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INFLUENCE OF PLASMA-FLUX PARAMETERS ON RAW-MATERIAL MELTING IN THE PRODUCTION OF MINERAL MICROFIBERS

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Factors that affect the production of mineral microfibers using an electric-arc plasma are analyzed. The characteristics of heating and melting of the initial material as functions of the parameters of the plasma flux and the "geometry" of the fiber-forming reactor are found.

Experimental investigations of the production of mineral microfibers from a continuous solid material in the form of a strip of mineral (basalt, quartz, or glass) 40 mm wide and 3 to 8 mm thick were carried out on a laboratory-scale plant consisting of a 100-kW d.c. plasmatron, a fiberizing reactor, and a mechanism for feeding the strip of material to the reactor. The strip of material was melted by a plasma flux and microfibers were drawn from the formed melt by a plasma flux.

Analysis of experimental and theoretical investigations in the field of fiberization [1-4 and others] shows that thermal and hydrodynamic processes have a dominant role in the mechanism of fiberization. In this case, we can distinguish the following fundamental problems of hydrodynamics and thermal physics: the melting of mineral raw material by a plasma flux, the formation and stability of melt filaments, and the formation from them of microfibers in the process of cooling. These problems should be solved to optimize the process of fiberization and to create a theory that enables us to calculate with accuracy sufficient for practice the length and diameter of the fibers produced and to select the regimes of fiber-forming reactor operation that maximize the yield of fiber of the required dimensions with a minimal amount of nonfibrous inclusions.

Our investigation seeks to optimize the operating conditions and geometric parameters of a plasma reactor for producing mineral fibers from a strip of solid continuous material. Specifically, we consider the formation of glass fiber, but the procedure and the recommendations given are applicable to other materials.

The fiber diameter and length that can be obtained by drawing are governed by the viscosity of the molten material. The molten viscosity for glass is substantially dependent on its composition and temperature [5, 6] and is given by the relation

$$\ln \eta = M + \frac{N}{T^n}, \tag{1}$$

where M, N, and n are constants.

The molten viscosity of "standard" glass ($Na_2O \cdot 2SiO_2$), which is given in tabulated form in [1], can be approximated by the expression

$$\ln \eta = 46{,}880/t^{1.73}, \tag{2}$$

where the temperature range is 780–1240°C, the viscosity range is 4600–11.7 N·sec/m^2, and the approximation error is ± 2–18%. The latter can be significantly decreased if the dependence log log $\eta = f(\log t)$ is approximated by two straight lines with a salient point at t = 1060°C. This temperature corresponds to the maximum of the solid–liquid transition of the glass. A similar result is obtained in [7], where the range of temperatures of the onset of "crystallization" for glasses of different compositions is 700–1150°C.

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In [8], the viscosity as a function of the temperature is represented as

$$\frac{\eta}{\eta_w} = \left(\frac{\vartheta}{\vartheta_w}\right)^{-n}, \tag{3}$$

where $\vartheta = T - T_0$; $T_0 = 273^\circ C$; $\vartheta_w = T_w - T_0$; T_w is the surface temperature.

For quartz glass, the region of the spread in the experimental data on viscosity in the temperature range of 2000–2600 K lies between two boundary dependences [6]:

$$\eta_1 = 10 \exp\left(\frac{68{,}800}{T} - 24.59\right), \tag{4}$$

$$\eta_2 = 10 \exp\left(\frac{61{,}000}{T} - 18.94\right). \tag{5}$$

Analysis of the literature data shows that the optimum viscosity and temperature of the melt are usually determined by experiment. The typical "production" molten viscosity in the production of glass wool fibers (glass wool) is 1 N·sec/m^2 (10 P) at $t = 1400^\circ C$ [9].

In the traditional spinneret-blowing process for producing mineral fibers, the glass melt passes through spinnerets with $d = 0.8-1$ mm that form filaments 600–800 μm in diameter, and then, once they have been heated in the gas flow to a temperature of 1270°C and the viscosity decreases to 10–15 N·sec/m^2, the filaments are drawn into fibers 5–7 μm in diameter. In this case, the velocity of the gas flow is 150–200 m/sec and the temperature is 1350-1450°C. In [5, 10, 11], optimum temperatures and viscosities of glass melts as well as the velocities of the energy-transfer agent similar to the above are given. As a consequence of the decrease in the temperature of the melt in its passage through the spinnerets, to ensure the required viscosity, the temperature of the melt in the tank is maintained above the temperature of the onset of glass "crystallization" [3, 5]. Since there are no spinnerets in the plasma fiber-forming reactor, and the fibers are drawn by a high-speed plasma flux directly from the melt bath due to the development of the Taylor hydrodynamic instability [12], the temperature of the melt can be maintained in the range of 700–1150°C.

The melt filaments should be drawn to the smallest possible diameter and be cooled rapidly. If the time of cooling to crystallization is smaller than τ_{melt}, drops (beads) do not form [12]

$$\tau_{cool} < \tau_{melt} \cong 5 \frac{d\nu_{liq}\rho}{2\sigma}. \tag{6}$$

The expression for the time in which a melt filament contracts to a drop (decreases in length by a factor of N) [12] has the form

$$\tau = \frac{3\eta_{eff} d}{\sigma_{eff}} \ln N. \tag{7}$$

The cooling time of the fiber must not exceed the critical time defined by relation (7). During this period, a tensile force must act on the fiber. According to formula (7), a melt filament with $d = 5 \cdot 10^{-4}$ m for σ 0.4 N/m and η = 0.4 N·sec/m^2 will turn to a "bead" in $7 \cdot 10^{-5}$ sec. This fiber cools down to solidification in $\sim 10^{-4}$ sec. Hence it follows that a significant decrease in molten viscosity can lead to an increase in the content of nonfibrous inclusions: the melt filament does not have time to solidify and contracts to a drop. Fiber cooling is determined by a criterial expression [6] (a fixed cylinder in an axial air flow); for example, for turbulent flow

$$\mathrm{Nu} = 0.325\,\mathrm{Re}^{0.3}. \tag{8}$$

The Re number is dependent on the fiber diameter and the velocity of the air flow. It is possible to use other criterial relations [6, 13].

Expressions for estimating the diameter and length of the fibers formed have been found in [11, 12]. For a fiber that is produced by blowing the melt filament, in [12] the following expression is proposed for the diameter:

$$d = A\sigma^{5/8}\left(r\frac{\rho_{liq}}{\rho_g}\right)^{1/5}\left(\frac{\nu_{liq}}{U}\right)^{5/6}, \tag{9}$$

i.e., the smaller the surface tension, the higher the velocity of the energy-transfer agent U, and the lower the viscosity, the smaller the diameter of the fiber. According to the experimental data, $A = 0.0725$. The length of an elementary fiber [12] is

$$L = 1.13\frac{\rho_{liq}}{\rho_g}\left(\frac{U}{2\nu_g}\right)^{0.5} d^{3/2}. \tag{10}$$

From (10) it follows that a decrease in the diameter of the fiber leads to a reduction in its length under ordinary conditions. When a plasma flux is used it is possible [12] to increase the length of elementary fibers with their diameter remaining constant by decreasing the coefficient of fiber resistance in the ambient medium c_f and the density of the ambient medium.

The process of melting of the sheet material fed to the reactor can be calculated by a scheme known in rocket engineering for the problem of destruction of a melted heatproof coating [6].

The thermal conductivity of a melted layer with a moving boundary is described by the equation [10]

$$\frac{d^2\theta}{dz^2} + W(0)\frac{d\theta}{dz} = 0, \tag{11}$$

where $W(0)$ is the dimensionless rate of material removal in the quasisteady regime

$$W(0) = \frac{c(T_d - T_0)\left[\sqrt{F(m)} + (d\theta/\theta z)|_{z=0}\right]}{\Delta Q + q_0\gamma/(\alpha/c_p)}; \tag{12}$$

$$\theta = \frac{T - T_0}{T_d - T_0}; \quad z = \frac{y - S(\tau)}{\sqrt{a\tau}};$$

$$\theta(0) = 1; \tag{13}$$

$$\theta(\infty) = 0. \tag{14}$$

A solution of problem (11)-(14) will be

$$\theta = \exp[-W(0)z], \tag{15}$$

from which it follows that the rate of removal of the material in the quasisteady regime is

$$\rho v_\infty = \frac{q_0}{\Delta Q + c(T_d - T_0) + q_0\gamma/(\alpha/c_p)}. \tag{16}$$

The heat that is absorbed by the melted material (the effective enthalpy of the material) is:

$$I_{eff} = \Delta Q + c(T_d - T_0) + \gamma q_0/(\alpha/c_p). \tag{17}$$

To calculate the temperature distribution, the thickness of the melt film, and the characteristics of molten glass removal, we take the dependence of the molten viscosity on temperature as (3), which describes most

accurately the tabulated data in the temperature range indicated below. In this case, for "standard" glass at $t = 1100-1700^{\circ}C$, $t_w = 1650^{\circ}C$ ($\eta = 1$ N·sec/m^2), $n = 8.125$

$$\frac{\eta}{\eta_w} = \left(\frac{t}{t_w}\right)^{-8.125}. \tag{18}$$

The given temperature range corresponds to the operating regimes of the process for the material under study. The viscosity distribution over the thickness of the melt film can be taken as the dependence

$$\frac{\eta}{\eta_w} = \exp(y/\delta). \tag{19}$$

where δ is the film thickness, which is governed by the condition of viscosity variation by a factor of e, since in an amorphous glassy solid, there is no clear boundary between the liquid and solid states.

Comparing (18) and (19), we can write

$$(T - T_0)/(T_w - T_0) = \exp(-y/\delta n). \tag{20}$$

Since the heat flux into the solid is equal to

$$q_{inn} = -\left(\lambda \frac{\partial T}{\partial y}\right)_w, \tag{21}$$

by substituting (20) into (21) we obtain for the thickness of the melt film

$$\delta = \lambda (T_w - T_0)/(nq_{inn}). \tag{22}$$

The heat flux that is directed into the solid can be found from the heat balance on the surface:

$$q_0 = G_w \Delta Q_w + \varepsilon\sigma T_w^4 + q_{inn}. \tag{23}$$

When the thickness margin of the glassy solid is sufficient (or this material is supplied to the melting zone) and the coordinate system is tied to the moving (molten) surface, the quasisteady regime of melting (15) and (16)

$$\frac{T - T_0}{T_d - T_0} = \exp\left(-\frac{v_\infty y'}{a}\right), \tag{24}$$

where $y' = y - S(\tau)$, is established in the solid.

The quasistationary rate of material removal $\rho V_\infty = G_w$ with blowing into the boundary layer is ignored is:

$$G_w = (q_0 - q_{rad})/[c(T_d - T_0) + \Delta Q] \tag{25}$$

and

$$q_{inn} = \rho c v_\infty (T_d - T_0). \tag{26}$$

In view of (20) and (21) expression (23) can be somewhat rearranged:

$$q_{inn} = -\frac{\bar{\lambda}(T_w - T_0)}{\delta n} \tag{27}$$

and

$$q_0 = \bar{c} G_w (T_w - T_0) + \varepsilon\sigma T_w^4 + \frac{\bar{\lambda}(T_w - T_0)}{\delta n}, \tag{28}$$

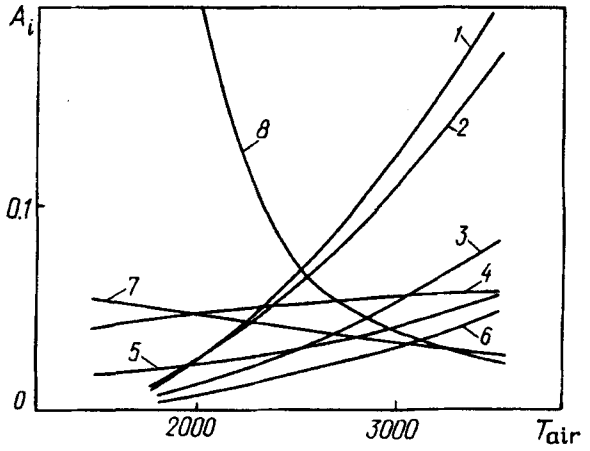


Fig. 1. Melting characteristics of glass strip versus plasma-flux temperature T_{air} (t_w = 1250°C): 1) $A_1 = 10^2 u$, m/sec and $10v_\infty$, m/sec; 2) $A_2 = 10^{-7} q_0$, J/(m^2·sec); 3) $A_3 = 10^{-7} q_{inn}$, J/(m^2·sec); 4) $A_4 = 10^{-4} W_{air}$, m/sec; 5) $A_5 = 10^{-5} h_0$, kJ/kg; 6) $A_6 = 10^{-1} G_w$, kg/(m^2·sec); 7) $A_7 = G_{air}$, kg/sec; 8) $A_8 = 10^2 \delta$, m.

where $\bar{c}$ and $\bar{\lambda}$ are the integral means of the quantities in the corresponding temperature range.

On the inner surface of the melt film (on the surface of the "frozen" layer)

$$q_{inn} = \frac{\bar{\lambda}_1 (T_w - T_0)}{e^{1/n} \delta n}. \tag{29}$$

From a comparison of (26) and (27) we have:

$$G_w = \frac{\bar{\lambda}}{e \delta n}. \tag{30}$$

By substituting (30) into (23) we obtain:

$$q_{inn} = \frac{q_0 - \varepsilon \sigma T_w^4}{2}. \tag{31}$$

The surface temperature T can be determined by the formula

$$T_w = T_0 + [q_0 - G_w \Delta Q_w - \varepsilon \sigma T_w^4] / (\bar{c} G_w). \tag{32}$$

Formulas (22), (23), (30), (31), and (32) enable us to calculate the basic characteristics of the process of glass melting by a plasma flux.

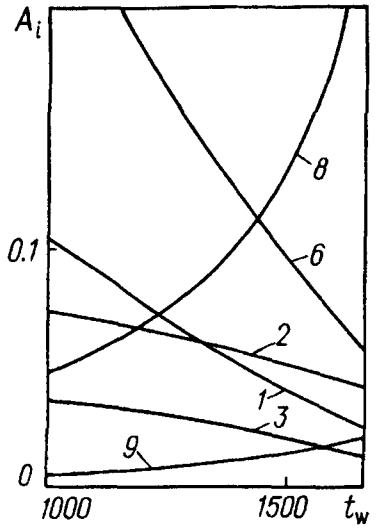
If the flux is directed normally to the surface, the main zone of heat transfer from the plasma flux to the glass surface is the region of the stagnation point, and to calculate q_0, we can use the dependence [15]

$$q_0 = 4.5 \cdot 10^{-8} R^{-0.5} p_0^{0.25} (p_0 - p_\infty)^{0.25} (h_0 - h_w). \tag{33}$$

For a flat surface, the right-hand side of formula (33) should be multiplied by 0.65.

Additionally, we used formulas that approximate the properties of air:

$$\rho_{air} = 112 h^{-0.815}, \tag{34}$$



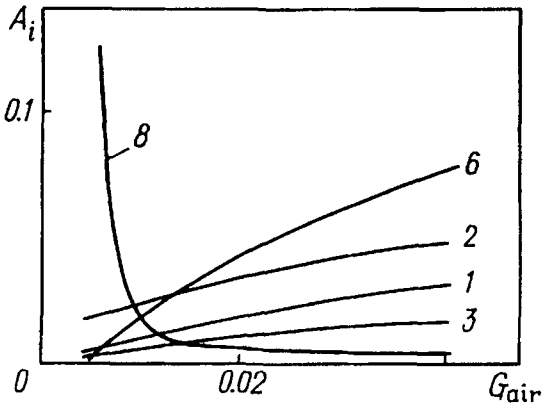


Fig. 2. Melting characteristics of glass strip versus surface temperature t_w, 0°C (T_{air} = 2500°K): 1-3, 6, 8) see Fig. 1; 9) $A_9 = 10^{-7} q_{rad}$, J/(m^2·sec).

Fig. 3. Melting characteristics of glass strip versus flow rate of energy-transfer agent G_{air}, kg/sec: 1-3) see Fig. 1; 6) $A_6 = G_w$; 8) $A_8 = 2\delta$, m.

$$h = 1.888^{T/10^3} \cdot 624\,, \tag{35}$$

The sound velocity is

$$a = 20.4\sqrt{T_0}\,. \tag{36}$$

Furthermore, for variants of the calculation in which the flow velocity in fractions of the sound velocity is given, it is taken that $W = ka$, where k is the specified fraction.

The minimum thickness of the glass in the solid phase in the melt tank can be equal to zero ($b_{min} = 0$), since ordinary water cooling of the copper tank is sufficient to remove heat from the plasma flux. The real value of b can be estimated by determining the drawing rate of the glass strip.

The melting time for a strip of thickness "b" is

$$\tau = b/v_\infty\,. \tag{37}$$

The feed rate of the strip is

$$u = l/\tau\,,\quad l = 2R\,. \tag{38}$$

Using the above procedure we calculated the characteristics of the process as functions of the plasma-flux parameters and the "geometry" of the fiber-forming reactor (Figs. 1-3). The results showed that with increasing temperature of the plasma flux (Fig. 1), qualitative characteristics of the process of melting such as linear removal and weight removal and the heat flux to the surface increase rapidly; an increase in surface temperature (Fig. 2) for a constant temperature of the plasma flux leads to their reduction, because of the decrease in the heat flux. As the velocity of the plasma flow (the flow rate of the energy-transfer agent) increases for constant temperatures of the flow and the surface the characteristics of removal (melting) grow, but more slowly than with increasing temperature of the flux (Fig. 3). An increase in the chamber length leads to a decrease in the linear rate of removal and an increase in the melt film thickness, because of the decrease in the intensity of heating.

The use of a thicker plate, without affecting the characteristics of removal, leads to a decrease in the required rate of feed of the material into the melting zone. The influence of thermophysical properties (composition)

of the glass is less substantial. Thus, as the thermal conductivity coefficient increases by a factor of 2, the characteristics of removal change insignificantly.

The developed procedure (formulas (22), (23), (30), (31), and (32)) and the results that have been obtained using it (Figs. 1-3) enable us to select the required parameters of the process of melting and in this manner to optimize it.

NOTATION

η, dynamic viscosity, N·sec/m^2; T, temperature, K; t, °C; ϑ, excess temperature, K; τ, time, sec; ν, kinematic viscosity, m^2/sec; ρ, density, kg/m^3; σ, surface tension, N/m; d, diameter of fiber and melt filament, m; Nu, Nusselt number; Re, Reynolds number; A, constant; U, velocity of the energy-transfer agent flow, m/sec; L, fiber length, m; r, radius of the filament in flow, m; z, dimensionless coordinate along the normal to the melt surface; c, heat capacity, J/(kg·K); $F(m)$, calculated function governed by the curves in Fig. 3.11 [6]; ΔQ, heat of melting, J/kg; q_0, specific heat flux on the outer surface of the melt film, J/(m^2·sec); γ, blowing coefficient [6]; α/c_p, reduced heat-transfer coefficient [6], kg/(m^2·sec); v_∞, linear rate of melt removal in the quasisteady regime, m/sec; I_{eff}, heat absorbed by melted material, J/kg; a, thermal diffusivity coefficient, m^2/sec; W, dimensionless rate of material removal; $m = c(T_d - T_0)/\Delta Q$; λ, thermal conductivity coefficient, J/(m·sec·K); y, dimensional coordinate along the normal to the surface, m; $S(\tau)$, coordinate of the melted surface in a fixed reference system; δ, melt film thickness, m; q_{inn}, specific heat flux into the solid at the boundary between the melt film and the solid, J/(m^2·sec); G_w, amount of the molten (removed) glass from unit surface per unit time, kg/(m^2·sec); $\varepsilon\sigma T_w^4$, heat flux by radiation from the surface, J/(m^2·sec); R, radius of the region of the action of the plasma flux on the glass surface, m; $p_0 - p_\infty$, excess pressure of the flux in the region of the stagnation point, N/m^2; h_0, h_w, enthalpy of the energy-transfer agent away from the heated surface and on it, kJ/kg; W_{air}, flow velocity, m/sec; b, thickness of the glass strip, m; l, tank length, m. Subscripts: liq, f, liquid; g, gas; 0, initial, d, surface damage (in this case, the melted surface); w, wall surfaces; air, air.

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