THERMOPROBE METHOD OF MEASURING THE TEMPERATURE OF MOLTEN METAL AND THE DIFFERENCE BETWEEN METAL TEMPERATURE AND CRYSTALLIZATION POINT

L. A. Sokolov and G. S. Sel'kin

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The authors propose a method of measuring T_m and $\Delta T_s = T_m - T_{cr}$ based on the laws of heat transfer between a cooled wall and molten metal.

At present, the temperature of the molten steel in steel smelting plants is measured with tungsten vs. rhenium or platinum thermocouples, protected by special sleeves. These instruments are capable of giving continuous readings for 3–5 melts. It is difficult to increase the life of the thermocouples since thermocouple and sleeve materials with adequate resistance to the thermal and chemical action of molten steel are not yet available [1].

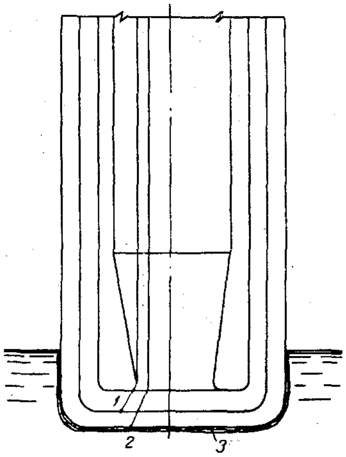

Fig. 1. Section through thermoprobe head: 1 and 2) thermocouple junctions, 3) crystallized skin.

A second important thermal smelting parameter is the difference between the temperature of the steel and its crystallization point. At present, there is no means of checking this parameter. Therefore the development of a new method of long-term (up to 1 furnace run) and continuous measurement of these quantities is a matter of immediate concern.

Such a method is described in this paper.

For the case of molten metal in contact with a copper wall calibration gives relations of the form

$$T_m = f(q, T_{cr}), \tag{1}$$

$$\Delta T_s = \varphi(q, T_{cr}). \tag{2}$$

In calibration the metal temperature T_m is measured by a reference immersion thermocouple, the crystallization temperature is determined from the percentage carbon content in the molten steel, and the heat flow q from the molten metal is measured from the temperature drop in the copper wall, since, with a sufficient degree of accuracy, the temperature distribution over the wall section may be assumed linear. In order to confirm the nature of the temperature distribution we solved the heat conduction equation (one-dimensional variant) for a copper plate with one face at constant temperature, the temperature of the other either varying at a constant rate or fluctuating sinusoidally.

For normal maximum rates of change of metal temperature of 0.08 deg/sec and local temperature fluctuations not exceeding one cycle every 3–4 sec, it was found that the temperature distribution over the section of a copper plate 0.01–0.015 m thick will be practically linear.

Moreover, the investigations showed that linearity of the temperature distribution in a copper plate 0.01 m thick is preserved even at a rate of change of surface temperature of 3 deg/sec, i.e., at values considerably above those normally encountered in practice.

Within these wall thicknesses the thermocouple junctions should be located on the wall surfaces, since in this case ΔT_w will be greatest.

We will consider certain features of heat transfer in molten metals. When molten metal comes into contact with a cooled copper wall, a skin is formed on the wall surface. As our own studies and theoretical and experimental investigations of the continuous steel casting process have shown, the rate of crystallization of metal on cold surfaces is initially very great. Therefore the skin crystallization process is almost instantaneous.

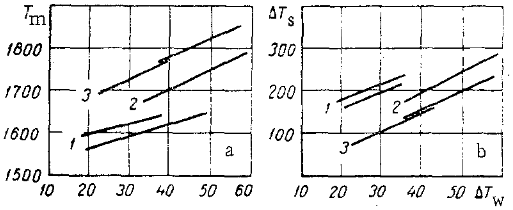

Fig. 2. Calibration curves for determining T_m, °K (a), and ΔT_s, deg (b), from ΔT_w, deg: 1, 2, and 3) for T_{cr} = 1403°, 1503°, and 1613° K, respectively.

Molten steel is one of the liquid-metal heat transfer agents in which an important role in the heat transfer process is played by thermal conduction. Thanks to good mixability the temperature of the metal bath close to the skin on the thermoprobe is the same. Heat transfer takes place in a thin layer at the skin-molten metal interface. In this case the effective metal transfer coefficient is very large. Our investigation has shown that under these conditions the heat transfer process is practically inertialess.

Therefore, for the given, strictly speaking, nonstationary heat transfer process it is possible to use the following equation for the heat flux:

$$q = \alpha_m (T_m - T_{cr}) = \alpha_m \Delta T_s. \qquad (3)$$

Clearly, then, the heat flow from the molten metal is determined only by the heat transfer coefficient α_m and the temperature drop ΔT_s, T_{cr} depending only on the chemical composition of the metal. Thus, the heat flow does not depend on the thermal resistances of the skin, the gap between skin and wall, and the wall, or on the temperature and flowrate of the wall coolant. The heat flow from molten metal to a cooled copper wall can be determined from the formula

$$q = \frac{\lambda}{\delta}(T_w^0 - T_w^i) = \frac{\lambda}{\delta}\Delta T_w. \qquad (4)$$

Determination of the ratio λ/δ involves certain errors. Therefore it is better to find relations of the form

$$T_m = f_1(\Delta T_w, T_{cr}), \qquad (5)$$

$$\Delta T_s = \varphi_1(\Delta T_w, T_{cr}). \qquad (6)$$

By using more heat-resistant, but less heat-conducting wall material, it is possible to increase the difference ΔT_w for the same wall thickness, and hence increase the accuracy of the measurements.

We have designed and built a water-cooled thermoprobe consisting of a seamless outer tube to which a copper head is welded, a seamless inner tube, connections for the circulation of cooling water, and seals for leading out the ends of the thermocouples to the terminal block. The seals and terminal block are contained in housings fastened to the top of the probe. To the outer and inner surfaces of the probe head there are welded the junctions of chromel-alumel thermocouples contained in brass tubes, whose ends extend out through the seals (Fig. 1).

In 1962 the electric arc furnace of the Experimental Plant of the Central Scientific Research Institute of Ferrous Metallurgy was used for a series of experiments on the immersion of a water-cooled copper thermoprobe head in molten metal. The experiment began after preparation of the melt, when the temperature difference ΔT_s in the bath reached 200–300 deg, and was conducted at constant chemical composition of the metal, which cooled with the furnace door open.

During the experiment measurements were made of the metal temperature, the percentage carbon content in the steel, the temperatures of the inner and outer wall surfaces, the temperature of the water at the thermoprobe inlet and outlet, and the rate of flow of water to the probe. After introduction of the copper head into the working space of the furnace the temperature drop in the measuring wall was 10 deg. On immersion of the copper head into the steel the temperature of the outer wall surface rapidly increased, reaching a certain maximum. Then, as the bath cooled, the temperature of the outer wall surface fell. Since every 120 sec the tip of an immersion thermocouple was inserted under the copper head, thus setting the molten metal in motion, the temperature of the outer wall surface fluctuated about a certain mean value. The temperature of the inner wall surface, over which water flowed, remained practically constant. The temperature of the water in the probe head scarcely varied and was equal to 280°–290° K.

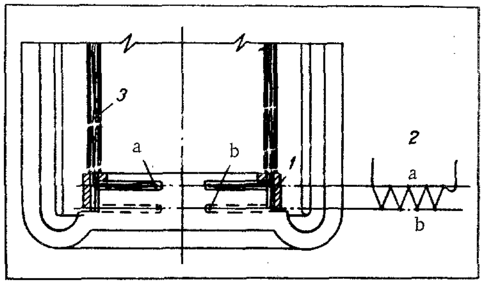

Fig. 3. Section through thermoprobe head: 1) annular gap, 2) thermopile connection diagram, 3) thermo-electrodes in tubes; a, b) thermopile junctions.

As shown by experiments on the immersion of a copper head into molten steel at the Novotulka Metallurgical Plant, the probe can be cooled with saturated steam; however, in that case the outer surface of the probe above the copper head must be thermally insulated.

The temperature drop in the steel at the beginning of the experiment was ΔT_s = 200–300 deg. The crystallization point of the steel remained constant during the experiment. As soon as the temperature drop ΔT_s became equal to 100 deg, the head of the probe was lifted out of the steel and the experiment terminated.

If we draw curves through the mean values of T_w^0 and construct relations (5), (6) on the basis of a series of experiments, we obtain the graphs shown in Fig. 2.

As may be seen from the figure, relations (5), (6) are quite regular, so that T_m and ΔT_s can be measured with a thermoprobe. Judging from the divergence of the curves, the accuracy in determining T_m and ΔT_s with the first type of thermoprobe is ±20° K. Two types of temperature sensors can be mounted in the measuring wall: the first (Fig. 1) involves the welding of a number of thermocouple junctions to the inner and outer surfaces of the measuring wall; the second (Fig. 3) the incorporation into the measuring wall of a ten-junction thermopile.

The first variant is distinguished by the simple mounting of the thermocouples. However, in this case the thermocouples intersect the isothermal lines in the wall at an angle, which is undesirable.

In the second variant the thermo-electrodes are located along the isothermal lines, and it is possible to sum the thermo-emf's of the individual temperature sensors. However, the assembly of the thermopile is more complex, the more so in that it is now necessary to insulate the thermo-electrode junctions from the wall without increasing their inertia. An annular air gap was created in order to reduce heat losses through the end faces of the measuring wall to the necessary minimum.

It should be noted that in the process of steel-making the carbon content of the steel changes. However, these changes take place slowly and can be checked by ordinary methods of chemical analysis. This makes it possible in measuring T_m and ΔT_s to introduce corrections for the change in crystallization temperature. In measuring the temperatures of nonferrous molten metals, in which the presence of an impurity often has no effect on T_{cr}, there is no need for this correction.

Before the copper head of the thermoprobe can enter the molten steel, it must pass through a thick layer of slag, and a dense film of slag may form on the surface of the head. The presence of slag prevents the formation of a metal skin and makes measurements impossible.

As experiments on an electric arc furnace have shown, characteristic signs of the presence of a slag film are a slight rise in the temperature of the outer wall surface at the moment when it comes into contact with the molten metal and the presence of a small constant temperature drop in the wall of the head when immersed in the molten metal.

To exclude this effect, the rate of penetration of the copper head through the slag layer and its surface temperature must be sufficiently high. This reduces the possibility of formation of a tough film of slag on the probe surface. Therefore it may be preferable to use heat-resistant heads that can operate at higher temperatures than copper.

NOTATION

T is the temperature; $\Delta T_s = T_m - T_{cr}$ is the difference between metal temperature and crystallization temperature; $\Delta T_w = T_w^0 - T_w^i$ is the difference between temperatures of outer and inner wall surfaces of thermoprobe head; q is the heat flux; λ is the heat conductivity; α_m is the coefficient of heat transfer from molten metal to wall of thermoprobe head; δ is the distance between thermocouple junctions measuring temperatures of outer and inner wall surfaces.

REFERENCE

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Moscow Institute of
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