CONTRIBUTION TO THE THEORY BEHIND THE BLOW-MOLDING PROCESS

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UDC 678.027.36.001

The blow-molding method of extrusion has been widely used in recent years in the fabrication of hollow wares from polymeric materials. This method has been used to manufacture products with capacities ranging from several cubic centimeters to 2000-3000 liter. But the theory underlying the blow-molding process has not been investigated sufficiently either in the Soviet literature [1, 2] or in the foreign literature, and this places difficulties in the way of designing the appropriate process equipment.

Let us consider the particular case of the process of blow-molding cylindrical hollow wares from tubular thermoplastic parisons (Fig. 1). The assumption is no air leaks from inside the parison occur, that the temperature of the parison remains constant during the molding period, and that the parison is of cylindrical configuration. This last assumption is valid for cases in which the ratio of product length to product diameter is equal to or greater than 1.5. The fringe effects and the air counterpressure in the cavity between the walls of the mold and the parison can be safely neglected in this treatment.

We assume here that compressed air in amounts dG_M enters the cavity of the parison, of variable volume V, through the blow nipple from an infinitely large volume (for example, a receiver or a main air line) in which the pressure p_M and the temperature T_M can be assumed constant. In response to the compressed air entering the system, the pressure p in the volume V rises, and varies subsequently by stages, as shown in Fig. 2.

We set up the energy balance equation of the air–parison system to begin with. According to the first principle of thermodynamics

$$dQ_M + dQ = dU + AdL, \tag{1}$$

where dQ_M is the amount of heat transmitted to the system by the inflowing air; dQ is the amount of heat supplied to the system through exchange of heat with the hot parison; dU is the internal energy of the system; A is the mechanical equivalent of the work done; dL is the work done in the expansion of the gas. We assume that the thermodynamical processes accompanying blow-molding of hollow products are quasistationary, and that they take place under steady-state outflow conditions.

Equation (1) is recast in the form

$$dQ + i_M dG_M = dU + AdL, \tag{2}$$

where i_M and dG_M are respectively the specific enthalpy and the amount of air present in the cavity of the parison.

The amount of heat imparted to the system via heat transfer between the air and the parison is determined by the law of convective heat transfer:

$$dQ = \alpha F'(T_c - T)\,dt, \tag{3}$$

where α is the heat transfer coefficient; F' is the instantaneous area available for heat transfer; T_c and T are the respective temperatures of the parison wall and of the air; t is the time.

The heat transfer coefficient can be determined from the dimensionless-ratio heat transfer equation in [3]. In the case in point

$$\alpha = A_3 \Delta T^{1/3}, \tag{4}$$

Translated from Khimicheskoe i Neftyanoe Mashinostroenie, No. 11, pp. 12-14, November, 1973.

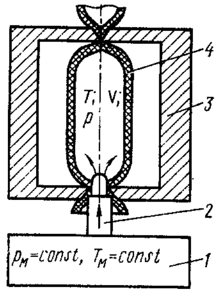

Fig. 1

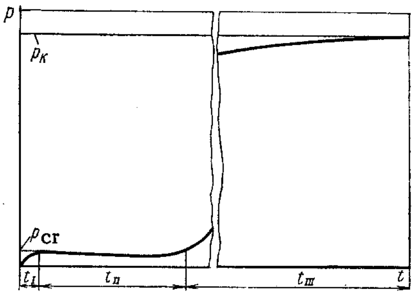

Fig. 2

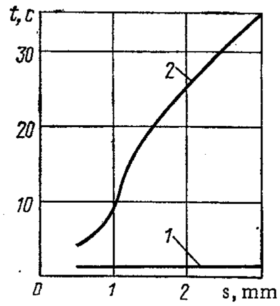

Fig. 3

Fig. 1. Diagram illustrating process of blow-molding tubular parison into a hollow cylindrically shaped product: 1) main air line or storage receiver; 2) blow nipple; 3) mold; 4) parison.

Fig. 2. Pattern of dependence of pressure p in parison cavity in blow molding of hollow products on the time t: t_I) time elapsed from the instant the control device is switched on till the parison forms (preparatory period); t_{II}) time during which the parison deforms, i.e., the parison is extended to the walls of the mold (period during which the parison is molded into the product); t_{III}) time during which the pressure in the cavity of the molded product rises to the final pressure (concluding period); $p_k = p_M$.

Fig. 3. Dependence of the hollow product blow-molding time t on the thickness s: 1) additional time ($t_a + t_e + t_{bl} + t_{pr}$); 2) blow-molding time, i.e., time required to blow-mold parison into product, and time required to cool the product ($t_p + t_0$).

where A_3 is a coefficient dependent solely upon the mean temperature, $T_{av} = 0.5\,(T_c + T)$; $\Delta T = T_c - T$ is the thermal head.

In order to determine the extent of instant of instantaneous heat transfer surface area available, for Eq. (3), we can resort in a first approximation to the equation

$$F' = 2\pi r_i (l + r_i),$$

where r_i is instantaneous inner radius of the parison; l is the length of the parison enclosed in the mold. In order to transform Eq. (2), we make use of the familiar thermodynamical equations

$$U = uG_M;\ dL = pdV;\ i_M = c_p T;\ u = c_V T. \tag{5}$$

The equation of state of compressed air is

$$pV = G_M RT \tag{6}$$

and the equation for the specific heats appears in the form

$$AR = c_p - c_V\ ,\ \frac{c_p}{c_V} = k; \tag{7}$$

where u is the specific internal energy; c_p, c_V are the specific heats of air respectively at constant pressure and at constant volume; R is the gas constant for air; k is the adiabatic exponent.

When Eqs. (3)-(7) are taken into account, Eq. (2) becomes

$$kRT_M dG_M + 2\pi r_i \alpha (l + r_i) \frac{k-1}{A} (T_c - T)\, dt = Vdp + kpdV. \tag{8}$$

When the quantity of air entering the volume V is replaced in Eq. (8) through the corresponding value of the flowrate, in the time interval dt, and the transformed formula for the flowrate of air out of an unrestricted volume is used for supercritical conditions

$$G_* = K\varphi(Y_*)\mu f p_M \sqrt{\frac{1}{RT_M}},$$

we end up with

$$k\sqrt{R}\,[\sqrt{T_M}\, K\mu p_M f \varphi(Y_*) + \frac{2\pi r_i \alpha (l + r_i)(k-1)}{k\sqrt{R}\,A}(T_c - T)\, dt = Vdp + kpdV; \tag{9}$$

where $K = \sqrt{2gk/k-1}$; g is the acceleration of gravity; $\varphi(Y_*)$ is a function of the air flowrate from unrestricted volumes at the critical pressure ratio; $Y_* = p_*/p_M\ (2/k+1)^{(k/k-1)} = 0.5282$; p_* is the critical pressure; μ is the flowrate ratio taking into account friction losses, the deviation of the real process from adiabatic behavior, and various other factors affecting the flowrate of gas, to be determined empirically [4]; f is the area of the passage hole through which the compressed air flows.

Compressed air is supplied under excess pressures of 2 kg/cm² or more in the blow molding of hollow products, as a rule. At that pressure, molding of tubular parisons is achieved under supercritical conditions of air flow from the compressed air line into the hollow of the parison.

Equation (9) characterizes the process by which the air pressure changes as the parison is blown into a product. In that equation the unknowns are, in addition to the time dt, the three variables: air temperature T, air pressure p, and cavity volume V. We resort to the equation of state of air and to the equation of motion of the parison in order to determine these variables as functions of the time.

The equation of state of air appears, in differential form, as

$$TdG_{\text{M}} + G_{\text{M}}dT = \frac{1}{R}(pdV + Vdp). \tag{10}$$

Substituting into Eq. (10) the value of the air flowrate from Eq. (9), we obtain, after appropriate transformations, the equation

$$\frac{dT}{T} = \frac{2dr}{r} + \frac{dp}{p} - \frac{\sqrt{RT_{\text{M}}}}{\pi r_{\text{B}}^2 Lp} K\varphi(Y_*)\mu f p_{\text{M}} \frac{T}{T_{\text{M}}} dt \tag{11}$$

(where r is the instantaneous radius), which characterizes the temperature change in the parison cavity.

The equation of motion of the tubular parison appears in the form [5]:

$$\frac{\partial \sigma_r}{dr} + \frac{\sigma_r - \sigma_\theta}{r} = \rho \frac{\partial^2 r}{\partial t^2}, \tag{12}$$

where σ_r and σ_θ are the radial and tangential stresses in the parison material at the instantaneous radius r; ρ is the density of the parison material.

The solution of Eq. (12), using the Von Mises–Hencky plasticity conditions, is

$$\frac{\sigma_\theta - \sigma_r}{r} = \frac{1}{r}\frac{2\sigma_s}{\sqrt{3}}$$

(where σ_s is the arbitrary yield limit of the parison material), and the mass conservation conditions in the presence of deformation and the appropriate boundary conditions yield the equation

$$p_{\text{cr}} = \frac{2\sigma_s}{\sqrt{3}} \ln\frac{b}{a},$$

where p_{cr} is the critical pressure at which the parison begins to be blow-molded into the product; b and a are the initial outer and inner radii of the parison.

Neglecting inertial forces in consideration of the preponderance of viscous forces, we obtain

$$p = \frac{2\sigma_s}{\sqrt{3}} \ln\frac{r_{\text{o}}}{r_{\text{i}}}, \tag{13}$$

where p is the instantaneous blow-molding pressure; r_o and r_i are the instantaneous outer and inner radii of the parison.

The values of the arbitrary yield limit σ_s for high-pressure polyethylene of melt index 1.5 to 9 gf /10 min at parison temperature 140-145° fall within the range from 0.22 to 0.35 kg/cm², and the arbitrary yield limit decreases with increasing melt index.

Equations (9), (11), and (13) describe the process of blow-molding a tubular parison into a hollow cylindrical type product, and facilitate calculating the cycle time for molding of hollow products. Numerical methods should be used in solving these equations.

As pointed out earlier, the blow-molding cycle consists of three stages (see Fig. 2). The time of the preparatory phase t_I and the time of the concluding phase t_{II} can be calculated on the basis of formulas derived in [7].

Equations (9) and (11) are recommended for exact calculations. In the case of engineering calculations, we can recommended, with accuracy sufficient for practical purposes, the semiempirical formula:

$$t_I + t_{II} = t_p = \beta \frac{(V_{pr} - V_0) p_{cr}}{G_* RT}, \tag{14}$$

where $\beta = 0.62$ is a coefficient taking into account the counterpressure in the hollow between the walls of · the mold and the parison; V_{pr} is the product volume; V_0 is the initial volume of the parison cavity.

Relying on Eq. (14) and the data cited in [1], can calculate the total cycle time t_{cy} for blow molding on the g basis of the equation

$$t_{cy} = t_z + t_c + t_p + t_o + t_{bl} + t_{pr},$$

where t_z is the time required to feed the parison material into position for blow molding; t_c is the closing time of the receiving device [4, 7]; t_p is the time required to blow the parison into a product; t_o is the cooling time of the product; t_{bl} is the time for opening the mold halves of the receiving device [4, 7]; t_{pr} is the time required to extract the finished product.

It is clear from Fig. 3 that as much as 90% of the product fabrication cycle time goes into the blow-molding time and the time required for the product to cool.

In conclusion, it should be pointed out that the formulas derived enable us to compute the work cycle and to design equipment components for blow-molding machinery.

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