

HEAT TRANSFER BETWEEN A LIQUID METAL AND THE SOLID METAL CRUST FORMED ON A WATER-COOLED COPPER WALL

L. A. Sokolov

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This paper describes the two-phase region at the interface of the solid and liquid phases. The effect of change in thickness of the crust on the heat transfer between the water-cooled copper wall and the liquid metal is examined.

Heat-engineering investigations led to the development of a method of continuous measurement of the temperature T_M of a liquid metal and the difference ΔT between the temperature of the metal and its crystallization point. The method is based on the principles of heat transfer between the liquid metal and the solid metal crust crystallized on the water-cooled copper wall. The method consists essentially in the use of calibration to find a relationship between the thermal parameters T_M and ΔT of the liquid metal and the heat flux q incident on a water-cooled copper head submerged in the liquid metal.

Comparative Data on Crystallization Points of Liquid Steel

Carbon content, %	Crystallization point of liquid metal		
	determined from iron-carbon diagram	Andreev's data	Pronin's data
0.1	1799	1789	1783
0.2	1790	1777	1773
0.3	1782	1666	1763
0.4	1773	1757	1755
0.5	1766	1753	1748

When the liquid metal comes in contact with the water-cooled copper wall a crust is formed on the surface of the wall; the thickness of this crust can vary in time. There is a two-phase region at the interface of the solid and liquid phases. The presence of the above-mentioned factors is a special feature of this kind of heat transfer.

The aim of the present paper is to reveal the nature of the crystallized solid crust and how the change in its thickness affects the heat flux q incident on the wall. The clarification of this question is important for estimation of the accuracy of the new method of measurement, since the heat flux is the main parameter from which the thermal parameters T_M and ΔT are determined.

To solve this problem we consider some aspects of the mechanism of heat transfer between a liquid metal and a water-cooled copper wall from investigations in a TsNIChM electric arc furnace.

The experimental procedure was as follows:

When the melt was ready a special device with a water-cooled copper head was lowered through the roof of the furnace. The experiment began when part of the copper head was immersed in the liquid metal. The copper head was a cylinder with a flat end wall.

The junctions of thermocouples were soldered close to the center of the inner and outer surfaces of the wall. At the start of the experiment the difference between the temperature of the metal and its crystallization point was $T_M - T_{Cr} = 200 - 250$ deg. The door of the furnace was then opened and the metal was allowed to cool. The rate of reduction of the temperature of the liquid metal was 0.3 deg/sec. The chemical composition of the steel during the experiment was constant.

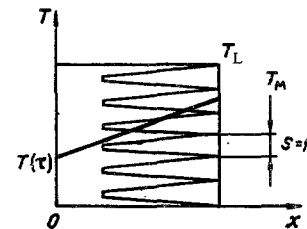


Fig. 1. Temperature distribution over cross section of crust.

The temperatures of the inner and outer surfaces of the end wall of the head, immersed in the liquid metal, were continuously measured. The temperature of the liquid metal in the furnace was measured every 60-120 sec by immersion thermocouples. The flow of water for cooling the copper head was constant. In the treatment of the experimental data the temperature of the liquidus line, determined by the percentage composition of carbon in the steel with the aid of the iron-carbon diagram, was taken as the crystallization point.

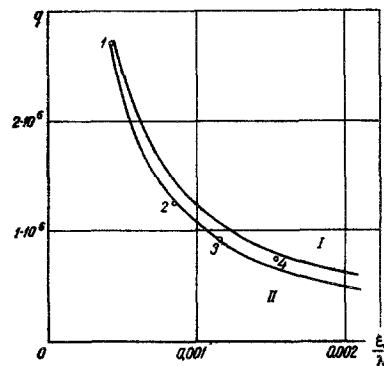


Fig. 2. Relationship between heat flux q , W/m^2 and thermal resistance ξ/λ , $deg \cdot m^2/W$ of gap (II). Points 1, 2, 3, and 4 are the thermal resistances of the same kind of steel.

Andreev and Pronin obtained values for the crystallization point [1], which are compared in the table

with the temperatures of the liquidus line determined from the iron-carbon diagram for the same percentage amounts of carbon in the steel. The compatibility of the figures in the table confirms that the crystallization point can be determined in this way. The thickness of the copper wall of the head was 0.008 mm. The maximum thickness of the crystallized crust at the end of the experiment was not more than 0.01 m.

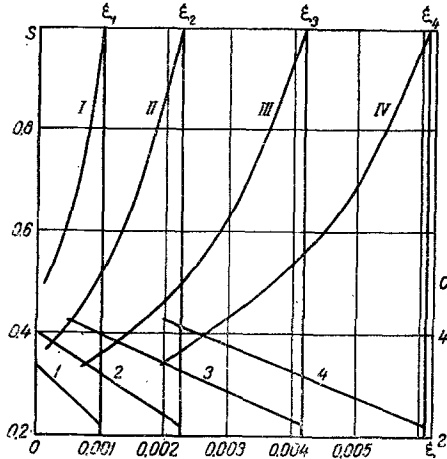


Fig. 3. Cross section S of liquid phase and carbon content C , % in relation to crust thickness ξ , m for different intervals of time: I and 1) $S(x)$ and $C(x)$ for τ_1 , respectively; II and 2) the same for τ_2 ; III and 3) for τ_3 ; IV and 4) for τ_4 .

Since the change in temperature of the metal in unit time is slight, the thermal conductivities of the copper wall and crystallized crust are high, and they are thin, the temperature distribution in cross sections of the wall and crust at different periods of time will be practically linear (first assumption).

The diffusion equation [2, 3] must be used to determine the dimensions of the two-phase region in the crystallized crust. This equation is derived on the assumption that the change in the impurity in an element of volume of the liquid phase in the two-phase region is due both to diffusion perpendicular to the lines of concentration of the impurity in the liquid phase and to direct removal of some of the impurity by solidification. As investigations have shown, the diffusion of carbon in crystallization processes has practically no effect on the final results.

It follows from this that the term containing the diffusion coefficient can be omitted from the diffusion equation (second assumption). In view of this the mathematical formulation of the problem (Fig. 1) will have the following form:

The mass balance equation [1, 2] is

$$KC \frac{\partial S}{\partial \tau} = \frac{\partial (CS)}{\partial \tau}. \quad (1)$$

Here $S(x, \tau)$, the cross-sectional area of the liquid phase, characterizes the two-phase state of the medium at each point, and C is the percentage amount of carbon.

The equation of the liquidus line on the iron-carbon diagram (we assume that the liquidus line is straight) is

$$T = T_A - \beta C. \quad (2)$$

The equation for the temperature distribution in the cross section of the crust is

$$T = a + bx. \quad (3)$$

The boundary conditions on the crust are

$$T(0, \tau) = T(\tau), \quad (4)$$

$$T(\xi, \tau) = T_L. \quad (5)$$

The solution of the system of equations (1)-(3) (the constants a and b in Eq. (3) are determined from the boundary conditions (4) and (5)) is

$$T = T(\tau) + \frac{T_L - T(\tau)}{\xi} x. \quad (6)$$

The amount of heat transmitted through the crust is

$$q(\tau) = \frac{\lambda}{\xi} [T_L - T(\tau)]. \quad (7)$$

In view of (7), Eq. (6) will take the form

$$T = T(\tau) + \frac{q(\tau)}{\lambda} x. \quad (8)$$

Substituting the value of T in (8) in formula (2), we find an expression for the carbon content C

$$C = \frac{T_A}{\beta} - \frac{T(\tau)}{\beta} - \frac{q(\tau)}{\beta \lambda} x. \quad (9)$$

The mass balance equation (1) is solved in the following way:

$$KCdS = d(SC); \quad S = (C_0/C)^{1/(1-K)}.$$

Assuming that when $S = 1$, $T = T_L$, $C = C_0$, $\beta C_0 = T_A - T_L$ (see (2)), and taking (9) into account, we obtain the solution of the mass balance equation (2)

$$S = \sqrt[1-K]{\frac{(T_A - T_L)}{\left(T_A - T(\tau) - \frac{q(\tau)}{\lambda} x\right)}} \quad (10)$$

for $T > T_{eut}$.

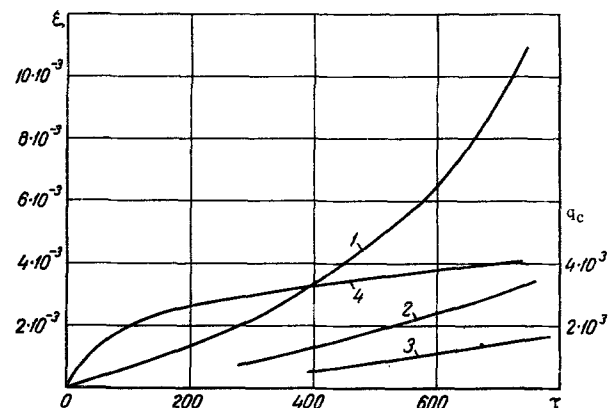


Fig. 4. Crust thickness ξ , m (1, 2, 3) and amount of heat q_c , W/m^2 (4) released due to crystallization against time τ , sec.

The amount of heat transferred from the liquid metal to the crust is given by the formula

$$q = \alpha_m (T_m - T_{cr}) = \alpha_m \Delta T. \quad (11)$$

The crystallization point T_{cr} depends only on the chemical composition of the steel. The heat transfer coefficient α_M for liquid steel in free-convection conditions depends on the temperature difference $\Delta T = T_M - T_{cr}$ and on the physical constants of the steel. The physical constants (particularly the thermal conductivity) depend on the temperature of the liquid steel at the boundary with the solid crust, the temperature of the outer surface of which is equal to the crystallization point. This means that relationships between T_M , ΔT , and q must be found for each chemical composition of steel and its corresponding crystallization point.

As a consideration of (11) shows, the heat flux associated with heat transfer between the liquid metal and the solid metal crust formed on the water-cooled copper wall depends only on the values of ΔT ($\Delta T \gg \gg 0$), α_M , and T_{cr} . It follows from this that the heat flux in the presence of a temperature difference is independent of the thermal resistance of the crust, the gap between the crust and the wall, and the rate of cooling of the wall itself. On the other hand, these quantities, being interrelated to some extent, depend on the heat flux. This is the essential difference from heat transfer through an ordinary wall where the heat flux depends entirely on the thermal resistance of the wall itself and the thermal resistances at its boundaries. This feature of the heat transfer is a favorable factor from the viewpoint of conducting measurements, since a change in the indicated quantities will not affect the accuracy of measurement of the heat flux.

The heat flux incident on the copper wall was calculated from the formula

$$q = \frac{\lambda}{\delta} [T_w^{ext} - T_w^{int}].$$

The thermal conductivity of the copper was determined on a special apparatus. The distance between the junctions of the chromel-alumel thermocouples, which measure the temperature of the wall surface, was measured after the wall had been cut across through the thermocouple junctions. It was 0.0076 m. The thermocouples were soldered to the wall surface with brass solder.

We will estimate the degree of accuracy of measurement of the heat flux. The aggregate effect of the errors in measurement of the distance between the junctions, calibration of the thermocouples, and determination of the relationship between the thermal conductivity of copper and the temperature led to an equal increase or decrease of the measured heat flux in all the experiments. It is difficult to estimate the absolute value of this over-all error. In the treatment of the results of investigations it would cause a slight shift of the corresponding curves along one of the coordinate axes. The qualitative nature of the investigated effect would not be affected.

The error in measurement of the wall surface temperature by the secondary instrument can have either sign and, hence, requires special consideration. The secondary instrument used for measurement of the temperatures was a EPP-09 electronic potentiometer.

The maximum error in measurement due to this instrument after a check calibration was $\pm 2^\circ \text{C}$.

During the experiments the temperature difference ΔT_w in the wall was $25^\circ\text{--}80^\circ \text{C}$. If we refer these two degrees to the lower temperature difference ΔT_w we obtain $2/25 \cdot 100 = 8\%$ as the error in measurement of the heat flux, and if to the greater difference ΔT_w , we obtain $2/80 \cdot 100 = 2.5\%$ as the error. Thus, the error in measurement of the heat flux from the temperature difference in the wall is 2.5–8%.

The thickness $\xi(\tau)$ of the crystallized crust was found in the following way. The initial data for the calculation were the thicknesses of the crust at the start, middle, and end of the experiment, obtained by direct measurement when the copper head was removed from the liquid metal for short periods. The thickness of the crust was measured on the flat end wall of the head at the position of the thermocouple junctions on its surface. Within this small area the thickness of the crust was practically uniform. Such measurements were carried out in several experiments. We first found the relationship between the heat flux q and the total thermal resistance of the crust and gap $(\xi/\lambda)_c + (\xi/\lambda)_g = (T_L - T_w^{ext})/q$ (curve 1 in Fig. 2).

The thermal conductivity of the thin crust at temperatures close to the crystallization point is $\lambda = 23.3 \text{ W/m}\cdot\text{deg}$. This and the initial data for the thickness of the crust were used to find the value of $(\xi/\lambda)_c$.

In Fig. 2 these values lie on curve I, while curve II is drawn through the points 1, 2, 3 and 4, after which $(\xi/\lambda)_c$ is converted to $\xi(\tau)$. Such a conversion is possible since the values of $(\xi/\lambda)_c + (\xi/\lambda)_g$ for a constant rate of cooling are determined by the heat flux, which varies in a known manner during the experiment.

The line segments from the y axis to curve II represent the thermal resistance of the gap. Hence curve II is the ratio of the thermal resistance of the gap and the heat flux. As an examination of curves I and II shows, the thermal resistance of the gap is much greater than that of the crust.

Knowing $q(\tau)$ and $\xi(\tau)$, we determine $T(\tau) = T_L - q\xi/\lambda$. Substituting $T(\tau)$ in formula (10), we obtain $S(x, \tau)$. The graphs in Fig. 3 are plotted from the data of one of the experiments.

When the liquid metal in the furnace cools, the thickness of the crust on the copper head steadily increases. For instance, in one experiment the thickness of the crust 120 sec after immersion of the head in the liquid metal was 0.001 m, after 270 sec it was 0.0023 m, and so on (Fig. 3). At time $\tau_1 = 120 \text{ sec}$ and the corresponding crust thickness $\xi_1 = 0.001$ the cross section of the liquid phase on the surface of the crust in contact with the metal wall was $S = 0.46$. At time $\tau_3 = 450 \text{ sec}$ and crust thickness $\xi_3 = 0.0041$ the

cross section of the liquid phase in the section of crust at a distance of 0.0003 m from its surface changed abruptly from $S = 0.3$ to $S = 0$. The reason for this is as follows: at the boundary of the two-phase region, where the cross section of the liquid phase is $S = 1$, the percentage amount of carbon is the same as in the liquid metal. As the cross section of the liquid phase decreases and the temperature in it drops, crystals which are poorest in carbon are precipitated first. Hence, the percentage carbon content increases steadily in the remaining part of the liquid phase. For a crust of thickness $\xi_3 = 0.0041$ in a cross section of liquid phase $S = 0.3$, the percentage amount of carbon is the same as that of the eutectic. At this chemical composition the liquid changes abruptly to a solid.

As an examination of Fig. 3 shows, at time $\tau_1 = 120$ sec and $\tau_2 = 270$ sec the whole crust is in the two-phase region. At $\tau_3 = 450$ sec and $\tau_4 = 540$ sec the two-phase region occupies a large part of the crust. There is only a small layer of completely formed crystals on the cold side of the crust. Calculations showed that the two-phase region formed by the crystallization of high-carbon steels has appreciable dimensions. The thermal conductivity of carbon steels close to the melting point is the same and is $\lambda = 23.3$ W/m·deg. One explanation of this may be that carbon steels at temperature close to the crystallization point are in a two-phase state.

We will determine the amount of heat released by crystallization as the thickness of the crust changes. Figure 4 shows plots, from the results of three experiments, of crust thickness against time for the case of cooling of metal in a furnace with constant flow of water for cooling the head and constant percentage carbon content of the liquid steel.

The different nature of the curves 1, 2, and 3 is due to the fact that the conditions of cooling of liquid metal in a furnace with an open door are different for various reasons.

Using curve 1, we can determine the amount of heat released by crystallization of the crust from the formula $q_c = q_{cr} \gamma \frac{d\xi}{d\tau}$. This curve is represented by the formula

$$\xi = 1.9 \cdot 10^{-6} \tau^{1.31}.$$

Using this formula to determine $\frac{d\xi}{d\tau}$, we find the heat flux q_c due to crystallization of the crust. In Fig. 2 the minimum value of q for $\Sigma \frac{\xi}{\lambda} = 0.002$ is $0.4 \cdot 10^6$ W/m². Comparing the maximum value $q_c = 4 \cdot 10^3$ W/m² (Fig. 4) with the minimum heat flux from the liquid metal side $q = 0.4 \cdot 10^6$ W/m², corresponding to the least probable case (Fig. 2), we see that the first value is 1% of the second. The calculation was carried out for the case where the rate of change of temperature of the steel during cooling in an electric-arc furnace was 0.3 deg/sec. In operational conditions in steel plants the maximum rate of temperature variation in the metal at the melting stage is 0.07 deg/sec. Hence, the change in crust thickness during measurement of the thermal parameters T_M and ΔT of liquid steel from the heat flux incident on a water-cooled copper wall, will lead to an error of less than 1%.

NOTATION

τ is the time; x is the variable coordinate; ξ is the crust thickness; T is the temperature; q is the heat flux; S is the proportion of liquid phase in the two-phase region; C is the carbon content; λ is the thermal conductivity; $K = C_{solid}/C_{liqu.}$; α_M is the coefficient of heat transfer from liquid metal to crust; T_A is the temperature of metal with carbon content $C = 0$; T_w^{ext} is the temperature of the wall surface in contact with liquid metal; T_w^{int} is the temperature of the wall surface in contact with water; β is the angle of inclination of the liquidus line; δ is the distance between the thermocouple junctions in the copper wall.

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Bardin Institute of Ferrous Metallurgy, Moscow