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ENGINEERING SOLUTION TO THE PROBLEM OF INGOT SOLIDIFICATION IN SLAB CONTINUOUS-CASTING MACHINES

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An engineering solution to ingot solidification and the regularities of growth of an ingot envelope thickness and the coordinate of the end of slab solidification directly on slab continuous-casting machines (SCCM) are given, and ingot solidification conditions are determined. Examples of calculation of the envelope thickness and the coordinate of the end of solidification are provided for slab continuous-casting machines utilized at the Cherepovetsk integrated metallurgical complex (CherMC) and at the cast-and-iron works of the Aisenhüttenstadt Joint-Stock Company. A graphical algorithm for determining the cooling capacity of the secondary cooling zone is presented, and a nomogram for calibration of the cooling capacity of forced secondary cooling against the major and minor radii of an SCCM is developed.

To control thermal processes of steel casting in slab continuous-casting machines, a mathematical model of solidification processes has been developed.

The thermal scheme of an SCCM is shown in Fig. 1. Liquid steel with a superheating temperature of $t_0 = 1530-1560$ C is brought in ladle 1 from a converter to intermediate ladle 2 and then to copper mold 3,where primary (zone I) formation of an ingot envelope occurs. A heat flux Q_m is removed to cooling water. Then an ingot with a thickness $\delta_m \approx 18-20$ mm of its envelope enters zone II of secondary cooling, where the heat flux is carried away by forced water or jet-type water-air cooling $Q_{w.a}$ and water-cooled rolls 4 Q_r. After that the ingot arrives at zone III, where it is cooled.

One of the main concepts of the heat technology of continuous steel casting is provision of complete solidification of an ingot over a horizontal section of an SCCM in the region of $h_{e.s}$. Before complete ingot solidification it is necessary to remove the heat flux

$$Q = [r\rho_{liq} + c_{liq}\rho_{liq}(t_0 - t_{s.s}) + 0.5(t_{s.s} - t_{e.s})\, c_s\rho_s]\, \frac{2Blv}{60}, \tag{1}$$

i.e., for the characteristic parameters of casting on SCCMs at $r = 220$ kJ/kg; $c_{liq} = 0.68$ kJ/(kg·K); $c_s = 0.65$ kJ/(kg·K); $\rho_{liq} = 7800$ kg/m^3; $t_0 = 1550^oC$; $t_{s.s} = 900$ C; $l = 1.5$ m; $B = 0.125$ m; $V = 0.9$ m/min. In accordance with (1), we obtain $Q \approx 20$ MW.

We may nowcalculate two components of balance, namely, the heat removed to the cooling water of the mold and to the internally cooled rolls.

In the mold, with the water flow rate $G_m = 360$ m^3/h, for the water temperature drop at the inlet and outlet $\Delta t_w = 8$ K the heat flux is equal to

$$Q_m = \frac{G_m\,\Delta t_w\, c_w \rho_w}{3600} = \frac{360\cdot 4.19\cdot 10^3\cdot 8}{3600} = 3.5 \text{ MW}.$$

In the case of water-cooled rolls, with the total water consumption $R_r = 600$ m^3/h and $\Delta t_r = 12$ K:

$$Q_r = \frac{G_r\,\Delta t_r\, c_w \rho_w}{3600} = \frac{600\cdot 12\cdot 4.19\cdot 10^3}{3600} = 8.5 \text{ MW}.$$

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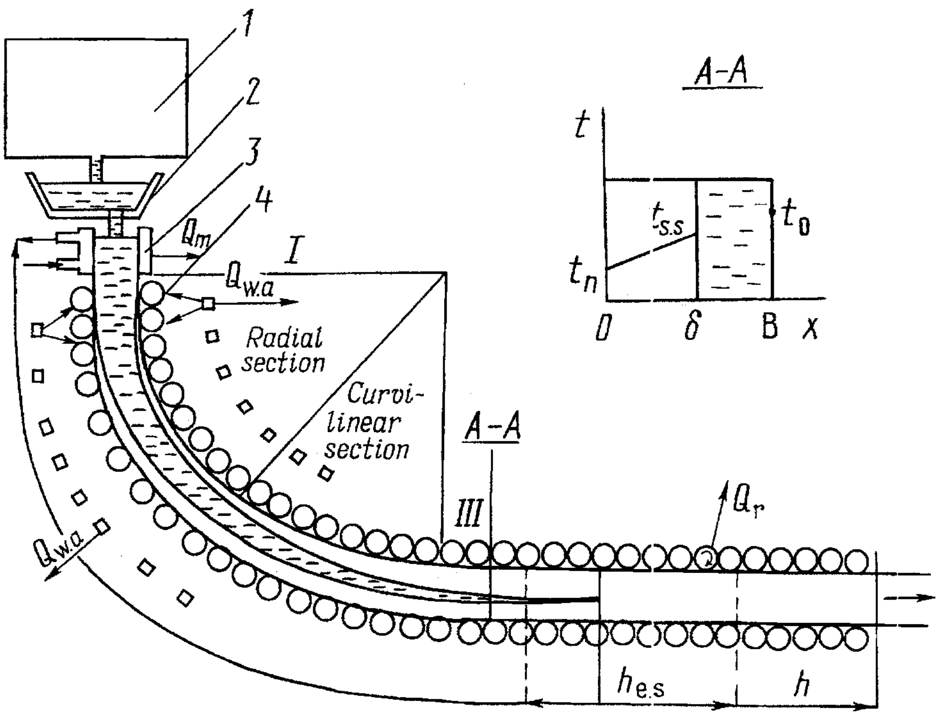

Fig. 1. Thermal scheme of an SCCM. Q_m, $Q_{w.a}$, Q_r, W; $h_{e.s}$, h, m; B, m; δ, m; t_0, $t_{s.s}$, t_{sur}, °C.

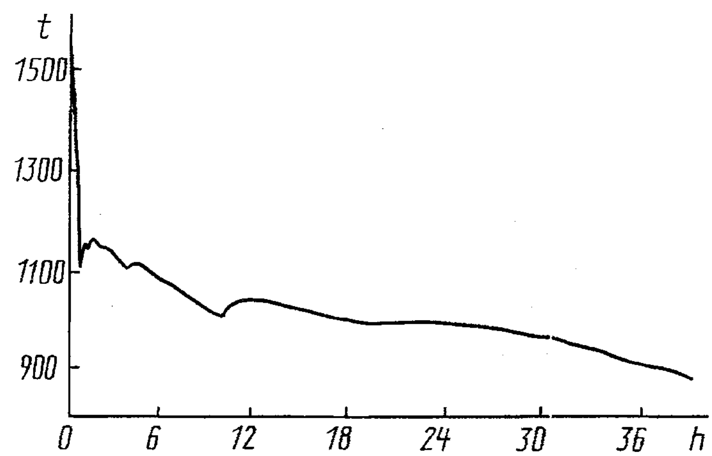

Fig. 2. Temperature variatrion over a slab surface. t, °C; h, m.

This means that the heat flux is removed in equal portions by the rolls or by the forced water or water-air cooling. In the case of unregulated roll cooling and absence of an algorithmic dependence of the cooling capacity of forced cooling, it is necessary to calibrate the secondary-cooling system directly on the machine and then to compose a calculation model for control of the heat technology of casting.

The design solution for SCCMs and experience in operating them have shown that the surface temperature in the middle part of an ingot, just beyond the section subject to jet-type forced cooling, is the most informative parameter that determines the intensity of ingot cooling in secondary zone II. We propose a method and a design of a probe that allows continuous measurement of this temperature directly in a machine. In connection with this it is reasonable to solve the problem of ingot solidification with boundary conditions of the first kind.

Full-scale measurements of the temperature fields on a slab surface in its middle part on different SCCMs (a representative dependence is given in Fig. 2) have enabled us to build a graphical algorithm of this dependence (Fig. 3).

The investigations conducted have revealed that the temperature distribution in zone 1 in a mold is close to linear and may be described by the expression

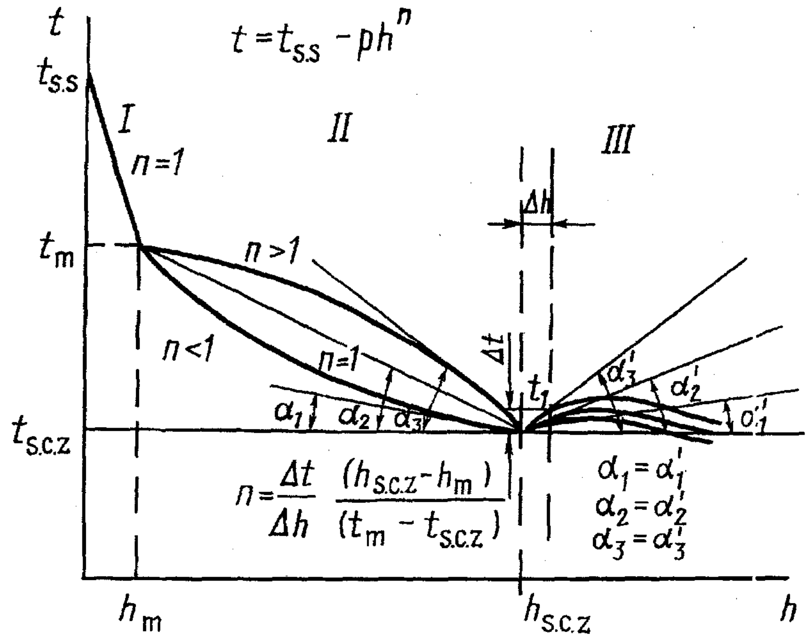

Fig. 3. Geometric algorithm for determining the cooling capacity of a secondary-cooling system. $t_{s.s}$, t_m, $t_{s.c.z}$, ^{0}C; h_m, $h_{s.c.z}$, Δh, m; α, deg.

$$t_m = t_{s.s} - Kh_1 = t_{s.s} - \frac{K_1}{V} h_1 , \quad 0 \le h_1 \le h_m \tag{2}$$

K_1 depends mainly on the mold design and is independent of the technological parameters of casting, and its value for engineering calculations may be assumed constant. For instance, for the third SCCM at CherMC $K_1 = 3.7$ K/sec at $h_m = 1.2$ m, while for a mold of the "Fest Alpine" machine installed at the cast-and-iron works of the Aisenhüttenstadt Joint-Stock Company $K_1 = 6$ K/sec at $h_m = 0.8$ m. This is explained by the fact that the heat is removed mainly in the upper part of the mold.

In zone II of jet-type cooling the integral temperature distribution on a slab surface is curvilinear and may be described in general form by the function

$$t_{s.c.z} = t_m - ph_2^n , \qquad h_m < h_2 \le h_{s.c.z} , \tag{3}$$

where n, p characterize the cooling intensity, $n \lesseqgtr 1$.

Investigations have shown that the intensity of secondary heating of a slab in the presence of an internal liquid phase is comparable to that of preceding cooling. This fact lies behind the determination of n and p. Figure 3 presents a graphical algorithm for their determination.

Knowing the casting rate v, we measure the temperature of the slab surface at the end of the forced cooling zone $t_{s.c.z}$, $\Delta h = (0.05-0.1) h_{s.c.z}$. The intensity of the secondary heating at the point $h_{s.c.z}$ is determined as

$$m_2 = \Delta t / \Delta h .$$

On the other hand, the derivative at this point is

$$m_1 = \left. \frac{dt_{s.c.z}}{dh} \right|_{h_2 = h_{s.c.z}} = n \frac{t_m - t_{s.c.z}}{h_{s.c.z} - h_m} .$$

As a result, we arrive at the design formulas

$$n = \frac{\Delta t}{\Delta h} \frac{h_{s.c.z} - h_m}{t_m - t_{s.c.z}} \quad \text{and} \tag{4}$$

$$p = \frac{t_m - t_{s.c.z}}{(h_{s.c.z} - h_m)^n}.$$

These parameters will be the initial ones for calculating the envelope thickness beyond the secondary cooling zone.

The solution of the one-dimensional Stefan problem [1] for ingot solidification in cross section AA (Fig. 1) with boundary conditions of the first kind is

$$t(x, \tau) = t_{sur} + (t_{s.s} - t_{sur}) \frac{\operatorname{erf}(x/2\sqrt{a\tau})}{\operatorname{erf}(\delta/2\sqrt{a\tau})}. \tag{5}$$

It is advisable to perform casting in an equilibrium regime when the heat removed from the surface is equal to that supplied in phase transformation, i.e., the temperature distribution over the envelope thickness is linear. This regime may be achieved under the condition

$$\frac{\delta}{2\sqrt{a\tau}} \leq 0.7; \tag{6}$$

In this case, the Gaussian error function may be approximated as follows:

$$\operatorname{erf}\frac{\delta}{2\sqrt{a\tau}} \sim \frac{\delta}{2\sqrt{a\tau}}, \tag{7}$$

and expression (5) takes the form

$$t_{(x)} = t_{sur} + (t_{s.s} - t_{sur}) \frac{x}{\delta}. \tag{8}$$

A linear temperature distribution over the ingot thickness makes it possible to pour a metal with minimum temperature stresses and maximum heat release. Moreover, with condition (6) the solidification problem may be solved for a piecewise-linear or curvilinear temperature distribution over the slab surface since an equilibrium process is a quasistationary one. Below, it will be shown that pouring in this regime does not contradict the trends in the development of steel continuous-casting technology. These considerations underlie the determination of the envelope thickness in a casting line: the envelope thickness beneath a mold may be calculated, in accordance with [2], by the formula

$$\delta_m = \sqrt{\left(\frac{K}{v\beta_0}\right) h_1} = \sqrt{\left(\frac{K_1}{\beta_0}\right) \frac{h_1}{v}}, \tag{9}$$

where

$$\beta_0 = \frac{\rho_{liq} + c_{liq}\rho_{liq}(t_0 - t_{s.s})}{\lambda_s}. \tag{10}$$

In the zone of forced cooling this dependence has the form

$$\delta_{s.c.z} = \sqrt{\left(\frac{2ph_2^{n+1}}{(n+1)\, v\beta_0}\right)} = \sqrt{\left(\frac{2\,(t_{s.s} - t_{s.c.z})}{(n+1)\, v\beta_0}\right)} \sqrt{h_2}. \tag{11}$$

Taking into account condition (6) and dependences (9, 10), we obtain an equilibrium criterion for the casting process:

$$\eta_t^m = \frac{K_1 h_1}{2a\beta_0 v} < 1 \tag{12}$$

and

$$\eta_t^{s.c.z} = \frac{ph_2^n}{(n+1)\beta_0 a} = \frac{t_m - t_{s.c.z}}{(n+1)\beta_0 a} < 1. \tag{13}$$

TABLE 1. Results of Calculation of the Envelope Thickness and the Coordinate of the End of Solidification for the Third SCCM and a "Fest Alpine" Machine

v, m/min	$t_{s.c.z}$, °C	t_1, °C	η_t^m	$\eta_t^{s.c.z}$	δ_m, mm	$\delta_{s.c.z}$, mm	$h_{e.s}$, m
Third SCCM							
0.9	907	940	0.36	0.4	17	81	29.4
0.8	862	907	0.4	0.36	19	77	28.9
"Fest Alpine" machine							
1.0	1015	1032	0.48	0.15	. 16	35	27.3

For continuous temperature measurement of the slab surface directly in an SCCM we have developed a thermal-state probe of hot metal and a method for calibrating it [3]. The measuring system and the algorithm for control of ingot solidification have allowed us to provide a metrology of the thermal processes of casting. For instance, for a mold:

h_m, m	K_1, K/sec	v, m/min	β_0, K	η_t^m
1.1	3.7	1.0	371	0.36
0.8	6.0	1.0	371	0.44

In the both cases the solidification regime is anequilibrium one.

For the secondary-cooling zone:

$t_{s.s}$, °C	$t_{s.c.z}$, °C	K_1, K/sec	h_m, m	v, m/min	β_0, K	n	$\eta_t^{s.c.z}$
1500	900	3.7	1.1	1.0	371	1	0.48
1500	850	3.7	1.1	1.0	371	0.3	0.84

In the first case, the cooling regime is an equilibrium one, and in the case of excess cooling (n = 0.3) the solidification regime is close to nonequilibrium, i.e., for the ingot solidification regime to be equilibrium, it is necessary to control the secondary cooling zone by the temperature of the slab surface.

With the intensity parameters n and p being known, the coordinate of the end of solidification (at $\delta_m + \delta_{s.c.z} = B$) is determined from the expression

$$h_{e.s} = h_m + \left[\frac{(b - (\delta_m)^2 (n + 1) \beta_0 v}{2p} \right]^{1/(n+1)} . \tag{14}$$

Based on the aforesaid, we shall provide examples of calculation of the ingot envelope thickness and the coordinate of the end of solidification.

A probe was placed on the third SCCM beyond the secondary cooling zone at the mark $h_{s.c.z}$ = 21.6 m. The temperature of secondary heating was measured in intervals Δh = 1.8 m. At v = 0.9 m/min (see Table 1) the total water flow rate over the minor radius in the secondary-cooling zone was ΣG = 25 m^3/h, and at v = 0.8 m/min, ΣG = 23.5 m^3/h. For the "Fest Alpine" machine, h_m = 0.8 m, Δh = 2 m, $h_{s.c.z}$ = 10 m.

The thermophysical parameters entering the formulas were as follows. For the third SCCM $2B$ = 0.250 m, t_0 = 1550°C, t_s = 1500°C, r = 220 kJ/kg, ρ_{liq} = 7500 kg/m^3, c_{liq} = 0.68 kJ/(K·kg), λ = 27.2 W/(m·K), $\beta_0 = 70 \cdot 10^6$

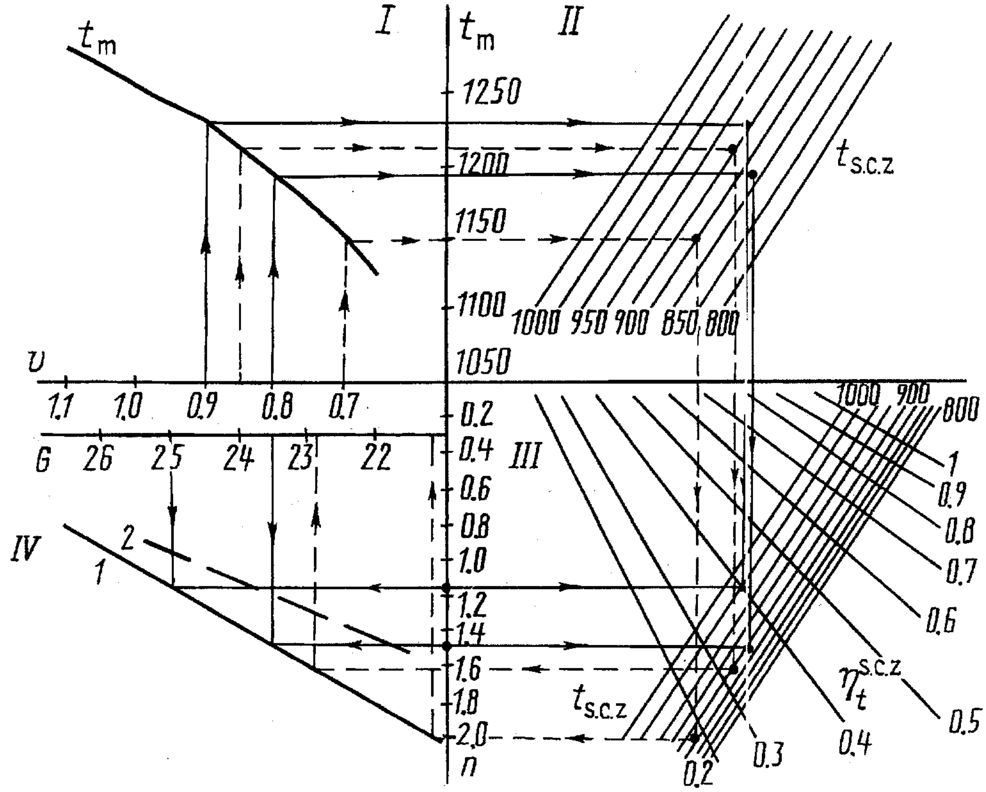

Fig. 4. Nomogram for calibrating the cooling capacity of forced secondary cooling: 1) minor radius; 2) major radius; t_m, $t_{s.c.z}$, °C; v, m/min; G, m^3/h;

$K \cdot sec/m^2$. For the "Fest Alpine" machine $2B = 0.200$ m, $t_0 = 1560$°C, $r = 272$ kJ/kg, $\beta_{liq} = 7500$ kg/m^3, $C_{liq} = 0.67$ kJ/(kg·K), $\lambda = 41.3$ W/(m·K), $\beta_0 = 57 \cdot 10^6$ K·sec/m^2.

Indirect measurements of the coordinate of the end of ingot solidification made by other methods confirm the reliability of these results.

A calibration system for the cooling capacity of forced secondary cooling against the major and minor radii of an SCCM is depicted in Fig. 4. In the first quadrant of the nomogram the temperature of the slab surface beneath the casting mold t_m versus the pouring rate at an intensity of heat release $K_1 = 3.7$ K/sec is constructed. The thermophysical properties of the steel are assumed to be constant and equal to the values used in the heat balance calculation.

In the second, third, and fourth quadrants the slab surface temperature just beyond the forced secondary-cooling zone $t_{s.c.z}$, the criterion $\eta_t^{s.c.z}$, and finally the total flow rate ΣG as a function of the intensity n of slab cooling over the minor and major radii are constructed.

The solid lines show the algorithm for constructing the calibration dependence of the cooling capacity of the regulated forced-cooling zone. The parameters v, $t_{s.c.z}$, n are measured, and $\Sigma G = f(n)$ is constructed.

The dashed line depicts the algorithm for control of slab cooling. For this, v, $t_{s.c.z}$ are prescribed, and the water flow rate is determined.

CONCLUSIONS

1. If machine cooling is unregulated and sprayers with unregulated parameters (flow rate vs pressure, spraying flare, the size of the dispersed liquid drop) are used, an algorithmic dependence of the cooling capacity of the secondary cooling zone of a slab is lacking. In this case, it is necessary to calibrate the forced cooling system directly on the SCCM and, on this basis, to control the pouring process.

2. Regularities of the growth of the envelope thickness and the coordinate of the end of ingot solidification are discussed. Formulas are derived for an equilibrium solidification regime that is characterized by equality of the

heat flux removed in the mold and the secondary-cooling zone to the heat of phase transformation at the solid-liquid interface.

3. A procedure for calibration of the secondary cooling system is proposed. At present, the third and fifth SCCMs operated at CherMC are equipped with measuring systems and secondary devices that permit calibration and control of the cooling capacity of a slab by the equipment and sprayers.

4. It is recommended to enterprises that SCCMs be equipped with the measuring devices and the procedure for calibrating the secondary-cooling system.

NOTATION

δ_m, envelope thickness in the mold, m; $\delta_{s.c.z}$, envelope thickness in the secondary-cooling zone, m; B, half-thickness of the slab; l, slab width, m; h_1, current length of the mold, m; h_m, mold length, m; h_2, current length of the secondary-cooling zone, m; $h_{s.c.z}$, length of the secondary-cooling zone, m; h, technological length of the machine, m; Δh, distance along which the secondary heating is measured, m; $h_{e.s}$, coordinate of the end of ingot solidification, m; t_0, temperature in the ladle, ^oC; $t_{s.s}$, temperature of steel solidification, ^oC; t_m, temperature of the ingot surface at the mold outlet, ^oC; $t_{s.c.z}$, temperature of the ingot surface at the end of the forced-cooling zone, ^oC; $t_{e.s}$, temperature of the slab surface at the end of complete solidification, ^oC; r, heat of the phase transformation of the ingot, J/kg; c_{liq}, c_s, specific heat of the liquid and solid steel, respectively, J/(kg·K); ρ_{liq}, ρ_s, density of the liquid and solid steel, respectively, kg/m^3; v, pouring velocity, m/min; K_1, rate of temperature change on the ingot surface in the mold, K/sec; ΣG, total water flow rate in the secondary-cooling zone, m^3/h; Q_m, heat flux removed to the cooling water of the mold, W; $Q_{w.a}$, heat flux removed by water or water-air cooling, W; Q_r, heat flux removed by water-cooled rolls, W; Q, removed heat flux required for complete solidification of the ingot, W; m_1, intensity of forced cooling; m_2, intensity of secondary heating; erf $(\delta/(2\sqrt{a\tau}))$, Gaussian error function; n, p, coefficients of the power function of the integral temperature distribution over the slab surface: η_t^m, equilibrium criterion of the casting process in the mold; $\eta_t^{s.c.z}$, equilibrium criterion of the casting process in the secondary-cooling zone.

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