steeluniversity.org

Continuous Casting Simulation, version 0.21 User Guide

Contents

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.

2.1 Limitations

- Only one of the four steel grades is available for the evaluation version. (Linepipe steel)
- The user level is limited to “University Student”
- Some events are still under development and will not occur, e.g. solidification of metal in the vessel, nozzle clogging.
- Casting powder has not yet been implemented.
- Extra information is available throughout the simulation to improve the possibility to review the simulation. These include quality of the strand and temperature of ladle and tundish. These will in the released version only be possible to view after completing the simulation.
- The Flash Player menu is not disabled, so at this stage a user could potentially reach a stage of the simulation which is not intended.

3 Introduction to Continuous Casting

Continuous casting of steel is a process in which liquid steel is solidified continuously into a strand of solid metal. Depending on the dimensions of the strand these semi-finished products are called slabs, billets or blooms. 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 lowered from a 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 into a tundish, a vessel that acts as a buffer between the ladle and the mold. As the tundish fills, stopper rods are raised 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 needs a sufficiently thick solid shell to carry the weight of the ferrostatic pressure caused by the liquid steel that it contains.

During the whole casting process, the mold oscillates to separate the solidified steel from the copper mold. This is facilitated by introducing a mold powder into the mold.

The strand guide is a system of withdrawal rolls which guides the steel through an arc until the strand is horizontal. These roll pairs are 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, a system of water sprays situated between the rolls, which begins immediately below the mold by spraying a fine water mist on the steel. 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.

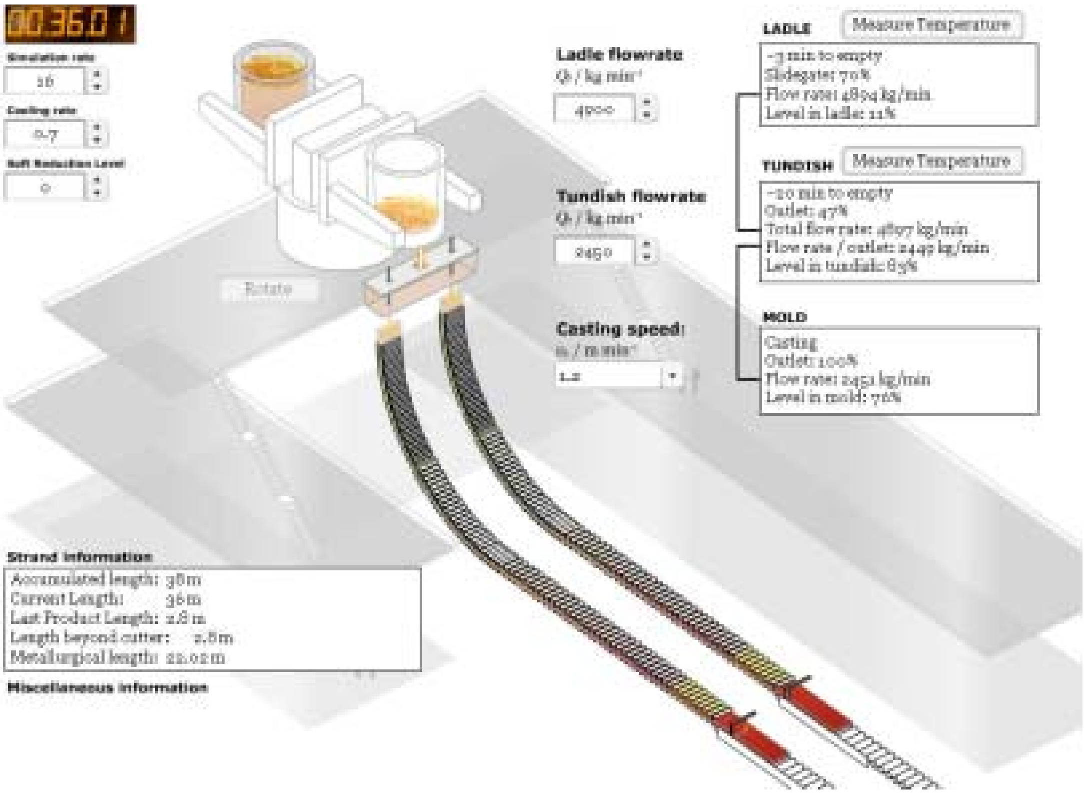
Component	Primary Task	Secondary Task
Ladle	Transport and hold the liquid steel	Facilitate inclusion removal
Ladle Turret	Position full ladles over the tundish and remove empty ones	Free the cranes for higher productivity
Tundish	Act as a buffer between ladle and mold	Facilitate inclusion removal
Mold	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



Simulation rate: 16

Casting rate: 0.7

Soft Reduction Level: 0

Ladle flowrate Q_L / kg min^{-1}: 4900

Tundish flowrate Q_T / kg min^{-1}: 2450

Casting speed: v_c / m min^{-1}: 1.2

LADLE
~3 min to empty
Slidegate: 70%
Flow rate: 4894 kg/min
Level in ladle: 11%

TUNDISH
~20 min to empty
Outlet: 47%
Total flow rate: 4897 kg/min
Flow rate / outlet: 2449 kg/min
Level in tundish: 83%

MOLD
Casting
Outlet: 100%
Flow rate: 2451 kg/min
Level in mold: 76%

Strand information
Accumulated length: 38m
Current Length: 36m
Last Product Length: 2.8m
Length beyond cutter: 2.8m
Metallurgical length: 22.02m

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 the Figure. At the start of the simulation, one full ladle is positioned over the tundish.

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 comprehensive treatments of continuous casting theory and practice – for this, the user is directed to other excellent publications.

6.1 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.

6.1.1 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.

6.1.2 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 changes to the time of arrival of ordered ladles, nozzle clogging, and so on.

6.2 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 has 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.

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

6.2.1 CRACK SENSITIVE GRADES:

Steel grades are in continuous casting 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.

6.2.2 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 mold. 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.

6.3 Soft Reduction Level

Soft reduction 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.

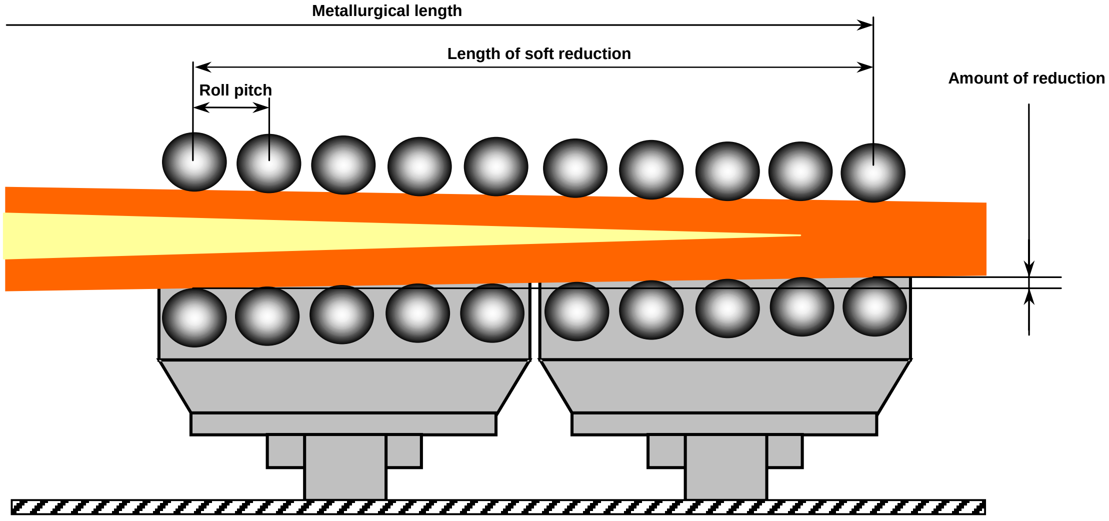


Figure 6-1 Graphical representation of the soft reduction zone

A drawing of the soft reduction zone is shown in Figure 6-1. 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 23 and 27 meters.

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 amount of secondary cooling rates which lead to an optimal condition of soft reduction.

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

6.4 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.

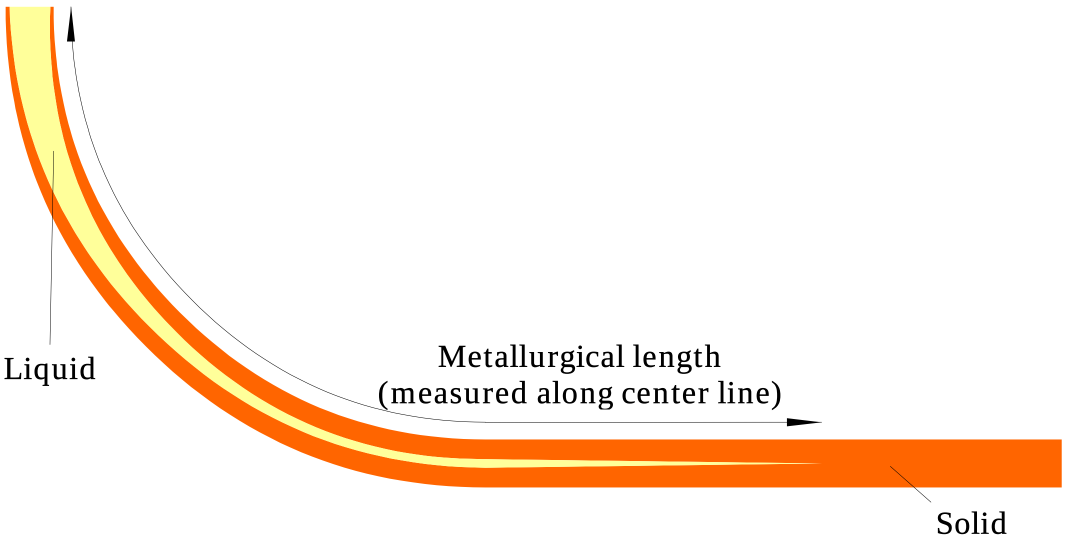


Figure 6-2 Diagram illustrating metallurgical length

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 length 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 length 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 length 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 length 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	15.80	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

6.5 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.

6.5.1 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:

$$t_{\mathrm{N}} = \frac{60}{\pi f} \arccos \frac{1000\, v_{\mathrm{cast}}}{\pi f S} \qquad \text{6-1}$$

where:

f = frequency, min^{-1}
S = stroke, mm
v_{cast} = casting speed, m min^{-1}

Oscillation mark depth, d [mm]: While oscillation 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.

$$d = 0.065 \cdot 1.145^{S} \cdot (200 \cdot 0.9^{S})^{t_{\mathrm{N}}} \qquad \text{6-2}$$

where:

t_{N} = negative strip time, s

6.5.2 OSCILLATION MARKS

The surface of continuously cast steel is characterized by the presence of oscillation marks that form periodically at the meniscus (see below) due to mold reciprocation. They have an important influence on the surface quality because they are often the source for transverse cracks.

Figure 6-3 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.

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.

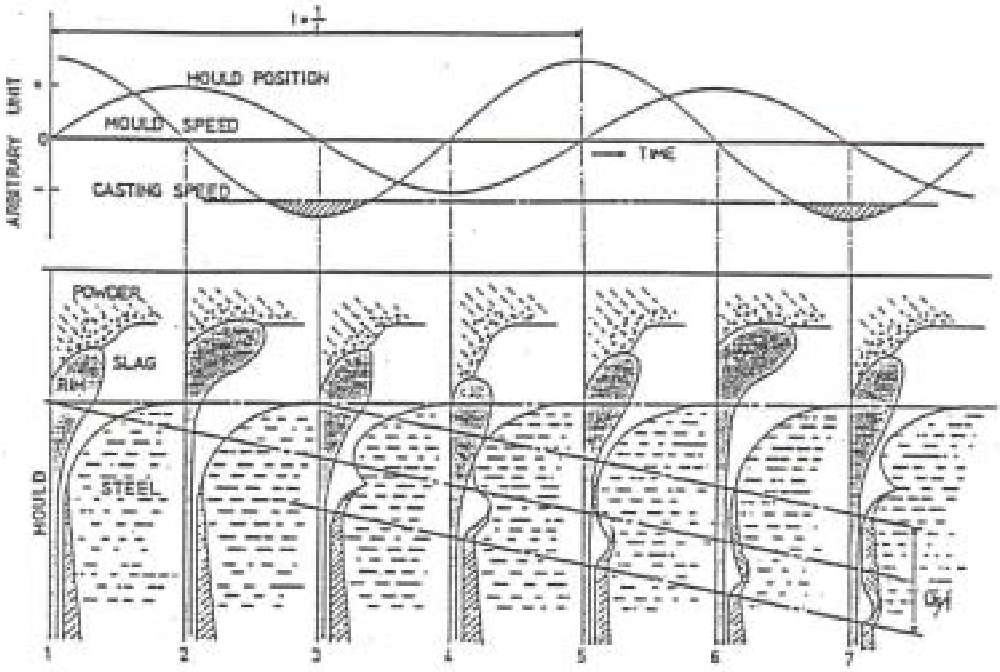


Figure 6-3 Formation of oscillation marks.

6.6 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 6-4 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.

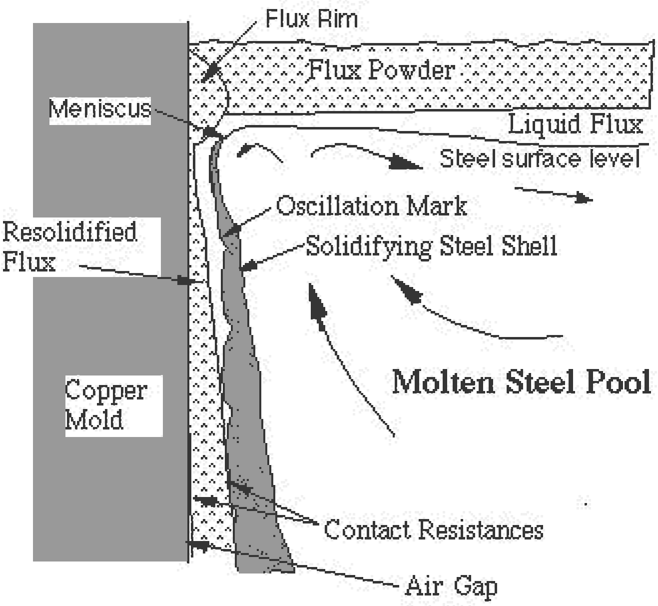


Figure 6-4 Function of mold powder.

6.6.1 IMPORTANT PARAMETERS

Mold powder consumption depends not only on the chosen type of mold powder but also on the oscillation settings and casting speed, it 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 has an essential influence on the mold powder consumption.

One of the most important properties of a mold powder is **break temperature**. It is defined as the threshold temperature at which the powders viscosity increases dramatically, i.e. the point where liquid lubrication starts to break down. Figure 6-5 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. Table 6-6 contains material property data on mold powders that can be used.

Table 6-6 Material properties of available mold powders.

Powder	Viscosity / Pas	Break temperature / °C	Purpose
A	0.12	1170	for crack sensitive grades
B	0.21	1190	
C	0.19	1130	for sticker sensitive grades
D	0.10	1050	
E	0.03	1050	for billet caster

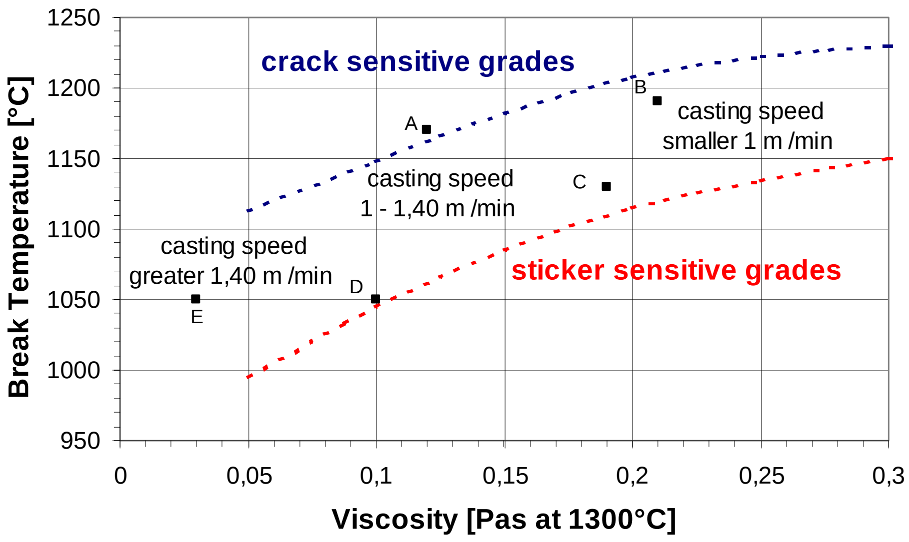


Figure 6-5 Break temperature and viscosity of the mold powder in relation to casting speed.

6.7 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. 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 loose temperature over time due to heat losses. It is assumed that the temperature loss for the ladle is 0.5 °C min^{-1}.

6.7.1 TIME

The time it takes to empty a ladle decides how long time 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:

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

where:

w = strand width, m
t = thickness of the strand, m
v_c = casting speed, m s^{-1}

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

$$\dot{M}_T = n \cdot \rho \cdot w \cdot t \cdot v_c \quad [\mathrm{kg\ min^{-1}}] \qquad 6\text{-}4$$

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:

$$\tau = \frac{m_{ladle}}{\dot{M}_T} = \frac{m_{ladle}}{n \cdot \rho \cdot w \cdot t \cdot v_c} \quad [\text{min}] \qquad 6\text{-}5$$

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 meters per minute 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%.

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

6.7.2 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.

6.7.3 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 very dependent on composition and can be calculated from the following equations:

T_{liq} = 78%C - 7.6%Si - 4.9%Mn - 34.4%P – 38%S

6.8 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.

After reaching a sufficient buffer level of steel in the tundish, raise the stopper rods to increase flow from the tundish to the mold.

Once the mold level is high enough, 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 inclusion 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 cleanness 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 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.

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.

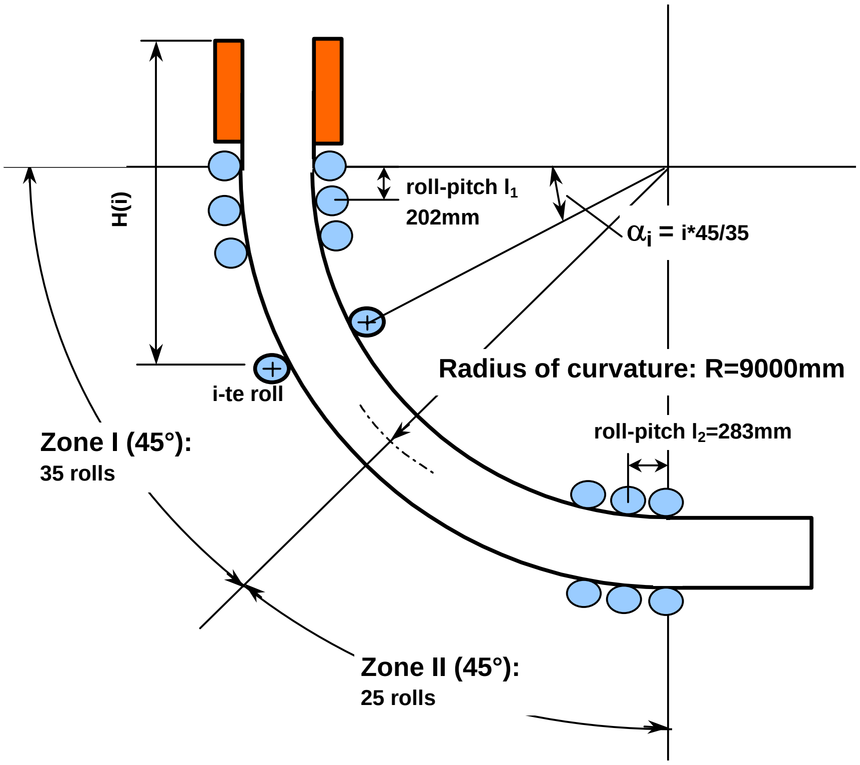


Figure 7-1 Schematic drawing of the slab caster

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.

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

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

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 takes 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.

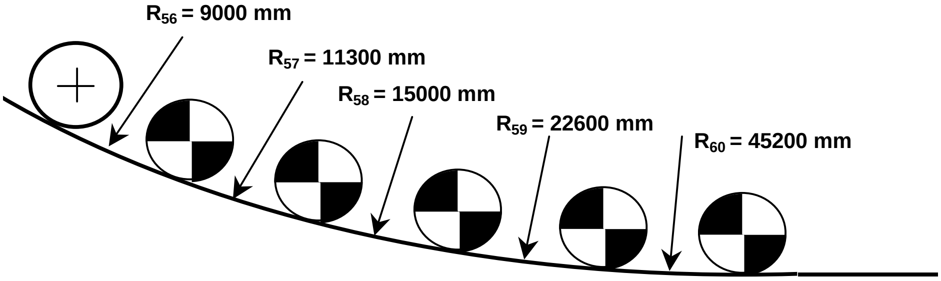


Figure 7-2 Five point straightening method

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

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

where:

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

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

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

where:

δ_M = is 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:

$$\varepsilon_{\text{intern}} = \varepsilon_{\text{BS}} + \varepsilon_{\text{B}} + \varepsilon_{\text{M}} \qquad 7\text{-}4$$

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. 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}:

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

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

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

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:

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

where:

R_0 = radius of original position
R_d = deviated position of the roll

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

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

To calculate the surface strain due to bulging it is assumed that the same equation to calculate the strain at the solidification front (equation 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 ε_{surf}^{tot} must be calculated, where n is the total amount of rolls.

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

To quantify the surface quality, the calculated surface strain is compared to a specific steel grade critical value of strain.

7.5 Avoiding Breakout

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, so require more careful casting to avoid cracks forming and propagating through the shell to cause breakout.

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:

- as high a mold level as possible
- 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 equipments, etc.

8.1 Simulation Controls

8.1.1 SIMULATION RATE

The simulation can be run at a range of different speeds between ×1 and ×32. The rate can be changed at any time during the simulation. Highest recommended speed is ×16. This is done either by clicking on the arrows on the so called numeric stepper to increase or decrease the simulation rate, or click inside the field with the current simulation rate and select the number(s), delete these, then enter the new simulation rate and 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 stepper labeled “Ladle flow rate”. The flow can also be controlled by selecting the current number in the box, entering a new number and then pressing “enter”. 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 stepper labeled "Tundish flow rate". It can also be changed by selecting the current number, entering a new flow rate and the pressing "enter". The flow rate from the tundish to the mold is controlled to a precision of 100 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 that the cast strand can meet any of the quality criteria.

Misaligned rolls changes color to indicate which roll pair that has been 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.

8.1.6 TEMPERATURE MEASUREMENT

The liquid steel temperature in the ladle and tundish can be measured at any time during the simulation. This is done simply by pressing either of the buttons labeled "Measure Temperature" located next to their respective label. Making a temperature measurement will incur a cost which will be added to your total operational costs.

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 have 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 flow out from ladle to tundish and from tundish to mold.

8.2.3 VIEW LEVEL OF STEEL (KEY L)

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

8.2.4 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.

8.2.5 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 RESTART SIMULATION (KEY X)

Select this option if you wish to re-start the simulation. You will be asked to confirm your decision. NOT IMPLEMENTED IN THE EVALUATION VERSION.

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 on one of the five detail 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 the length meeting 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 how the quality varies as the strand has been cast. 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

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.

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.