the mold, until the dynamic angle of natural slope is exceeded by the entire powder mass. At this point, a major portion of the mass falls off the mold and moves in a cascade manner along the remaining portion of the powder layer. Then the layer becomes stationary and is raised by the rotating mold again. Collapse is sometimes observed during the heating stage when the powder layer is depleted.

Sliding flow occurs when the mold surface is very smooth. There are two types of sliding flow: *stable sliding* (Fig. 2c) and *cyclic sliding-adhesive motion* (Fig. 2d). In stable sliding, the layer remains virtually stationary relative to the horizontal axis of the mold, whereas the latter simply slides under it. In cyclic sliding-adhesive motion, the originally stationary material is raised together with the mold, until a point at which friction between the powder and the mold wall no longer ensures the resistance to sliding over the rig surface is reached. At this point, the entire static layer simply slides down to the mold bottom. Then the material ceases to slide and is raised by the rotating rig again. Powders showing these types of motion belong to Coulomb ones. Sliding is also observed in the cases where the volume of the powder is large compared to the volume of the mold's cavity [4].

Conclusions. The results of the investigations carried out demonstrate that the theoretical substantiation of heat and mass transfer during the rotational molding is suitable for determination of the optimum parameters of the process and the optimum design of a moling tool for practical application.

NOTATION

a, thermal duffusivity of the mold's material, m^2/s; C_p, specific heat of the mold's material, J/(kg·deg); F, area of the particle surface, m^2; L, thickness of the mold wall, m; r, radius of a spherical particle, m; T, temperature, $^{\text{o}}$C; V, volume of a particle, m^3; α, coefficient of heat transfer by convection, $\text{W}/(\text{m}^2\cdot\text{deg})$; λ, thermal conductivity, W/(m·deg); ρ, density of the mold's material, kg/m^3; τ, rime, s. Subscripts: 0, initial value; ext, exterior mold surface; int, interior mold surface; air, environment; eq, equality of the heating rates; r, running value of the mold's material.

REFERENCES

1. F. F. Tsvetkov and B. A. Grigor'ev, *Heat and Mass Transfer: Textbook* [in Russian], 3rd ed., Izd. MÉI, Moscow (2006).
2. *Theoretical Principles of Heat Engineering. Heat-Engineering Experiment: Handbook* [in Russian], 3rd ed., Izd. MÉI, Moscow (2001).
3. M. A. Rao and J. L. Throne, Theory of rotational molding. Part I: Heat transfer, *SPEANTEC Tech. Papers*, **18**, 752–756 (1972).
4. J. L. Throne, Powder characteristics in rotational molding, *SPEANTEC Tech. Papers*, **43**, 518–523 (1997).