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Simulation parameters of temperature in the process of manufacturing a glass-metal composite*

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A mathematical model is proposed for solving the problem of the glass cylinder deformation under the action of temperature and pressure in a confined region. Experimental investigations were made to confirm modeling parameters.

Key words: mathematical simulation of technological processes, Reynolds problem.

Introduction

A search for fundamentally new strong and economical materials sometimes leads to the idea of the vector of using the properties of some conventional materials. For example, at the use of glass-metal pipes in chemical industry, such properties of the glass are put into the foreground as the inactivity and thermal resistance.

At present, the investigations of the properties of a new construction material applied for the needs of underwater robotics — glass-metal composite (GMC) are carried out. GMC is a new layered material at the manufacturing of which the idea of introducing the compressing stresses in the glass as a result of its junction with a metal (steel, aluminum or titanium alloys) is employed, which leads to the prevention of the formation of surface micro-defects in the glass. Due to this, a high practical overall strength of the material is reached [1]. To study the possibility of the glass hardening at its junction with the steel and for investigating the properties and structure of this new material a technology has been developed for manufacturing the exemplary junctions based on the glass and steel — the GMC rods [2], which consist of a glass core and steel shell. The technology of their manufacturing means the obtaining of a junction with special properties in the junction zone; the strength properties of the obtained junction are determined by the stress of the materials in its composition, the junction quality, and its influence on the residual stresses in the material.

The modeling of the technological process of manufacturing an exemplary junction at all stages (heating, maintenance, and cooling) has its peculiarities and problems. For example, at the stage of heating up to the temperature of maintenance, the following processes must occur in the junction: the physical contact formation, the rise and development of activation centers,

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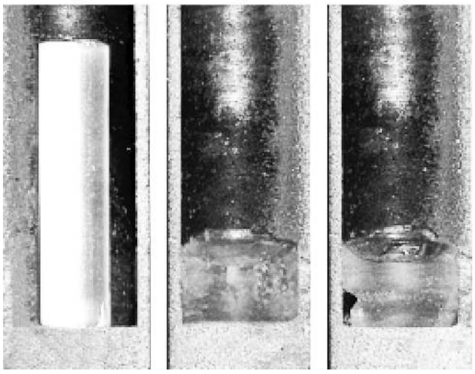

Fig. 1. The longitudinal sections of specimens.
a — a metal cylinder and a glass core without heat treatment,
b — the sample after the heat treatment,
c — an example of defects at incorrectly chosen parameters of temperature treatment.

the rise of diffusion processes at the junction boundary. The physical contact formation occurs as a result of the glass deformation with time. Taking into account the rheological properties of the glass one can suppose that the physical contact formation will take a significant time interval, and the incorrectly chosen parameters of the technological process (the temperature, pressure, and time) may lead to the presence of considerable volumes of faulty fusion in the joint zone (Fig. 1). The mathematical modeling enables one to control the technological process without the costs for the resource-intensive experimental determination of technological parameters.

The absence of a mathematical model of the glass deformation process at the glass joining with a metal does not enable the determination of time with the aid of computations, which is spent for the physical contact formation that is it does not enable the estimation of the first stage of the one-piece joint formation.

The purpose of the present work is the selection of a mathematical model, which will enable us to determine the time of the physical contact formation, to control the temperature and pressure with account for the rheological peculiarities of the glass.

The physical and mathematical statement of the problem

For joining the heterogeneous materials one solves at first a technological problem of ensuring their contact with a maximum contiguity of joint surfaces. In some technologies, especially at joining the metals, a more plastic material deforms under the action of the temperature and pressure and repeats the relief of the other material.

At the manufacturing of the experimental samples of the GMC rods, a glass core is placed into the steel cylinder, and there is a gap from 0.5 to 1 mm (Figs. 1 and 2) between them. The core and the cylinder have a circular cross section. The sample is subjected to a temperature treatment in the regime “heating–maintenance”.

At the experimental sample heating, a deformation of the glass rod occurs starting from temperature T_p under the pressure action, and it fills a free volume between the glass and the metal. Since the viscosity drops gradually and continuously in the process of heating [3], the passage from the solid state to the viscous-fluid state occurs in a transitional temperature region rather than at a strictly definite temperature (as this is typical of crystals) (Fig. 3). The technology of manufacturing the samples of the GMC rods assumes their maintenance at the softening temperature T_s, however, the pressure is applied already at T_p, therefore, the physical contact may realize in the interval (T_p, T_s) and depends on the heating velocity. The geometric sizes of experimental samples are limited and lie in the ranges: the diameter is up to 40 mm, the length is up to 400 mm. At a preliminary solution of the temperature problem of the temperature field distribution in the given samples it has been noted that as a result of a uniform heating, the temperature for the given sample is practically the same over the cross section, the maximum difference of temperatures in the sample does not exceed 7 °C [4]. The viscosity variation for the glasses does not exceed here 5 % and lies within the error of its experimental estimate. Therefore, an assumption is accepted about a constant viscosity over all sections of the sample.

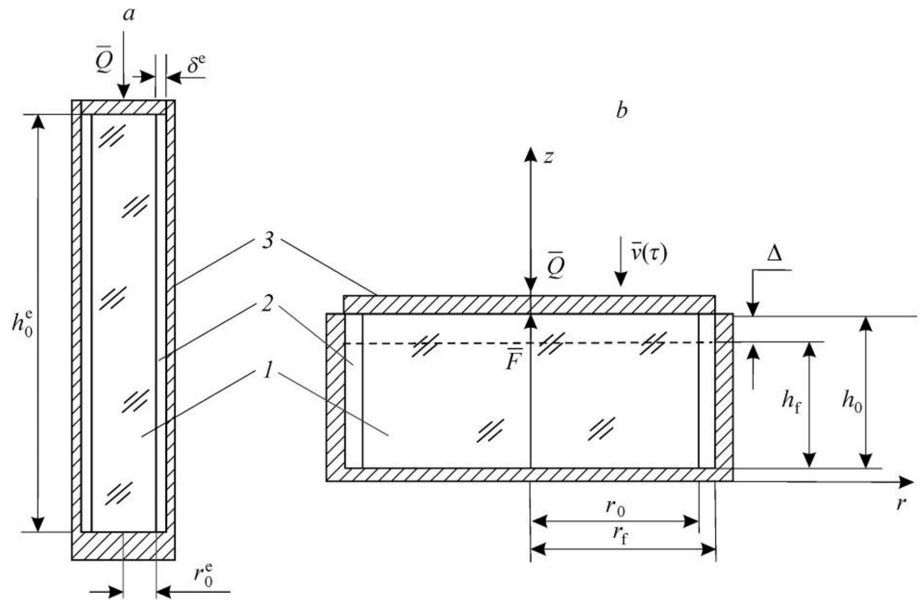

Fig. 2. GMC rod.

a — the scheme of an experimental sample, *b* — model: glass (*1*), free volume (*2*), metal (*3*).

To control some parameters of the technological process it is proposed to solve the problem of the glass cylinder deformation under the temperature and pressure action in a confined region by analogy with the classical Reynolds problem of the hydrodynamics theory [5, 6] for determining the time of the physical contact formation at the manufacturing of the GMC rods.

The process of the compression of a viscous (glass) layer between two cylindrical plates is considered under the condition that the layer thickness h_0 is much less than the radius of cylinders, the lower sample is at rest, and the upper sample, to which the constant load Q is applied, moves at some velocity $v(\tau)$ (see Fig. 2) until the free volume is filled. The axial symmetry, neglecting the acceleration of the particles of the viscous layer and the thickness of metal plates, as well as the condition of a uniform motion of the upper plate enable us to rewrite the Navier–Stokes equations and the continuity condition in the form

$$\eta \frac{\partial^2 v_r}{\partial z^2} = \frac{\partial p}{\partial r}, \quad \frac{\partial p}{\partial z} = 0, \tag{1}$$

$$\frac{1}{r} \cdot \frac{\partial (r v_r)}{\partial r} + \frac{\partial v_z}{\partial z} = 0 \tag{2}$$

under the boundary conditions:

$$\text{at } z = 0: v_z = 0, v_r = 0, \tag{3}$$

$$\text{at } z = h: v_z = dh/d\tau = v(\tau), v_r = 0, \tag{4}$$

$$\text{at } r = r_f: p = 0, \tag{5}$$

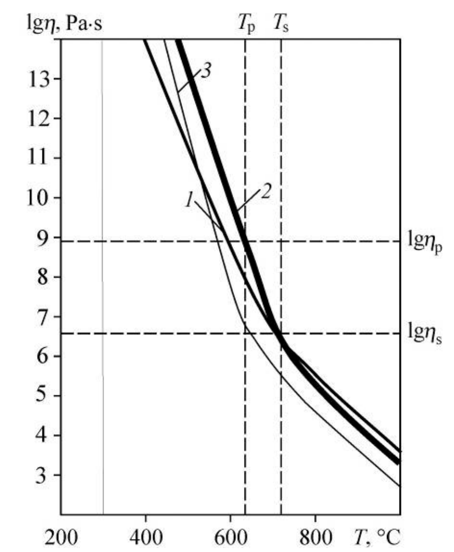

Fig. 3. Dependence of viscosity on temperature for industrial glasses [4].

T_s — the temperature at which the glass deforms under its own weight, T_p — the temperature at which the glass deforms under load; glass brands: C38-1 (*1*), C49-1 (*2*), C89-2 (*3*).

where η is the viscosity coefficient, r and z are the radial and axial coordinates of the viscous layer particle, respectively, v_r is the viscous layer velocity in radial direction, p is the pressure in the viscous layer, τ is the time, v_z is the viscous layer velocity in the axial direction, h is the current thickness of the glass layer, $v(\tau)$ is the motion velocity of the upper cylinder in the axial direction, r_{f} is the final glass layer radius after reaching the physical contact.

Analytic solution

Integrating twice equations (1) over z and using the boundary conditions (3) and (4), we obtain:

$$v_r = \frac{1}{\eta} \cdot \frac{dp}{dr}\left(\frac{z^2}{2} - \frac{zh}{2}\right). \tag{6}$$

Using (6) at the integration of equation (2), one can write:

$$v_z = -\frac{h^3}{12\eta} \cdot \frac{d}{dr}\left(r\frac{dp}{dr}\right). \tag{7}$$

The integration of (7) over r and expressing dp/dr yields

$$dp/dr = -6\eta v(\tau)/h^3. \tag{8}$$

Substituting (8) in (6), we obtain the final dependence of the radial velocity on the motion velocity of the upper plate

$$v_r = 3v(\tau)r\left(z/h - z^2/h^2\right)/h. \tag{9}$$

Integrating (8) over r and using the boundary condition (5), we find the pressure in the layer

$$p = 3\eta v(\tau)\cdot\left(r_{\mathrm{f}} - r^2\right)/h^3. \tag{10}$$

Employing (10), one can calculate the total pressure force on the upper sample:

$$F = -3\pi\eta r_{\mathrm{f}}^4 v(\tau)/(2h^3). \tag{11}$$

If a constant loading acts on the upper sample, then, neglecting the acceleration of the sample, we obtain $-Q + F = 0$ or

$$-Q - 3\pi\eta r_{\mathrm{f}}^4 v(\tau)/(2h^3) = 0. \tag{12}$$

When solving the Reynolds problem one usually finds the values of the resistance force of the viscous layer to the pressure. In the present work, the motion velocity of the upper plate is assumed equal to the velocity of the temporal variation of the viscous layer thickness, then one obtains after integrating the equilibrium equation a nonlinear equation, which couples the time of the formation of a physical contact with all remaining parameters of the technological process, including the loading and glass viscosity. One can rewrite equation (12) as

$$-Qdr = \frac{3\pi\eta r_{\mathrm{f}}^4}{2h^3}dh. \tag{13}$$

One should consider the dynamic viscosity coefficient as temperature-dependent: $\eta = \eta(T)$. One employs most frequently the simplified dependencies of viscosity on temperature within certain temperature intervals, for examples, the dependencies of Arrhenius type [7]

$$\eta(T) = \eta_{\mathrm{b}} \cdot \exp\left(\frac{E}{RT}\right), \tag{14}$$

where E is the viscosity activation energy [J/mole], T is the temperature [K], R is the universal gas constant = 8.31 J/(mole·K), η_b is some reference dynamic viscosity, it generally depends on temperature. Approximating the temperature by a linear function in the interval (τ_p, τ_s), we rewrite dependence (14) in the form

$$\eta(\tau) = A \cdot \exp(B\tau), \tag{15}$$

here $A = \eta_b \cdot \exp\left(\frac{E}{RT_p}\left(1+\frac{T_s - T_p}{T_p(\tau_s - \tau_p)}\right)\right)$, $B = -\frac{E}{RT_p}\cdot\frac{T_s - T_p}{T_p(\tau_s - \tau_p)}$, and $A > 0$, $B > 0$, because $T_p > T_s$, $\tau_p > \tau_s$ at heating.

Solving the differential equation (13), we obtain a nonlinear equation coupling τ_f with the main parameters of the technological process:

$$\int_0^{\tau_f} \frac{1}{\eta(\tau)} d\tau = \frac{3\pi r_f^4}{4Q}\left(\frac{1}{h_f^2} - \frac{1}{h_0^2}\right), \tag{16}$$

where τ_f is the time of the physical contact formation, h_0 is the initial thickness of the glass layer, $h_f = r_0^2 h_0 / r_f^2$ is the final thickness of the glass layer. Formula (16) enables one to investigate the character of the variation of τ_f versus Q, $\eta_p(T_p)$, $\eta_s(T_s)$, h_0, and h_f.

Solution analysis

The character of the variation of τ_f and $\Delta = h_f - h_0$ was investigated as a function of the glass grade and the regime technological parameters. Figures 4 and 5 show the computational results for the following parameters: $r_f = 40 \cdot 10^{-3}$ m, $r_0 = 1 \cdot 10^{-3}$ m, $h_0 = 4 \cdot 10^{-3}$ m, $h_f = 3 \cdot 10^{-3}$ m.

One can see from Figs. 5*a* and 5*b* that at high τ_f, the dependence of η_s on η_p is substantially nonlinear. One can note in Fig. 5*b* that after $\eta_p = 1 \cdot 10^8$ Pa·s, the parameter τ_f has practically constant values. One can observe the following peculiarities in Fig. 5*c*: the τ_f values differ insignificantly from one another for different η_p on curves *1*–*8*, therefore, one can formulate

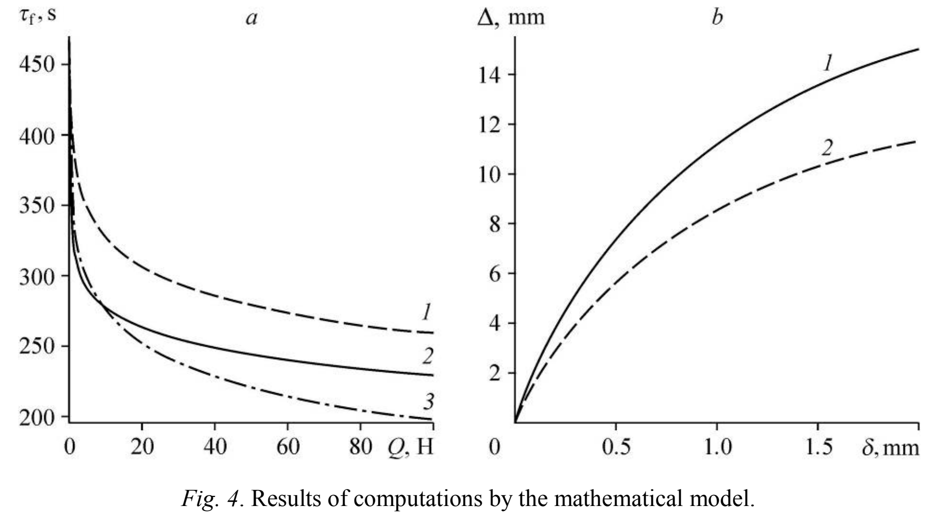

Fig. 4. Results of computations by the mathematical model.
a — the dependence of τ_f on Q for various glasses: C38-1 (*1*), C49-1 (*2*), C89-2 (*3*);
b — the dependence of Δ^{mod} on δ (see Fig. 2): h_0 = 20 (*1*), 15 (*2*) mm.

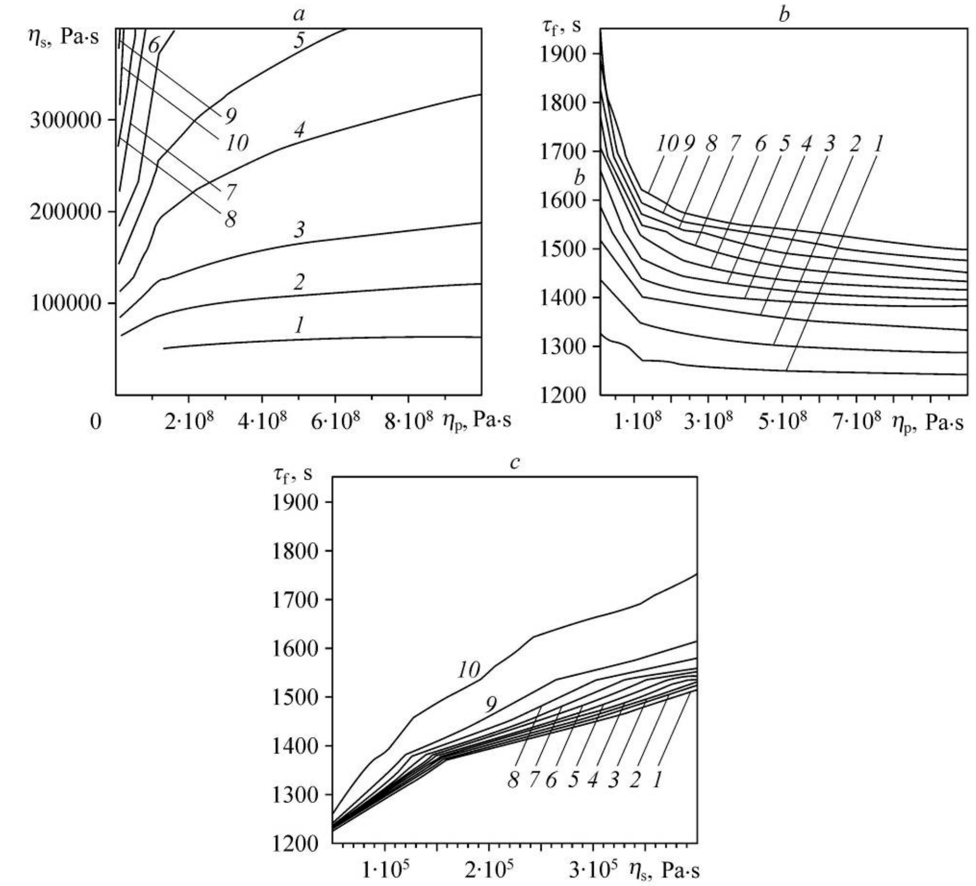

Fig. 5. Level lines $\Phi(\tau_f, \eta_p, \eta_s) = 0$ at different values of τ_f (*a*), η_f (*b*), and η_p (*c*).
a — τ_f = 1225 (*1*), 1302 (*2*), 1379 (*3*), 1456 (*4*), 1533 (*5*), 1610 (*6*), 1687 (*7*), 1764 (*8*), 1841 (*9*), 1918 (*10*);
b — $\eta_s\cdot(10^{-4}$ Pa·s) = 6.5 (*1*), 10 (*2*), 13,5 (*3*), 17 (*4*), 20.5 (*5*), 24 (*6*), 27.5 (*7*), 31 (*8*), 34.5 (*9*), 38 (*10*);
c — $\eta_p\cdot(10^{-8}$ Pa·s) = 9.5 (*1*), 8.5 (*2*), 7.5 (*3*), 6.5 (*4*), 5.5 (*5*), 4.5 (*6*), 3.5 (*7*), 2.5 (*8*), 1.5 (*9*), 0.5 (*10*).

a hypothesis on the validity of replacing curves *1 – 8* (which in fact characterize the types of glasses) with a single averaged curve; curve *10* lags considerably behind the other curves, which may point to a specific behavior of the material with small initial values of viscosities ($\eta_p \approx 0.5\cdot10^8$·Pa·s).

An analysis of the results of analytic modeling shows the following: with increasing pressure and temperature maintenance, the time of the physical contact formation drops; at a slow heating with a speed of less than 15 °C/min, the physical contact forms already at the heating stage for a pressure above 5 MPa, therefore, it is necessary to account for the temperature dependence of the glass viscosity; in the case of a rapid heating, more than 15 °C/min, the physical contact occurs in the interval corresponding to a maintenance at the temperature T_s, and may take, under a pressure below 5 MPa, over 30 % of the time of the entire interval.

Experiment

To estimate the theoretical results an experiment was done on determining the shrinkage magnitude and the time of the physical contact formation, that is the time during which the glass fills the free volume (Fig. 6). The experimental results were compared with computed

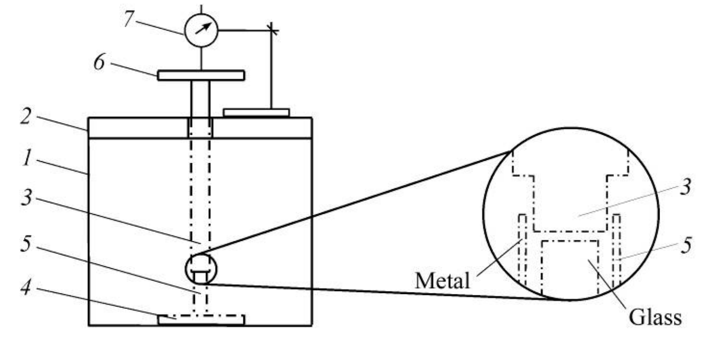

Fig. 6. Schematic diagram of the experimental setup.

1 — the casing of the laboratory heat furnace, *2* — the furnace cover, *3* — rod for transmitting pressure to the sample, *4* — a platform for mounting the sample, *5* — the sample GMC rod, *6* — load, *7* — a micrometer of hour type.

data. The equality of free volumes (see Fig. 2) was taken as the basis for the passage from the Reynolds model problem to the real model of the GMC rod:

$$\delta h_0^{\mathrm{e}}(2r_0^{\mathrm{e}}+\delta)=(r_{\mathrm{f}}^2-r_0^2)h_0,\quad \delta=\left(-\sqrt{h_0^{\mathrm{e}}}\,r_0^{\mathrm{e}}+\sqrt{h_0^{\mathrm{e}}\left(r_0^{\mathrm{e}}\right)^2+h_0 r_{\mathrm{f}}^2-h_0 r_0^2}\right)\Bigg/\sqrt{h_0^{\mathrm{e}}},$$

where δ is the gap between the glass and the metal in the experimental sample of the GMC rod, h_0^{e} is the initial height of the glass in the sample, r_0^{e} is the initial radius of the glass in the sample. With regard for the model parameters and the GMC rod sizes, the gap δ was chosen in such a way that the free volume of the experimental sample was equal to the free volume of the constructed model.

The samples of the GMC rods were subjected to a temperature treatment according to the regime “heating–maintenance” (Fig. 7). The glass shrinkage measurements were done with the aid of the micrometer of hour type (*7* in Fig. 6), with regard for the variation of the rod linear sizes at temperature treatment. One can see in Fig. 7 that at T_{p}, the variation of the linear size of the entire assembly is proportional to the temperature increase, and further, the glass starts softening, and the curve changes its inclination angle (point A), upon reaching the temperature T_{s}, the shrinkage velocity of the softened glass exceeds the velocity of the metal thermal expansion, therefore, the extremum point B appears on the graph. Upon reaching the physical contact the shrinkage stops, and the experiment is terminated (point C).

Two series of experimental samples containing 15 pieces in each series were prepared, which had a different height of the glass rod (series No. 1 — h_0^{e} = 20 mm, series No. 2 — h_0^{e} = = 15 mm), to which the same technological regime was applied. The results of experiments were processed by statistical methods. Figure 8 shows the values of the shrinkage magnitude and time (region B–C from Fig. 7). For processing convenience, the inflection point is adopted as the graph origin; it is shifted to the coordinate origin.

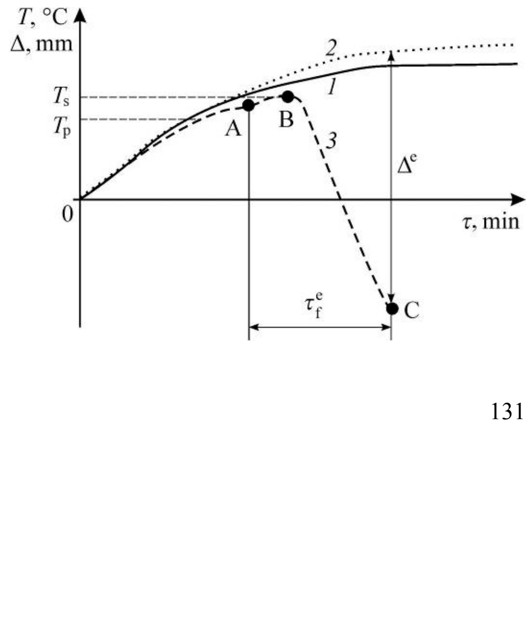

Fig. 7. Schematic diagram of the experimental curves with characteristic points.

1 — temperature conditions (maintenance temperature T_{p} = 800 °C), *2* — lengthening of the rod, *3* — change the length of the components *3–5* (see Fig. 6).

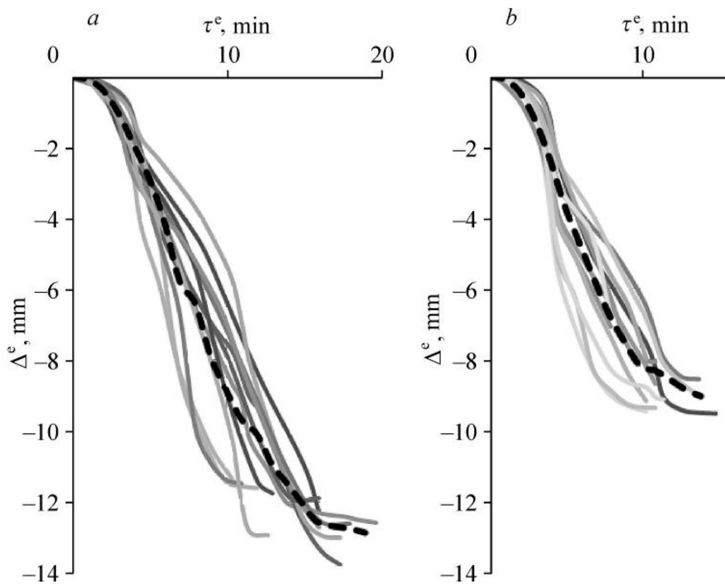

Fig. 8. Mean values of the experimental data for the shrinkage.
Series No. 1 (*a*), No. 2 (*b*).

As a result of the experimental studies, the data on the time of the formation of the physical contact τ_f^e and the shrinkage magnitude Δ^e of the glass layer were obtained (see Fig. 7). The corrections were made for the Δ^e values for the metal expansion: for series No. 1 — $\Delta^e = 12.88 + 2.6 = 15.48$ mm, and for series No. 2 — $\Delta^e = 9.04 + 2.4 = 11.44$ mm. The time of the physical contact formation is counted from point A, which corresponds to the start of the glass softening The table presents the results of the mathematical modeling and mean values of experimental data.

Table

Comparison of the results of simulation and experiment

Series No.	Time, min		Shrinkage, mm	
	τ_f	τ_f^e	Δ	Δ^e
No. 1	22.9	21.4	15.1	15.48
No. 2	19.6	18.2	11.4	11.44

It is seen from the table that the experimental data on shrinkage exceed insignificantly the theoretical ones: for series No. 1, by 2.5 %, for series No. 2, by 0.6 %. On the contrary, the actual time of the physical contact formation proves lower than the computed one: for series No. 1, by 6.6 %, and for series No. 2, by 7.1 %. The difference in the magnitude of experimental and theoretical values may be explained, first of all, by a probabilistic character of the variation of glass properties and an not quite accurate approximation of the glass viscosity in the temperature range (T_p, T_s).

Conclusions

A model has been proposed, which enables one to estimate the degree of the physical contact formation at a junction of the glass with the metal and to carry out the parametric investigation of the technological process, namely, to control the maintenance temperature, heating velocity, the pressure, and the time of the physical contact formation. The adequacy of the model has been tested experimentally. The model can be used not only for the technological process under consideration but also at the junction of such heterogeneous materials as the metal and ceramics, the metal and plastic, and the glass and ceramics, etc.

Nomenclature

Q — constant load applied to the sample,
F — total pressure force on the upper sample,
r, z — radial and axial coordinates of the particle of the layer, respectively (the same quantities with an index are constants),
h — the current thickness of the glass layer (the same quantity with an index is a constant),
$v(\tau)$ — the motion velocity of the upper cylinder in the axial direction,
v — the viscous layer velocity (the same quantity with an index is the velocity in a certain direction),
T — temperature,
τ — time of heating up to temperature T,
η — dynamic viscosity coefficient,
δ — gap between the glass and the metal,
Δ — glass layer shrinkage,
E — energy of the viscosity activation,
R — universal gas constant,
η_b —reference dynamic viscosity,
p — pressure in the layer.

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