METHOD OF CALCULATING THICKNESS AND COOLING INTENSITY OF STRIPS OBTAINED BY SUPERFAST COOLING OF METAL FROM THE LIQUID STATE

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From analysis of the balance of forces the authors have obtained expressions to determine the thickness of a strip on solidification in a rotating crystallizer, and have solved the problem of defining the cooling rate of these strips.

In the last 15 years there has been widespread use of processes producing materials by methods of rapid cooling (usually faster than 10^3 K/sec) of a metal from the liquid state. Here considerable morphological changes have occurred in the structure of metals and alloys because of large deviations from equilibrium conditions of the crystallization process. It has become possible to stabilize metastable phases, to expand the region of solid solubility, and to form an amorphous state, and in the final analysis to obtain materials with physical and mechanical properties considerably superior to those of traditional alloys [1].

At present two main methods of rapid cooling have been applied: contact with a heat-removing solid; and in a liquid or gaseous medium. The end product takes the form of strips, fibers or filaments when formed on a heat-removing solid, and the form of dispersed particles or fibers when formed in a liquid or gas. The strip materials are frequently obtained on one or two rotating crystallizer shafts. When there is outflow into one crystallizer shaft, the supply of liquid metal to the cooling surface is achieved by one of three methods: discharge upward from a casting system under the action of a metal-static head or excess pressure (spinning); capture of a thin strip of melt by a shaft in a bath underneath (extraction); and freezing on the shaft from an open casting box located at the side.

In designing technical equipment one must calculate the influence of the geometrical parameters and the operating regimes (diameter of the crystallizer shaft, its thickness, width, the material, the rotation frequency, the mass flow rate of melt from the casting system, etc.) on the output and quality of the production. The thinner the strip, the lower is the output, other conditions being equal. However, thin strips are cooled more rapidly, i.e., one obtains a better quality of output. If one could calculate the strip dimensions (the thickness, in particular) and its rate of cooling one could optimize the geometrical parameters of the technical equipment and regimes for obtaining rapidly cooled materials.

The literature contains studies to determine the melt layer thickness formed when the melt is deflected from the bath by a rotating shaft [2, 3], and when it is cast on a single rotating shaft [4, 5]. Theoretical relations have been developed, based either on reduction of experimental data [4], or on analysis of vortex flow of the melt captured by the shaft [3]. Some of these dependences are suitable only for special cases of the process, while others are too complex for widespread use.

A number of studies [6-8] have calculated the intensity of cooling of a strip of melt on the basis of an analytical solution of the one-dimensional heat conduction equation. A defect of these calculations is the significant number of simplifications and assumptions (heat transfer of the captured strip and the crystallizer with the surrounding medium is not accounted for, etc.), which resulted in an inaccurate determination of the cooling rate.

In this paper we address the problem of developing a method of calculating the thickness of strips and their cooling rate when cast on a single rotating shaft, allowing for the specific technical conditions.

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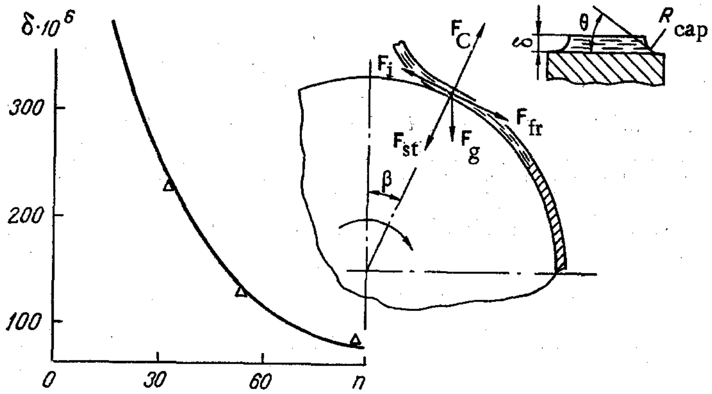

Fig. 1

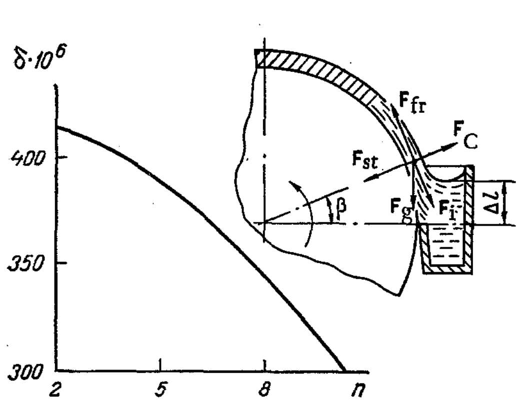

Fig. 2

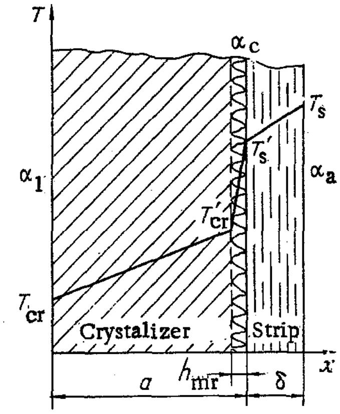

Fig. 3

Fig. 1. Balance of forces acting on an elementary section of the melt, and dependence of the strip thickness δ on the frequency of rotation n of the crystallizer shaft in the spin method; R_{cr} = 0.1 m; the curve is theory, and the points are experiment.

Fig. 2. Balance of forces acting on an elementary section of the melt, and the calculated dependence of the strip thickness δ on the rotational frequency n of the crystallizer shaft when casting by freezing; R_{cr} = 0.3 m.

Fig. 3. Calculated scheme for determining the effective coefficient of contact heat transfer α_c and the strip cooling rate ε.

We have proposed a model for the process of forming the strip thickness, based on the premise that the spreading out and retention of the melt layer at the periphery of the rotating shaft is governed by surface tension forces. This model makes sense only in the case when the material of the crystallizer shaft is wetted by the liquid metal. Evidence for the validity of this postulate are the results of analysis of the energy balance for a jet, a drop, a cooling surface, and an air boundary layer [4]. The calculations were performed for two schemes for the supply of liquid metal: 1) supply under the action of the metal-static head (spin method); 2) on capture of the melt by a shaft in contact with a volume of liquid metal (casting by freezing).

With the melt supplied by the first scheme (Fig. 1) the calculation of thickness is based on analysis of the balance of forces acting on an elementary section of the melt. The forces of friction, gravitation and surface tension hold the melt on the shaft, and the centrifugal force and the inertia force disrupt it. In vector form the force balance is expressed as:

$$F_{st} + F_g + F_{fr} + F_C + F_i = 0. \quad (1)$$

The liquid metal particle is captured only when the inertia force is equal to the friction force plus the projection on it of the gravitational force.

The centrifugal forces, the gravitational forces, and the surface tension forces are:

$$F_C = 4\pi^2 n^2 \rho\delta R_{cr} A, \quad (2)$$

$$F_g = \rho\delta g A \cos\beta, \quad (3)$$

$$F_{st} = \frac{\sigma}{R_c} A = \frac{\sigma}{\delta} A \cos\theta. \quad (4)$$

From the solution of Eqs. (2)-(4) we find the maximum thickness of liquid metal strip formed on a rotating crystallizer shaft:

$$\delta = \sqrt{\frac{\sigma\cos\theta}{4\rho\pi^2 n^2 R_{cr} - \rho g\cos\beta}}. \quad (5)$$

When the gravitational acceleration is less than 5% of the centripetal force, Eq. (5) is simplified:

$$\delta = \frac{1}{2\pi n}\sqrt{\frac{\sigma\cos\theta}{\rho R_{cr}}}. \quad (5')$$

When the melt is supplied according to the second scheme (Fig. 2) the balance of inertia and friction forces is written as follows:

$$F_g + f(F_{st} + F_C) + F_i = 0. \quad (6)$$

If we assume that the captured liquid metal particle, accelerated in the section $\Delta\ell$ to velocity v, moves with uniform acceleration, then the acceleration is

$$a_p = \frac{v^2}{2\Delta l}. \quad (7)$$

In this case the friction coefficient is expressed from Eq. (6), taking into account Eqs. (2)-(4) and (7), as:

$$f = \frac{\rho\delta(a_p + g\cos\beta)}{\frac{\sigma}{\delta}\cos\theta - 4\pi^2 n^2 R_{cr}\rho\delta + \rho\delta g\sin\beta}. \quad (8)$$

From Eq. (8) we find the thickness of strip formed to be:

$$\delta = \sqrt{\frac{f\sigma\cos\theta}{\rho(a_p + g\cos\beta + 4f\pi^2 R_{cr} n^2 - fg\sin\beta)}}. \quad (9)$$

As can be seen from Eqs. (1)-(9), to calculate the strip thickness we need to determine the wetting contact angle, which was found here from the height of a column of melt contained in a copper capillary. It was established experimentally that the wetting angle of aluminum on copper (allowing for shrinkage on solidification) is 50...55° for σ = 0.86 N/m.

In determining the cooling rate of the strip of melt of aluminum alloy, a number of assumptions were made to simplify the formulation. We considered an elementary length section of the copper crystallizer shaft, and therefore assumed that the temperature gradient was negligibly small over the length and curvature of the section. The water stream cooling the shaft from within had a temperature of T_ℓ = 293 K. The temperature of the air, cooling the strip from the outside, T_a was also 293 K. The heat transfer between the air and the side walls of the crystallizer and the strip was negligibly small. The melt temperature at the moment of injection onto the crystallizer shaft (τ = 0) was T_s = 1300 K. The thermal conductivity of the melt strip was λ_s = 104 W/(m·K).

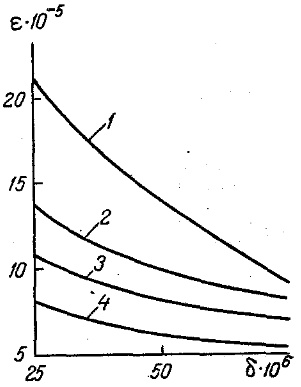

Fig. 4. Dependence of the cooling rate ε of the melt strip on its thickness δ for various values of α_c: 1) $\alpha_c = 150 \cdot 10^3$ W/(m²·K); 2) $75 \cdot 10^3$; 3) $50 \cdot 10^3$; 4) $15 \cdot 10^3$.

The cooling rate of the melt layer of a specific thickness formed (as a function of the outflow conditions) was determined by solving the system of homogeneous equations (Fig. 3):

$$\frac{\partial T}{\partial \tau} = \varkappa \frac{\partial^2 T}{\partial x^2}; \qquad 0 < x < a + \delta, \ \tau > 0, \tag{10}$$

$$\alpha_l (T_{cr} - T_l) = -\lambda_{cr} \frac{\partial T_{cr}}{\partial x}; \ x = 0, \ \tau > 0, \tag{11}$$

$$-\lambda_s \frac{\partial T_s}{\partial x} = \alpha_c (T_s' - T_{cr}'); \ x = a, \ \tau > 0, \tag{12}$$

$$-\lambda_{cr} \frac{\partial T_{cr}}{\partial x} = \alpha_c (T_s' - T_{cr}'); \ x = a, \ \tau > 0, \tag{13}$$

$$\alpha_a (T_s - T_a) = -\lambda_s \frac{\partial T_s}{\partial x}; \ x = a + \delta, \ \tau > 0. \tag{14}$$

The effective coefficient of contact heat transfer α_c from the strip to the crystallizer was calculated as the ratio of the thermal conductivity of the air in the gap λ_a to the mean height of microroughnesses of the periphery of the shaft forming the gap (Fig. 3). The calculations were performed for crystallizer shafts obtained by rough milling [h_{mr} = 23 μ, $\alpha_c = 15 \cdot 10^3$ W/(m²·K)], semifinished milling [h_{mr} = 7 μ, $\alpha_c = 50 \cdot 10^3$ W/(m²·K)], finished milling [h_{mr} = 4.6 μ, $\alpha_c = 75 \cdot 10^3$ W/(m²·K)], and polished finish [h_{mr} = 2.3 μ, $\alpha_c = 15 \cdot 10^4$ W/(m²·K)].

The problem was solved numerically on a computer.

Figure 1 shows the influence of the rotation frequency of the shaft on the thickness of the strip formed during outflow of the melt under the metal-static pressure. The calculated values are compared with the experimental obtained on an equipment with radius R_{cr} = 0.1 m at rotation frequency 33, 50, and 83 rev/sec. One can see that experiment and theory are in good agreement (the errors are not more than 12%).

The experiments were conducted at a rotation frequency of 2.67 rev/sec on the equipment operating on the principle of melt capture from an open casting box having a copper shaft of radius 0.3 m and a casting system inclined at an angle of 17.5°. The normal flow of the process was accomplished with a free height $\Delta \ell$ of the molten aluminum layer of not less than $3.5 \cdot 10^{-3}$ m. From the experiments we can determine the coefficient of friction between the melt and the wall of the crystallizer, f ≈ 0.3. From the data obtained we calculated the dependence of the strip thickness on the shaft rotation frequency (see Fig. 2).

Figure 4 shows the calculated intensity of cooling for strips of different thickness of aluminum alloys, cooled in copper crystallizers with surfaces of different finish. It can be seen that the coefficient of contact heat transfer has a great influence on the cooling rate, which varies in the range ε = $10^6 \ldots 10^5$ K/sec with $\alpha_c = 15 \cdot 10^4$ W/(m²·K) for strips of thickness from $25 \cdot 10^{-6}$ to $100 \cdot 10^{-6}$ m. Correctness of the calculation was monitored indirectly according to the quality of the output. The specimens obtained on the polished shaft (h_{mr} = 2.3 μ) had a fine-grained structure and an increased strength limit (by 10-15%) compared with specimens obtained on the shaft with the rough surface (h_{mr} = 23 μ).

NOTATION

A, area, m^2; a, thickness of the crystallizer, m; a_p, acceleration, m/sec^2; F, force, N; f, friction coefficient; g, gravitational acceleration, m/sec^2; h, height, m; $\Delta\ell$, free height of the melt layer, m; n, frequency of rotation, sec^{-1}; R, radius, m; T, temperature, K; T', temperature of the contact, K; v, velocity, m/sec; x, coordinate; α, coefficient of heat transfer, $W/(m^2 \cdot K)$; β, slope angle of the casting system, deg; δ, thickness of the melt strip, m; ε, rate of cooling, °K/sec; θ, wetting contact angle, deg; λ, thermal conductivity, $W/(m^2 \cdot K)$; κ, thermal diffusivity, m^2/sec; ρ, density, kg/m^3; i, coefficient of surface tension, N/m; τ, time, sec. Subscripts: a, air; g, gravitation; ℓ, liquid; i, inertia; c, contact; cap, capillary; cr, crystallizer; s, strip; mr, microroughness; st, surface tension; fr, friction; C, centrifugal; p, particle.

LITERATURE CITED

1. R. A. Andrievskii and A. A. Nuzhdin, Powder Metallurgy, Vol. 2 (Scientific and Technical Results of VINITI, Academy of Sciences of the USSR) [in Russian], Moscow (1986), pp. 3-64.
2. V. A. Vasil'ev and P. S. Mitin, Izv. Akad. Nauk SSSR, Met., No. 6, 71-76 (1982).
3. T. R. Anthony and H. E. Cline, J. Appl. Phys., Vol. 50, No. 1, 239-244 (1979).
4. Sh. Kavesh, Metallic Glasses [Russian translation], J. J. Hillman and H. J. Lim (eds.), Moscow (1984), pp. 39-66.
5. I. V. Zolotukhin, Physical Properties of Amorphous Metallic Materials [in Russian], Moscow (1986).
6. I. S. Miroshnichenko, Quenching from the Liquid State [in Russian], Moscow (1982).
7. Yu. K. Kavneristyi, N. P. Bolotina, A. A. Ravaev, et al., Izv. Akad. Nauk SSSR, Met., No. 4, 76-79 (1983).
8. O. A. Ivanov and Sh. M. Sheikhaliev, Izv. Akad. Nauk SSSR, Met., No. 5, 70-73 (1985).

EFFECTIVE THERMAL CONDUCTIVITY OF A STRUCTURED POWDER

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The effective conductivity in a granular bed may be substantially dependent on the transport at granule contacts.

Interest attaches to heat and mass transfer in granular layers because these are widely used in engineering [1-4]; it is difficult to examine theoretically the transport in such media particularly because there are numerous particles, which may pack in various ways, and because there are simulatneous mechanisms differing in nature, whose contributions to the total flux in general are not additive. For example, there may be major components due to conduction in the particles and in the gaps between them, convection in the pores, and phenomena in the contact zones involving surrounding gas and liquid lenses.

A single model cannot incorporate all the phenomena affecting transport here; a more constructive approach involves examining the various mechanisms separately.

The framework conductivity in a granular bed has been examined in experiments on the effective thermal conductivity for a lightly pressed layer of nickel spheres less than a micron in diameter. The pressing has been placed in various media. To insure that the specimen maintained its shape, it was sintered at 750°C and 10^2-10^3 atm. The particles adhered but did not fuse. The pressing increased the contact areas and increased the framework conductivity, while reducing the importance of conduction in the pores. Small parti-

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