EFFECT OF MELT PROPERTIES AND THERMAL STATE ON ELECTROMAGNETIC RADIATION PRODUCED DURING CRYSTALLIZATION

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The effect of thermal characteristics of the melt on electromagnetic radiation which develops upon crystallization is analyzed qualitatively and related to an increase in gas temperature within the bubbles formed near the growing solid phase.

Experiments have shown that upon crystallization of melts electromagnetic waves of various frequency are radiated, in particular, in the optical range [1-4]. In principle analysis of the spectrum and intensity of radiation can provide information on the kinetics of structure formation during the crystallization process and make possible operative control of the process in order to obtain optimum structural characteristics in the cast metal [4-6]. In connection with this, it is of great practical importance to qualitatively analyze the dependence of such radiation on the properties of the melt and crystallization parameters defining its thermal state. This is the goal of the present study.

Electromagnetic radiation is most marked upon rapid crystallization [1-3]. In this case the phenomenon of crystallization cavitation is significantly developed, with gas bubbles being formed near the growing crystals [7, 8]. For adiabatic change in the state of the gas within the cavity its temperature T_g is related to the bubble radius R by the expression [9]

$$T_g = T_{g0}(R_0 R^{-1})^{3(\gamma-1)}, \tag{1}$$

where T_{g0}, R_0 are the initial values of the gas temperature and the bubble radius and γ is the adiabatic index.

For adiabatic change in the gas state, it is assumed that heat exchange with the surrounding melt is absent, and that upon compression of the bubble the gas temperature therein increases significantly. For example for $R = 0.1\ R_0$ ($\gamma = 1.4$) the quantity $T_g \approx 16\ T_{g0}$. The gas pressure in the cavity then reaches a value of the order of 10^4 atm [9, 10]. Gas temperature increase leads to transition of electrons in its atoms to higher energy levels and the appearance of electromagnetic radiation upon the subsequent relaxation of the excited states. Experiments have shown, for example, that at T_g = 1000 K radiation is observed in the optical (visible) range, while at T_g = 10000 K it occurs in the ultraviolet [10].

In real crystallization processes heat exchange does occur between the cavity and the melt. Upon compression of a bubble the gas temperature increases by an amount $\Delta T_g = T_g - T_{g0}$, upon which a thermal power

$$Q_1 = \frac{4}{3}\pi R^3 \rho_g c_g \Delta T_g \tau^{-1}. \tag{2}$$

is liberated. Here ρ_g, c_g are the gas density and heat capacity, τ is the characteristic time for change in R, which can be assumed equal to the period of natural oscillation of the cavity. On the bubble boundary there develops a thermal flux q directed into the melt:

$$q = Q_1(4\pi R^2)^{-1} = \frac{1}{3} R \rho_g c_g \Delta T_g \tau^{-1}. \tag{3}$$

When the bubble radius R is much less than its distance ℓ_c from the crystallization front (see Fig. 1, $R \ll \ell_c - R$), the unique features of heat exchange in the melt near the cavity may be neglected, and we may assume that from the bubble into the liquid metal there is a thermal flux

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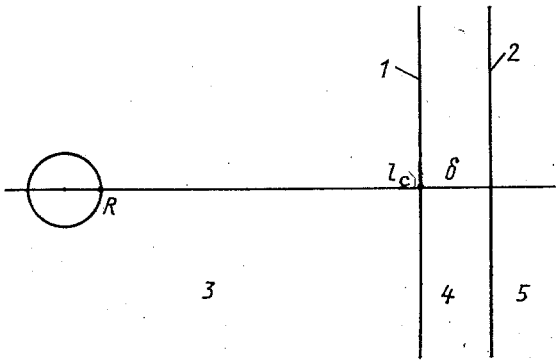

Fig. 1. Diagram of bubble location: 1) crystallization front; 2) cooled casting surface; 3) liquid phase; 4) solid phase; 5) cooled medium.

$$q_1 = \alpha \Delta T_l, \ \Delta T_l = T_2 - T_1, \tag{4}$$

where ΔT_ℓ is the increase in melt temperature due to heat coming from the bubble; T_1, T_2 are the temperatures of the melt in the vicinity and at the boundary of the bubble respectively; α is the heat exchange coefficient between the cavity boundary and the liquid metal, determined mainly by the turbulent motion of the melt near the bubble as the latter is compressed.

The character of the electromagnetic radiation depends on the fraction of heat removed from the bubble, which is characterized by the ratio $\chi = q_1/q$. From Eqs. (3), (4) we have

$$\chi = 3\alpha \Delta T_l a_g \tau (\lambda_g \Delta T_g R)^{-1}. \tag{5}$$

Here $a_g = \lambda_g (\rho_g c_g)^{-1}$ is the gas thermal diffusivity coefficient and λ_g is the gas thermal conductivity coefficient. It follows from Eq. (5) that with increase of thermal diffusivity of the gas the quantity of heat supplied from the bubble to the melt increases, and thus, the intensity of the electromagnetic radiation emitted by the heated gas decreases. This principle is confirmed by the experimental data presented in [10]. The radiation intensity also decreases with increase in thermal conductivity of the melt [4].

As an example we will consider a hydrogen bubble in solidifying iron. Taking $a_g = 1.27 \cdot 10^{-3}$ m^2/sec, $\lambda_g = 0.463$ W/(m·K), $R = 10^{-3}$ m, $\alpha = 1000$ W/(m^2·K), $\Delta T_\ell / \Delta T_g = 0.4$; $\tau = 10^{-4}$ sec [9, 11], from Eq. (5) we obtain $\chi = 0.33$, i.e., a third of the thermal flux from the bubble enters the melt. The lowest electromagnetic radiation intensity occurs at $\chi = 1$. In this case maximum heating $\Delta T_{\ell m}$ of the surrounding metallic liquid occurs. When $\chi = 1$, from Eq. (5) we find

$$\Delta T_{lm} = \lambda_g \Delta T_g R (3\alpha a_g)^{-1}. \tag{6}$$

Upon an increase in gas solubility in the melt the probability of gas bubble formation decreases, and thus, the intensity of electromagnetic wave radiation upon crystallization decreases as well. This principle was observed experimentally for gas bubbles in water in [10].

The situation changes qualitatively when the bubble is located near the crystallization front ($\ell_c - R \ll R$). Here heating of the surrounding metal occurs due to liberation of the latent heat of phase transition κ, which decreases the thermal flux removed from the bubble. It can be shown that the increase in melt temperature comprises κc_ℓ, where c_ℓ is the specific heat of the liquid metal. Then the expression for the thermal flux removed from the bubble takes on the form

$$q_1 = \alpha (T_2 - T_1 - \varkappa c_l^{-1}). \tag{7}$$

Decrease in q_1 implies an increase in gas temperature within the bubble and growth in the intensity of electromagnetic radiation.

At normal crystallization rates gas accumulates near the interphase boundary due to a drop in its solubility in the solid phase [12]. Growth in gas concentration increases the probability of bubble formation and intensity of electromagnetic radiation. However at high crystallization rates v_c, greatly exceeding the gas diffusion rate, where the crystallization diffusion Peclet number $P_c = v_c R_c D^{-1} \gg 1$ (where D is the diffusion coefficient, and R_c is the characteristic crystalline dimension), gas accumulation near the interphase boundary is absent [12]. In this case the closeness of the crystallization front leads to decrease in the intensity of electromagnetic radiation and its shift toward longer wavelengths due to liberation of the latent heat of phase transition.

If the thickness of the solidifying crust of the casting δ is sufficiently small, so that its thermal resistance $\delta\lambda_s^{-1} \sim \alpha_2^{-1}$, where λ_s is the thermal conductivity coefficient of the solid phase, α_2 is the heat liberation coefficient from the casting surface to the external coolant, then the melt temperature in the vicinity of the cavity decreases by an amount $q_2\alpha_1^{-1}$. Here q_2 is the thermal flux removed from the casting, α_1 is the effective heat liberation coefficient:

$$\alpha_1 = (\alpha_2^{-1} + \delta\lambda_s^{-1})^{-1}. \tag{8}$$

Decrease in metal temperature due to external heat removal leads to an increase in the thermal flux removed from the bubble:

$$q_1 = \alpha(T_2 - T_1 - \varkappa c_l^{-1} + q_2\alpha_1^{-1}). \tag{9}$$

External cooling of the casting compensates the increase in melt temperature due to liberation of the latent heat of crystallization at $\varkappa c_\ell^{-1} = q_2\alpha_1^{-1}$. This occurs at $\alpha_1 = \alpha_{1*} = q_2 c_\ell \varkappa^{-1}$. As follows from Eq. (8), the quantity α_{1*} corresponds to the critical value of the solidifying casting shell δ_*:

$$\delta_* = \lambda_s(\alpha_{1*}^{-1} - \alpha_2^{-1}). \tag{10}$$

The physical meaning of the quantity δ_* is that at $\delta > \delta_*$ the melt temperature increase due to liberation of the latent heat of crystallization dominates with a corresponding increase in the intensity of electromagnetic radiation, while at $\delta < \delta_*$ there is a decrease in metal temperature caused by external heat removal, with a decrease in electromagnetic wave radiation. We will evaluate δ_* using the example of iron solidification. Taking $\varkappa = 2.7 \cdot 10^5$ J/kg, $c_\ell = 0.75 \cdot 10^3$ J/(kg·K), $q_2 = 3 \cdot 10^5$ W/m^2, $\lambda_s = 40$ W/(m·K), $\alpha_2 = 1500$ W/(m^2·K) [11], we find $\alpha_{1*} = 833$ W/(m^2·K), $\delta_* = 21.2$ mm. Thus, in the case considered, from the viewpoint of its effect on intensity of electromagnetic radiation during crystallization the critical thickness of the solid phase is of the order of 20 mm.

CONCLUSIONS

1. It has been shown that with increase in thermal diffusivity of the gas, its solubility in the melt, and the thermal conductivity of the crystallizing liquid, the intensity of electromagnetic radiation decreases and it shifts toward longer wavelengths.

2. An analogous situation occurs for decrease in latent heat of crystallization and increase in heat removal from the crystallizing melt.

3. The results obtained agree with experimentally established principles of electromagnetic wave radiation during crystallization.

NOTATION

R, bubble radius; T, temperature; q, thermal flux; λ, thermal conductivity coefficient; c, specific heat; ρ, density; a, thermal diffusivity coefficient; α, heat exchange coefficient; $\varkappa$, latent heat of crystallization; δ, thickness of solidifying casting crust. Subscripts: 0, initial value; g, gas; ℓ, liquid phase; s, solid phase; *, critical value.

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