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Some peculiarities of the use of sapphire light guides in metallurgy

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Components of radiation extracted by cylindrical sapphire light guides were determined. Shown is the influence of the growth and working conditions on their effective transmission

Определены составляющие излучения, выводимого через футеровку металлургических печей иммерсионными цилиндрическими сапфировыми световодами. Показано влияние режимов выращивания и эксплуатации световодов на их эффективное пропускание.

Advance in optoelectronic, fiber optical and microprocessor engineering has made it possible to reduce instrumental errors of optical thermometry to the level of those of contact temperature measurements of metal melts. The errors of optical thermometry are mainly defined by systematic and random components which, in their turn, depend on the radiative ability of the melts (ε) and the transmission of intermediate media (T), in our case this is sapphire.

The processes of melting and casting of metals are optimized in accordance with the scale of real temperatures. To pass to the latter, it is necessary to know the values of ε and T and to make the corresponding corrections for the indications of pyrometric systems. This can be achieved only in the case when such corrections are stable. It is impossible to realize metrological control of radiation pyrometry in industry without studying optical thermometric characteristics of melts and light guides under particular conditions. Therefore, investigations in this field were started immediately after the introduction of first pyrometers into metallurgy [1–5].

The use of immersion light guides essentially reduces, or, in ideal cases, practically excludes methodological errors of optical thermometry. In [6–8] and in other works the influence of temperature on the transmission of sapphire is studied, and some desired, though insufficient, thermometric data are obtained. However, effective radiation pyrometry using light guides requires more detailed information on the influence of the conditions of the growth and use of sapphire crystals on the thermometric characteristics of sapphire light guides.

A stationary immersion light guide works under the conditions of considerable temperature gradients in the depth of the lining. Shown in Fig. 1 is the distribution of temperatures in the depth of quartzite lining of the wall of the induction furnace IChT-10 at filling of the crucible with metal (PH) and in the steady-state regime (SR), the melt temperature being 1500°C. The distribution pattern is defined by the thermal

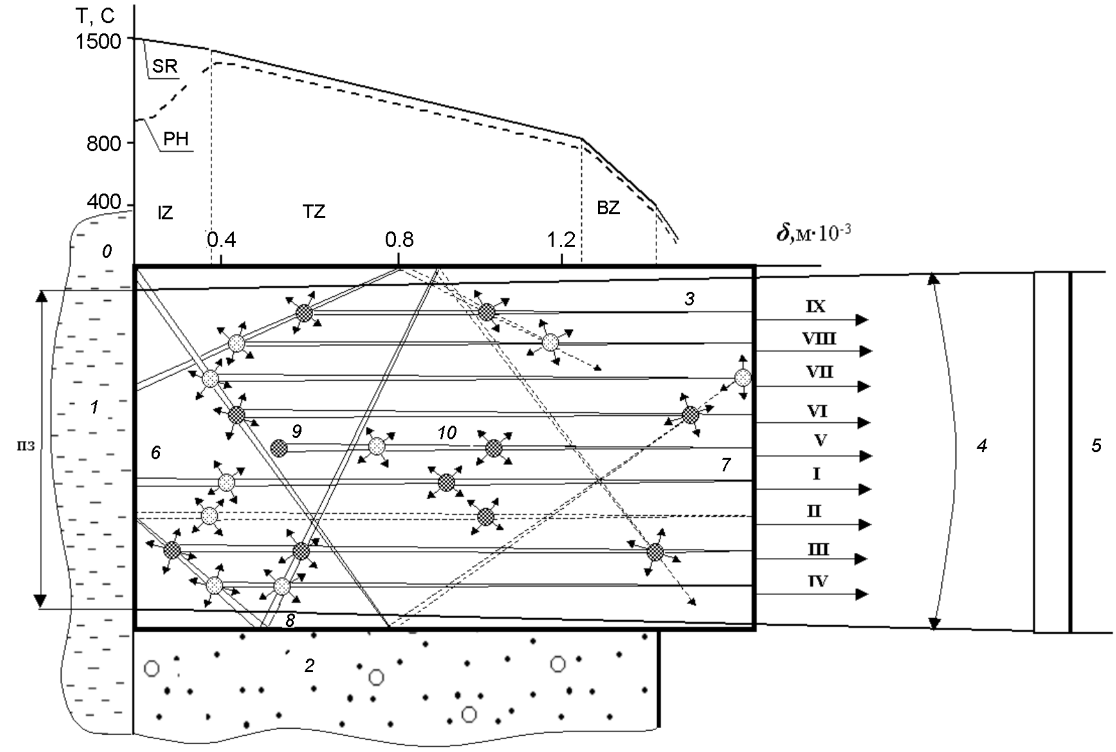

Fig. 1. Scheme of melt thermometry using immersion light guide: *1* — melt, *2* — furnace lining, *3* — light guide, *4* — solid angle of view, *5* — radiation converter, *6* — immersion light guide end, *7* — outer light guide end, *8* — side light guide surface, *9*, *10* — colloidal and molecular light guide inhomogeneities.

characteristics of the lining zones: inner (IZ), transient (TZ) and buffer (BZ), and by their thermal and temperature conductivity. The light guide operates under the action of varying temperature and, consequently, mechanical factors. At selective registration of the radiation within the solid angle of view *4* of the converter *5*, the output signal of the detector is defined by the intensity of the own, reflected, absorbed and scattered radiation of the ends *6*, *7* and of the light guide side surface 8, as well as by the density of colloidal and molecular optical inhomogeneities *9* and *10* of the light guide.

The mentioned characteristics change under the varying mechanical loads and temperature gradient which affect the light guide in the process of its operation. They influence the intensity, polarization, spectral and spatial radiation distribution. The reflection coefficient depends on the ratio of the refractive index of the medium surrounding the outer light guide end to the refractive index of the light guide. At non-uniformly varying distribution of stresses and temperatures, the refractive index changes along the light guide length, too, and this influences the intensity and spatial distribution of the transmitted radiation. Molecular scattering of the radiation in light guides linearly depends on the temperature. As is known, the light scattered by crystal lattice defects is proportional to the absolute temperature [9]. The processes of light scattering in non-uniformly heated light guides are much more complex than those in isothermal media. At non-uniform heating the intensity of bulk molecular scattering depends on the temperature and its distribution within the crystal. In real light guides molecular scattering is complemented by more essential scattering on colloid optical inhomogeneities.

Now consider the main components of the radiation extracted by a cylindrical light guide with flat ends in the solid angle of view (Fig. 1). The intensity of the own radiation of the immersion end (*IE*), the side surface (*SS*) and the optical inhomogeneities (*OI*) is defined by their temperature and radiative ability: $IE = f(T_{it}, \varepsilon_{it})$; $SS_{бn} = f(T_{бn}, \varepsilon_{бn})$; $OI = f(T_{oi}, \varepsilon \mathrm{oi})$.

Proceeding from the above-said and taking into account the conditions when the light guide works in a lining, it is difficult to estimate the influence of each component on the transmission. Therefore, the light guide transmission should be estimated by the effective value of this parameter P_{ef}, which includes all the components. The value informative for thermometry is the radiation of the immersion end within the field of view of the primary parametric converter PZ.

The light guide P_{ef} is also defined by the loss due to light scattering on optical inhomogeneities, light absorption by the light guide, internal reflection, the Fresnel reflection from the outer end and the own radiation of the inhomogeneities.

As found while analyzing the work of the light guide in a lining, the metrological characteristics of thermometry using light guide are essentially dependent on the initial optical characteristics of sapphire, first of all, on its transmission within the working spectral range. The initial transmission is the integrated characteristic of the quantity and properties of optical inhomogeneities in the light guide bulk which defines the level of losses in the light guide radiation. The initial light guide transmission defines the intensity of the incident radiation and, consequently, the output signal of the detector and the instrumental error of the pyrometric system.

To measure the temperature of Fe–C and Cu melts by means of light guide, there are silicon photon radiation detectors work in photodiode and generator regimes.

Valid from the viewpoint of metrology is the regime of short circuit. To realize the latter, the output signal of the detector is to be increased by raising the initial light guide transmission. When the signal is increased twofold in the real range, the basic error of the secondary converter becomes less practically by half.

At preset parameters of the raw material, the stuff used for the crucible and shaper, as well as the composition of the atmosphere, the transmission of sapphire is defined by the growth conditions and the crystallographic features (Fig. 2). Sapphire rods with a diameter of 5.5 mm and a length of 100 mm were grown by the Stepanov method at a rate of 20–60 mm/h in the crystallographic directions <0001> and <11$\bar{2}$0>. The transmission was measured within the spectral range from 0.3 μm to 1.1 μm overlapping the working range of silicon detectors (0.4–1.1 μm).

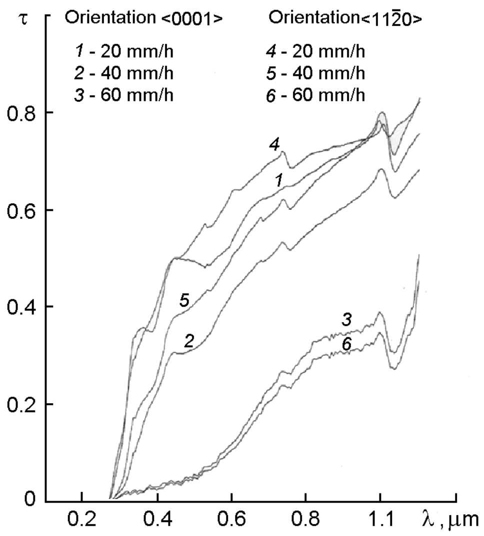

Fig. 2. Transmission of sapphire light guides depending on their orientation and growth rate.

The Stepanov method allows the growth of sapphire rods at a rate up to $\nu \sim 150$ mm/h. The most essential influence of the growth rate is observed within 20–60 mm/hr interval. At $\nu > 60$ mm/hr the transmission diminishes down to inadmissible values. At $\nu < 20$ mm/hr the transmission coefficient exponentially rises to a small extent. The crystallographic directions <0001> and <11$\bar{2}$0> are mutually perpendicular. More preferable for thermometry using light guides is the direction <0001>. In this case the light guide geometrical axis coincides with the principal optical axis of the crystal, and birefringence is absent. This simplifies the optical junction of the light guide with the primary pyrometric converter or the focuser of the pyrometric system. Moreover, at the growth of the crystal along the direction <11$\bar{2}$0> the basal plane is parallel to the growth direction. In comparison with other planes, the basal plane is easily facetted with subsequent formation of a plane on the light guide side surface. To prevent such a faceting, process engineers must take special measures.

The rise of the growth rate leads to the increase of the density of dislocations, vacancy centers and their aggregates. Vacancy coagulation gives rise to the formation of scattering centers and, consequently, diminishes the transmission of sapphire. Naturally, this diminution is observed at the growth of sapphire crystals in any crystallographic direction.

The dependence of the transmission on the crystallographic direction is less obvious. In the literature such data are absent [10]. The measurement of the transmission of a sapphire cube in different directions does not show noticeable distinctions. At the same time, the transmission of the light guides grown along the direction of the principal optical axis at $\nu = 20$–40 mm/h (Curves 1, 2) is lower in comparison with that of the crystals with the orientation $<11\bar{2}0>$ (Curves 4, 5). This is connected with the fact that in the former case the crystallization front coincides with the plane (0001) which is most closely packed. The growth rate in this direction is minimal, and the crystal tends to overgrow with adjacent crystal planes. This increases the density of scattering centers and diminishes the light guide transmission which is especially noticeable when the length of the crystal considerably exceeds its diameter. At $\nu \geq 60$ mm/hr the quantity of optical imhomogeneities rises, the influence of the growth rate becomes dominating and even suppresses the influence of crystallographic direction.

In the shorter-wave part of the studied spectral range the transmission for all the crystallographic directions decreases, as sapphire absorbs the testing electromagnetic radiation.

Thus, there are determined the components of the radiation extracted by immersion cylindrical light guides mounted in the lining of metallurgical furnaces. Shown is the influence of the working regimes of the light guides on their effective transmission. To diminish the methodological and instrumental errors of the temperature measurements realized using light guides, it is necessary to increase the initial transmission of the light guides. The influence of the regimes of the growth of sapphire light guides on their transmission is studied. Established is the influence of the growth rate and crystallographic direction of the light guides on their transmission. The maximal transmission of electromagnetic radiation in the visible and near infrared spectral regions optimal for thermometry using light guides is achieved for sapphire grown at a rate not exceeding 20 mm/h in the crystallographic direction $<11\bar{2}0>$.

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Особливості використання сапфірових світловодів у металургії

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Визначено складові випромінювання, що виводиться крізь футерівку металургійних печей імерсійними циліндричними сапфіровими світловодами. Доведено вплив режимів вирощування та експлуатації світловодів на їх ефективне пропускання.