Journal of Engineering Physics and Thermophysics, Vol. 82, No. 4, 2009

SELECTION OF CONVECTIVE HEAT TRANSFER COEFFICIENT FROM COMPARISON OF EXPERIMENTAL DATA WITH RESULTS OF MATHEMATICAL MODELING

I. Yu. Puzakov, E. N. Kondrashov, and A. Yu. Maksimov

UDC 621.74;669

We propose a simple method for determining the convective heat transfer coefficient from a vacuum arc remolten ingot into a helium atmosphere upon cooling after removing power from the furnace. To this end, the consumable electrode end temperature was measured experimentally upon furnace depressurization. The heat transfer coefficient was determined with the aid of a mathematical model of the process under consideration by the trial-and-error method.

Keywords: *vacuum arc melting, cooling, helium, heat transfer, modeling.*

Introduction. Earlier [1] we proposed a simple mathematical model of thermal processes in vacuum arc melting and compared the results of numerical calculations with the data of radiographic experiments on molten pool depth for the Russian titanium alloy VT3-1. It was shown that the proposed model describes experimental data quite adequately. However, in [1] we did not perform calculations for the regime of bringing up the pipe and for the subsequent cooling of the ingot upon removing power from the furnace. Under industrial conditions, in melting ingots by the method of vacuum arc remelting cooling is often carried out in a helium atmosphere. Moreover, for example, in melting steels and nickel alloys helium is also supplied into the shrinkage gap directly in the process of melting [2]. In this connection, we propose a combined ("experimental-theoretical") method for determining the convective heat transfer coefficient in a helium atmosphere.

The proposed method is as follows. The consumable electrode is charged into a vacuum arc furnace and its small part is allowed to melt. Then the furnace is de-energized and helium is supplied into it. The electrode and the ingot obtained (templet) are allowed to cool for some time, after which the furnace is depressurized and the temperature of the consumable electrode end is measured. From the results of the experiment, selection of the convective heat transfer coefficient is carried out with the aid of a certain mathematical model of the process under consideration.

In the general form, the process under consideration can be divided arbitrarily into three stages: heating, melting, and cooling.

For each stage, one has to formulate its own heat problem. The solution of the first problem is the initial condition for the second one, and the solution of the second problem is the initial condition for the third problem. We shall consider the problem in one dimension (in the axial direction), which presupposes a uniform radial temperature distribution over the cross-section of the consumable electrode. A similar problem for circonium and nickel alloys was considered in [3]. In the present work, the initial differential equations were discretized by the finite volume method [4]. For the calculations, we employ the thermophysical parameters used by us earlier to analyze the molten pool depth in vacuum arc remelting of titanium alloy VT3-1 [1].

Experimental. The experiment was performed on a vacuum arc furnace of the type of DTV8, 7-G10. A cast electrode of diameter 770 mm from titanium alloy Ti-6Al-4V was charged into a crystallizer of diameter 840 mm and 2400 mm in length. Upon heating the electrode at a current strength of 8 kA (voltage of 28 V) for 20 min the current strength was increased to 25 kA and 50 mm of an ingot were molten. Then the current was switched off and helium was supplied into the furnace up to a pressure of 8 torr. Moreover, to reduce the thermal influence of the obtained ingot, the consumable electrode was raised through 250 mm. Upon cooling in the helium atmosphere for 60 min the

Verkhnyaya Salda Metallurgical Association, 1 Parkovaya Str., Verkhnyaya Salda, Sverdlovsk Region, 624670, Russia; email: evgeniy.kondrashov@vsmpo.ru. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 82, No. 4, pp. 718–720, July–August, 2009. Original article submitted March 5, 2008; revision submitted October 8, 2008.

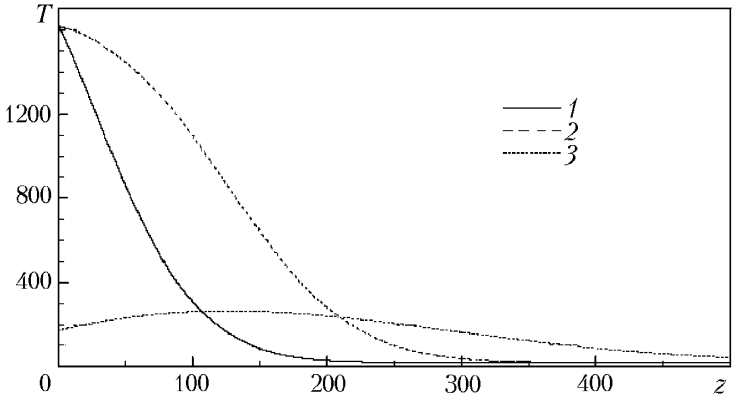

Fig. 1. Consumable electrode temperature versus the coordinate upon completion of different stages of the process: 1) T_h; 2) T_m; 3) T_c. T, °C; z, mm.

furnace was depressurized and the consumable electrode end temperature was measured by means of a contact thermocouple. The maximum temperature of the electrode was 170°C.

General Model of Cooling the Consumable Electrode End. Below we consider the above-described three-stage mathematical model.

Heating stage. The corresponding heat problem is formulated as follows. Initially we have an infinitely long consumable electrode at a certain temperature T_0. A heat flow from electric arc q is applied to the electrode end ($z = 0$). From the lateral surface of the electrode the heat is removed by radiation into a space with temperature T_0. Thus, the heat problem for the heating stage can be given by the following equations:

$$\rho C_p(T)\frac{\partial T}{\partial \tau} = \frac{\partial}{\partial z}\left(k(T)\frac{\partial T}{\partial z}\right) - \frac{2}{R}\varepsilon(T)\sigma_0\left(T^4 - T_0^4\right), \quad T(\tau = 0, z) = T_0, \quad k(T)\frac{\partial T}{\partial z}\bigg|_{z=0} = q, \quad T\big|_{z\to\infty} = T_0.$$

The problem on the electrode end heating is solved until the electrode end reaches the liquidus temperature of the alloy. Denote the solution of the problem at the heating stage as $T_h(z)$.

Melting Stage. In the process of melting, on the consumable electrode end the temperature corresponding to the liquidus temperature of the alloy T_{liq} remains constant. Thus, we neglect the possible heating of the liquid film on the end to a temperature above the liquidus temperature. In all probability, under real conditions the overheating is very small and the given assumption will not have a substantial effect on the final result. As the electrode melts, its end moves with a linear velocity v, which is determined by the system geometry and the arc current. At this stage of the process it is necessary to take into account in the heat conduction equation the convective term connected with the motion of the consumable electrode end. The problem for the melting stage can be finally formulated as follows:

$$\rho C_p(T)\left(\frac{\partial T}{\partial \tau} + v\frac{\partial T}{\partial z}\right) = \frac{\partial}{\partial z}\left(k(T)\frac{\partial T}{\partial z}\right) - \frac{2}{R}\varepsilon(T)\sigma_0\left(T^4 - T_0^4\right),$$

$$T(\tau = 0, z) = T_h(z), \quad T\big|_{z=0} = T_{liq}, \quad T\big|_{z\to\infty} = T_0.$$

Denote the solution of the problem at the melting stage as $T_m(z)$.

Cooling Stage. At the final stage of the process the arc current is switched off and helium is supplied into the furnace. We shall describe the heat removal due to the helium by the Newton equation, i.e., the heat flow will be defined as $\alpha(T - T_0)$. The quantity α is key in the present work and, as mentioned above, the aim of the work is its determination by the trial-and-error method from comparison of experimental data with calculation results. The boundary condition on the electrode end (as well as on its lateral surface) at the cooling stage corresponds to the simultaneous heat removal by the radiation and the heat transfer through the helium atmosphere. Therefore, the problem for the cooling stage can be given in the form

$$\rho C_p(T)\frac{\partial T}{\partial \tau}=\frac{\partial}{\partial z}\left(k(T)\frac{\partial T}{\partial z}\right)-\frac{2}{R}\tilde{\alpha}(T)\sigma_0\left(T^4-T_0^4\right),\quad T(\tau=0,z)=T_{\rm m}(z),$$

$$k(T)\frac{\partial T}{\partial z}\bigg|_{z=0}=\tilde{\alpha}(T)(T-T_0),\quad T\big|_{z\to\infty}=T_0,$$

where

$$\tilde{\alpha}(T)=\varepsilon(T)\left(T^3+T^2T_0+TT_0^2+T_0^3\right)\sigma_0+\alpha.$$

Denote the solution of the problem at the melting stage as $T_c(z)$. The figure presents the results of calculations for conditions corresponding to the experimental conditions (T_0 = 20°C). To obtain a calculated temperature of the electrode end coinciding with the experimentally measured one, one has to assume α = 94.0 W/(m^2·m). Note one specific feature of $T_c(z)$. This function is not monotonous and has a maximum. Such behavior is due to the intensive cooling of the electrode end and the rather low heat conductivity of titanium-based alloys. The simultaneous action of both factors leads to a shift of the thermal center (temperature maximum) into the depth of the consumable electrode. A similar situation also takes place in the molten ingot when the thermal center from the sub-intake zone goes down to the lower-lying horizons.

Conclusions. A method for determining the convective heat transfer coefficient upon cooling of the consumable electrode after vacuum arc remelting in a helium atmosphere has been considered. A thermal model of the consumable electrode that permits determining the temperature distribution along its length in the considered experiment has been constructed. From a comparison of the experimental data on the electrode end temperature with the calculation results, the heat transfer coefficient for titanium alloys has been determined.

NOTATION

C_p, constant-pressure heat capacity, J/(kg·K); k, heat conductivity coefficient, W/(m·K); q, heat flow, W/m^2; R, ingot radius, m; T, temperature, K; v, melting rate of the electrode, m/sec; z, axial coordinate, m; α, convective heat transfer coefficient, W/(m^2·K); $\tilde{\alpha}$, overall heat transfer coefficient, W/(m^2·K); ε, reduced emissivity factor of the electrode surface and the ingot mould wall; ρ, density, kg/m^3; σ_0, Stefan–Boltzmann constant, W/(m^2·K^4). Subscripts: 0, initial; h, heating; liq, liquidus; m, melting; c, cooling.

REFERENCES

1. E. N. Kondrashov, M. I. Musatov, A. Yu. Maksimov, A. E. Goncharov, and L. V. Konovalov, Calculation of the molten pool depth in vacuum arc remelting of alloy Vt3-1, *J. Eng. Thermophys.*, **16**, No. 1, 19–25 (2007).
2. V. I. Potapov, *Mathematical Models of Thermophysical Processes in Multilayer-Structure Objects* [in Russian], Izd. YuUrGU, Chelyabinsk (2004).
3. A. Jardy, L. Falk, and D. Ablitzer, The energy exchange during vacuum arc remelting, *Ironmaking Steelmaking*, **19**, No. 3, 226–232 (1992).
4. S. Patankar, *Numerical Heat Transfer and Fluid Flow*, Hemisphere, New York (1980).