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Continuous Casting Simulation, version 1.60 User Guide

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1 Introduction and Disclaimer

This document has been prepared as a user guide to the **continuous casting simulation**, available at <http://www.steeluniversity.org/>. The interactive simulation has been designed as an **educational and training tool** for both students of ferrous metallurgy and for steel industry employees.

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2 About this Version

This is the first public release of this simulation, intended for evaluation purposes. The full version of the continuous casting simulation will be available online at the end of July 2005.

Changes since version 1.51

- It is now possible for registered users to load simulation results from the Secondary Steelmaking simulation.
- The model now takes into account the level of inclusions from the ladle. A higher level of inclusions may necessitate lower casting speeds in order to allow more time for the inclusions to float off in the tundish.

Changes since version 1.41

- The underlying model has been improved and the quality graph changed accordingly.
- Changed mold powder costs.
- Too low a mold powder consumption will now result in a breakout because excessive friction between mold and strand causes the strand to stop.
- The underlying model is now updated when the EMS state is changed.
- The soft reduction level can now be changed during casting.

Changes since version 0.36

- SEN changes now take 15 seconds instead of 30 seconds.
- Soft reduction level is now chosen after casting speed, cooling rate and mold oscillation settings.
- Choice of mold powder will now influence production cost and the chances for successful casting.
- It is now possible to toggle between hidden or shown inner strand rolls.

Changes since version 0.23

- All four steel grades are now available.

- Both "Works Technical" and "University Student" user levels are available.
- Solidification of metal in a vessel can now occur.
- Ladle state of repair, nozzle clogging and delay of ladle arrival has been added for "Works Technical" level.

Limitations

- All strands behave identically, which is of course not the case in real life.
- The tundish temperature at the start of cast is based on a simplified model to simulate pre-heating of the tundish.
- Strand surface temperature and strand wall thickness has been pre-calculated using a finite element model for the different combinations of casting speeds, cooling rates and steel grades.
- Misaligned rolls can be adjusted during casting which is absolutely not the case in real life.
- To optimize the overall performance of the simulation, all of the underlying model calculations are executed sequentially. However, one implication is that the mold level decreases as the simulation rate is increased and vice versa. Be sure to maintain a high mold level before using a high simulation rate.

3 Introduction to Continuous Casting

Continuous casting of steel is a process in which liquid steel is continuously solidified into a strand of metal. Depending on the dimensions of the strand, these semi-finished products are called slabs, blooms or billets. The process was invented in the 1950s in an attempt to increase the productivity of steel production. Previously only ingot casting was available which still has its benefits and advantages but does not always meet the productivity demands. Since then, continuous casting has been developed further to improve on yield, quality and cost efficiency.

Liquid steel is supplied to the continuous caster from the secondary steelmaking shop. The ladle is usually delivered by crane and positioned into a ladle turret, which subsequently rotates the ladle into the casting position. A slidegate in the bottom of the ladle is opened to allow the liquid steel to flow via a protective shroud into a tundish, a vessel that acts as a buffer between the ladle and the mold. As the tundish fills, stopper rods are raised in order to allow the casting of steel into a set of water-cooled copper molds below the tundish. Solidification begins at the mold walls and the steel is withdrawn from the mold by a dummy bar. As it leaves the mold, the strand of steel requires a sufficiently thick solid shell to carry the weight of the liquid steel that it contains, i.e. the ferrostatic pressure.

Throughout the entire casting process, the mold oscillates vertically in order to separate the solidified steel from the copper mold. This separation is further enhanced by introducing a mold powder into the mold.

The strand is withdrawn from the mold by a set of rolls which guide the steel through an arc until the strand is horizontal. The rolls have to be positioned close enough together to avoid bulging or breaking of the thin shell.

As the steel leaves the mold, it has only a thin solidified shell which needs further cooling to complete the solidification process. This is achieved in the so-called secondary cooling zone, in which a system of water sprays situated between the rolls are used to deliver a fine water mist onto the steel surface. At this point, the steel, solidified shell and liquid center, is called the strand.

After the strand has been straightened and has fully solidified, it is torch-cut to pre-determined product lengths. These are either discharged to a storage area or to the hot rolling mill.

Table 3-1. Summary of different components in the continuous casting process.

Component	Primary Task	Secondary Task
Ladle	Transport and hold the liquid steel	Facilitate inclusion removal
Ladle Turret	Position full ladles over the tundish and remove empty ones	Free the cranes for higher productivity
Tundish	Act as a buffer between ladle and mold	Facilitate inclusion removal
Mold	Cool down the liquid steel to form a solidified shell	
Strand System	Further cool the strand to fully solidified and straighten the strand	

4 Simulation Objectives

The aim of the simulation is to successfully sequence cast three ladles meeting the specified criteria of **surface quality**, **internal quality** and **inclusion content**.

You should also aim to **minimize the cost** of the whole operation.

5 Plant Layout and Description

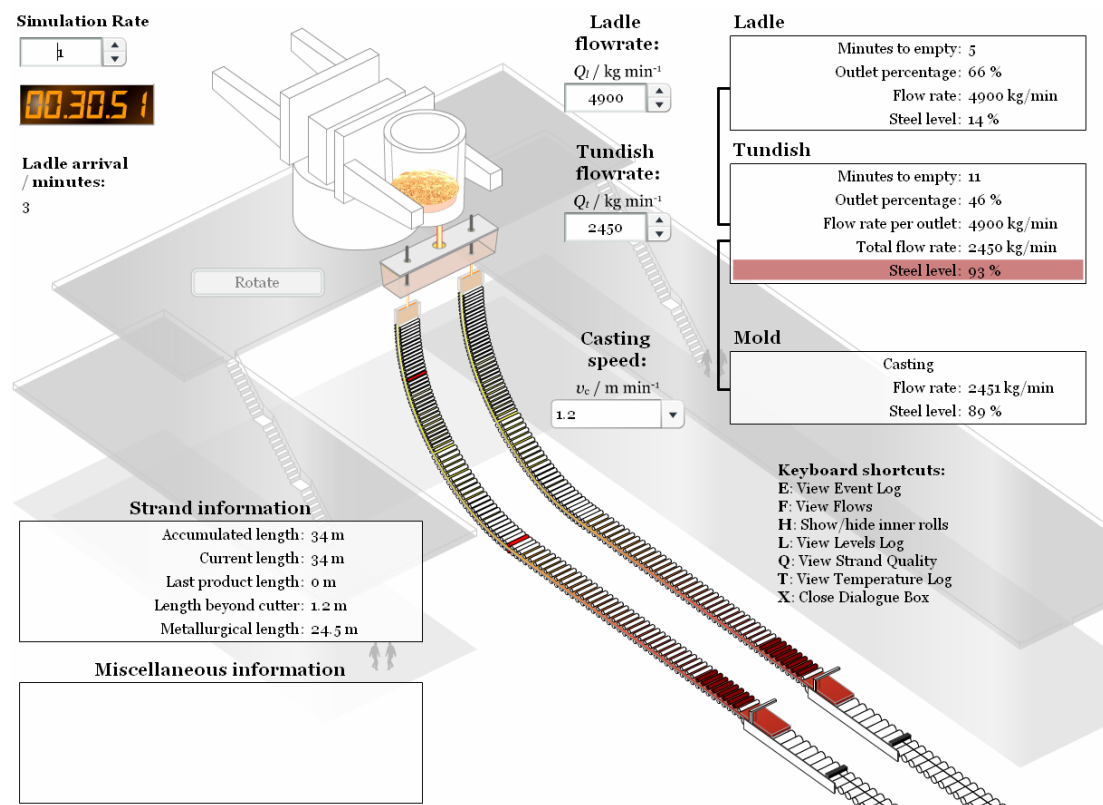





Figure 5-1 Screenshot showing the plant layout used in the simulation. Two ladles are positioned in the ladle turret which turns to position the ladle over the tundish.

The plant in the simulation is laid out as shown in Figure 5-1. At the start of the simulation, one full ladle is positioned over the tundish.

5.1 Dimensions of the Casting Machines

The simulation includes three different casting machines that are used for casting four different steel grades. These are slab, bloom and billet caster. Properties of the different casting machines are listed in the table below.

Table 5-1 Table of casting machine properties

Type	Slab	Bloom	Billet
Steel grade(s)	Linepipe steel ULC steel	Construction steel	Engineering steel
Ladle size / metric ton	250	100	100
Radius / m	9	12	8
Number of strands	2	5	6
Casting speed / m min ⁻¹	1.0-2.0	1.2 - 1.8	3 - 5
Cross section dimension / mm	1200 × 230 	250 × 250 	130 × 130 
Typical use	flat products, i.e. plate, sheet, coils	long products, i.e. bars, beams, pilings	long products, i.e. bars, channels, wires
Roll spacing, section I / mm	202 (35 rolls in 45°)		
Roll spacing, section II / mm	283 (25 rolls in 45°)		
Radii at bending/straightening / m	R ₅₆ =9, R ₅₇ =11.3, R ₅₈ =15, R ₅₉ =22.6, R ₆₀ =45.2		

6 Simulation Options

Before you start the simulation, it is important that you plan ahead. The first thing to do is to choose a target casting speed that allows the steel to be cast in such a manner that all quality criteria are met. Secondly, the mold oscillation settings are important to ensure a good enough surface quality. Finally, the temperature of the liquid steel and the arrival of ladle two and three need to be planned accordingly.

This section presents the key underlying scientific theories and relationships that are required in order to successfully complete the simulation. In no way is it designed to be a comprehensive treatment of continuous casting theory and practice – for this, the user is directed to other excellent publications.

6.1 Simulation Mode

The simulation can be run in one of either two modes:

- Standalone mode
- Linked mode

6.1.1 STANDALONE MODE

In this mode you will be able to select your user level, the grade of steel and all the casting parameters, including ladle scheduling and temperatures. Initial simulation parameters, such as composition, ladle mass, inclusion content are set by default.

6.1.2 LINKED MODE

In this mode parameters such as user level, steel grade, ladle steel composition, temperature, mass and inclusion content are all loaded from any of your Secondary Steelmaking casts. Use the drop-down menu to view and select the available casts (Cast ID); the details will be displayed below (see Figure 6-1). Note that the inclusion content is represented by a scale. To access this feature you must be registered and logged into the site.

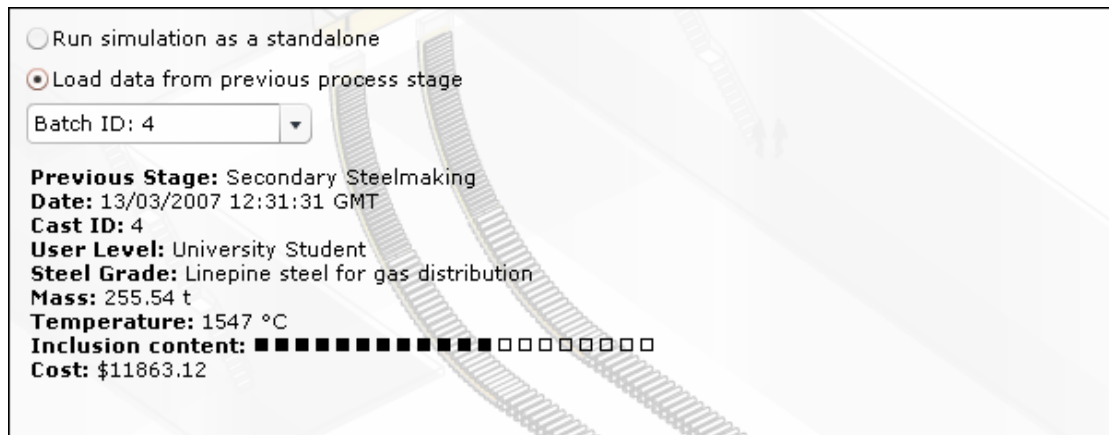


Figure 6-1 Screenshot showing data loaded from previous process stage

6.2 User Levels

The simulation has been developed for use by two different user groups:

- University students of metallurgy, materials science and other engineering disciplines.
- Steel industry works technical.

6.2.1 UNIVERSITY STUDENT LEVEL

At this level the user will be expected to approach the problem scientifically, using the relevant thermodynamic and kinetic theories to make decisions on the various processing options.

For example, the user will need to decide which combination of casting speed and secondary cooling rate that will yield a good quality strand.

At this level there will be no operational problems to overcome and casting will be relatively straightforward.

6.2.2 STEEL INDUSTRY WORKS TECHNICAL LEVEL

At this level, you will be expected to approach the problem scientifically. However, you may also experience a range of operational problems that require you to make adjustments to your planning and use your experience to make rapid decisions.

Typical examples of the operational problems you might encounter are delays to the time of ladle arrival, nozzle clogging, and different states of repair for the ladles in use.

To simulate that ladles are being worn down there are three different states of repair; good, acceptable and poor. The cooling rate of liquid steel in the ladle is affected by the state of repair and the corresponding values are 0.50, 0.75 and 1.00 °C min⁻¹.

Ladles may be delayed by up to 10 minutes. Remember to compare the ordered delivery time with the estimated arrival time, which is shown in text above the ladle turret station after the simulation starts.

You will also have to monitor the state of the submerged entry nozzles (SEN) to determine when these need changing due to "nozzle clogging". Nozzle clogging is the progressive build-up of inclusions in the nozzle during casting. It reduces the flow rate from the tundish into the mold due to the reduced area of flow and eventually the SENs have to be changed. To minimize the rate of nozzle clogging, you should maintain a high liquid steel level in the tundish at all times (this gives inclusions time to float to the surface). The only way to detect clogged nozzles is by monitoring the flow rate from the tundish. When it is no longer possible

to maintain the required flow rate for the target casting speed, you will need to change the nozzles. This is achieved by:

- Decrease the casting speed
- Stop the flow from the tundish.
- Press the "Change SEN" button. This costs \$200 per strand and it will take 15 seconds to change.
- Re-start the flow from the tundish to refill the mold.
- When the mold is refilled, return to the target casting speed

NOTE: It is essential to avoid emptying the mold during the nozzle change. It may be necessary to further decrease the casting speed if the mold level is running low.

6.3 Steel Grades

The simulation includes a number of different steel grades to illustrate a range of different processing options.

The general-purpose **construction steel grade** is a crack sensitive relatively undemanding steel grade that is recommended for the **novice user**. Construction steel is cast using a bloom casting machine with the cross section dimensions being 250 × 250 mm. The inclusion level can be moderate without suffering any quality problems.

The **TiNb ultra-low carbon steel** is a sticker sensitive steel grade used for automotive body parts with a carbon specification of less than 0.0035 %C in order to optimize formability. This steel is cast in a slab casting machine with the cross section dimension 1200 × 230 mm. To meet the cleanness requirements of this steel grade it is of the utmost importance that the inclusions levels are very low.

The **linepipe steel** for gas distribution is a very demanding grade as the combination of high strength and high fracture toughness having extremely low levels of impurities (S, P, H, O and N) and inclusions. Together with the ultra-low carbon steel grade, this steel has got the highest demands on having very low inclusion levels and both steel grades are cast using the slab casting machine with a cross section of 1200 × 230 mm. Depending on composition, this grade can be either crack sensitive (peritectic) or sticker sensitive (hypo-peritectic).

The **engineering steel** is a heat-treatable low alloy grade, which is cast at high speeds in a billet caster using cross section of 130 × 130 mm.

6.3.1 CRACK SENSITIVE GRADES

Steel grades in continuous casting are divided into two subgroups: cracking and sticker sensitive grades.

Cracking (longitudinal cracks) is a serious problem in medium carbon steels (0.06 – 0.18 %C). There is a 4 % mismatch between the thermal shrinkage coefficients for δ -ferrite and austenite. This results in stress in the shell and stress release comes through longitudinal cracking of the steel shell. The usually adopted strategy involves the reduction of the stresses by keeping the thickness of the shell to a minimum. This is achieved by reducing the horizontal heat transfer by increasing the thickness of the solid layer and the crystallinity of the solid slag layer.

6.3.2 STICKER SENSITIVE GRADES

In contrast, sticker breakouts occur when the shell is not strong enough to withstand the ferrostatic pressure and the liquid steel pours out of the shell. The strategy adopted here is to build a thicker shell and this is achieved by increasing the horizontal heat flux by decreasing the thickness and increasing the glassy fraction of the solid slag layer.

Table 6-1 Table of compositions for steel grades available in the simulation.

	Construction steel	TiNb ULC steel for car bodies	Linepipe steel	Engineering steel
C	0.1450	0.0030	0.0700	0.4150
Si	0.2000	0.2100	0.1800	0.4000
Mn	1.4000	0.7500	1.0500	0.7500
P	<0.0250	0.0650	<0.0120	0.0350
S	<0.0200	<0.0120	<0.0030	0.0350
Cr	<0.1000	<0.0500	<0.0600	1.0500
Al	0.0350	0.0450	0.0300	0.0225
B	<0.0005	0.0030	<0.0050	0.0050
Ni	<0.1500	<0.0800	<0.0500	0.3000
Nb	0.0500	0.0200	0.0150	0.0000
Ti	<0.0100	0.0300	<0.0100	0.0000
V	<0.0100	-	<0.0100	0.0100
Mo	<0.0400	<0.0100	<0.0100	0.2250
As	-	<0.0010	-	0.0000
Ca	-	-	<0.0050	0.0000
N	<0.0050	<0.0040	<0.0045	0.0050
H	<0.0005	<0.0005	<0.0002	0.0002
O	<0.0010	<0.0005	<0.0007	0.0005

6.4 Soft Reduction Level

Soft reduction is only available during slab casting and it is used for reducing the severity of center segregation. For soft reduction to have any effect, casting speed and secondary cooling rate must be chosen so that the metallurgical length, i.e. the length to which steel is still liquid in the center, is in the soft reduction zone.

A drawing of the soft reduction zone is shown in Figure 6-2. The soft reduction takes place over two segments each with a length of 2 meters. Each segment consists of 5 rolls and the roll pitch is about 400 mm. The reduction zone is positioned at a strand length between 27 and 31 meters when casting Linepipe steel and between 21 to 24 meters when casting Ultra-low carbon steel.

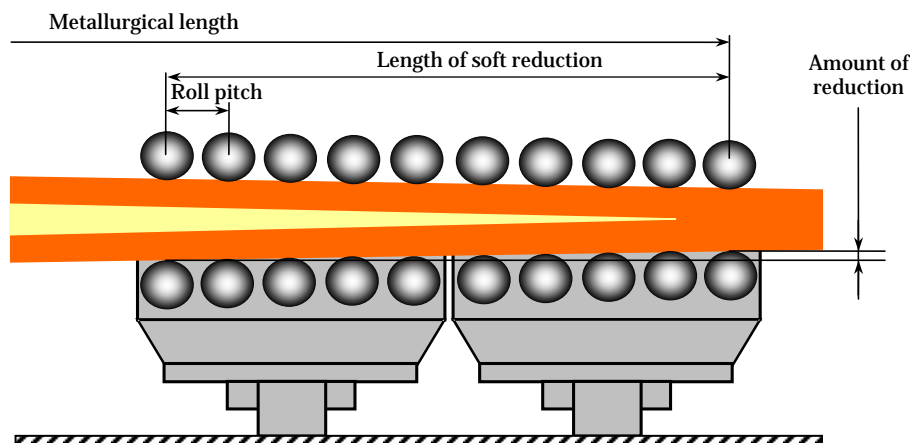


Figure 6-2 Graphical representation of the soft reduction zone

In the simulation, three different amounts of reduction can be selected. These are soft, medium and hard with corresponding strand thickness reduction of 2.4 mm, 6.0 mm and 10.8 mm, respectively. The same conditions apply to both ultra-low carbon steel (ULC) and line-pipe steel (LPS). Since the position of the soft reduction cannot be changed, there are only a few combinations of casting speed and secondary cooling rate which lead to an optimal condition of soft reduction.

This option is only available when casting a steel grade in the slab caster.

6.5 Casting Speed and Secondary Cooling Rate

Choosing the right combination of casting speed and secondary cooling rate is of the utmost importance. This choice will influence many different parameters during casting and is one of the key choices for getting a good quality cast. One parameter that is directly influenced by this choice is the **metallurgical length**, the distance from the mold at which the strand becomes totally solid.

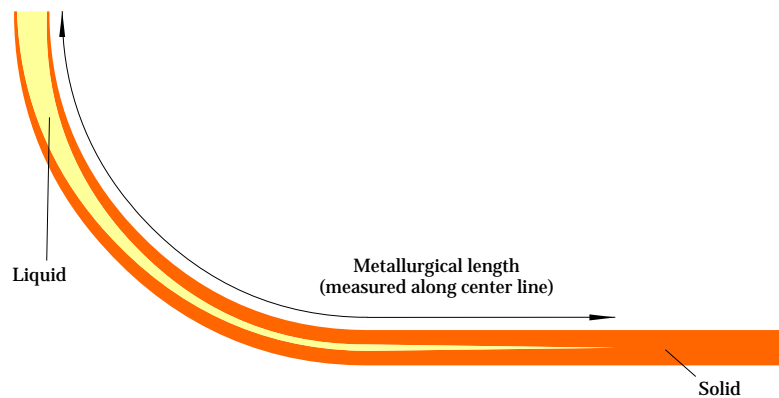


Figure 6-3 Diagram illustrating metallurgical length

The metallurgical length is a complex function of steel composition, casting speed, cooling rate and strand dimensions, the calculation of which is beyond the scope of this simulation. To help you make informed decisions about your casting parameters, the tables below are provided.

The different types of casting machines have different possible casting speeds and cooling rates, see below for tables of metallurgical lengths depending on these parameters.

Table 6-2 Metallurgical lengths for construction steel cast in the bloom caster, 250 × 250 mm.

Cooling Rate / kg water per kg steel	Casting Speed / m min ⁻¹			
	1.2	1.4	1.6	1.8
0.3	22.48	26.55	30.43	34.65
0.4	21.78	25.57	29.10	33.12
0.5	20.96	24.43	27.55	31.26
0.6	20.04	23.17	25.57	29.22

Table 6-3 Metallurgical lengths for ultra-low carbon steel cast in the slab caster, 1200 × 230 mm.

Cooling Rate / kg water per kg steel	Casting Speed / m min ⁻¹					
	1.0	1.2	1.4	1.6	1.8	2.0
0.4	19.03	23.06	27.23	31.55	36.06	40.73
0.5	18.30	22.16	26.16	30.30	34.62	39.10
0.6	17.67	21.38	25.23	29.22	33.36	37.70
0.7	17.11	20.70	24.43	28.30	32.28	36.47
0.8	16.63	20.10	23.70	27.46	31.35	35.40

Table 6-4 Metallurgical lengths for linepipe steel cast in the slab caster, 1200 × 230 mm.

Cooling Rate / kg water per kg steel	Casting Speed / m min ⁻¹					
	1.0	1.2	1.4	1.6	1.8	2.0
0.4	20.17	24.50	28.98	33.65	38.55	43.56
0.5	19.40	23.56	27.86	32.35	37.02	41.87
0.6	18.75	22.74	26.88	31.20	35.70	40.37
0.7	18.17	22.02	26.04	30.21	34.56	39.10
0.8	17.65	21.40	25.30	29.33	33.57	37.97

Table 6-5 Metallurgical lengths for engineering steel cast in the billet caster, 130 × 130 mm.

Cooling Rate / kg water per kg steel	Casting Speed / m min ⁻¹		
	3.0	4.0	5.0
0.8	17.20	22.40	28.00
0.9	16.70	21.53	26.83
1.0	16.20	20.73	25.66
1.1	15.70	19.86	24.42
1.2	15.20	19.06	23.33

6.6 Mold Oscillation Settings

An oscillating mold is used primarily to reduce the friction between the mold plate and the strand shell. This is facilitated by the induced flow of mold powder from the meniscus down the gap between the strand shell and the mold plates.

6.6.1 SETTINGS

Stroke, S [mm]: Normally, the stroke ranges between 3 and 10 mm. By increasing the stroke, the negative strip time (see below) increases proportionally. Hence, the depth of oscillation marks and the consumption of mold powder also increase.

Frequency, f [min⁻¹]: Customary hydraulic mold oscillators realize frequencies between 100 and 250 cycles per minute. By increasing the frequency, the negative strip time decreases, hence, the depth of oscillation marks and mold powder consumption decrease as well.

Negative strip time, t_N [s]: The negative strip time is the period where the downward velocity of the mold is higher than the casting speed, as given by:

$$t_N = \frac{60}{\pi f} \arccos \frac{1000 v_{\text{cast}}}{\pi f S} \quad [\text{s}] \quad 6-1$$

where:

$$\begin{aligned}
 f &= \text{frequency, min}^{-1} \\
 S &= \text{stroke, mm} \\
 v_{\text{cast}} &= \text{casting speed, m min}^{-1}
 \end{aligned}$$

Oscillation mark depth, d [mm]: While oscillating the mold is a necessity for continuous casting it also decreases surface quality due to so called oscillation marks. The surface of continuous castings is characterized by the presence of oscillation marks that form periodically at the meniscus due to mold reciprocation. They have an important influence on the surface quality because they are often the source for transverse cracks.

Oscillation mark depth depends on the chosen mold powder, oscillation stroke, oscillation frequency and casting speed. A regression of values from literature [1] yields:

$$d = 0.065 \cdot 1.145^S \cdot (200 \cdot 0.9^S)^{t_N} \quad [\text{mm}] \quad 6-2$$

where:

$$t_N = \text{negative strip time, s}$$

6.6.2 OSCILLATION MARKS

Figure 6-4 shows the formation mechanism for oscillation marks. The top of the figure shows the mold position varying with time. The formation mechanism of oscillation marks is outlined in the bottom part of the figure. The negative strip time (hatched areas) is the main influencing factor for the formation of oscillation marks. Increasing negative strip time is accompanied with increasing depth of oscillation marks.

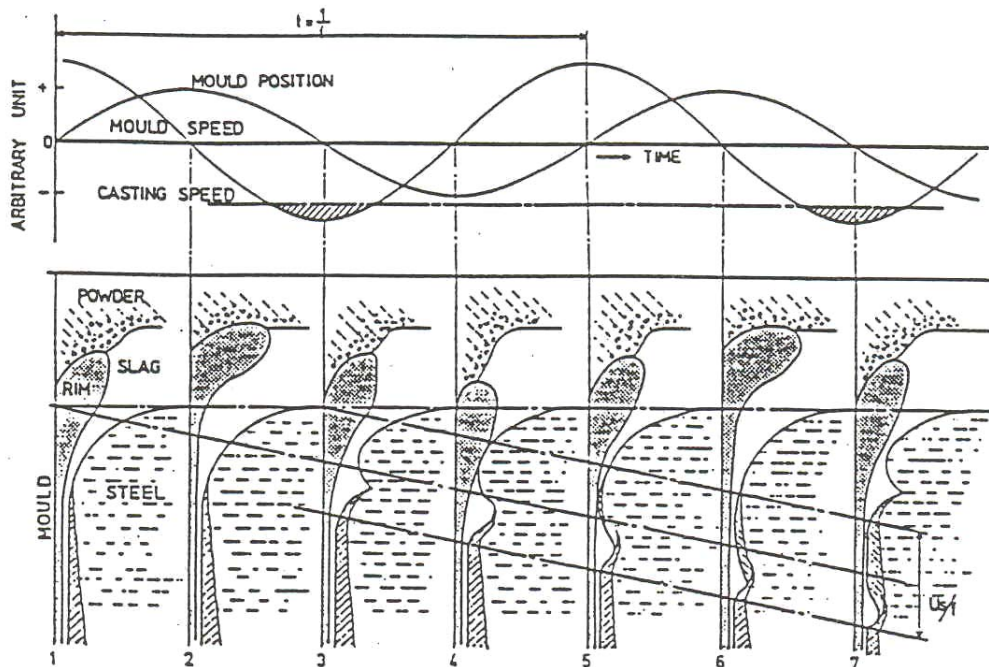


Figure 6-4 Formation of oscillation marks [2]

In order to minimize the depth of the oscillation marks it is essential to properly optimize the oscillation settings. The negative strip time should be as close to 0.11 s as possible combined with a stroke that results in the smallest possible oscillation mark depth.

Note that the maximum acceptable oscillation mark depth is 0.25 mm for ultra-low carbon steel while a depth of 0.60 mm is acceptable for the other steel grades.

6.7 Mold powder

Mold powder is a synthetic slag which is continuously fed onto the liquid pool surface during casting. The powder melts and flows down between the mold walls and the strand shell. Choosing the right mold powder is a critical choice to ensure a good enough surface quality of the cast material. The chosen powder primarily influences oscillation mark depth and mold powder consumption.

The function of casting powders is to:

- Act as a lubricant between strand and mold
- Improve heat transfer from strand to mold
- Provide thermal insulation of the top surface of the molten pool
- Protect liquid steel against reoxidation
- Absorb inclusions that rise to the metal surface

Figure 6-5 shows the general disposition of a powder in the continuous casting mold. Mold powder is added to the top of the liquid steel in the mold. The powder melts and infiltrates the mold/strand gap at the meniscus. This infiltration is the key process in continuous casting because it is necessary to ensure both good lubrication and a uniform heat transfer between the strand and the mold.

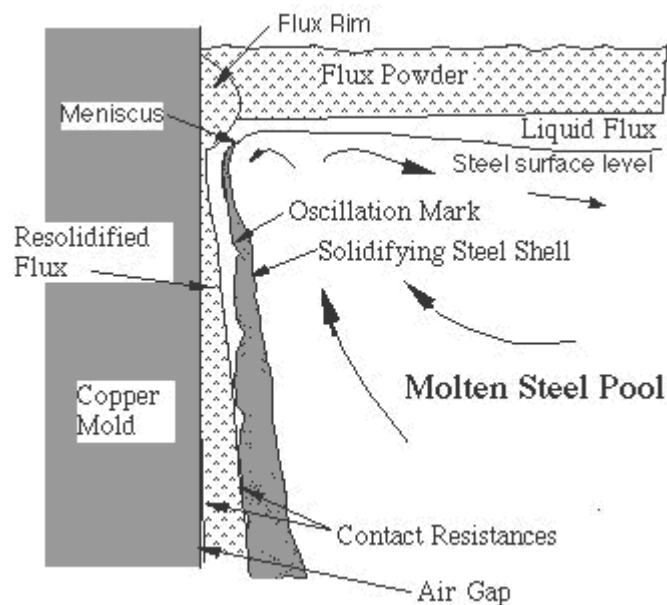


Figure 6-5 Function of mold powder [3]

6.7.1 IMPORTANT PARAMETERS

Mold powder consumption depends not only on the chosen type of mold powder but also on the oscillation settings and casting speed. The consumption is measured in mass per unit area of strand surface, e.g. kg m⁻². Since the molten mold powder is pumped by the oscillating

movement of the mold into the mold/strand gap the oscillation settings have an essential influence on the mold powder consumption.

There is a great variation within literature of fitted relations for mold powder consumption. In this simulation the following expression is used to calculate mold powder consumption:

$$Q = \frac{1.7 \times t_N}{\sqrt{\eta \times v_c}} \text{ [kg m}^{-2}\text{]} \quad 6-3$$

where

- Q = mold powder consumption per unit area, kg m⁻²
- t_N = negative strip time, s
- η = mold powder viscosity, Pa s
- v_c = casting speed, m min⁻¹

Too low a mold powder consumption rate will cause sticking between the strand and the mold, eventually resulting in a breakout. To avoid this, the powder consumption rate should be above 0.30 kg m⁻² except for engineering steel where 0.15 kg m⁻² is adequate.

One of the most important properties of a mold powder is **break temperature**. It is defined as the threshold temperature at which the powder's viscosity increases dramatically, i.e. the point where liquid lubrication starts to break down.

Figure 6-6 shows how the break temperature varies with different casting speeds. A crack sensitive grade should be cast using casting powder A or B to provide as good conditions as possible, while sticker sensitive grades should be cast using powder type C or D.

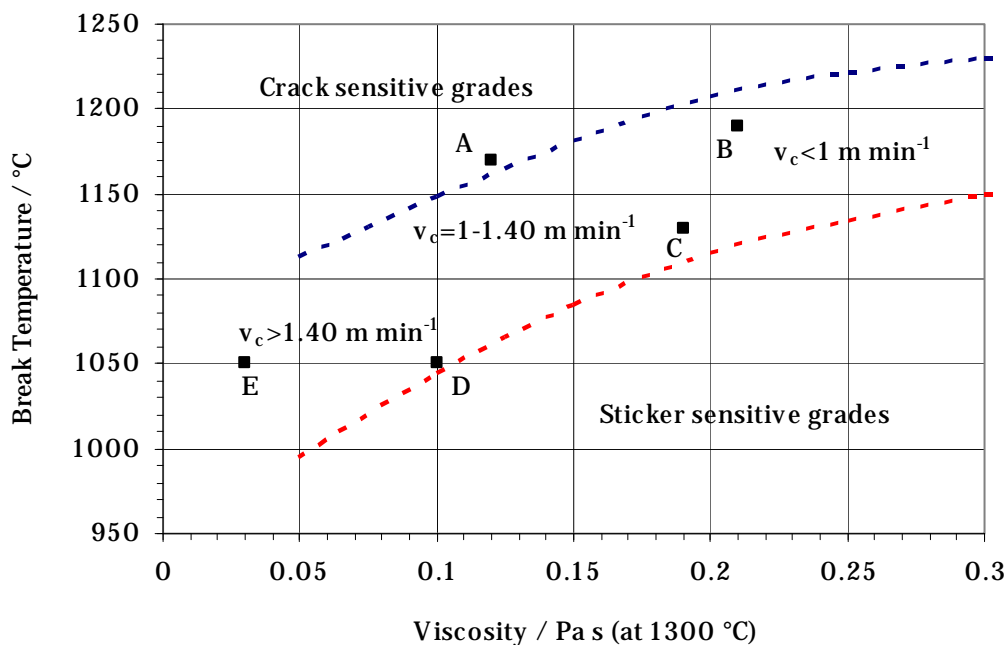


Figure 6-6 Break temperature and viscosity of the mold powder in relation to casting speed [4]

Table 6-6 contains material property data and costs for the five different types of mold powders that can be used.

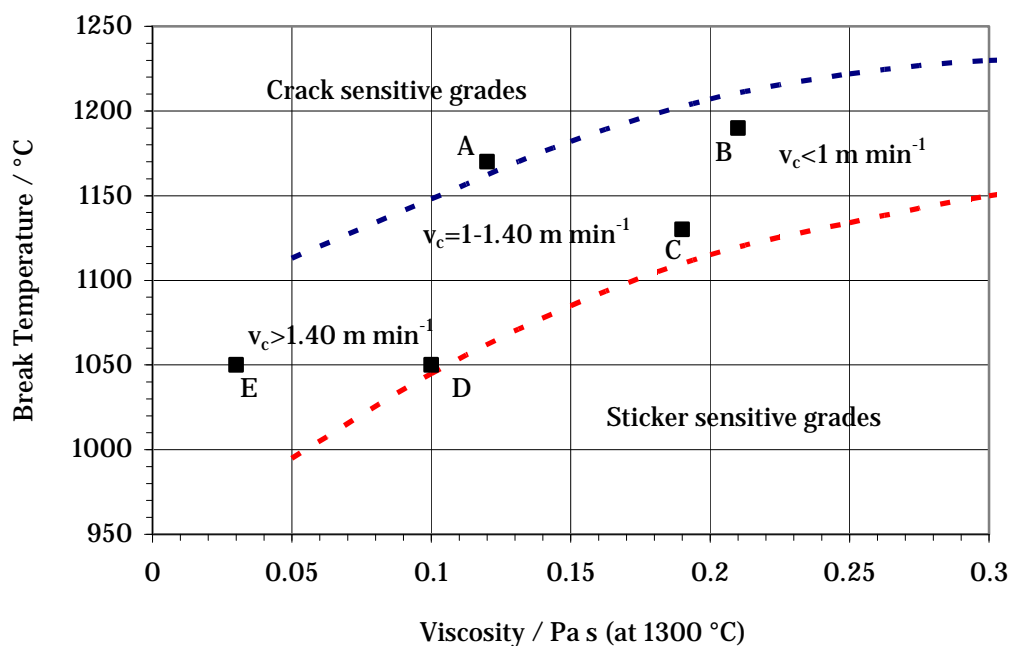


Figure 6-6 Break temperature and viscosity of the mold powder in relation to casting speed [4]

Table 6-6 Material properties of available mold powders.

Powder	Viscosity / Pa s	Break temperature / °C	Cost / \$ per kg	Purpose
A	0.12	1170	0.40	Used for crack sensitive grades
B	0.21	1190	0.35	
C	0.19	1130	0.45	Used for sticker sensitive grades
D	0.10	1050	0.50	
E	0.03	1050	0.55	Used for high speed casting

6.8 Ladle Ordering

The objective of the simulation is to sequence cast three ladles. The first ladle is in place over the tundish when the simulation begins, but the other two will arrive at a later point. You can choose the arrival temperature for all three ladles and the estimated arrival time for the last two ladles. Note that in linked simulation mode (see Section 6.1.2) the actual delivery times of ladles will be influenced by your performance in the Secondary Steelmaking simulation. The closer you are to the target delivery time in Secondary Steelmaking, the more reliable will be the timings of delivery of the second and third ladles in Continuous Casting. This gives ample opportunity to optimize time-temperature control to achieve the right casting conditions in the mold.

Estimated arrival time is input as the number of minutes passed after the simulation begins and the **estimated arrival temperature** is input as °C.

Remember that the steel loses temperature over time due to heat losses. It is assumed that the temperature loss for the ladle is $0.5 \text{ } ^\circ\text{C min}^{-1}$.

6.8.1 TIME

The time it takes to empty a ladle determines how long you should allow between ladles, e.g. adjust the arrival time of ladle 2 so that ladle 1 is emptied just before or after ladle 2 arrives. The emptying time depends on cross sectional area of the mold/strand, the number of strands per tundish and casting speed.

The **volume** of material cast per strand per minute is given by:

$$\dot{V} = w \cdot t \cdot v_c \text{ [m}^3 \text{ min}^{-1}] \quad 6-4$$

where:

- w = strand width, m
- t = thickness of the strand, m
- v_c = casting speed, m min⁻¹

Therefore the **mass** of material per minute for the tundish is given by:

$$\dot{M}_T = n \cdot \rho_{\text{liq}} \cdot w \cdot t \cdot v_c \text{ [kg min}^{-1}] \quad 6-5$$

where:

- n = number of strands
- ρ_{liq} = liquid steel density, 7400 kg m⁻³

Under steady state casting conditions (i.e. constant v_c) the time to drain a ladle to a given level of steel will be given by:

$$\tau = \frac{m_{\text{ladle}}}{\dot{M}_T} = \frac{m_{\text{ladle}}}{n \cdot \rho_{\text{liq}} \cdot w \cdot t \cdot v_c} \text{ [min]} \quad 6-6$$

where:

- m_{ladle} = mass of liquid steel to be teemed from the ladle, kg. Note that teeming automatically stops when slag is detected at the slidegate, typically when the steel level reaches 5 %.

Example

You are casting a linepipe steel using a 1.5 by 0.2 m cross section twin strand slab casting machine. The casting speed is 1.8 m min⁻¹ and the caster is supplied via 200 tonne ladles. Calculate the time to teem a ladle at steady state assuming that teeming stops at a level of 5 %.

$$\tau = \frac{200\,000 \times 0.95}{2 \times 7400 \times 1.5 \times 0.2 \times 1.8} = 23.8 \text{ [min]}$$

6.8.2 TEMPERATURE

In order that the steel has the optimum temperature in the mold, it is important that the ladles are ordered with the correct temperature. For University Student level the liquid steel in the ladle cools at 0.5 °C min⁻¹ but for the Works Technical level the cooling rate depends on the state of the ladle and will vary between 0.5 and 1.0 °C min⁻¹.

By carefully calculating the overall time from start of simulation to the time when the ladle is emptied, the temperature loss is possible to compute. Subsequently, the necessary steel temperature at arrival can be calculated.

6.8.3 CALCULATION OF LIQUIDUS TEMPERATURE

It is imperative to prevent the liquid steel temperature falling below the liquidus temperature (i.e. the temperature at which the steel begins to solidify). The liquidus temperature, T_{liq} , is dependent on composition and can be calculated from the following equation [5]:

$$T_{\text{liq}} = 1537 - 78\%C - 7.6\%Si - 4.9\%Mn - 34.4\%P - 38\%S$$

In practise it is necessary to keep the steel temperature slightly higher than the liquidus temperature, due to temperature variations within the steel (i.e. edges and corners tend to have a lower temperature). The difference between liquidus temperature and actual temperature is called superheat. Make sure that the superheat always is above 10 °C to avoid freezing.

Increasing superheat reduces the shell thickness of the strand due to the extra heat energy that has to be extracted by the mold. If the shell at any part of the strand is too thin to support its own weight there will be a breakout. Maximum superheat is 50 °C for slab casting machines and 60 °C for bloom and billet casters.

6.9 Review of Choices

The last screen before the simulation starts allows you to review the choices that you have made. After pressing 'next', the simulation starts and you cannot go back and change these choices without restarting the simulation.

7 Running the Simulation

Having selected the different settings for your continuous casting operation it is time to start casting. The aim is to control the flow of liquid metal from ladle to tundish to mold so that the selected casting speed can be maintained and a good quality casting achieved. You will also need to exchange ladles, check the rolls for any excessive misalignment and cut the strand into semi-finished products.

7.1 Starting the Cast

The first step is to start teeming the ladle. Open the slidegate to increase the flow rate of steel from the ladle to the tundish. This can either be done by clicking on the up or down arrow or by directly entering a number in the flow rate controller labeled "Ladle flowrate".

After reaching a sufficient buffer level of steel in the tundish, raise the stopper rods to increase the flow from the tundish to the mold. This can be done by done either clicking on or entering a number in the flow rate controller labeled "Tundish flowrate".

Wait until the mold level is high enough (preferably over 70 %), then start casting by choosing a relevant casting speed.

You will need to balance the flow between ladle, tundish, and molds to ensure that the levels are sufficiently high at all times. Typically you should aim to maintain an 80-90 % level in both tundish (see Section 7.3) and molds (to avoid breakout, see Section 7.5). Clearly however you do not want to overfill either of the vessels.

7.2 Ladle Change

Subsequent ladles are automatically lowered into the turret. At works technical level there may be delays in delivery of up to 10 minutes so be prepared to counteract this.

Make sure to stop the flow from the ladle before attempting to rotate the new ladle in place over the tundish.

The level in the tundish will inevitably decrease while the ladles are being exchanged, so make sure you have a sufficiently high level in the tundish beforehand. You will need to start teeming the new ladle at a higher rate in order to replenish the tundish to its target level after a completed ladle exchange.

7.3 Steel Cleanness

Certain applications, such as linepipes for oil and gas distribution require very 'clean' steels – i.e. with very low levels of oxide and sulfide inclusions, since these can act as crack initiation sites. The chemistry of oxide and sulfide formation and subsequent removal during secondary steelmaking is extremely complex and the subject of ongoing research. For more comprehensive information it is kindly suggested that articles and books about these subjects are consulted.

In the simulation you will aim to achieve 'moderate', 'low' or 'very low' levels of inclusions depending on the chosen steel grade. Various factors influence the end-level of inclusions. The level of inclusions at arrival to the casting station is assumed to be appropriate to the level that is needed in order to achieve a clean enough steel. For example, if you are casting engineering steel the inclusion level does not need to be very low, it is sufficient for the purpose to have a low level of inclusions so the cleanliness of the steel in the provided ladle will be low from the start. This does not however mean that the casting will automatically succeed.

The inclusion level of the steel can be kept at its present level or even be slightly lowered by using the tundish as a buffer. This allows for removal of inclusions to the walls of the tundish and to the slag layer on top of the liquid steel. Thus, having a long residence time in the tundish is very important for casting as clean steel as possible. A higher level of inclusions in the ladle may necessitate lower casting speeds in order to allow more time for the inclusions to float off in the tundish. Note that in linked simulation mode (see Section 6.1.2) the level of inclusions is loaded from your Secondary Steelmaking results.

7.4 Strain Analysis Model for Slab Casting Machine

For the ULC steel and the linepipe steel, a uniform casting machine is assumed. Figure 7-1 shows a schematic drawing of the slab caster. The strand guide is curved from the mold all the way down to the end of the straightening section. The curvature is divided into two zones with 35 and 25 rolls, respectively.

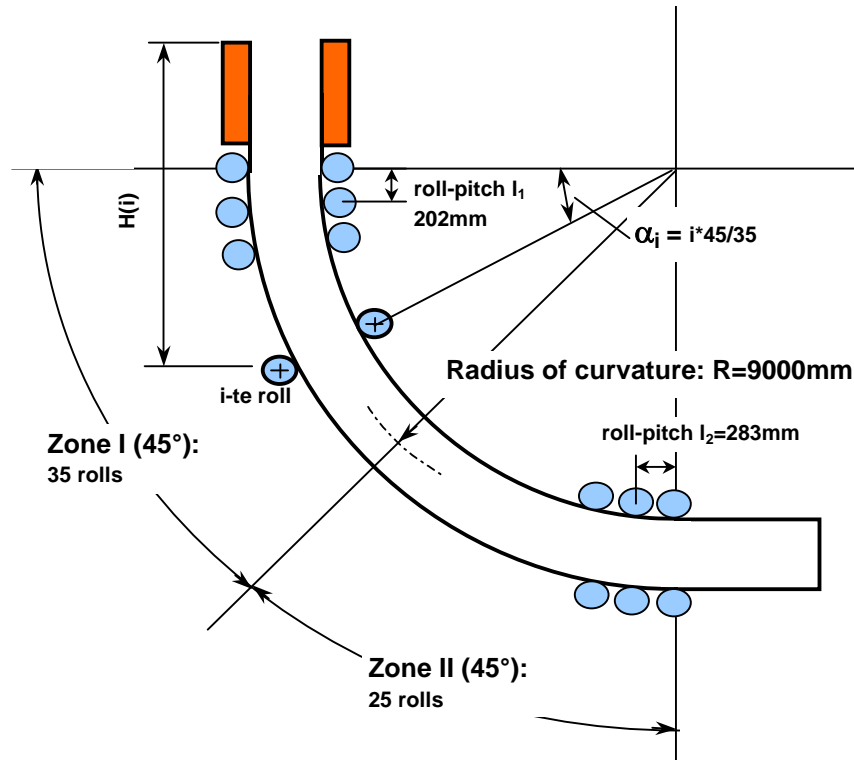


Figure 7-1 Schematic drawing of the slab caster

In the following section the theoretical background on internal cracking and surface cracking will be given together with the working equations from which the simulation calculates these phenomena.

7.4.1 ESTIMATION OF INTERNAL CRACKING

To estimate the possibility of internal cracking the strain on the solidification front is compared with a critical strain. Therefore, the strain on the solidifying front caused by the process on each roll can be calculated as follows [6-8].

The tensile strains at the solidifying front caused by bulging, bending, straightening and misalignment of supporting rolls are calculated using the following empirical equations. The strain caused by bending and straightening is given by:

$$\varepsilon_{BS} = 100 \cdot \left(\frac{d}{2} - S \right) \cdot \left| \frac{1}{R_{n-1}} - \frac{1}{R_n} \right| \quad 7-1$$

where:

- d = slab thickness, mm
- S = shell thickness, mm
- R_{n-1} and R_n = radii of roll number $n-1$ and n , mm

Both the bending and straightening take place with a multi point (five-point) method. Figure 7-2 shows the five point straightening method with the assumed radii. The bending method is the same as the straightening with identical radii.

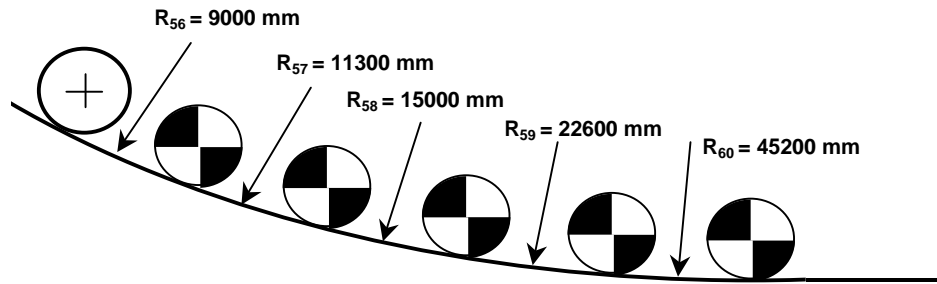


Figure 7-2 Five point straightening method

To calculate the bulging strain ε_B (%), a typical empirical formula can be used:

$$\varepsilon_B = \frac{0.101972 \cdot P \cdot l^3}{3800 \cdot S^3} \cdot 100 \quad 7-2$$

where:

- S = solidifying shell thickness, mm
- P = the static pressure of liquid steel, N mm^{-2}
- l = the roll pitch, mm

The strain due to roll misalignment ε_M (%) can be evaluated from following equation:

$$\varepsilon_M = 1.15 \cdot \frac{3 \cdot S \cdot \delta_M}{l^2} \cdot 100 \quad 7-3$$

where:

- δ_M = the roll misalignment amount, mm

Finally, the total strain at the solidifying front $\varepsilon_{\text{intern}}$ during continuous casting of slab is considered to be given by a sum of strains caused by bending/straightening, bulging and roll misalignment as:

$$\varepsilon_{\text{intern}} = \varepsilon_{\text{BS}} + \varepsilon_B + \varepsilon_M \quad 7-4$$

When the total strain exceeds the critical strain, internal cracks will be formed. The critical strain depends on the steel composition and the strain rate [8]. The construction and engineering steel grades can withstand a critical strain of about 1%, while linepipe and ultra-low carbon steels have a critical strain of roughly 2%.

Internal crack formation will be a limiting factor in increasing the casting speed. The demands on LPS and ULC steel are such that failing internal quality results in a downgrading of the slab.

7.4.2 ESTIMATION OF SURFACE CRACKING

To estimate the surface quality in slab casting of the ultra-low carbon and linepipe steel, it is assumed that only transverse cracking can occur [9]. The surface strain $\varepsilon_{\text{surf}}$ arising during continuous casting is considered to be given by a sum of strains caused by bending/straightening ε_{BS} , roll misalignment ε_{M} , bulging of solidifying shell ε_{B} and thermal contraction ε_{th} :

$$\varepsilon_{\text{surf}} = \varepsilon_{\text{BS}} + \varepsilon_{\text{M}} + \varepsilon_{\text{B}} + \varepsilon_{\text{th}} \quad 7-5$$

The strain on the surface caused by bending/straightening can be approximated by:

$$\varepsilon_{\text{BS}} = 100 \cdot \frac{d}{2} \cdot \left| \frac{1}{R_{n-1}} - \frac{1}{R_n} \right| \quad 7-6$$

where:

- d = slab thickness, m
- R = strand radius, m
- N = roll number

As already described (Figure 7-2) the bending and straightening takes place with a five point method. The strain due to the roll misalignment can be evaluated from the change of radius caused by the deviation from the original position of any roll as:

$$\varepsilon_{\text{M}} = 100 \cdot \frac{d}{2} \cdot \left| \frac{1}{R_0} - \frac{1}{R_d} \right| \quad 7-7$$

where:

- R_0 = radius of original position, mm
- R_d = deviated position of the roll, mm

The surface strain due to bulging of solidifying shell is assumed to be equal to the strain at the solidifying front due to bulging and therefore, can be calculated with equations (7-2) and (7-3). The thermal strain is calculated as a product of thermal expansion coefficient α and temperature difference ΔT :

$$\varepsilon_{\text{th}} = \alpha \cdot \Delta T \cdot 100 \quad 7-8$$

To calculate the surface strain due to bulging it is assumed that the same equation to calculate the strain at the solidification front (Equation 7-2) can be used.

A volume element on the surface of the strand travels through the total continuous casting process and therefore, a total accumulated surface strain $\varepsilon_{\text{surf}}^{\text{tot}}$ must be calculated, where n is the number of rolls.

$$\varepsilon_{\text{surf}}^{\text{tot}} = \sum_i^n \varepsilon_{\text{surf}}(i) \quad 7-9$$

If the total surface strain exceeds the critical strain, surface cracks will be formed. The critical strain depends on steel composition, depth of oscillation marks and surface temperature in the straightening zone [9]. Nb-alloyed steels (linepipe and construction steel) are very prone to surface crack formation. The surface temperature should not fall below 1050 °C for linepipe steel and not below 1100 °C for the construction steel. Furthermore, oscillation marks should be as shallow as possible. A depth of below 0.2 mm will result in higher critical strain. Slabs and blooms with surface cracks have to be scarfed. The cost for scarfing amounts to 3 % of the production costs. ULC slabs with surface cracks will be scarfed and downgraded because of the high surface finish requirements.

7.5 Avoiding Breakout

A breakout will occur if the ferrostatic pressure exceeds the strength of the strand shell. It is avoided by ensuring that the shell thickness at any given point in the strand is sufficient to carry the weight of the liquid steel above this point.

Since the probability of breakout increases with a decreasing shell thickness, it is very important to maintain a high steel level in the mold and to have as low superheat as possible. This allows the shell to solidify to an adequate thickness before the steel leaves the mold. Given that a thin shell might break under the pressure of the liquid steel, oscillation marks should be kept as shallow as possible.

Depending on its precise composition, the linepipe steel grade can either be peritectic or hypo-peritectic. Peritectic compositions are very crack sensitive, and so require more careful casting to avoid cracks forming and propagating through the shell to cause breakout.

The following equation for carbon equivalent can be used to determine if the steel is peritectic or not. Peritectic steel will have a carbon equivalent over 0.1 wt-%C [10].

$$C_{eq} = \%C - 0.1\%Si + 0.04\%Mn - 0.04\%Cr + 0.1\%Ni - 0.1\%Mo \quad 7-10$$

Using the correct mold powder for the selected steel grade is also very important. Selecting a mold powder that is optimized for the wrong type of steel increases the probability of a breakout. Also, the mold powder level must at all times be kept sufficiently high to maintain a full lubrication between strand and mold.

In summary, avoid breakout by having:

- a mold level between 80 and 90 %
- a low superheat
- shallow oscillation marks
- the correct mold powder

8 User Interface

This section describes the basic 'mechanics' of running the simulation, e.g. how to move the ladle, how to make alloy additions, how to control the various pieces of equipment, etc.

8.1 Simulation Controls

8.1.1 SIMULATION RATE

The simulation can be run at a range of different speeds between $\times 1$ and $\times 32$. The rate can be changed at any time during the simulation. Highest recommended speed is $\times 16$. This can be

done by clicking on the arrows on the so called numeric stepper to increase or decrease the simulation rate with an increment of 1. Another way is to double-click inside the field with the current simulation rate to select the current number, delete it, enter the new simulation rate and then press "Enter".

8.1.2 LADLE TURRET

The ladle turret can be rotated by pressing the button labeled "Rotate". The turret cannot be rotated as long as a ladle is missing in the turret or if the turret is currently rotating. Neither can it be rotated if the ladle slidegate is open. If you are having difficulties to get the ladle turret to rotate, please make sure that these three criteria are being met.

8.1.3 LADLE

Flow rate from the ladle to the tundish is controlled by using the numeric stepper labeled "Ladle flowrate". The stepper is operated like the simulation rate controller. The flow rate from the ladle is controlled to a precision of 100 kg min⁻¹.

8.1.4 TUNDISH

The liquid steel flow from the tundish is controlled by using the numeric stepper labeled "Tundish flowrate". The stepper is operated like the simulation rate controller. The flow rate from the tundish to the mold is controlled to a precision of 25 kg min⁻¹.

8.1.5 STRAND

Casting speed is controlled by selecting one of the choices listed in the "Casting Speed" drop-down box. The choices pre-fixed with '*' are used for starting the cast. Please note that it is only after choosing a valid casting speed, i.e. a casting speed that is not marked with '*', that the cast strand can meet any of the quality criteria.

Misaligned rolls change color to indicate which roll pair that has become misaligned. To view how big the misalignment is and how much it would cost to repair this, move the mouse over the colored rolls. To align the rolls, i.e. repair the roll pair, simply click on the colored roll. The repair cost will automatically be added to your total operational cost.

NOTE: In reality, misaligned rolls are repaired between castings, not during.

8.1.6 CHANGE SEN (WORKS TECHNICAL ONLY)

SENs can be changed by pressing the button "Change SEN". SENs can only be changed when the flow from the tundish has been stopped. It takes 15 seconds to change the SENs and it also adds \$200 per strand to the total cost.

8.1.7 EMS (ONLY FOR BLOOM AND BILLET CASTER)

Electro-magnetic stirring (EMS) can be used while using the bloom or billet caster. Using the EMS decreases the segregation in the strand, thus improving the internal quality. If you are having difficulties meeting the segregation quality requirement, try casting with EMS on. Clicking on the button "EMS" will turn EMS on or off depending on the current state. The button border is highlighted when EMS is on.

8.1.8 SOFT REDUCTION (ONLY FOR SLAB CASTER)

The amount of soft reduction used during casting can be changed by using the "Soft reduction" drop-down box located next to the soft reduction zone marked as dark red. It is possible to choose between off, low, medium and high.

8.2 Casting Information

It is possible to view detailed information about the casting during and after the simulation. The following views are available by pressing the relevant key.

8.2.1 VIEW EVENT LOG (KEY E)

The event log keeps a chronological record of all the major events including some simulation settings. This is useful for keeping track of what you have done and what has occurred so far during the simulation. It is also very useful in helping you analyze your results at the end of the simulation, as the log will often contain clues as to why you passed or failed the different criteria.

8.2.2 VIEW FLOWS (KEY F)

Pressing 'F' shows a graph of the liquid steel flows from ladle to tundish and from tundish to mold.

8.2.3 SHOW/HIDE INNER ROLLS (KEY H)

Pressing 'H' will toggle between shown and hidden inner strand rolls. This is most useful for being able to see the whole strand whilst casting ULC or LPS steel in the slab caster.

8.2.4 VIEW LEVEL OF STEEL (KEY L)

Pressing 'L' shows how the level of liquid steel has changed in the ladle and in the tundish.

8.2.5 VIEW QUALITY (KEY Q)

Pressing 'Q' shows a graphical representation of the strand such as it has been cast. Good and bad areas are marked and key figures about the strand are also displayed. This choice is only available after completing the simulation.

8.2.6 VIEW TEMPERATURE (KEY T)

Pressing 'T' shows the variation of temperature over time in the ladle and in the tundish. This choice is only available after completing the simulation.

8.2.7 CLOSE CASTING INFORMATION DIALOG BOX (KEY X)

Pressing 'X' will close the casting information dialogue box.

8.3 Simulation Results

When the last steel has been cast and the strand is finished, the simulation will end and the results of the casting operation will be displayed. Four key figures are shown immediately and then you also have the possibility to further investigate the success or failure of the casting by looking in further detail at one of the five detailed views. The key figures include:

Total Length of the Cast, expressed in meters.

Length Meeting Quality Criteria, expressed in both meters and in %.

Total Operating Cost, expressed in \$, which includes the hourly operating cost and additions for repairing misaligned rolls, taking temperature measurements, etc.

Cost per Metric Ton, which is the total operating cost divided by mass of cast steel meeting the quality criteria.

The detailed views include information about temperature, level and flow variations in the ladle and tundish as well as the event log and the quality log. These views are intended to help in analyzing the casting operation in order to find where problems might come from and give ideas on where casting conditions might be improved upon.

The **quality log** show quality variations in the cast strand. The first cast material is therefore at $x = 0$ in the diagram and the last cast material is at the right hand edge. There are five categories of failure for the strand:

- Internal Cracking
- Surface Cracking
- Center Segregation
- Inclusion Content
- Oscillation Marks

The diagram shows the strand quality using these five criteria. Shaded areas indicate where quality requirements have not been met. Such defects have different impact for different steels. Some surface defects can be removed by scarfing, other defects cause downgrading of the steel and in the worst case the whole length will be scrapped. Lengths without any defects are always adequate for their intended purpose. See Table 8-1 for which countermeasures that will be taken depending on which defects that are present in the cast steel.

Table 8-1 Quality defects and their countermeasures.

Steel	Scarfe	Downgrade	Scrap
CON	Surface cracking	Any two defects	More than two defects
ULC	Surface cracking or Oscillation marks	Any defect	More than two defects
LPS	Surface cracking or Oscillation marks	Internal cracking or Center segregation or Inclusion content	More than two defects
ENG	-	Any two defects	More than two defects

Downgrading a cut length will reduce the profit by 20 %, while scrapping reduces profit by 80 %. The cost for scarfing a cut length is about 2.5 % of the cost for the steel grade. To improve cost effectiveness it is therefore very important to try to cast a strand without defects.

Internal cracking and **surface cracking** is decided by the strains and stresses in the strand during casting. Possible measures to prevent crack formation are optimizing mold powder and mold oscillation to result in an oscillation mark depth < 0.2 mm and to provide good machine maintenance regarding misaligned rolls.

Center segregation can be reduced by choosing a combination of casting speed and secondary cooling rate so that the point of final solidification is well within the soft reduction zone. Having done so, the next step of optimization is to increase the soft reduction level further to achieve a greater thickness reduction.

Inclusion content can be lowered by making sure that the residence time for liquid steel in the tundish is as long as possible. This is achieved by maintaining a high level of steel in the tundish and/or casting at lower speeds.

Oscillation marks are decided by the oscillation settings that are chosen before the simulation is started. A failure here means that these settings must be optimized further to result in smaller oscillation marks.

9 References

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