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Development of Production Regimes for Twin-Roll Casting of Metal Alloys

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Abstract—Physical and mathematical modelling have been used to study twin-roll casting of metal alloys. It has been found that overheated temperature, casting speed, and the melt level in the gap between rolls are the main production parameters that determine stability of twin-roll casting of metals. Equation of the form $v = f(\delta, \beta, R, \Delta T)$ has been derived that makes it possible to determine the optimal twin-roll casting speed for all examined alloys as a function of specified casting parameters: strip thickness, metal meniscus angle, roll radius, and melt overheat temperature. Experiments carried out using a laboratory setup for twin-roll casting of metals have shown good agreement of the regimes calculated for all the examined alloys with their actual values. Based on the good correlation between the calculated and laboratory results, a conclusion can be drawn that the proposed mathematical model provides a correct description of the actual process of twin-roll casting of metals.

Keywords: twin-roll casting of metals, cast ingot, rolled flat stock, mathematical and physical simulation, casting regimes

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Rolled flat stock is currently produced using primarily conventional technology, in which blank products are first produced as ingots or continuously cast slabs and further subject to mechanical (reduction, rolling) and thermal treatment [1]. However, following the global trends in the development of metallurgy, manufacturers have to implement innovative and leaner technologies. A list of such energy-saving technologies includes twin-roll casting of metal alloys that enables direct production of rolled flat stock directly from liquid metal.

The process, which is common for all production schemes of casting on a moving (roll) crystallizer, is freezing out of the skins of overheated metal melt on the working surfaces of continuously rotating water-cooled crystallizing rolls [2]. The metal melt crystallizes in the process of twin-roll casting under conditions of highly intensive heat exchange, absence of a gap between the skin and the crystallizing roll surface, and unhindered feed of overheated melt to the crystallization front. Thus, favorable conditions for the production of dense cast sections with fine crystalline structure are formed.

The following schemes are used for twin-roll casting of ingots: freezing out on a single roll (Figs. 1a, 1b); freezing out on two rolls rotating in opposite directions with welding of skins without rolling (casting into a roll crystallizer using the liquid rolling scheme (Fig. 1c); freezing out on two rolls with rolling of crystallized skins (casting into a roll crystallizer using the molten-metal strip rolling scheme) (Figs. 1d–1f).

In the case of casting into a roll crystallizer in the liquid rolling scheme (Fig. 1c), the strip stock material is formed by wielding under pressure of two skins frozen out in a bath with melt on the surfaces of two rolls rotating in opposite directions. The stock material outputted from the rolls can contain some amount of liquid phase, since crystallization fronts with a nonuniform profile stick together, and the melt in the reduction zone is not fully squeezed out from the solid/liquid part. The thickness X of the cast is in this case

$$X = \xi_s + \xi_l, \quad (1)$$

where ξ_s is the reduced thickness of the solid phase of the skins frozen out on two rolls and ξ_l is the reduced thickness of the liquid component of the cast.

After leaving rolls, the cast is finally crystallized due to redistribution of temperature in the strip and heat exchange with the environment. The fully crystallized part of the cast is not rolled; therefore, the speed of skin motion in the bath and the strip exit speed are equal to the linear speed of roll rotation.

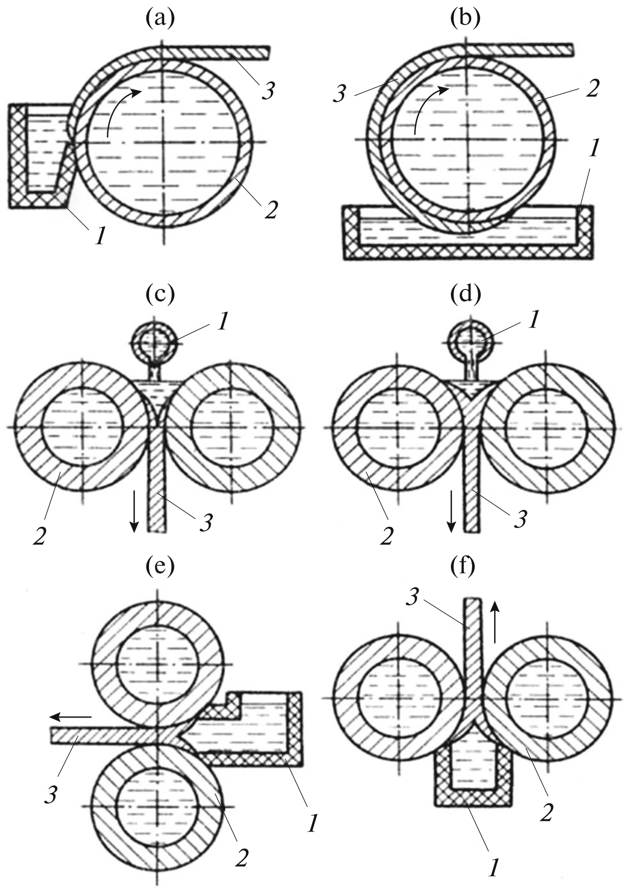

Fig. 1. Scheme of casting by freezing out on roll crystallizers [2]: (*1*) the melt feeder, (*2*) the roll crystallizer, and (*3*) the cast section.

In the case of casting into a roll crystallizer with rolling (below, molten metal strip rolling), the strip is formed as a result of rolling the skins frozen out on roll surfaces (Figs. 1d–1f). The thickness X of the strip that exits rolls is less than the total thickness of the skins frozen on the rolls:

$$X = 2\xi_{opp}(1-\varepsilon), \quad (2)$$

where ξ_{opp} is the skin thickness in the zones where the crystallization fronts moving in opposite directions stick together, and ε is the degree of frozen skin reduction.

The following processes occur in the rolling zone: reduction of frozen skins; rapid cooling of the cast due to contact heat exchange with the crystallizer; and a change in the primary crystal tilt angle and dimensions. The deformation zone length is selected in such a way that to ensure production of a strip without cracks and ruptures and with a structure close to the hot-rolled structure. If casting is combined with rolling, the speed of skin motion in the freezing zone is less than the roll motion speed, while the speed of the strip that exits rolls is higher, i.e., the forward creep inherent to rolling occurs ranging from 5 to 30%.

Although there is no operative industrial facility in the CIS that uses twin-roll casting of metals, the technology of molten metal strip rolling has been used in the world's aluminum industry for a long time [3–5]. Roll machines for casting metal strips differ by the way metal is fed into roll crystallizers: from the side, from above, or from below (Figs. 1e, 1c, 1f).

Before the 1990s, in total about 160 casting machines, in which casting and rolling were combined, were operated in the world's metallurgy [6]. All these machines were primarily used to produce rolled products and strips for construction and food-processing industries. However, of most interest for machine building are iron-based alloys (carbon and alloyed steels), and for rocket and aviation industry, aluminum alloys of the Al–Cu and Al–Zn type. However, the technology for production of steel strips (flat products) by means of molten metal rolling has not been developed yet in the CIS, and for high-strength aluminum alloys, such twin-roll casting scheme is lacking globally, which is due to a very broad (over 100°C) temperature range of crystallization of alloys of such systems.

We used in this study mathematical and physical modelling to develop production regimes of molten metal rolling heat hardenable aluminum alloys and carbon steels.

In simulating twin-roll casting of metals, we used the Comsol software package to analyze how speed regimes of twin-roll casting of metals affect formation of strips made of the alloys under study with thickness 1, 2, 3, and 4 mm and under various overheat temperatures of their alloys (5–60°C). The computer experiment was carried out for the following production parameters: roll radius R = 200–400 mm; meniscus angle β = 33°; heat removal rate at the metal-roll interface 15000 W/(m K); and the strip width was up to 200 mm. The level of metal in the crystallizer H was determined using the formula $H = R\sin\beta$. It was assumed that the melt level in the bath is maintained at a constant height by synchronizing the fed metal volume with the roll rotation speed, and the heat transport in the direction perpendicular to the transverse cross section of the crystallization/deformation zone plane is negligibly small. In addition, due to the symmetry with respect to the vertical plane of the space between rolls, only 1/2 of the metal volume was considered in simulations. The melt temperature at the initial moment of time was considered to be equal to the temperature of metal in the intermediate ladle.

As initial data for modelling, the thermal physical characteristics of the alloys under study, which are known and/or determined using the differential thermal analysis method, were used (Table 1).

To examine the effect of geometric and production parameters of twin-roll casting on the conditions

Table 1. Thermophysical properties of the alloys under study

Characteristics	Alloy				
	AD35	AMr5	D16	V95	Steel 30
Density, kg/m	2720	2650	2770	2850	7800
Specific thermal capacity, J/(kg K)	1180	922	922	922	690
Thermal conductivity, W/(m K)	75	126	130	128	29
Thermal diffusivity, 10^{-5}, m^2/s	23.5	51.56	50.9	48.7	13.5
Phase transition heat, kJ/kg	180	180	180	180	267.5
Liquidus temperature, °C	641	632	635	630	1520
Solidus temperature, °C	564	567	503	470	1470
Crystallization temperature range, °C	77	65	132	160	50

Table 2. Results of computer experiments for forming strips with a thickness of 2, 3, and 4 mm (melt overheat temperature 5°C)

Parameter	Alloy			
	AD35 (641/564)	AMr5 (632/567)	D16 (635/503)	V95 (630/470)
Strip thickness 2 mm				
Casting speed, m/s	1.238	1.354	1.008	0.87
Time to reaching the roll exit level ($H = 0$ mm), s	0.093	0.08507	0.11428	0.1324
Strip surface temperature, °C	527.45	529.5	476.4	441.12
Strip core temperature, °C	590.11	568.27	507.33	470.09
Temperature gradient over strip thickness , °C/mm	63	39	31	29
Strip thickness 3 mm				
Casting speed, m/s	0.773	0.859	0.649	0.56
Time to reaching the roll exit level ($H = 0$ mm), s	0.15	0.1336	0.1776	0.2057
Strip surface temperature, °C	502.3	512.235	457.9	428.08
Strip core temperature, °C	591.9	568.09	502.68	470.3
Temperature gradient over strip thickness , °C/mm	60	37.33	29.85	28
Strip thickness 4 mm				
Casting speed, m/s	0.535	0.619	0.471	0.406
Time to reaching the roll exit level ($H = 0$ mm), s	0.216	0.186	0.245	0.284
Strip surface temperature, °C	477.47	496.24	444.51	415.27
Strip core temperature, °C	588.25	568.04	501.8	469.17
Temperature gradient over strip thickness , °C/mm	110.78	71.8	57.29	53.9

under which thin strip is formed, mathematical simulation was applied. The following production characteristics were chosen as variable parameters: strip thickness $\delta = 1$–4 mm, meniscus angle $\beta = 10$–33 degrees; roll radius $R = 200$–400 mm, and the cast melt overheat temperature $\Delta T = 5$–60°C.

Results of the computer study of the conditions under which aluminum alloy strips with a thickness of 2, 3, and 4 mm are formed when their melt overheat (ΔT) is, for example, 5°C, are presented in Table 2. The table displays the following casting parameters: v, m/s, casting speed; τ, s, time when metal exits rolls; δ_{ss}, mm, solidified skin thickness at the roll exit; ε, s, time during which a solid skin whose thickness is equal to that of the strip is formed; T_{m-r}, °C, temperature at the metal-roll interface at the crystallizer exit (at the time τ); and T_c, °C, temperature in the strip core at the crystallizer exit (at the time τ).

The most important production parameter of the twin-roll casting technology, which determines the strip quality and the facility performance, is the roll-crystallizer rotation speed, i.e., the casting speed. The

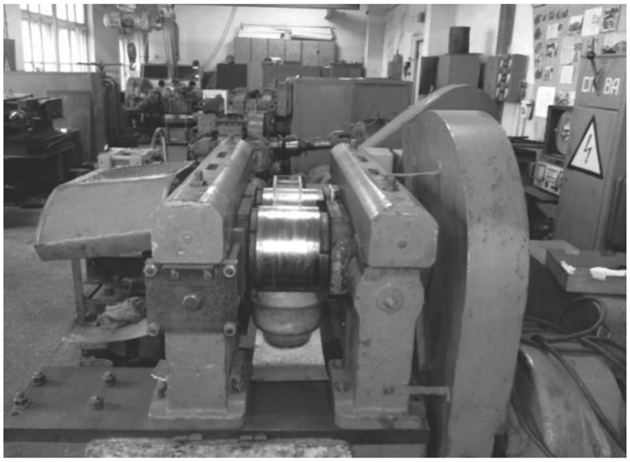

Fig. 2. Experimental facility for twin-roll casting.

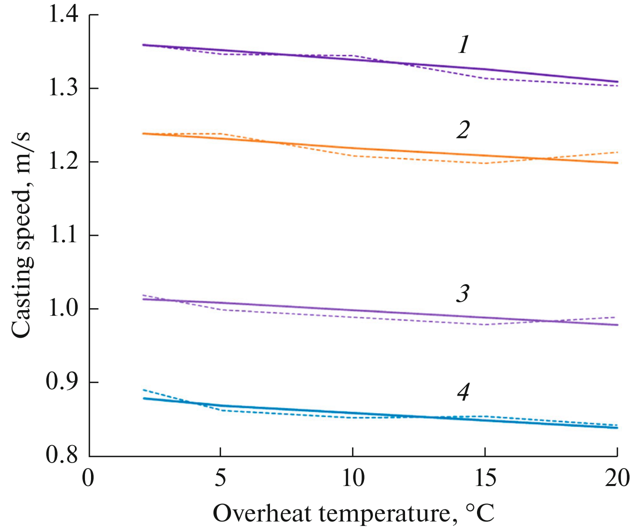

Fig. 3. Casting speed as a function of melt overheat temperature in forming a 2-mm-thick strip: (*1*) AMr5; (*2*) AD35; (*3*) D16, and (*4*) V95; the solid line shows results of the computer experiment, and the dotted line, those of the laboratory experiment.

casting speed primarily depends on the rate of heat exchange between the solidifying metal and the crystallizer [7, 8]. Published data on actual and calculated casting speeds are rather controversial [9, 10]. Therefore, we pay special attention in this study to the determination of this parameter. Mathematical simulation was used to calculate the casting speed for strips of all alloys under study with a thickness of 2, 3, and 4 mm for fixed overheat temperature of their alloys, 5, 10, 30, and 60°C. In determining the casting speed, a condition was set that that the speed ensures complete (end-to-end) solidification of strips in the roll exit plane.

The stepwise regression method applied to the results of mathematical simulation with subsequent exclusion of insignificant factors yielded equations of the type $v = f(\delta, \beta, R, \Delta T)$ for the specified casting production parameters: strip thickness δ = 2–4 mm, meniscus angle β = 10–33 degrees; roll radius R = 200–400 mm, and the melt overheat temperature ΔT = 5–60°C.

The equations have the following form:

for the AD35 alloy:

$$\begin{aligned} v &= -0.554349 + 0.047554313\beta \\ &+ 0.00323754R - 0.0147693\delta\beta \\ &- 0.001095455\delta R + 0.000123445\beta R \\ &- 0.000112264\beta\Delta T + 0.056446\delta^2; \end{aligned} \quad (3)$$

for the AMr5 alloy:

$$\begin{aligned} v &= -0.5917 + 0.0518209\beta \\ &+ 0.00336569R - 0.016948\delta\beta \\ &- 0.001155526\delta R + 0.000143401\beta R \\ &- 0.000115017\beta\Delta T + 0.060388\delta^2; \end{aligned} \quad (4)$$

for the V95 alloy:

$$\begin{aligned} v &= -0.440354 + 0.0306303\beta + 0.00249233R \\ &- 0.0110831\delta\beta - 0.000883578\delta R \\ &+ 0.000102798\beta R + 0.0473633\delta^2; \end{aligned} \quad (5)$$

for the D16 alloy:

$$\begin{aligned} v &= -0.39715 + 0.0355903\beta \\ &+ 0.00244194R - 0.0115194\delta\beta \\ &- 0.000846548\delta R + 0.000107717\beta R \\ &- 0.0000658956\beta\Delta T + 0.04276\delta^2; \end{aligned} \quad (6)$$

and for steel 30:

$$\begin{aligned} v &= -0.4974 + 0.07598\beta + 0.00786549R \\ &- 0.001409\delta\beta - 0.000046378\delta R + 0.0006897\beta R \\ &- 0.0000324158\beta\Delta T + 0.08527\delta^2. \end{aligned} \quad (7)$$

The determination coefficient r^2 of the derived regression equations (i.e., the percent of experimental data that can be explained within the model) is no less than 98.5%, which is an evidence of the correct description of the process under study.

Next, a laboratory facility for twin-roll casting of metal melts (Fig. 2) was used to check (dis)agreement of the calculated casting parameters with their actual values for low-temperature aluminum alloys. The results of the computer experiment agree well with the actual casting parameters for the alloys under study (Fig. 3). For example, the difference in the casting speed between the computer and laboratory experiments was: for the AD35 alloy, about 5%; for the Amr5 alloy, 7%, for the D16 alloy, 2.2%, and, for the V95

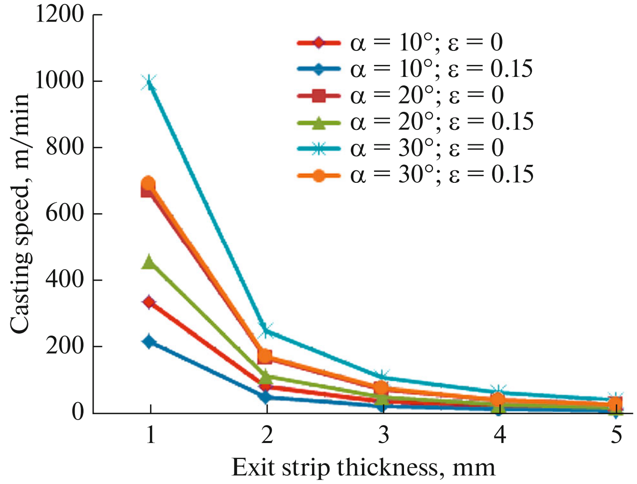

Fig. 4. Calculated maximum speed of steel casting as function of strip thickness at the exit from rolls.

alloy, 4% (Fig. 3). This difference was found to diminish with an increase in the strip thickness. It can be seen that the difference in the casting speed between the computer and actual experiments is insignificant, which evidences that the proposed mathematical model provides a good description of the actual process.

The twin-roll casting speed significantly depends on deformation of the cast section. For example, the deformation degree in the production of aluminum alloy strips can be as high as 40 to 60%, which results in a significant decrease in the casting speed [11]. In the case of steel strip casting, roll crystallizers cannot provide a high degree of reduction due to insufficient strength and rigidity of their belts. As a result of this, the steel strip casting speed is in practice significantly higher than that of aluminum alloys. However, to ensure high quality of cast steel strips, the deformation degree of no less than 15% is needed [11]. Therefore, we calculated the casting-rolling speed in this study based on a reduction degree of 15%.

Figure 4 displays the speed of casting of steel strip of various thickness h_n in roll crystallizers with radius $R = 500$ for the metal-roll contact angle $\alpha = 10$, 20, and 30 degrees without deformation and with a 15% deformation. For example, the casting speed diminishes for a 2-mm-thick strip with a deformation degree of 15% from 164 to 52 m/min. An increase in the metal-roll contact angle (the level of molten metal between roll), on the contrary, results in an increase in the calculated casting/rolling speed. For a 1-mm-thick strip produced with a 15% reduction and without it, an increase in this angle by 10 degrees results in more than doubling of the casting speed.

The results obtained show that the speed of twin-roll casting of metal strips is most sensitive to cast strip thickness, molten metal level, roll-crystallizer radius, and the degree of solidified metal reduction. It should be noted as well that the calculated speeds of twin-roll casting for steel strips are quantitatively close to those provided by the commercially available Castrip facility manufactured by Nucor [11]. Given that the roll radius in this facility is 500 mm, the strip thickness is 1.6 mm, and the main casting speed is 80 m/min, the calculations enable a conclusion that the strip is cast in the facility with a 15% reduction.

Thus, we have confirmed in a theoretical and experimental way that the main production parameters, which ensure stability of twin-roll casting of metal alloys, are overheated temperature, casting speed, and the level of melt in the gap between rolls. The computer experiments carried out for all the alloys under study yielded analytical dependences that make it possible to determine the optimal speed of twin-roll casting of these alloys with consideration for the various production parameters (strip thickness, meniscus angle, roll radius, and melt overheat temperature).

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