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STRIP CASTING OF LIGHT METALS

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Process Technology

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The Importance of Heat Removal for Productivity in Industrial Twin Roll Casting of Aluminium

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Keywords: Twin-roll casting (TRC); Aluminium production; Heat balance; Tip simulation

Abstract

Twin roll casting is a highly cost and energy-efficient way to produce aluminium strip directly from liquid aluminium. The limiting step in increasing productivity is heat removal from the melt and solidification which must be finalized before the material reaches the roll gap. A simple heat balance model is used to evaluate the role of the decisive components for heat removal with a special focus on transversal temperature variations. Especially the design of the melt distribution system proved to be important for the reduction of transversal variations. Hydro's tip design provides a more homogeneous melt temperature along roll width than standard designs and hence allows lower furnace temperatures as well as higher casting speeds leading to reduced energy consumption and higher productivity.

Introduction

Twin roll casting (TRC) is the continuous production of strip directly from the melt in only one process step that combines casting and rolling between two internally cooled counter-rotating rolls. The process chain for continuously cast material is considerably shorter than for the conventional DC route as intermediate process steps like pre-heating and hot rolling are omitted. Therefore, investment costs as well as energy input per ton of aluminium are reduced. This makes TRC a valuable alternative for production of low alloyed strip in the aluminium industry. Commonly this process is used for the production of 1xxx, 3xxx, 5xxx and 8xxx series alloys for use in container & packaging, building & construction, electronics industry, transportation and mechanical engineering.

In the process the melt is guided horizontally through a ceramic nozzle or tip into the gap between the work rolls. These rolls are internally water-cooled, usually consisting of a core and a shrink fitted shell, which provides the surface to the metal. The shell is commonly made of steel but also copper is a highly interesting option mainly due to the high thermal conductivity [1-4]. The melt leaves the tip in a certain distance to the centre line between the rolls which is called set-back. Solidification of the melt starts at the contact point between melt and shell surface. Through ongoing solidification strip shells on both roll surfaces are formed which meet at the so-called kissing point (see Fig. 1) and unify under the roll pressure to one strip. At this point, solidification is finalized and rolling deformation takes place uniformly down to the centre line. On the solid side of the caster a release agent, mostly an aqueous graphite suspension, is applied by a spraying process. On the one hand this acts as a thermal barrier for heat flow between solidifying metal and the roll surface, but on the other hand it is necessary to avoid sticking of the strip on the roll.

The general condition for a stable operation of TRC is finalizing solidification of the melt before the exit plane is reached. That means that both, superheat of the melt as well as latent heat of solidification have to be completely dissipated by the cooling system until this point. The total amount of heat to be dissipated increases largely with increasing alloying element content as the solidification range widens. Especially considering aluminium alloys with a higher content of alloying elements like Mg or Si needed for applications of TRC material in automotive and other strength demanding applications, the casting speed has to be considerably lowered to finalize solidification under identical circumstances. Secondly when transversal variations of metal temperature or cooling capacity are severe, an increased superheat of the melt becomes necessary. The former problem is metallurgically defined for any given alloy but the latter can be influenced by materials and design of the applied components in the TRC process like the tip, shell, and core.

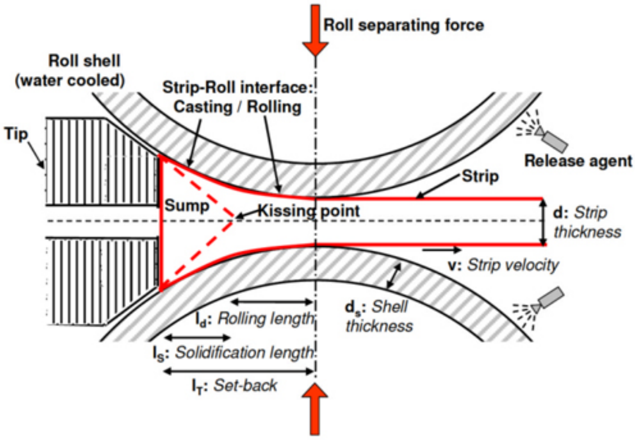


Fig.1: Sketch of twin roll casting process zone and relevant parameter [1].

For estimating the effect of different components, their design and their material properties on potential productivity in the TRC process, a simple heat balance of the solidification and cooling process during twin roll casting is used and is supported by fluid mechanics simulations as well as temperature measurements at Hydro's TRC casthouse at Karmøy, Norway. This is done in sequence of the process starting with the melt temperature in the headbox and transversal variation of temperature in the ceramic tip towards contact length, thermal conductivity of the shell and cooling design in the roll core. The analysis is meant to show the importance of the named components, their design and their material properties with regard to heat removal and hence productivity in the TRC process with special emphasis on transversal thermal variations.

The heat balance model

The heat balance model applied in this investigation is based on defining the heat flow into the system via the melt to match the heat flow out of the system via the remaining thermal energy in the strip as well as the heat transferred to the roll shell. In the model, the thermal conductivity of the solidified aluminium, the heat transfer at the solid-liquid interface and at the interface of solid aluminium to the roll shell are not considered for reduction of complexity. Instead these parameters are collected in a semi-empirical pre-factor which can be determined from a combination of simulations and temperature measurements. The roll shell is simply used as a heat sink neglecting the heat flow within the roll towards the cooling water. The amount of heat transferred to the shell and further on into cooling water is based on temperature measurements on the shell surface at 90 ° with an IR-camera as well as 270 ° rotation after the exit with thermocouples.

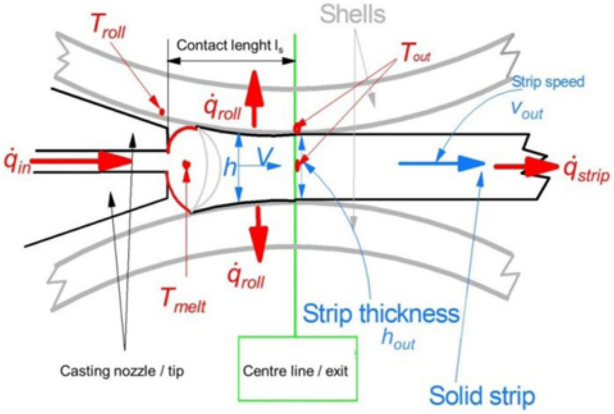


Fig. 2: The heat balance model of the TRC process with heat fluxes and measured parameter.

Heat into the system via melt:

$$\dot{q}_{in} = \rho_{melt} \cdot h_{in} \cdot v_{in} \cdot w \cdot \left[c_{s\_Al} + c_{p\_Al} \cdot T_{melt}\right] \tag{1}$$

Heat out of the system via strip and rolls:

$$\dot{q}_{out} = \dot{q}_{strip} + \dot{q}_{roll} = h_{out} \cdot v_{out} \cdot w \cdot \rho_{strip} \cdot c_{p\_Al} \cdot T_{out} + \frac{2}{3} \cdot d \cdot v_{roll} \cdot w \cdot \rho_{roll} \cdot c_{p\_roll} \cdot \left[T_{out} - T_{roll}\right] \tag{2}$$

Applying conservation of mass additionally gives

$$\rho_{melt} \cdot h_{in} \cdot v_{in} = \rho_{strip} \cdot h_{out} \cdot v_{out} \,. \tag{3}$$

With the heat penetration depth d

$$d \sim \sqrt{\frac{\lambda_{roll} \cdot t}{\rho_{roll} \cdot c_{p\_roll}}} \tag{4}$$

and contact time t

$$t = \frac{l_s}{v_{roll}} \tag{5}$$

the heat balance

$$\dot{q}_{in} = \dot{q}_{out} \tag{6}$$

can be set up and solved for the strip speed v_{out} with a as pre-factor including numerical values and accounting for process limitations e.g. in heat transfer through the application of release agent as well as melt temperature and cooling water variations in the process.

$$v_{out} = a \cdot \frac{\sqrt{\lambda_{roll} \cdot l_s \cdot v_{roll} \cdot c_{p\_roll} \cdot \rho_{roll}} \cdot \left[T_{out} - T_{roll}\right]}{\rho_{Al} \cdot h_{out} \cdot \left[c_{s\_Al} + c_{p\_Al} \cdot (T_{melt} - T_{out})\right]} \tag{7}$$

Table 1: Variables and constants used in the sample calculation

	Description	**Value**
$\dot{q}_{in}$	heat flow into the system	
$\dot{q}_{out}$	heat flow out of the system	
$\dot{q}_{strip}$	heat flow out with the strip	
$\dot{q}_{roll}$	heat flow out via the rolls	
h_{in}	thickness of metal in (melt)	
h_{out}	thickness of metal out (strip)	4.9 mm
w	width of metal (melt and strip)	1,570 mm
v_{in}	average speed in (melt)	
v_{out}	speed of strip	
v_{roll}	speed of shell	
T_{melt}	temperature of the melt	660 °C
T_{out}	temperature of strip and rolls at exit	400 °C
T_{roll}	roll temperature before melt contact	80 °C
ρ_{melt}	specific density of liquid Al	
ρ_{strip}	specific density of Al strip	2,700 kg/m^3
ρ_{roll}	specific density of shell	7,900 kg/m^3
$c_{p\ Al}$	specific heat capacity of Al	900 J/(kg·K)
$c_{p\ Roll}$	specific heat capacity of shell	490 J/(kg·K)
$c_{s\ Al}$	solidification heat for Al	387,000 J/kg
λ_{roll}	thermal conductivity of shell	34 W/(K·m)
l_s	contact length between Al and the shell	46 mm
a	numerical pre-factor	4

Melt supply

The melt is typically supplied to the process through a tundish or headbox and a ceramic nozzle system commonly called tip. Besides good machinability and the need to be free of any hazardous fibre material, the component has to withstand aluminium melt in continuous production for some days to a few weeks with respect to thermal, abrasive and chemical aspects. Furthermore it shall have a low coefficient of thermal expansion and low heat conductivity. As important as these material properties is the design of the tip with the target of achieving a homogeneous distribution of melt temperature over casting width as well as of avoiding any entrapment or enrichment of oxides or other particles in local areas.

A reliable measurement of melt temperature distribution within the tip is hardly possible without disturbing the process fundamentally. Combined with some deeper insights into the process this is the reason for studying melt flow with simulations. The temperature distribution of the melt within the tip was calculated with ANSYS Fluent 15.0. In these calculations the velocity distribution is computed from an imposed strip speed of 1,920 mm/s and a pressure boundary condition at the tundish inlet. The heat losses inside the tip are modelled by an averaged heat transfer coefficient of 2 W/K/m^2 and an ambient temperature of 20 °C. This model was utilized to optimize flow conditions in the wake of the large separator parts on both sides of the tip inlet (see Fig. 3a). A region with locally reduced temperature due to lower melt velocity was observed (see Fig. 3b) at these specific locations in the original design. The optimization of flow was finally achieved by a geometrical modification of the separator shape, which clearly improved flow conditions at theses specific positions. The temperature distribution in the tip (see Fig. 4) shows that the dead zones, where melt freezing or oxide accumulation could occur, are fairly eliminated by the modified tip design.

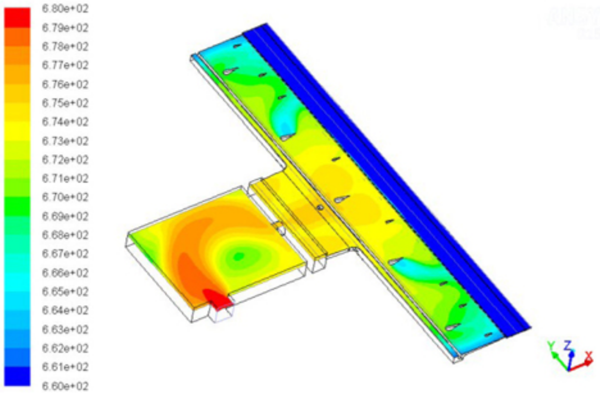


Fig. 3a: Temperature field in the metal distribution system consisting of headbox and tip.

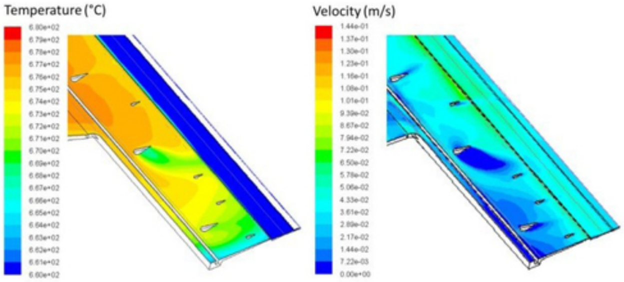


Fig. 3b: Temperature and velocity fields focused on the large separators.

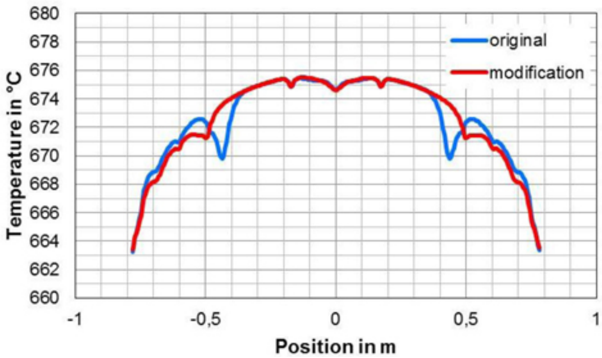


Fig. 4: Transversal temperature profiles of original and modified tip design at the tip exit according to numerical simulation. In the optimized layout the temperature notches behind the separators are clearly reduced.

The results shown in Fig. 4 are pointing to a transversal temperature variation at the tip exit of only ΔT = 12 K. This appears to be lower than e.g. the value ΔT = 21 K reported by Kavaklioglu et al. [5], but it has to be kept in mind that these authors used different thermal boundary conditions for the heat losses in the simulation of a standard tip design. The lowest temperatures within the tip are observed at the edges of the tip lip due to the longest path for the melt to reach these positions. Hence the potential risk encountered with low headbox temperature is freezing at these edge locations. In general the headbox temperature has to be raised to a level which prevents freezing edges and therefore depends strongly on the temperature loss of the melt on this streamline. In the center position the temperature of the melt when leaving the tip is by ΔT higher than at the edges. The stability condition requires that melt of this temperature is completely solidified before the roll exit and thus determines the applicable roll speed.

Applying the heat balance model to this temperature variation at the tip exit by setting

$$T_{melt} = 660°C + \Delta T \tag{8}$$

results in potential strip speeds of 1,936 mm/min for ΔT = 12 K and 1,882 mm/min for ΔT = 21 K applying a standard set of reference process parameters (see Table 1). This equals a difference in productivity of 2.6 % caused by the improved tip design. An ideal tip design without any temperature variation at exit would allow a possible strip speed of 2,004 mm/min and hence this shows the remaining potential in tip design.

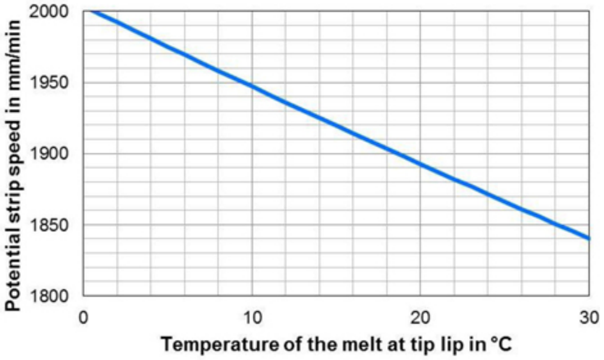


Fig. 5: Influence of temperature variation ΔT at tip lip on the potential strip speed.

Cooling length

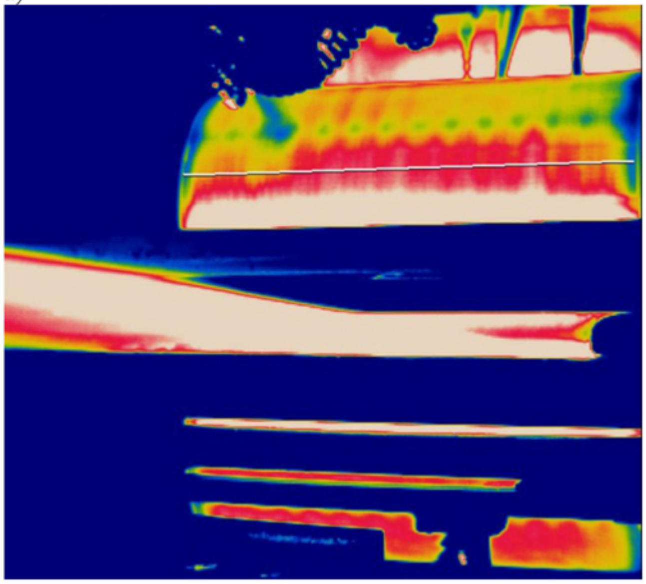
Directly after the tip exit, rapid cooling and solidification start. Here two segments have to be distinguished: In the liquid zone or casting area, the dissipation of caloric as well as latent heat has to be considered and the thermal energy has to be transported from the melt via the solidified metal and the roll shells into the cooling water. In the solid zone or rolling area the solid metal is further cooled down by heat transfer through the roll shell to the cooling water [1]. The heat removal with cooling rates assumed to be between 100 K/s and 1,000 K/s takes place for a contact time t which depends on the cooling length l_s and the roll speed v_{roll} (see eq. 5). The cooling length is commonly approximated by the set-back. Obviously this is a rather important factor for cooling and it should be adjusted to the highest possible value regarding productivity. But it also influences the process in different other ways like e.g. transversal strip profile, strip thickness and degree of rolling deformation and surface shear. Nevertheless within the bounds of technical possibilities the set-back should be chosen on a high level.

Roll shell and roll core

The rolls, being composed of the core and the shell are the essential components in twin roll casting for heat removal. With regard to cooling, the task of the shells is to absorb as much heat as possible in the contact zone. The cooling system inside the roll cores is designed to divert this heat from the shell into the cooling water system and hence to homogeneously cool down the shells to their initial temperature T_{roll} during one revolution.

The material of the roll shell is of high importance for the cooling and solidification process as it diverts the heat from the melt within the model and hence its thermal conductivity, density and heat capacity are part of the governing equation. When copper shells are used instead of more conventional steel shells, the strip speed can be strongly increased if the cooling system in the roll can restore the shell surface temperature T_{roll} within one revolution also under these drastically changed conditions especially with the clearly shorter period of revolution. This might not be possible and hence other limitations in heat removal rather than shell material shall be limiting the process speed when copper shells are used. A detailed analysis of this potential going beyond the heat transfer model has been conducted by Badowski et al. [1].

a)



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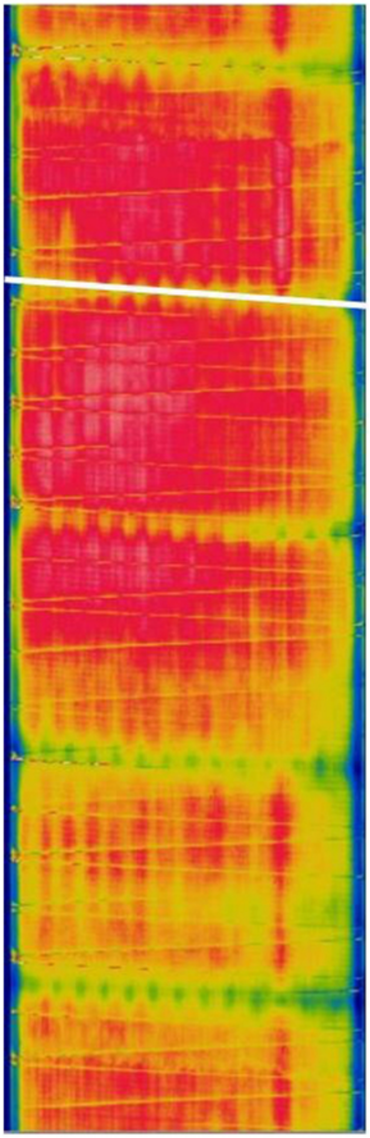

c)

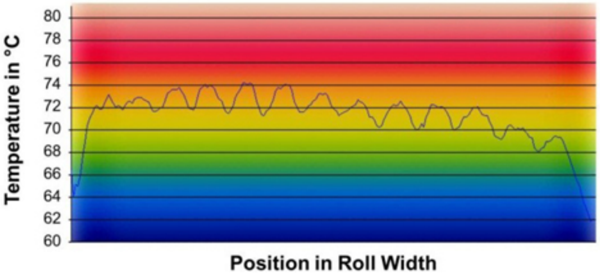

Fig. 6: Thermal variation on shell surface in the case of a thin shell: a) Overview IR-picture of caster during measurement; b) IR-camera color code representation in line-scanner view; c) measured temperature variation at a water outlet position (marked in Fig. 6b with a white line).

Besides specific situations when the capacity of the cooling system might become limiting, the variation of roll shell surface temperature T_{roll} before contact in strip longitudinal as well as transversal direction is generally relevant for the process. There are different variations of T_{roll} superimposed as can be seen in Figure 6 showing a measurement with an IR camera during production in a plant. Comparable to the transversal temperature variation of the melt at the tip exit also the shell surface temperature typically has a maximum in the center position. The reasons are firstly the variation of temperature of incoming melt and secondly the proximity to the ending of the hot zone leads to a temperature gradient at the edges. A second kind of transversal temperature variation on the shell surface clearly depends on shell thickness. Especially when rather thin shells are used, the cooling water outlets and the respective channels lead to rather localized variations of a few °C in transversal direction as shown in Figure 6c. The third kind of variation is in strip longitudinal direction and is caused by the geometry of the cooling systems [6]. The size and geometry of areas between cooling water inlet and outlet are resembled on shell surface temperature to a certain degree. In particular the frequency of cooling water outlets along shell circumference shown in line-scanner view in Figure 6b is quite pronounced. In this figure also the total variation of shell surface temperature can be observed.

This variation has a severe impact on productivity as a certain shell temperature may not be underrun at the colder edges to prevent residues of water from release agent application to remain on the rolls until melt contact. On the other hand shell surface temperature should be as low as possible to optimize the cooling performance and hence the potential strip speed. Figure 7 shows the considerable influence of shell temperature on strip speed in the heat balance model when the temperature of rolls and strip at exit T_{out} is kept constant.

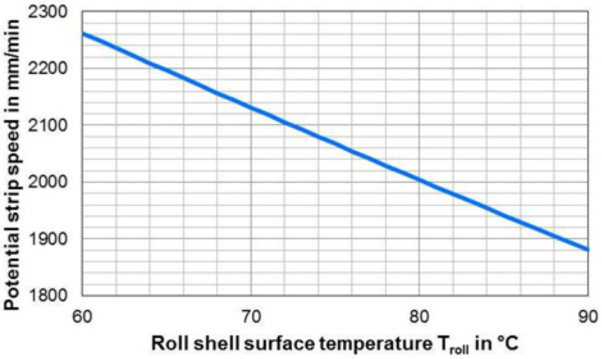

Fig. 7: Influence of roll shell surface temperature (variation) T_{roll} on the potential strip speed.

Summary & Conclusion

As productivity in twin roll casting is limited by removal of thermal energy during the rather short contact time, a simple heat balance model has been applied to investigate the influence of a few selected components and parameters decisive for heat removal in the process. Special focus was laid on transversal thermal variations originating mainly from melt temperature distribution at tip exit as well as roll shell surface temperature. The spatial variations of melt temperature at tip exit were studied by CFD simulations (see Fig. 3) and showed rather small variations in strip transversal direction of 12 K with Hydro's design while standard designs are in the range of 20 K [5]. The difference in thermal variation can be fully exploited both, in lowering furnace temperature which leads to additional energy savings and in increasing strip speed and hence productivity as less heat has to be removed by the cooling system. Additionally the lower melt temperature is also beneficial regarding strip quality (e.g. less centreline segregations, improved strip profile, etc.).

The maximum of melt temperature at strip center position is one of the reasons why also roll surface temperature develops a maximum at this position as demonstrated by measurements of roll shell surface temperature (see Fig. 6) at Hydro's Karmøy plant. Hence the transversal variation originating from melt temperature distribution at tip exit is intensified by a similar temperature profile on the rolls. This emphasizes the relevance of tip design on productivity in the twin roll casting process as heat removal and solidification is the limiting process step in production of metal strip by TRC.

In the spirit of further reducing energy input for the production of aluminium strip via the twin roll casting route as well as for improving productivity more attention should be paid to reducing transversal thermal variations in the process. These mainly originate from melt temperature distribution at tip exit as well as from inhomogeneous cooling of the caster rolls.

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