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TEKNILLINEN TIEDEKUNTA

Review of selection rules for casting powders

Toni Matias Pyhtilä

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ABSTRACT

Review of selection rules for casting powders

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University of Oulu, Degree Programme of Process engineering

Master's thesis 2022, 89 pp. + 18 pp. Appendixes

Supervisor(s) at the university: Jari Ruuska, Aki Sorsa and Tuomas Alatarvas

The aim of this thesis was to investigate the update potential of Raahe steel mill's casting powder selection rules for existing slab grades and to reduce the amount of defected product. Casting powders separate mould surfaces from steel strand by forming a thin layer of glassy or crystalline slag between them. This layer's physicochemical properties affect the lubrication and heat transfer occurring in the mould. Inappropriate casting powder increases the amount of occurring defects, because slab grades with different chemical compositions have different solidification routes. Additionally, casting powder offers protection from outside atmosphere and dissolves inclusions within steel.

In the theoretical part of this thesis, the casting process is shortly introduced, but the overall focus is on casting powder properties and selection rules for casting powders. In the experimental part, an analysis is carried out to determine the slab grades that could benefit from a casting powder change. Thus, a set of industrial tests were scheduled and later reviewed.

Generally, the results were quite promising. The test period was continued for nine out of the ten slab grades tested. It is still recommended to continue close supervision of the tests because the number of heats during the test period was quite small for most slab grades. Quality increased for seven slabs grades and remained similar for two slab grades according to the indicators used in this thesis. Overall, it can be recommended to start using ferrite potential in classification of slab grades to peritectic and non-peritectic.

Keywords casting powder, continuous casting, slab surface quality, ferrite potential

TIIVISTELMÄ

Valupulverien valintasääntöjen tarkastelu

Toni Matias Pyhtilä

Oulun yliopisto, Prosessitekniikan koulutusohjelma

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Työn ohjaajat yliopistolla: Jari Ruuska, Aki Sorsa ja Tuomas Alatarvas

Tämän diplomityön tavoitteena on selvittää mahdollisuutta päivittää Raahen tehtaan valupulvereiden valintasääntöjä olemassa oleville aihiolaaduille ja mahdollisesti vähentää aihiovikojen määrää. Valupulveri erottaa kokillin ja teräsnauhan toisistaan ohuella kerroksella, joka koostuu lasisen ja kristallisen kuonan sekoituksesta. Tämän kerroksen fyysiset ja kemialliset ominaisuudet vaikuttavat voiteluun ja lämmönsiirtoon kokillissa. Vääränlainen valupulveri lisää esiintyvien vikojen määrää aihioissa, sillä eri koostumuksen omaavat teräslaadut jähmettyvät eri faasimuunnoksien kautta. Lisäksi valupulveri tarjoaa suojaa ilma-atmosfääriltä ja liuottaa sulkeumia teräksestä.

Työn teoriaosiossa käydään läpi lyhyesti valuprosessi sekä tarkemmin valupulvereiden ominaisuudet ja niiden merkitys. Valupulvereiden valintaan liittyviä tekijöitä korostetaan erityisesti. Työn kokeellisessa osiossa analysoidaan aluksi aihiolaadut, joille valupulverin vaihto olisi perusteltua. Tämän perusteella suunniteltiin koeohjelma, jonka perusteella pyrittiin varmistamaan valintasääntöjen muutoksien toimivuutta.

Suurelta osin testijakson tulokset olivat lupaavia. Kymmenestä valitusta koelaadusta yhdeksää koejaksoa päätettiin jatkaa tämän työn tuloksena. Tämä on suositeltavaa, sillä kokeiden määrä jäi useiden laatujen kohdalla vähäiseksi. Kokonaislaatu parani tässä työssä käytettyjen indikaattorien perusteella seitsemällä koelaadulla ja pysyi samana kahdella laadulla. Kokonaisuutena kirjallisuuden ja tehtyjen kokeiden perusteella voidaan suositella ferriittipotentiaalin käyttöönottoa osaksi aihiolaatujen luokittelua peritektisiin ja ei-peritektisiin aihiolaatuihin.

Asiasanat: valupulveri, jatkuvavalu, aihion pinnanlaatu, ferriittipotentiaali

PREFACE

This master's thesis was done within the process development team of steel for SSAB between September 2021 and February 2022.

I would like to thank my instructors Leena Määttä and Maija Kärkkäinen for their guidance and supervision. I'm especially thankful for Agne Bogdanoff for giving me this great opportunity. I would also want to thank my supervisors from the University of Oulu, D.Sc. Jari Ruuska, D.Sc. Aki Sorsa and D.Sc. Tuomas Alatarvas for their constant support and guidance.

Collaboration between SSAB's other factories was an important factor for this thesis. I would like to express my thanks to Christer Nilsson from Luleå, Pouyan Pirouznia from Oxelösund and Abraham Sunday from the United States.

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Oulu, 31.5.2022

Toni Matias Pyhtilä

TABLE OF CONTENTS

ABSTRACT

TIIVISTELMÄ

PREFACE

TABLE OF CONTENTS

SYMBOLS AND ABREVIATIONS

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A	Moulds and strands contact area [m^2]
A_a	Constant
A_w	Constant
B	Basicity
B_a	Activation energy
B_w	Activation energy
C_p	Heat capacity [kJ/ °C]
d_l	Thickness of molten slag layer [mm]
F	Frictional force between steel and solid slag film [N/m^2]
NBO/T	Number of non-bridging oxygen per tetrahedrally-coordinated atom
Q_{reg}	Required powder consumption
p	Water flow [kg / min]
R	Surface area ratio of mould
t	Thickness of the mould [m]
T_{br_1}	Break temperature for casting powder [°C]
T_{br_2}	Break temperature for crack-sensitive grades [°C]
T_{br_3}	Break temperature for sticker-sensitive grades [°C]
T_{br_4}	Break temperature for intermediate grades [°C]
T_k	Temperature [K]
T_{liq}	Liquidus temperature [°C]
T_m	Water temperature change [°C]
V_c	Casting speed [m/min]
Vm	Oscillation [strokes/min]
$X_{substance}$	Mole fraction for that substance
w	Width of the mould [m]
$\%_{cryst}$	Fraction of crystalline phase [%]
$\%_{substance}$	Mass percentage of corresponding substance

CCM4	Continuous casting machine 4
CCM5	Continuous casting machine 5
CCM6	Continuous casting machine 6
CP	Carbon potential

CS	Casting speed
FP	Ferrite potential
HC	High carbon steel
HT	Heat transfer
K	Plate grade
ML	Mould surface level
MW	Mould width
N	Strip grade
NP	Non-peritectic
PER	Peritectic
RP1	Reference point 1
RP2	Reference point 2
RP3	Reference point 3
SD	Standard deviation
SEN	Submerged entry nozzle
SP	Position of stopper rod
STD	Standard carbon steel
TC	Thermocouple
ULC	Ultra-low carbon steel
wt-%	Weight percentage
γ	Austenite
δ	Ferrite
η	Viscosity [dPas]
Φ	Heat transfer [kJ / min]

1 INTRODUCTION

Increasing quality, safety and production requirements are keeping the continuous casting process in a constant phase of development. Casting powders are an important part of a successful casting process, and they have a great effect on the quality of steel slabs. It is important to choose the correct casting powder to minimize possible defects, which impact the quality of products.

Selection rules for casting powders vary between steel mills and standardization of those rules is rare. Selection rules vary greatly even at SSAB's own production sites. There are multiple reasons for this variation, but the most important ones are different casting machine properties, like oscillation parameters, width, thickness, fluid flow and differences between casted slab grades. The most important factor, which has been causing variation of the rules, is the lack of collaboration in the development of the rules. This is mainly caused by the fact that rules for casting powder selection have been formed before fusion of SSAB and Ruukki.

The main aim of the theoretical part of this thesis is to give a reader an understanding of the casting process, casting powder selection rules and the factors affecting them. The theoretical part also goes through different types of casting powders and casting powder-related slab defects. A short literature review about the origin of defects is included as well.

The main goal of the experimental part of this thesis is to find the slab grades that have a higher amount of casting powder-related problems and to find solutions for them. Casting powder selection rules are compared with other rule sets from other factories. Industrial tests were carried out for slab grades that showed a relatively high risk for defect occurrence and a valid reason for testing a different casting powder. Ferrite potential and carbon potential values were used to estimate if the change in casting powder could be justified.

2 CONTINUOUS CASTING AS A PART OF CARBON STEEL

The purpose of this chapter is to introduce the continuous casting process and give a short view of the whole carbon steel manufacturing process from pellet to slab. Continuous casting is the last production process in the steel plant and the point where steel solidifies to slabs, billets and blooms. The casting process has multiple parameters, which greatly affect the quality of the cast products and the success of the process.

2.1 Overall process at Raahe Works

The whole process of carbon steel manufacturing in SSAB's Raahe Works is presented in Figure 1. The main subject in this thesis is the casting process, which is presented inside the blue rectangle. SSAB is one of the leading steel manufactures in the world in terms of quality and environmental friendliness. Raahe Works produces many different products, but the main ones are steel coils and steel plates.

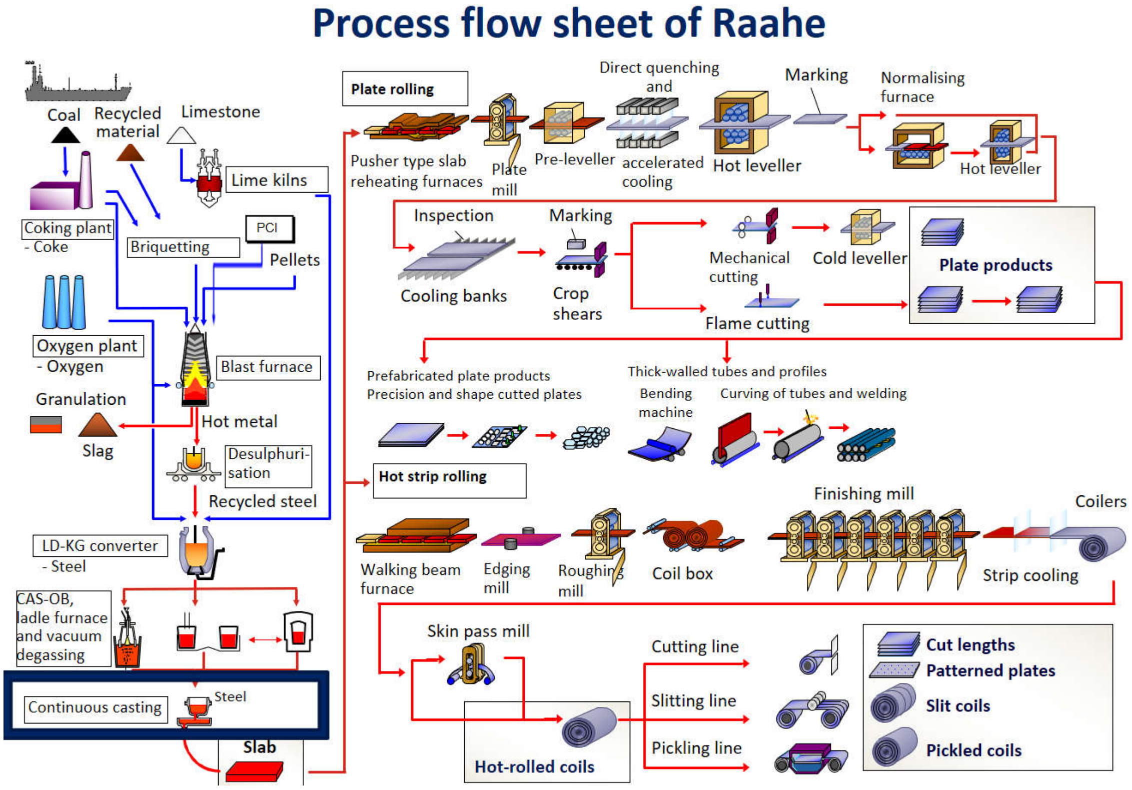

Figure 1. The process flow sheet of Raahe Works (retell SSAB 2014a).

2.2 Continuous casting process

Cooling liquid steel to form solid steel is necessary for follow-up processes. This is achieved mainly with the continuous casting process. Henry Bessemer first suggested the continuous casting process in 1856 but the technology was not mature enough for it to work. The first industrial continuous casting machines cast nonferrous metals during the 1930s. The high casting temperature and relatively low thermal conductivity of steel made it much harder to cast than nonferrous metals. The first continuous casting machines for steels started operating in the 1960s but continuous casting became the main way of casting steel in the 1980s. Continuous casting has several advantages over ingot casting or bottom-pouring casting, which were the preceding main casting methods. In continuous casting, the quality of steel is higher, and less energy and workforce are needed compared to alternative methods. Today, continuous casting presents over 95% of world steel production. (Louhenkilpi 2014, pp. 373-375)

There are several different types of continuous casting machines, but three main types of casting machines exist in the field of steel casting: vertical casting machine, bent casters with a straight mould and bow-type casters with a curved mould (Louhenkilpi 2014, p. 375). The second way of classifying casting machines is by the shape of the cast steel. The most common shapes are billet, bloom, and slab (Thomas 2004, pp. 1-3). All types of casting machines have their own advantages and disadvantages. These properties affect the quality of the steel and production capacity.

Continuous casting machines have developed from the vertical type of machine to curved machines to reduce the required installation height while still being able to cast at high speeds. Mechanical structure has been becoming increasingly complex and sophisticated over the years of development. Bending and straightening of the steel causes defects to the steel on newer types of machines. As a solution, many types of machines are dividing bending and straightening into several steps to reduce the stress exerted to the cast strand. (Thomas 2004, pp. 1-3)

The vertical casting machine represented the first type of continuous casting machines. Vertical casting machines uses gravity in the casting process, and it is the simplest type of casting machine. There is no need for bending or straightening, which results in less defects. Disadvantages for this type of casting machine include the required high machine heigh and limited production speed. (Louhenkilpi 2014, pp. 373-375)

Common modern casting machines are the bent caster-type with a straight mould or bow-type casters. The driving force of development for these types of casting machines was the increased demand for production speed and simultaneously keeping costs within a reasonable range. Bow-type casters are the most popular, but generally increasing quality standards are driving industry towards bent caster-type machines due to their better steel cleanliness and generally better casting results. (Louhenkilpi 2014, pp. 373-375)

The casting process begins right after the secondary metallurgy processes. This process is quite plain in principle but in practice it is complex with many changing factors that cannot be modelled yet. Continuous casting happens as follows. First, a dummy bar is placed inside the mould with the help of a crane or dummy bar cart/train. The dummy bar has the same dimension as the strand to be cast. Gaps between the mould and dummy bar are sealed with paper rope, oil and silicone. Some cooling scrap is placed inside the mould to speed up the steel solidification. The steel is then raised in the steel ladle over the casting machine and placed on the ladle turret. Casting begins by opening the nozzle in the bottom of the ladle, which allows the steel to flow to the tundish. After the tundish has enough steel, the submerged entry nozzle (SEN) is opened by the operator or by the automation system. When the SEN is open, steel can flow into the mould, which has water-cooled copper walls and the steel starts to solidify. Next, rollers under the mould start to pull the dummy bar and steel starts to move down forming the strand shell inside the mould before entering the secondary cooling zone, where it is sprayed by secondary cooling nozzles. Depending on the type of the casting machine, bending can start at the mould, under the mould or not happen at all. The solidified steel is cut into slabs at the end of the machine and then sent to the cooling hall. Depending on the quality of the slabs and successfulness of previous sub processes, slabs can be placed in hydrogen removal hoods or they can be repaired with machine scarfing or manually. (Louhenkilpi 2014, pp. 373-400; SSAB 2015a)

2.2.1 Continuous casting machine and auxiliary equipment

The ladle is the container that holds the molten steel after the converter process and during secondary steelmaking. At the continuous casting machine, the ladle releases the molten steel to the tundish. Ladle sizes can vary substantially depending on the design. Some of them can hold up to 300 tonnes of steel, but at Raahe steel plant the maximum amount is 125 tonnes. (Louhenkilpi 2014, pp. 373-375; SSAB 2015a)

The tundish functions as a steel reservoir between the ladle and the mould. The tundish also enables ladle changes without stopping the casting process. Inclusions can be removed in the tundish if the right operational practices are used with the correct slag. Commonly, the tundish is shaped like a rectangular box. Nowadays almost all steel mills use a SEN to reduce the amount of re-oxidation. These ceramic bricks are used to target the steel flow in the desired direction, while simultaneously providing protection of the steel from air by providing a thermal barrier. Argon gas flow is used to reduce clogging of the nozzle. Typically, three different mould flow patterns can be monitored: double roll flow, single roll flow and permanent unstable flow. (Louhenkilpi 2014, pp. 378-382)

The mould is the part of the casting machine where solidification of the steel takes place. Many defects can be traced back to mould phenomena and operation. Different shaped moulds are used in industry to cast different products. They can be tubular, plate, square, etc., and curved or straight types. Many different materials are in use for the mould surface, but typically copper and its alloys are generally used. In most cases, copper plates are coated with some harder metal to reduce wear. Flowing water inside the mould is used for cooling and for transferring heat from the steel. (Louhenkilpi 2014, p. 382)

Secondary cooling typically consists of several different zones, which all have their own specific segment and cooling practices. Secondary cooling is done by using water or a combination of water and air sprays. Some cooling happens also due to the contact of the steel strand and support rolls. All three basic heat transfer methods occur in secondary cooling. Radiation is the dominant way of cooling in the later phases of secondary cooling. Conduction occurs between the steel strand and rollers. Convection happens when sprayed water droplets penetrate the steam layer and evaporate from the surface of the steel. Cooling needs to be appropriate for each slab grade due to the variation in low ductility areas, which is caused by different compositions. Generally, straightening and bending should not be done in low ductility areas. (Louhenkilpi 2014, p. 388)

2.2.2 Chemical and physical phenomena in the casting process

Fluid flow in the mould is a key factor in continuous casting. Mould phenomena are illustrated in Figure 2. Steel flow affects major mould phenomena like lubrication, heat transfer and solidification, which further affect slab quality and other variables. Controlling fluid flow precisely is difficult due to fluctuation of other variables and the turbulent nature of steel flow (Kastelli 2020, p. 14). In general, flow patterns should be uniform and steady during casting to produce good strand and to maintain a steady rate of heat transfer (Louhenkilpi 2014, p. 383-384). Mould level fluctuations are commonly linked to various defects and process problems like transversal cracking and SEN erosion. SEN erosion is commonly avoided by changing the set point value of the mould level by 5 – 15 mm during casting to avoid wear only at one point of the SEN (Joensuu 2011, p. 25).

Mould movement up and down during casting is called oscillation. Mould oscillation is done to prevent the steel from sticking on the copper walls of the mould and facilitate the casting powder's penetration between the mould and steel strand. Oscillation has two main parameters: oscillation frequency and stroke length. Oscillation cycle contains a negative strip time and positive strip time. Negative strip time describes the time when the mould is moving downward with greater velocity than the steel strand. Positive strip time describes the time when the mould's speed in the casting direction is slower than the strand's speed and moving upwards. (Louhenkilpi 2014, p. 382-383)

Steel flow dynamics in a mould is determined by several variables: nozzle geometry, nozzle position, stopper rod position, immersion depth of the SEN, argon injection, casting speed, mould dimensions and temperature. These variables affect each other so optimizing flow is generally a challenging task. The desired flow pattern for casting powder to work is a double roll flow. (Kastelli 2020, p. 15-16)

Controlling heat transfer is an important part of the casting process because it determines partially the strength of the shell by affecting the thickness of the shell. Heat transfer between steel and mould depends on radiation and conduction across the interfacial gap between solidifying steel and the mould as well as the cooling water and its flow inside the mould. Additionally, the casting powder used, and its heat transfer capability has an important role. (Pineda Huitron 2020, p. 13)

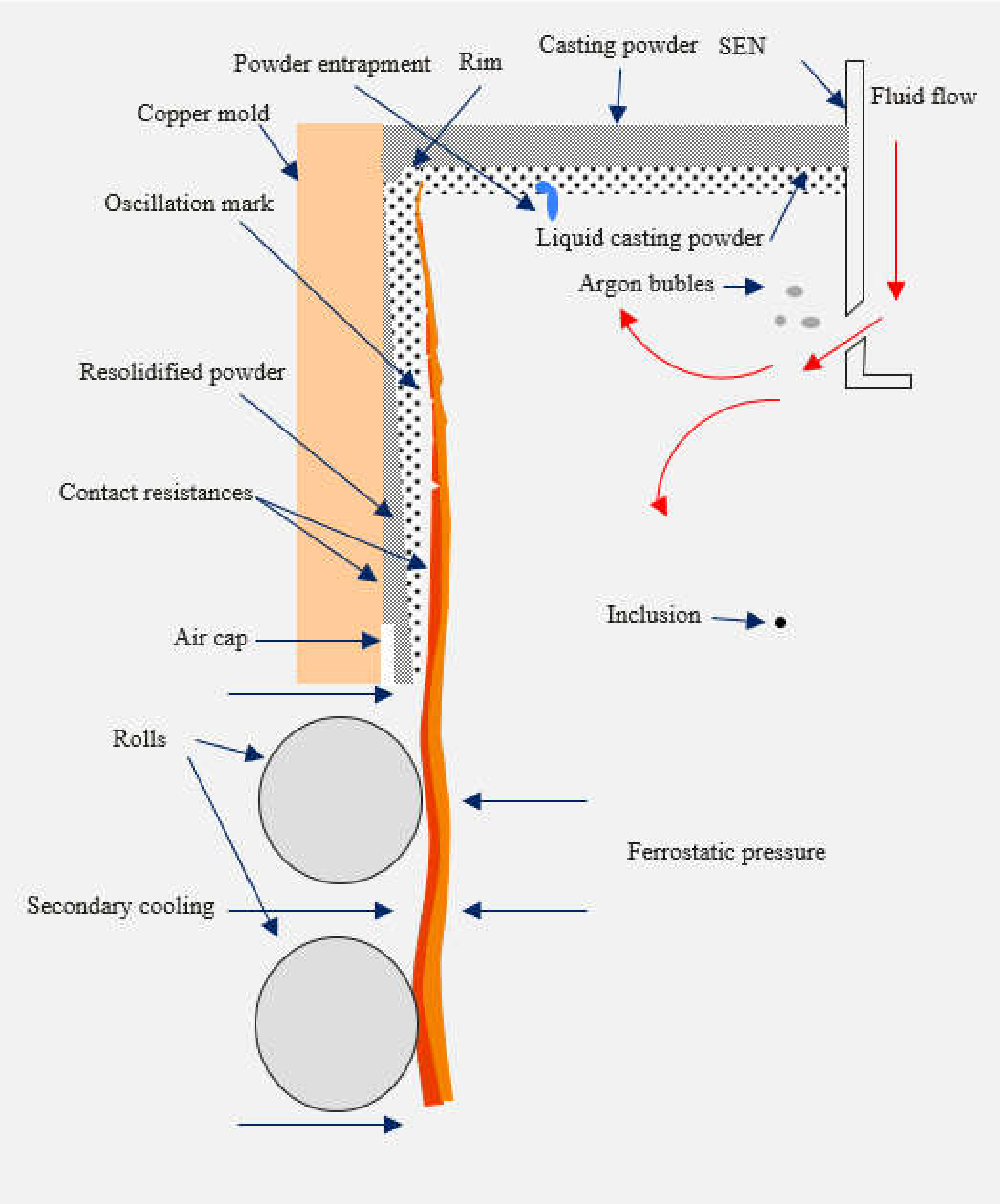

Figure 2. Schematic presentation of mould phenomena (retell Thomas 2001).

2.2.3 Continuous casting machines in Raahe

There are three continuous casting machines in Raahe’s steel mill. Machines 4 & 5 (CCM4 and CCM 5) are almost identical. Strip slabs are mainly produced with machines 4 & 5 and plate slabs are produced only with machine 6. All machines have half-automatic casting powder feeding systems, which require constant attention from operators in order to work correctly and from time to time physical position adjustments and powder feeding speed adjustments.

Casting machines 4 & 5 are single-strand curved casting machines, and both were modernized in year 2000. Over one million tonnes of steel are cast annually with each machine. These machines have mechanical oscillation systems, powered by electric motors. Figure 3 presents the cross section of the CCM 4 and 5. Important specifications of these machines are presented in Table 1. (SSAB 2015b)

Table 1. Specifications of the CCM 4 & 5 (SSAB 2015b).

Specification	
Type	Curved casting machine
Main product	Strip slabs
Tundish	28 tonnes
Mould size	Adjustable 210 x 900 – 1850mm
Secondary cooling	Air-mist
Casting speed, maximum	1.8m / min
Metallurgical length	29 m
Ladle capacity	125 tonnes
Tundish temperature measurement	Manual
Hydrogen measurement	4 Yes / 5 No
Oscillation	Mechanical

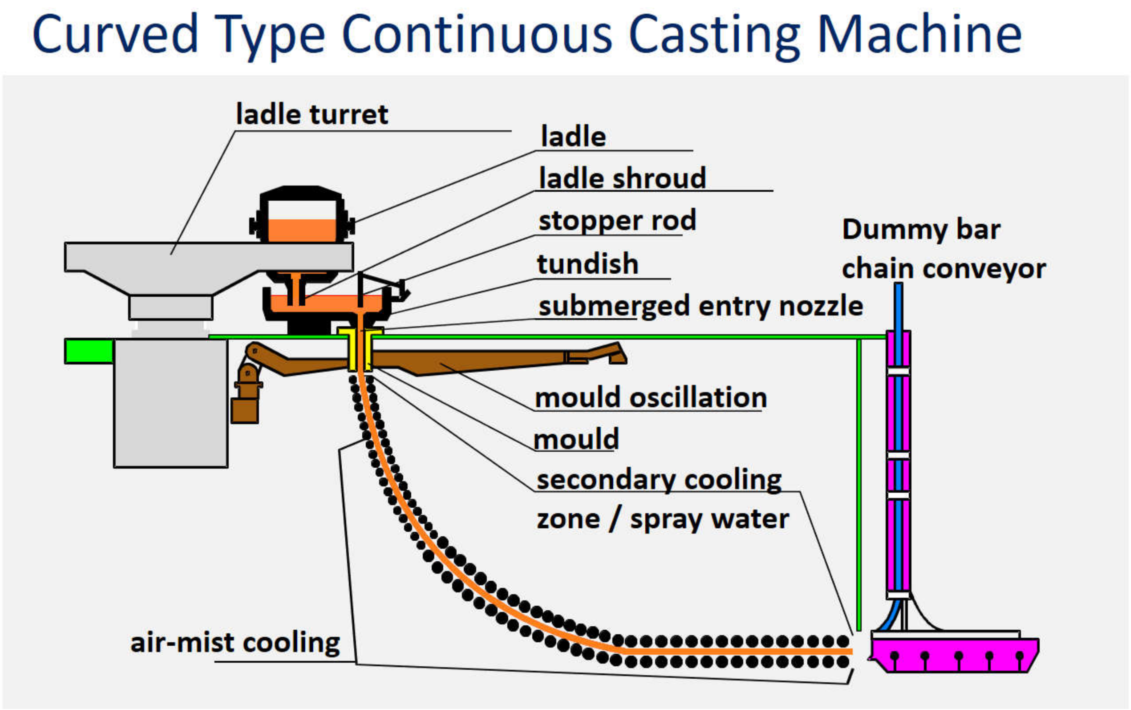

Figure 3. Schematic presentation of CCM 4 & 5 (SSAB 2015b).

Casting machine 6 (CCM6) is a vertical bending, single-strand sequence casting machine. Slabs that are used in plate rolling are usually cast with casting machine 6. Annually, over 0.7 million tonnes of steel are casted by machine 6. The hydraulic oscillation system allows the adjustment of oscillation parameters in an extremely wide range. Figure 4 is a cross section of the machine and specifications of CCM 6 are presented in Table 2. (SSAB 2015b)

Table 2. Specifications of casting machine 6 (SSAB 2015b).

Specification	
Type	Vertical bending casting machine
Main product	Plate slabs
Tundish	28 tonnes
Mould size	Width 900 – 1975 mm
	Thickness 165/210/270 mm, quick change
Secondary cooling	Air-mist
Casting speed, maximum	1.8m / min
Metallurgical length	29.3 m
Ladle capacity	125 tonnes
Tundish temperature measurement	Continuous and manual
Hydrogen measurement	Yes
Oscillation	Hydraulic

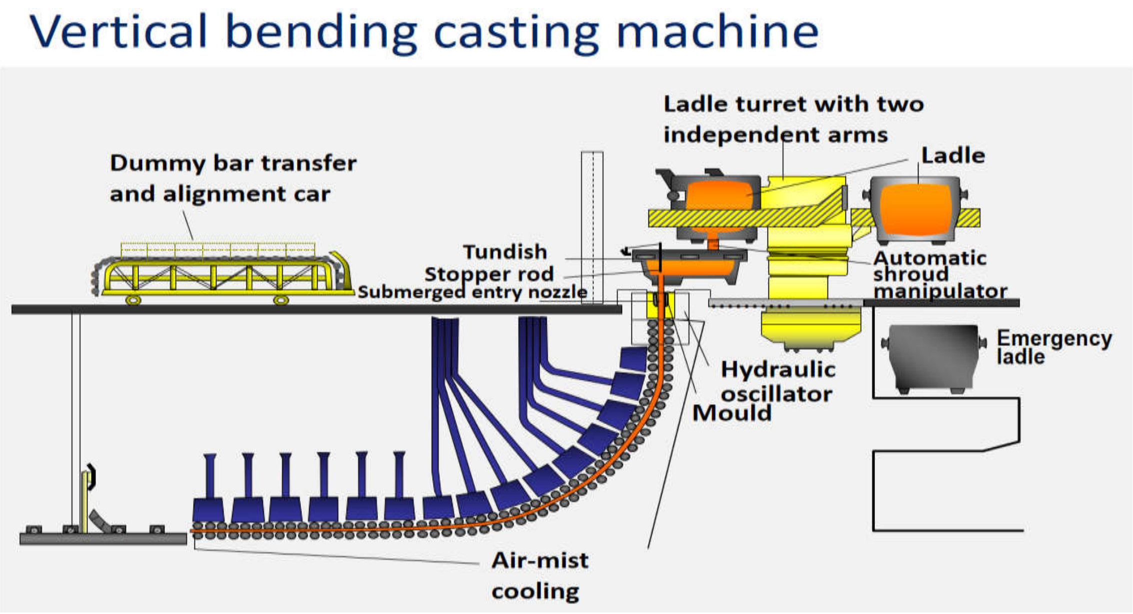

Figure 4. Schematic presentation of CCM 6 (SSAB 2015b).

2.3 Peritectic reaction and peritectic transformation

According to Mills and Däcker (2017), the definition of peritectic reaction is a "*reaction where a solid phase and liquid phase forms a second solid phase at a particular temperature and composition*". The thickening and growth of the secondary phase is in many cases referred to as peritectic transformation and the peritectic reaction as a reaction between the melt and the existing solid phase to form a secondary solid phase (Nassa Hani 2009, p. 1).

Peritectic reactions are not as common as eutectic or eutectoid reactions but happen in iron-carbon alloy systems. Peritectic reactions have some problematic qualities for steel casting: these reactions are relatively slow, and the product phase forms a boundary between the two reactive phases and separates them. This causes faster cooling in the outer layers of steel strand compared to in non-peritectic steel and endorses a higher amount of stress in the steel strand, which will result in more product defects if the heat transfer is too high in the mould. (Azizi et al. 2020, p. 1-3)

Peritectic steels are the hardest steel group to cast without breakouts or defects. Peritectic reaction occurs when steel solidifies if its content of iron and carbon are in range $C_a - C_b$ presented in Figure 5, which is drawn with FactSage 8.1 using the FSstel data base (Bale et al. 2002). Alloyed materials affect the steel's solidification route, but in many cases only carbon content is considered. During solidification of the peritectic steel the peritectic reaction ($L + S \rightarrow S2$) occurs. This reaction causes the solid-state transformation (peritectic transformation) ferrite (δ) → austenite (γ), which is linked to surface defects. Defects are caused by shrinkage of the strand, which happens during peritectic phase transformation. Reduction of the strand volume leads to air gaps between the steel shell and mould affecting heat transfer and leading to temperature differences in the strand, which leads to uneven shell growth and further to defects and process problems like surface depressions, deep oscillation marks, cracks, and breakouts. (Azizi et al. 2020, p. 1-3)

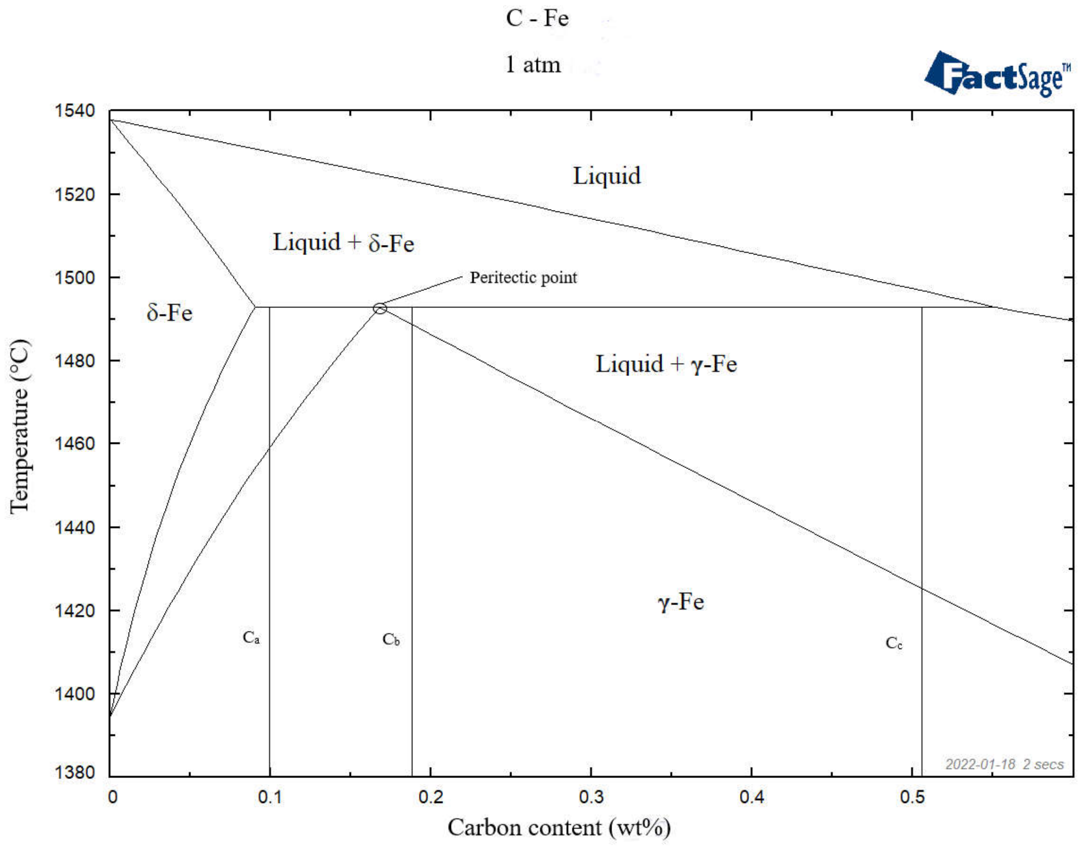

Figure 5. Iron carbon phase diagram (retell Pineda Huitrón 2020, p.20).

Peritectic transformation can happen in two different ways: hypo-peritectic and hyper-peritectic. These transformations are separated by a peritectic point. Hypo-peritectic transformation occurs on left side of the peritectic point and hyper-peritectic transformation happens on right side of the peritectic point. The peritectic point is marked in Figure 5. (Pineda Huitrón 2020, p. 20-23)

The hypo-peritectic area is a critical area for crack formation during continuous casting and the hyper-peritectic area is not. The hypo-peritectic reaction is critical due to strand shrinking, which is linked to fast hypo-peritectic transformation where large amounts of δ-Fe transform to γ-Fe. The reason why peritectic transformation is not a problem in the hyper-peritectic region is austenite's coexistence and smaller fraction of δ-Fe. (Pineda Huitrón 2020, p. 20)

The effect of the alloying elements depends on their ability to stabilize ferrite and austenite (Pineda Huitrón 2020, p. 21). Alloying elements can have major impacts on Fe-C phase diagram shapes and points. Alloying elements and impurities can be divided into three groups, which are presented in Table 3. (Louhenkilpi 2011, p. 31-34; Pineda Huitrón 2020, p. 21)

Table 3. Effect of the alloying elements (Louhenkilpi 2011, p. 31-34; Pineda Huitrón 2020, p. 21).

Effect group	Element
Austenite formers	Ni, Mn, Co, Cu, C, and N
Ferrite formers	Cr, W, Mo, V, Al, Si, P, Ti, Zr, B, S, and Nb
Elements that produce carbides and nitrides	Cr, W, Mo, V, Ti, Nb, Ta and Zr

2.4 Solidification routes of carbon steel

The solidification of carbon steels can be divided into four categories if steel is low alloy and carbon content is under 2 wt-% (Louhenkilpi 2011, p. 27). The points of carbon contents where solidification routes change vary in the literature but are generally as follows: 0.1 wt-%, 0.18 wt-%, 0. 51 wt-%. From the perspective of this thesis, the most important area is between 0.1 – 0.51%, which includes the peritectic point 0.18 wt-%. (Louhenkilpi 2011, p. 27)

The first range consists of steels, whose carbon content is between 0.0 wt-% – 0.1 wt-%. In this area, the steel solidifies directly to delta ferrite. The phase transformation of ferrite to austenite happens far from the solidus temperature when carbon content of the steel is close to 0 wt-%. On the other hand, while carbon content is close to 0.1 wt-% solid state, phase transformation happens near the solidus. (Louhenkilpi 2011, p. 27-28)

The second carbon content range consists of steel, whose carbon content varies between 0.1 wt-% and 0.18 wt-%. This range is usually referred to as a peritectic steel range. Solidification in this range starts always as a delta ferrite. When the temperature lowers to the peritectic line, stability between solid ferrite and austenite is reached. At this point, the peritectic reaction starts and molten steel reacts with delta ferrite to form austenite. After the peritectic reaction begins peritectic transformation of delta ferrite to austenite. The peritectic transformation $\delta \rightarrow \gamma$ causes shrinkage up to 0.6% by volume. (Louhenkilpi 2011, p. 28)

The third carbon range consists of steels whose carbon content varies between 0.18 wt-% and 0.51 wt-%. Steels in this range of carbon solidify almost as the previously described case. The difference is that in the previous case the peritectic reaction continued as long as there was ferrite but, in the current case, it continues as long as there is molten steel. This means that steels in this range have one additional solidification reaction, which is molten steel to straight austenite and thus do not have the same problems as the earlier case. (Louhenkilpi 2011, p. 29-30)

The fourth carbon range consists of steels that have over 0.51 wt-% carbon. These steels will solidify straight to austenite (Louhenkilpi 2011, p.30). These steels are not included in this thesis, because slab grades casted in the Raahe Works do not have over 0.51 wt-% carbon.

3 CASTING POWDERS

Development of casting powders started over 60 years ago. The main aim of this chapter is to give an overview of the development of casting powders and illustrate their properties and functions. The chapter is concluded with a review of selection rules for casting powders.

3.1 Main functions and types of casting powders

Casting powders have different functions in the casting process. Those functions are explained in the following according to Mills and SSAB's internal research (Mills and Däcker 2017, p. 3; SSAB 2012):

- Prevent the steel meniscus from freezing by providing a good thermal barrier between air and meniscus.
- Prevent oxidation of liquid steel. Slag prevents air from contacting with steel, which inhibits air infiltration and re-oxidation.
- Lubricate the newly formed shell. Liquid slag between steel and mould lowers friction between mould and strand.
- Controlling the horizontal heat transfer from shell to mould by different layer thickness and structure variations.
- Absorb inclusions from the steel. Particles that flow up to the surface of the meniscus can be removed by right constitution of liquid slag, increasing steel quality.

Casting powders, also known as mould fluxes or mould powders, have a major role in the continuous casting process. Originally, rapeseed oil was used in preventing the steel from sticking to the copper mould (Mills 2014, p. 436). Powders used today can be divided into the following seven main groups based on the structure of the powder or based on raw material: fly ash based, synthetic, powders, pre-fused, granulated powders, exothermic powders, and starter powders.

The casting process is characterized by many variables like oscillation parameters, casting speed, slab grade, mould dimensions and fluid flow in the mould. To minimize the defects, all these variables need to be optimized. This is a hard task to achieve and generally, mould powder is expected to be the “forgiving variable” in the process. (Mills and Fox 2003, p. 1480)

Generally, casting powder melts as described in the following. Casting powder is fed via the feeding system or by the operator on top of the meniscus, where the powder forms three layers: a powder layer, a sintered layer, and a liquid layer (Mills 2014 p.440). Melting of the powder happens in five steps: 1) moisture evaporates from the powder, 2) carbonates decompose around 500 °C to oxide and CO_2, 3) carbon particles react with oxygen and form a reductive atmosphere at around 500 – 900 °C, 4) sintering of mineral components starts, between 900 – 1100 °C and 5) the casting powder starts to form a liquid pool, which penetrates the channel between the mould and the steel strand. The liquid slag pool should be at least 10 mm deep to ensure the infiltration of liquid slag for effective lubrication. (Mills and Fox 2003, p. 1-2; Mills 2014, p. 339-441)

The slag film usually consists of a 1 – 2-mm-thick solid slag film (which can be glassy or crystalline) and 0.1-mm-thick liquid slag film (Mills and Fox 2003, p. 1; Mills 2014, p. 440). These layers prevent the steel strand from sticking to the plated copper wall of the mould by separating the wall and the strand (Mills and Fox 2003, p. 1).

Fly-ash powders are still available even though other powder types are generally superior in everything but price. Problems with this type of powder include variation in composition and structural inconsistency, which prevent the use of automatic feeding systems. In addition, special design of chemical composition is usually impossible. (Mills 2014, p.437)

Exothermic powders consist of chemicals or mineral that have exothermic properties like calcium silicate, iron silicate, etc. Exothermic powders provide decreased vertical heat flux since the exothermic agents react with air releasing heat (Mills 2014, p. 436). Benefits of this type of powder are increased depth of the molten slag pool, reduced carbon pickup by the strand and in some cases better inclusion absorption. They also reduce the thickness of meniscus, which will lead to better evaporation of gas bubbles but can cause a thinner strand shell. (Mills and Däcker 2017, p. 196)

Starter powders are used in the beginning of the cast to produce a slag pool as fast as possible to start lubrication and protect the steel surface from oxidation (Mills 2014, p. 436). Many researchers argue that usage of starting powders is unnecessary in most cases and these types of powders should be used only, if necessary, but SSAB internal tests have shown that usage of starting powder significantly increased quality of the first slabs. Characteristics of starting powders contain a large number of low-heating components like fluorides, borates, Na_2O, low amount of carbon to ensure high heating rate and they contain exothermic agents to further increase heating rate. (Mills and Däcker 2017, p. 195; Niska 1998, p 29)

In general, pulverized casting powders are cheaper and have better thermal insulation qualities. The problem with the powdery texture of casting powders is their tendency of forming blockages in piping, which means pulverized powders cannot be used in automatic or semi-automatic feeding and pulverized substances tend to be blown around in the air and represent health risks to workers (Mills 2014, p. 437). Granulated powders are more expensive but still cheaper than pre-fused ones. Granules are the best solution to automatic or semi-automatic feeding systems (Mills 2014, p. 437). Pre-fused (pre heated) powders are the most expensive type of powders. Their superior qualities are steady and fast heating (Mills 2014 p.437). Characteristics of different physical forms of casting powders are presented in Table 4.

Table 4. Casting powders' physical properties affected by physical type (retell Ludlow et al. 1999, p. 30)

	Pulverized	Spray dried granular	Extruded granular	Pre fused
Prices	++	+	-	-
Insulation	++	+	-	-
Cold flowability	-	++	+	+
Heating	++	+	+	++
Chemical similarity	+	++	+	++
Dusting amount	-	++	++	++

Components of casting powders can be divided into five groups: network formers, network breakers, fluxes, carbon particles and other chemicals. Some minerals and impurities are present in casting powder too. Common casting powder components are divided and presented as groups in Table 5. (Mills and Däcker 2017, p. 5)

Table 5. Components of casting powders divided into groups (Mills and Däcker 2017 p.5; SSAB 2012)

Component type	Component
Network formers	SiO_2, Al_2O_3
Network breakers	CaO, MgO
Fluxes	Na_2O, K_2O, Li_2O, CaF_2, FeO, MnO, B_2O_3
Others	TiO_2, ZrO_2
Carbon particles	Coke, graphite, carbon black, acid-treated graphite

Manual feeding of casting powder is declining in use and is generally only used in two situations: when a starting powder is used in the beginning of the cast or if the feeding system stops working. In the case of a semiautomatic system, the input setting value of the feeding machine can be too low and it can result in a situation where manual feeding is necessary. Manual feeding is commonly carried out by shovel or by pushing powder bags into the mould. (Mazza et al. 2017, p. 25-29, SSAB 2012)

A semi-automatic casting powder feeding system usually contains a powder silo, pipes, outer tank, feeding nozzle / nozzles, pressured gas (commonly N_2) unit or suction unit and controlling unit. These systems require an operator to put them in the correct place in the beginning of casting and remove them at the end of the casting. If multiple casting powders are in use, it is necessary to use a different silo between heats. These feeding systems also require constant supervision of feeding and correction of set point by the operator if too much / not enough powder is fed into the mould. (Mazza et al. 2017, p. 25-29, SSAB 2012)

Automatic powder feeders are slowly increasing in industrial use, due to their ability to keep the thickness of the powder bed at the correct level and avoid thermal differences in the mould surface. Several different variables have been studied in the development of these machines to be used as controllable variables, for example, powder bed thickness measured by ultrasonic devices, thermal differences measured by thermal image systems, friction force calculated from an oscillation system and heat transfer calculated from cooling water measurements. (Mazza et al. 2017, p. 28-29)

Manual powder feeding is still the most common way of feeding powder. Despite the obvious drawbacks. In the report, Mazza observed that when using manual or semiautomatic feeding systems the thickness of the powder bed is constantly changing and can vary substantially. This variation leads to an unstable meniscus, varying heat transfer and lubrication and even raises the possibility of breakouts. Inconsistent and varying powder feeding can also disturb the measurement of a steel's meniscus position, especially if a radioactive sensor is used in mould level control. (Mazza et al. 2017, p. 29)

3.2 Chemical composition of casting powders

The chemical composition of casting powders is engineered to respond to the requirements of a steel plant and more specifically the composition and size of casted slabs. The composition of different casting powder types varies greatly depending on the type of casting. However, in this thesis, casting powders are only viewed in the context of slab casting. The phases that form during the use of casting powder depend on casting powder composition. In Figure 6, the liquidus projection of the Al_2O_3-CaO-SiO_2 ternary system is presented, acquired from the documentation of the FToxid database of FactSage 8.1 thermodynamic calculation software (Bale et al. 2002). The three components presented in Figure 6 comprise most of the casting powder and these basically determine the formation of the major phase.

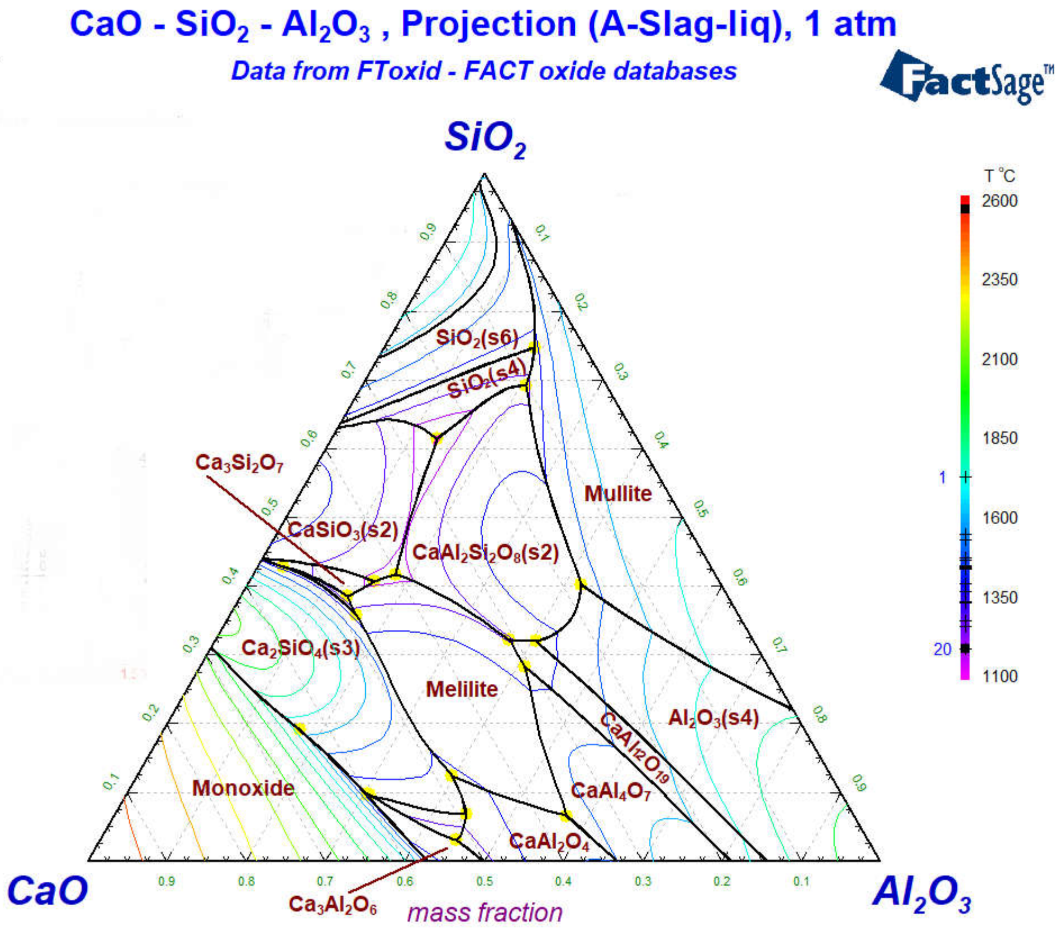

Figure 6. Liquidus projection of the Al_2O_3-CaO-SiO_2 ternary system.

Casting powders consist of slag-creating oxides SiO_2, CaO and Al_2O_3, generally over 70 weight percent of their total weight, with the ratio of ratio of CaO to SiO_2 around 1.0 – 1.3. Fluxes such as MnO, Na_2O, K_2O, Li_2O, Fe_2O, CaF_2, MgF_2, NaF, LiF are liquefying additives, which decrease viscosity and heating temperature and are present in small quantities. Steels with special alloying elements or relatively high weight of alloying additives like Ti or Al require additions of more special components like TiO_2 to ensure that alloying elements will not transfer to slag phase. Typical composition ranges for casting powders are presented in Table 6 and component effects on the most important powder properties are listed in the Table 7. (Kania et al. 2017, pp. 1-6)

Table 6. General chemical compositions areas of casting powders.

Component	Typical concentration (wt-%) Elahipanah 2012, p.14-15	Typical concentration (wt-%) Niska A 1998, p.14
CaO	22–45	25–45
SiO_2	17–56	20–50
MgO	0–10	0–10
Fe_2O_3	0–6	0–5
Al_2O_3	0–13	0–10
Na_2O	0–25	1–20
K_2O	0–2	0–5
F	0–15	4–10
C	2–20	1–25

Table 7. The effect of different components on casting powder properties (Niska 1998, p 15; Mills and Däcker 2017, pp.109-142; SSAB 2012).

Component	Viscosity	Solidification point	Melting point
SiO_2 ↑	Increase ↑	Decrease ↓	Decrease ↓
CaO ↑	Decrease ↓	Increase ↑	Increase ↑
Al_2O_3 ↑	Increase ↑	Decrease ↓	Increase ↑
MnO ↑	Decrease ↓	Decrease ↓	Decrease ↓
Na_2O ↑	Decrease ↓	Decrease ↓	Decrease ↓
F ↑	Decrease ↓	Increase ↑	Decrease ↓
Fe_2O_3 ↑	Decrease ↓	Decrease ↓	Decrease ↓
LiO_2 ↑	Decrease ↓	Decrease ↓	Decrease ↓
MgO ↑	Decrease ↓	Decrease ↓	Decrease ↓
CaO/SiO_2 ↑	Decrease ↓	Increase ↑	Increase ↑
B_2O_3 ↑	Decrease ↓	Decrease ↓	Decrease ↓
BaO ↑	Decrease ↓	Decrease ↓	Decrease ↓
TiO_2 ↑	No change	Increase ↑	Increase ↑
K_2O ↑	Decrease ↓	Decrease ↓	Decrease ↓
C free ↑	-	-	Increase ↑

3.3 The physical and chemical properties of casting powders

Heat transfer is one of the major parameters in continuous casting of steel. This is since it determines the thickness of the forming steel shell and consequently the strength. Usually, the heat transfer consists of two different parameters: horizontal and vertical heat transfer. The composition of steel, casting powder properties and casting speed have the greatest effect on heat transfer. The other parameters affecting heat transfer are presented in Table 8. (Mills and Däcker 2017, pp. 19-55)

Table 8. Parameters that affect heat transfer (retell. Niska 1998, p.14; Mills and Däcker 2017, p. 188).

Parameter	Change	Effect on heat transfer
Viscosity	Increase ↑	Decrease ↓
Crystallization point	Increase ↑	Decrease ↓
Freezing point	Increase ↑	Decrease ↓
Crystallinity of slag	Increase ↑	Decrease ↓
Glassy slag	Increase ↑	Increase ↑
Liquid slag layer	Increase ↑	Increase ↑
Air gap	Increase ↑	Decrease ↓
Casting speed	Increase ↑	Increase ↑

Vertical heat transfer happens from steel across the powder bed to air. Gaseous convection is the main mode of heat transferring in vertical heat transferring. Other heat transfer methods are present in only liquid phase. Vertical heat transfer can be controlled by adjusting the depth of the powder bed, using exothermic agents, by changing particle size of the powder or by utilizing electromagnetic braking. In addition, the existence and position of the meniscus affects the vertical heat flux. (Mills and Däcker 2017, pp. 109-140)

Horizontal heat transfer happens between the mould and steel strand, and it is the main way to extract energy from steel in the primary cooling area. Horizontal heat flux has a greater effect on the quality and the whole casting process compared to vertical heat flux since it determines the thickness of the formed shell in the meniscus area. This type of heat transfer can be viewed from two perspectives, magnitude and variability. Heat transfer happens mainly via three mechanisms: lattice conduction, radiation, and convection in the liquid layer of the slag film. The amount of heat transferred can be controlled by changing the thickness of the slag film or changing the ratio between crystalline and glass phases in the slag film. (Mills and Däcker 2017, pp. 109-140)

Many factors affect horizontal heat flux like casting speed, mould shape, oscillation marks and oscillation characteristics. Additionally, measurement position in the mould affects this as well (Mills and Däcker 2017, pp. 109-140). Equation 1 gives the amount of heat removed from steel based on the temperature change in the cooling water.

$$\Phi = C_p \cdot p \cdot T_m, \tag{1}$$

where Φ is heat transfer [kJ / min], C_p is heat capacity [kJ / °C], p is water flow [kg / min] and T_m is water temperature change [°C] (Kania et al. 2017, p. 1).

The main way of controlling horizontal heat transfer is by controlling the amount of crystal in slag film. Crystal is determined mostly by the basicity of the slag. Generally, the ratio of CaO and SiO_2 is between 0.6 – 1.3 and the crystal phase consists mainly of cuspidine. Environmental issues have driven the removal of fluorine and thus cuspidine has been replaced by perovskite (Mills and Däcker 2017, pp. 299-314). Table 9 present common basicity for different slab grades.

Table 9. C/S commonly used ratios for different slab grades (Mills and Däcker 2017, pp. 393-414).

Other (ULC, LC)	Peritectic (MC)	Sticker sensitive (HC)
1.0	1.3	0.7–0.9

Liquidus temperature of the casting powder is the temperature at which the casting powder becomes completely molten. Higher T_{liq} values result in a thinner slag pool and vice versa. T_{liq} is directly linked to the chemical composition of the casting powder. Commercial thermodynamic calculative programs can provide good estimates of the T_{liq} temperature, but also some numerical equations can be used to estimate its value. The numerical method presented in Equation 2 has an uncertainty of 30 °C but can be used to estimate T_{liq} if the chemical composition of the casting powder is known (Mills and Däcker 2017, pp. 315).

$$T_{liq} = 1191 + 11{,}4 * \%_{\mathrm{SiO_2}} - 11 * \%_{\mathrm{CaO}} + 4{,}2 * \%_{\mathrm{Al_2O_3}} + 5{,}7 * \%_{\mathrm{MgO}} - 10{,}1 * \%_{\mathrm{Na_2O}} - 15{,}8 * \%_{\mathrm{K_2O}} + 1{,}9 * \%_{\mathrm{F}} + 8{,}3 * \%_{\mathrm{FeO}} + 11{,}6 * \%_{\mathrm{MnO}} \qquad (2)$$

where T_{liq} is liquidus temperature [°C], $\%_{substance}$ is mass percentage of the corresponding substance (Mills and Däcker 2017, p. 315).

Break temperature (T_{br}), also known as solidification temperature, is the point where solids start to form with even slight temperature decreases. Due to solid formation from cooling, viscosity will increase vastly if the powder cools under the T_{br} value. It is important to notice that T_{br} is not constant for any powder composition, and it depends on the actual cooling rate in the mould. T_{br} values generally decrease when cooling rate is raised. Due to this variability, the value is typically bound to some cooling rate, usually 10 K/min for a specific powder composition. The importance of the T_{br} is shown well by its correlation with the boundary between solid and liquid slag film. Consequently, it affects horizontal heat flux and friction forces, which ties it to lubrication. Equation 3 presented below is numerical and tends to have an uncertainty of 25°C. (Mills and Däcker 2017, pp. 318)

$$T_{cryst} = T_{br\_1} = 1241.6 - 0.0215 * \mathrm{X_{MgO}} - 0.0141 * \mathrm{X_{AL_2O_3}} - 0.0449 * \mathrm{X_{Na_2}} - 0.0855 * \mathrm{X_{CaF_2}} - 0.0641 * \mathrm{X_{LI_2O}} - 0.1528 * \mathrm{X_{B_2O_3}} (3)$$

where T_{br_1} is break temperature for casting powder [°C], $X_{substance}$ is the mole fraction of the corresponding substance (Mills and Däcker 2017, p. 318).

Slag film consists of a mixture of different phases between mould and strand. At the steady state, the balance between crystalline and glassy phases affects heat transfer and lubrication. Crystallization of casting powder directly affects the heat transfer happening in the mould. Glassy slag structure increases the amount of heat transferred, and crystalline slag structure reduces it. The type of forming crystal layer depends on the chemical composition of the casting powder. Generally, the first forming crystal layers have been cuspidine, but due to environmental and safety reasons more and more perovskite-forming powders have been taken into use (TiO_2 replaces F). Commonly, when casting powder heats, it first forms a glassy layer, which then crystallizes because the crystallization values are usually given as steady state values. Higher SiO_2 values tend to make crystallization times longer. Equation (4) can be used to calculate the fraction of crystalline phase between mould and strand. The equation requires NBO/T as an input, which can be calculated with Equation 5. (Mills and Däcker 2017, pp. 135-139; Mills 2014, p. 468; Li et al. 2004)

$$\%_{cryst} = 100 * \mathrm{F}_{cryst} = -255.5 + 120.9 \cdot \mathrm{NBO/T} \tag{4}$$

where $\%_{cryst}$ is the fraction of crystalline phase [%], NBO/T is presented under (Mills 2014 p.468).

$$\mathrm{NBO/T} = 2 * (\mathrm{X_{CaO}} + \mathrm{X_{MgO}} + \mathrm{X_{FeO}} + \mathrm{X_{MnO}} + \mathrm{X_{Na_2O}} + \mathrm{X_{K_2O}} - \mathrm{X_{AL_2O_3}}/(\mathrm{X_{SiO_2}} + 2 * \mathrm{X_{AL_2O_3}}) \tag{5}$$

where NBO/T is the number of non-bridging oxygen per tetrahedrally-coordinated atom, $X_{substance}$ is the mole fraction for that substance (Mills 2014, p. 468).

Structure of the slag is commonly illustrated with the basicity index. It provides information about how the slag's structural components affect the silicate network. Chemicals can be network formers or breakers and different equations have been composed with different emphases. The simplest and most common way of basicity calculation is to calculate the ratio between CaO and SiO_2. Other more complex ways also exist like the optical basicity calculation (Elahipanah 2012, pp.16-17)

$$B = \frac{\mathrm{CaO}}{\mathrm{SiO_2}} \tag{6}$$

where B is basicity, CaO is mass percentage of CaO [wt-%], SiO_2 is mass percentage of SiO_2 [wt-%] (Elahipanah 2012, pp. 16-17).

Viscosity is the arguably most important casting powder property. It affects the lubrication between the mould and steel strand, slag entrapment and wear rate of the SEN. Casting powder viscosity depends on the chemical composition of the powder and temperature to which it is exposed. Chemical components that are previously stated as network formers in Table 5 increase viscosity and network breakers decrease viscosity. Temperature's relationship with viscosity can be described by Weymanm in Equation 8 or Arrhenius in Equation 7. General practice is to calculate the casting powder's viscosity in 1300 °C. This is because 1300 ℃ is the approximate mean temperature of liquid slag film in a continuous casting of steel. (Mills and Däcker 2017, p. 321)

$$\eta = A_a * \exp(B_a/T_K) \tag{7}$$

where η is viscosity [dPas], A_a is constant, B_a is activation energy, T_k is temperature [K] (Mills and Däcker 2017, p. 321).

$$\frac{\eta}{T_K} = A_w * \exp(B_w/T_K), \tag{8}$$

where η is viscosity [dPas], A_w is constant, B_w is activation energy, T_k is temperature [K] (Mills and Däcker 2017, p. 321).

Several equations have been developed by various researchers to calculate viscosity based on the chemical composition of the casting powder. The uncertainty of these methods is quite high, around 25%, due to the fact that uncertainty with experimentally measured viscosities are in the range of 10 – 25% (Elahipanah 2012, pp.20-25; SSAB 2012).

Success rate of the lubrication can be partially concluded from the actual powder consumption. Originally, powder consumption was monitored from the cost of casting powder per tonne of produced steel. It was quickly discovered that powder consumption per mould area better enabled monitoring of lubrication. Casting powder consumption generally rises when slag viscosity, oscillations frequency or casting speed are lowered. The required consumption of casting powder is formed from the three parameters presented in Equation 11 (Mills and Fox 2003, pp. 2-3.; SSAB 2012; Mills and Däcker 2017, pp.20-55).

The most common unit for powder consumption Q_t is [kg/tonne], which is the mass of consumed powder per casted tonne of steel. It is important to point out the difference between the terms slag and powder. In this context, slag is the actual heated casting powder, which has a different composition than the used casting powder. Equation 9 shows the most common ways of calculating the required slag consumption (Mills and Fox 2003, p. 1481-1483; SSAB 2012; Mills and Däcker 2017, pp. 20-55).

$$Q_{reg} = 0.55 \,/\, \eta\text{^}(0.5) * v_c \tag{9}$$

where Q_{reg} is powder consumption, η is viscosity [dPas], V_c is casting speed [m/min] (Mills and Däcker 2017, p. 34).

Frictional forces that are occurring in the mould are formed from two parts. Friction between liquid slag and solid strand and friction between solid slag and strand the second of which can lead to splitting slag layers, air holes and unexpected variations in heat transfer. Equation 10 gives the frictional force between steel and solid slag film. Usage of this Equation requires that speed gradient is assumed constant between the mould and strand. (Mills and Däcker 2017, p. 20-55)

$$F = A * \eta * (V_m - V_c)/d_l \tag{10}$$

where F is frictional force between steel and solid slag film [N/m^2], A is the contact area of mould and strand [m^2], V_m is oscillation [strokes/min], d_l is thickness of molten slag layer [mm] and V_c is casting speed [m/min] (Mills and Däcker 2017, p.45).

3.4 Casting powder selection

Methods 1 – 5 presented in this chapter are the general ways of selecting casting powder, when there is no intention or specific reason to start developing a process for a new casting powder. Each steel plant has their own practices for powder selection. These rule sets have usually many levels and can contain specific rules for special grades. Almost all rule sets are formed based on methods presented below with the addition of special exceptions.

3.4.1 Suppliers' recommendations

The recommendation of the powder producer is probably the most common way of choosing a casting powder. This method is based on long-term development work, where powder composition has been changed gradually over time. Usually, new powder goes through test castings before it is accepted into general usage. Mills and Fox (2003) claim that probably powder producers have applications for calculation of powder composition even though it seems like the decisions are made in an ad hoc manner. Suppliers commonly bundle slab grades based on ferrite potential (FP), carbon potential (CP), or carbon content. Casting machines' physicals properties and casting variables like casting speed and mould dimension are also considered. After this, powder properties are most likely calculated as presented in the last section of this chapter. Powder producers have a wide selection of powder compositions and knowledge about which ones have the right qualities for specific casting machines. Producers generally recommend one of their existing products, but they also offer special powder types like those for high Al steels and steels with other special contents. (Mills and Fox 2003, pp. 1479-1489)

3.4.2 Iron-carbon phase diagram

The iron-carbon phase diagram is used widely for classification of low alloy carbon steels. This kind of diagram is presented in Figure 5 in the former chapter 2.3. Points C_a, C_b and C_c divide low alloy carbon steels in four groups, whose solidification methods are presented in chapter 2.4 and corresponding ductility problems in chapter 4. Based on a steel’s classification, casting powder can be assigned to a new slab grade. Some factories also divide steel into micro-alloyed steels and other steels, which takes limited account of the effect of alloying elements. These kinds of powder rules are used when a steel mill already has powders and has no intention to change the composition of the powder. Usually, peritectic grades have their own powder due to the required low heat transfer. Other grades are often cast with higher heat transfer properties, having powders with exceptions like high Al or ultra-low carbon (ULC) slab grades. (Azizi et al. 2020, pp.1-7)

3.4.3 Carbon potential calculation

Carbon potential (CP) is one of the main methods used in classification of slab grades. Several different equations have been proposed in the literature with the same basic structure but difference in the factors affecting the effect of specific alloying elements. In the equations, austenite-forming elements are added to carbon potential and Mo is subtracted due to its ferrite-forming nature. Still, the elements P, Al and Nb are added to carbon potential although they are ferrite-forming. The effect of Si, Cr, Ti and V are commonly not considered (Azizi et al. 2020, pp. 1-3). Equation 11 was chosen to be used as a calculation method for this thesis due to its use in other SSAB’s factories.

$$\mathrm{CP} = \mathrm{C} + 0{,}04 * \mathrm{Mn} + 0{,}1 * \mathrm{Ni} + 0{,}7 * \mathrm{N} - 0{,}14 * \mathrm{Si} - 0{,}04 * \mathrm{Cr} - 0{,}1 * \mathrm{Mo} - 0{,}24 * \mathrm{Ti} \quad (11)$$

where CP is the value of carbon potential, elements are in weight percentage (Azizi et al. 2020, pp. 1-3).

3.4.4 Ferrite potential calculation

Ferrite potential (FP) describes the amount of peritectic reaction taking place in the solidification of steel. The maximum amount of the peritectic reaction is present in solidification of steel when FP = 1. Calculation of FP requires calculation of CP and the right kind of value for each parameter. In this thesis, FP values are calculated by utilizing Equation 14 due to its usage in other of SSAB's factories. Table 10 presents the forming phase and type of shell according to the ferrite potential. (Mills and Däcker 2017, p. 401)

$$\mathrm{FP} = 2{,}5 * (0{,}5 - \mathrm{CP}) \quad (12)$$

where FP is the value of ferrite potential, CP is the value of carbon potential (Mills and Däcker 2017, p. 401).

Table 10. Phase transformations taking place in solidification of steel according to ferrite potential (retell Mills 2014, p. 463; Mills and Däcker 2017, pp. 419-420).

FP (Mills)	FP (Wolf)	Phase	Shell
<0.8	<0.85	Austenite	Strong and ductile, sticker sensitive
0.8–1.05	0.85–1.05	Ferrite → austenite	Irregular and strong, crack sensitive
>1.05	>1.05	Ferrite	Weak and ductile, sticker sensitive

3.4.5 Powder consumption and powder properties calculation

Casting powder selection can be done based on the required properties for specific slab grade and casting conditions according to Mills (2014). This method assumes that powders are chosen for minimization of longitudinal cracking and breakouts (Mills 2014, p. 469).

The method requires completing five calculations for each slab grade / set of casting conditions by utilizing Equation 13 – 18 presented below. The first step is to calculate the ratio between surface area and volume of used mould. The second step is to calculate the required powder consumption. The third step is to calculate the required viscosity for the used casting speed. The fourth step is to calculate CP or FP to classify the slab grade as peritectic or non-peritectic. This can be done as presented in above. The last step is to calculate the T_{br}. At this point, the required powder consumption, viscosity and T_{br} of the powder is known and powders with corresponding values can be chosen for use. This method works in 85% of cases (Mills 2014, p. 469).

$$\mathrm{R} = 2\frac{\mathrm{w+t}}{\mathrm{w}} * \mathrm{t} \tag{13}$$

$$Q_{req} = \frac{2}{\mathrm{R}-5} \tag{14}$$

$$\eta_{req} = \frac{0{,}55}{\mathrm{Vc}} * \mathrm{Q_{req}} \tag{15}$$

$$T_{br\_2} = 1157 + 60 \ln(\eta_{\mathrm{reg}}) \tag{16}$$

$$T_{br\_3} = 1051 + 74.4 \ln(\eta_{\mathrm{reg}}) \tag{17}$$

$$T_{br\_4} = 1103 + 68.5 \ln(\eta_{\mathrm{reg}}) \tag{18}$$

where R is surface area ratio of the mould, w is width of the mould [m], t is thickness of the mould [m], Q_{reg} is required powder consumption, η_{req} is required viscosity [dPas], Vc is casting speed [m/min], T_{br_2} is break temperature for crack-sensitive grades [°C], T_{br_3} is break temperature for sticker-sensitive grades [°C] and T_{br_4} is break temperature for intermediate grades [°C] (Mills 2014, p. 469).

3.5 Composition engineering of casting powder

Composition engineering of casting powder is a complex and long process which usually includes extensive laboratory testing, industrial testing, and calculations. Usually, powder development is started for a specific reason, like getting rid of fluoride or introduction of high Al content new slab grades. Methods generally use known effects of casting powder components and known requirements and past experiences, but more and more calculative and model-based methods are applied in development projects. Two different ways of developing new casting powders are reviewed briefly below. In the analytical approach, the problem is that empirical equations used are not always reliable. On the other hand, non-calculative methods are expensive, rely highly on prior knowledge and can cause poor results in new casting machines or slab grades.

3.5.1 Analytical approach for casting powder design

The casting powder compositions design problem was approached in the study by Kania et al. (2017, p. 1) with empirical equations and by calculating physicochemical parameters based on casting machines' properties and slab grades' compositions. The actual composition design included the following steps in the study. First, FP was used to classify slab grade into the right group. Then, optimal lubrication was determined, in other words the needed powder consumption based on oscillation and casting variables. Finally, calculations were made for parameter R based on mould and strand dimensions. (Kania 2016, p. 2-8)

After the previous steps, the basic parameters are known and the selected physical parameters of the casting powder can be determined. This was done by using known good composition ranges as a base and calculating limit values for different physical parameters in the following order: basicity, viscosity, T_{br}, T_{liq}, T_{sol}, thermal conductivity of powder and the required crystalline phase. Choosing the right amount of free carbon was done based on the classification specified by FP. Final composition was chosen based on testing and further calculation of powder values. (Kania 2016, p. 2-8)

3.5.1 Experimental approach for casting powder design

The driving force in Wen et al.'s (2007) casting powder development study was a need to get rid of fluoride due to environmental reasons. In addition, improvement in surface quality was targeted. A key difference associated with fluoride-free powders is that the crystalline phase is perovskite instead of normal cuspidine. According to their study, the F-free powder developed had good heat transfer qualities and strand surface quality. Casting powder development started with choosing F free powder component ranges based on a targeted basicity range of 0.6 – 1.2 and general knowledge about usual component amounts. In laboratory tests, 35 different powder compositions were analysed. Based on the laboratory tests, two powder compositions for continuous casting of peritectic steel were chosen, and according to the study they performed well. (Wen et al. 2007, pp.1-9)

4 DEFECTS IN CONTINUOUS CASTING

The purpose of continuous casting is to produce high-quality steel for further processing. It would be optimal if defects would not occur at all, but that is not possible. Therefore, it is important to recognize defects and their formation mechanisms. In this chapter, common casting powder-related defects are introduced, and their typical origins are discussed. Methods to avoid these defects by correct casting powder usage is discussed also.

4.1 Different casting-related defects and steel low ductility zones

Casting machines produce solidified steel in different shapes for further processing. In a way, the casting machine can be seen as a large heat transferring machine. Amount, variation, and location of heat transfer has a great effect on product quality. A good rule of thumb is that when the casting speed is increased, more defects occur. Other variables affecting defect formation are oscillation parameters, slab grade, casting powder, steel cleanliness, heat transfer in primary and secondary cooling, etc. Only slab defects and the plate or strip defects that are linked to casting machines are introduced in this chapter and later considered in the defect analysis. It is important to understand that defects may have different names, depending on the source, and identifying them requires trained personnel. (Louhenkilpi 2014, pp. 373-380)

It is obvious that slab defects are formed during the casting and cooling of slabs. Formation of these defects takes place in all sections of the casting machine. Defect formation can happen in the mould, bender, secondary cooling zone and even while cooling down in the slab hall. Defects are caused by mechanical or thermal stress, which are related mainly to bending and heat transfer. Amount and effect of the stress depends on casting variables and steel quality. (Joensuu 2011, p. 3; Pirinen 2011, pp. 5)

These defects are commonly classified differently depending on the source. The most common way is to divide defects in three groups: surface defects, internal defects, and shape defects. In this thesis, only surface defects are considered. Figure 7 illustrates the internal and surface defects that are used in the defect classification in SSAB Raahe steel works. Names of surface defects are presented in Table 11. The Defect Table has Finnish names for defects to avoid conflicts in reading this thesis, because in some cases naming of defects can vary considerably. (Joensuu 2001, p. 3; Pirinen 2011, p. 5)

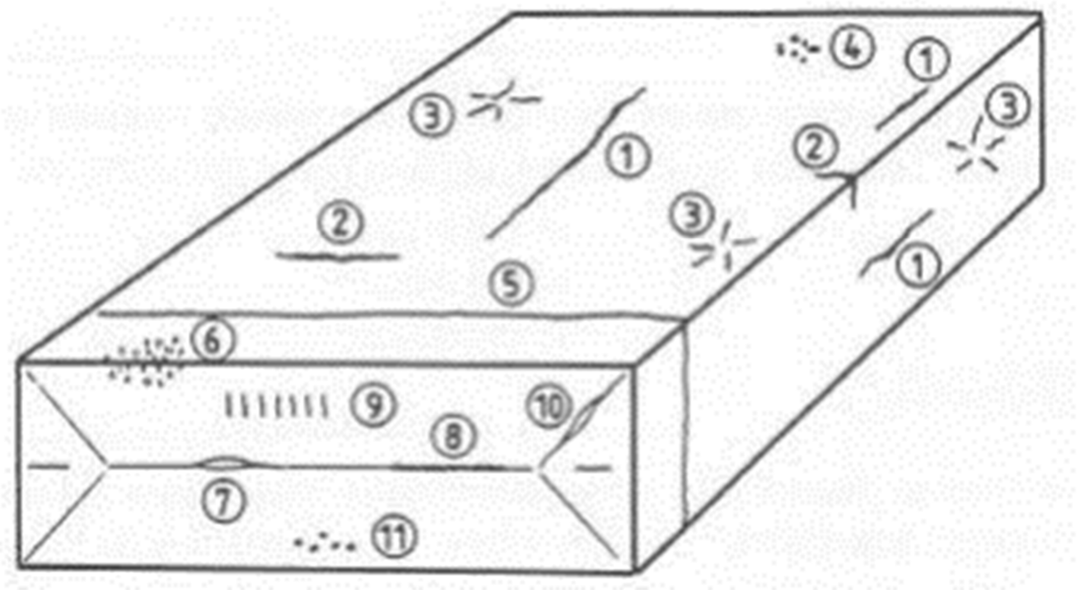

Figure 7. Internal and external defects in steel slabs (retell. Joensuu 2011, p. 5).

Table 11. Internal defects and their Finnish equivalents (SSAB 2020).

Number	Surface defects in slabs	Ulkoiset viat aihioissa
1	Longitudinal crack	Pitkittäishalkeama
1 (corner)	Off corner cracks	Reunahalkeama
2	Transverse surface crack	Poikittaishalkeama
2 (corner)	Corner crack	Nurkkahalkema
3	Star crack	Syheröhalkeama
4	Inclusion	Kuonasulkeuma
5	Slag belt	Kuonavyö
6	Porosity	Kaasuhuokonen

Generally, steels ductility has three weak points during solidification. These low ductility zones are the most likely places for cracking-related defects to occur. Existence and precise areas of these ductility zones are greatly affected by a steel's chemical composition. In most cases it is recommended not to bend or predispose steel strand to high thermal or mechanical stress in these areas to avoid cracking and formation of defects. (Louhenkilpi 2011, pp. 22-24; Louhenkilpi 2014, pp.417-421)

The first low ductility zone usually occurs 20 – 50 °C below solidus temperature. Steel composition can affect its location greatly. In the best cases the first low ductility zone can have a small range, but in the worst cases the range can increase to 100 – 150 °C. Hot cracking is especially common for slab grades that have a large low ductility zone 1, which will lead to internal cracks. Carbon, sulphur, manganese, and phosphorus are the main components affecting this area's existence. Commonly, it can be said that carbon content affects the solidification route (austenite route or ferrite route) and sulphur and phosphorus affect the amount of micro segregation, which lowers the ductility in certain areas. (Louhenkilpi 2011, pp. 22-24; Louhenkilpi 2014, pp. 417-421)

The second low ductility zone is usually located in the temperature range 900 – 1200 °C, which is in the austenite area. Oxygen, sulphur, and manganese are the main chemical elements affecting the size of this area. The main cause of this low ductility zone is the formation of Mn/Fe-S/O sulphides and oxides. These chemical compounds arrange lines in grain boundaries, which prevents the moving of boundaries and causes a pinning effect and weak structure. Simultaneously, low heating elements like Ti and C can enrich to the borders of the austenite phase, keeping the boundary in the molten phase. (Louhenkilpi 2011, pp. 22-24; Louhenkilpi 2014, pp.417-421)

The third low ductility zone is located in the temperature range between 700 – 900 °C depending on the composition of the steel. Many reasons for the ductility loss have been presented in the literature but commonly the following two are presented. Existence of precipitate-free areas next to austenite grain boundaries, which causes a weaker matrix area. The second presented reason for ductility loss is slow recovery of grain boundaries due to the precipitations and existence of thin ferrite film in austenite grain boundaries in the beginning of the austenite to ferrite phase transformation. (Louhenkilpi 2011, pp. 22-24; Louhenkilpi 2014, pp.417-421)

4.2 Casting powder impact on defects and sticker breakouts

Mills (2014, p. 469) describes the significance of casting powders in the following: "*defects and process problems result from changes in casting speed, etc., and mould fluxes are frequently used to minimize their impact*". This section presents the defects and process disruption and ways to minimize them by correct casting powder composition or selection.

4.2.1 Sticker breakouts

Sticker breakouts are complex and the most serious process problem in continuous casting of any metal. Common factors for all sticker breakouts are formation of the thin shell and loss of lubrication at the same time. Usually this happens in upper parts of the mould and cracks form in the steel strand. These cracks then move downward and when exiting the mould, the molten steel can flow freely outside of the casted strand. Factors affecting sticker breakouts are slab grade, mould dimensions, mould condition, large amounts of Al_2O_3, TiN or ZrO_2 in the steel, loss of lubrication, carbon pickup or low heat transfer across the slag film. (Mills and Däcker 2017, pp. 434-443)

The first way to reduce sticker breakouts is to modify powder composition in a way that a thicker and stronger shell forms, which can be achieved by using casting powders with low T_{br} and glassy slag film-producing powders. The second way to reduce sticker breakouts with casting powders is to reduce TiN and ZrO_2 particles in steel by maintaining a thick slag pool and minimizing the ZrO_2 content of casting powders. Additionally, minimizing the H_2 levels in steel by pre-heating and storing powder correctly has been shown to be effective. (Mills and Däcker 2017, pp. 434-443)

4.2.2 Longitudinal cracks

Longitudinal crack defects are a consequence of hot crack formation in the mould, typically in the upper parts of the mould near the SEN. Mechanical stress in bending, bulging or thermal stress causes opening of the hot cracks (Louhenkilpi 2014, pp. 428). Peritectic steels with high amounts of sulphur and phosphorus are especially sensitive to longitudinal surface cracking. Uneven heat transfer caused by peritectic transformation and shrinkage causes uneven shell growth and subsequently leads to gaps between mould and shell. (Louhenkilpi 2014, pp. 427-433)

Longitudinal cracking is one of the most common defect types occurring in continuous casting. Commonly, these defects are classified into two groups: sub-surface and cross cracks. Sub-surface cracks are common in medium carbon and peritectic slab grades and they are generally smaller than cross cracks. Cross cracks are usually located in longitudinal depressions and are primarily caused by poor process control, mainly by excess mould level fluctuation. (Mills and Däcker 2017, pp. 418-428)

Several factors affect the formation of longitudinal cracking: slab grade, horizontal heat flux in the meniscus area, lubrication, powder consumption, metal flow and use of electromagnetic devices to reduce turbulence. Longitudinal cracking is known as the main problem of the peritectic steels and medium carbon steels. Transformation of ferrite to austenite causes a stronger but less ductile shell, which causes shrinkage of 0.4 – 0.6% of volume. This causes hoop stress, which is finally relieved by cracking. Heat fluxes' effects on longitudinal cracking comprise two components: horizontal heat flux and local variations in heat flux (hot spots). (Mills and Däcker 2017, pp. 418-428)

The main ways to avoid longitudinal cracking are to keep heat transfer and shell growth uniform. This can be done by with correct powder use. The aim is to reduce horizontal heat flux and thus variations in shell thickness. A more uniform and thinner shell can be achieved with the following actions. Using casting powder which forms crystalline slag film and decreasing horizontal heat flux. This is achieved by using a casting powder with high T_{br} and basicity. A common way to do this is increasing the CaO/SiO_2 ratio. (Mills and Däcker 2017, pp. 418-428)

4.2.3 Transversal cracks

Transversal cracking is commonly divided to transversal corner cracks and transversal facial cracks. These types of defects commonly coincide with transversal depressions and deep oscillation marks (Camisani-Calzolari et al. 2003, p.2). Increase of these defects happens if the steel strand is straightened at low ductility temperatures. Micro alloyed steels with high Nb or V in carbon range 0.08 – 0.14 wt-% are likely to have these defects (Louhenkilpi 2014, pp. 427-433).

Transverse cracks and corner cracks are present in the surface and inside steel slab. These defects form at the base of deep oscillation marks because of stress concentration rising from micro segregations, improper taper in the mould, badly adjusted process parameters, improper casting powder and from bending or straightening of strand in low ductility areas. (Mills and Däcker 2017, pp. 461-467)

Common ways to reduce the number of transverse cracks and corner cracks are reducing the depth of the oscillation marks, increasing the strand temperature to avoid the low-ductility range of the steel in the straightening region, minimizing the concentration of Cu, Sn and Sb in the steel or adding Ni. Casting powder can be used to reduce transverse cracks and corner cracks by increasing T_{br} and F_{cryst} values of the casting powder. (Mills and Däcker 2017, pp. 461-467)

4.2.4 Inclusions and slag defects

In general, inclusions lower steel quality. Four main types of inclusions are present in steel: oxides, sulphides, nitrides and carbides, which originate from metals and slag reactions or are entrapped mould slag resulting from metal flow turbulences (Mills and Däcker 2017, pp. 480-506). A common classification method is to divide inclusions into endogenous and exogenous inclusions. Exogenous inclusions originate from external sources and endogenous inclusions are a product of the deoxidation reaction. (Louhenkilpi 2011, pp. 36-37; Louhenkilpi 2014, pp. 431-433)

Non-metallic inclusions can be removed from steel by transporting inclusions on the surface of the steel where they can be absorbed by mould slag. The main way is to use the flotation difference between steel and the inclusion. Casting powder can affect inclusions by delaying solidification of strand with high T_{br} and high F_{cryst}. and giving more time for inclusion removal (Mills and Däcker 2017, pp. 480-506). Casting powders' inclusion absorption ability gets better when: F content is increased, Na_2O is substituted with LiO_2, basicity is raised, amount of Al_2O_3 is lowered in the powder or slag viscosity is reduced. (Mills and Däcker 2017, pp. 480-506)

4.2.5 Star cracks

Star cracking, also known as sponky cracking, is a crack type that tends to form in the lower half of the mould. In the past, star cracking was commonly associated with copper droplets in the strand. Copper diffuses from the mould to the shell, where it penetrates into grain boundaries and is oxidized. Usually, this problem is countered by coating the mould with metals with high melting temperatures such as Ni, Cr, and Mo. Later it was discovered that star cracking correlated with fluctuations in heat flux, which are caused by a lack of lubrication and too thin liquid slag film. Star cracks result from weakening of the intergranular bond between austenite grains. Ductility loss and copper pickup are the most common reason for this defect. The main way to avoid these defects is to avoid strong cooling in the secondary area. (Louhenkilpi 2014, pp.427-433)

Especially casting powders with crystalline slag film and high basicity are prone to cause this phenomenon. Avoiding star cracking is a challenging task, but the following procedures are widely recommended in the literature: using a casting powder that provides a liquid slag film of sufficient thickness, reduced water flow rates, increased superheat and reducing overall heat loss in the mould. (Mills and Däcker 2017, pp. 469-471)

5 ANALYSIS OF CURRENT STATUS CONSIDERING CASTING POWDER SELECTION

This chapter first goes through the defect and process disturbance analyses done to find slab grades with casting powder-related problems. The slab grades that had relatively many problems are chosen for the test period. After this, the casting powder selection rules of Luleå and Oxelösund are reviewed. A short summary of SSAB America steel mill casting powder usage is also included.

The main target of this thesis was to study different casting powder selection rules used in other steel mills and presented in the literature. Based on some of the studies, casting powder selection rules were changed partly for the test period. Prior to this thesis, multiple casting powders tests had been conducted at the Raahe steel mill. The target of these tests was testing the suitability of new casting powders by running short test periods. Casting powder performances have been evaluated based on defect data, process disturbances and process parameter analysis.

5.1 Defect and process disturbance data analysis

The casting process is a very complex process, and many different variables affect the amount and severity of slab defects. Casting powder has a major impact on the quality of the casted steel slab as presented in previous chapters 3 and 4. Casting powder impacts heat transfer and it is also the key to optimal lubrication when used with correct process parameters such as oscillation and casting speed. During this thesis, a casting powder already in use could be changed to another existing option, but other process parameters could not be changed. From the viewpoint of this thesis, defects and disturbances, which are commonly linked to poor performance of casting powders, are used as indicators of a possible need for a change in the casting powder selection rules.

It is important to note that casting powder changes are not always the answer to these problems. Grades with casting powder-related problems were inspected with the following factors: composition, FP, CP, required powder consumption and required T_{br}. In addition, many grades have special needs based on their composition. Such grades are high boron and aluminium content grades and interstitial-free treated grades. These grades were excluded from tests based on known reasons for casting problems or special requirements for used casting powders.

Reference period also applies its own restrictions and requirements for the tests. It was clear that the time period for data analysis should be long enough to mitigate effects of non-casting powder-related defects or disturbances and give a good general overview of the frequency of reviewed problems, and if they are common or not.

To keep the results reliable and ensure the possibility of carrying out casting powder tests within the time frame of this thesis, some restrictions were made. Only slab grades that had more than 42 heats in the reference period are included and grades with special casting powder requirements are excluded.

5.1.1 Process disturbance analysis

The automation system records and monitors a wide range of different casting-related parameters. These parameters are then used to analyse and control the process. Based on these parameters, the automation system records casting disturbances, which gives information to operators about the state of the process. From the viewpoint of this thesis, these disturbance recordings can be used to evaluate casting powder performance. Disturbance analysis is comprised of two parts in this thesis: the first part consists only of the sticking alarm (40); the second part in chapter 6 consists also of alarms including spontaneous opening of the SEN (96), dynamic surface fluctuation (97) and extra strand cooling (98).

As presented in the literature review part of this thesis, breakouts are a severe process problem in continuous casting of steel. Breakouts presented in Table 12 have occurred during the reference period 1.1.2020 – 29.9.2021. Slab grade 0891 stands out in the Table with two breakout occurrences. Grade 0891 clearly had problems and these problems could be caused by poorly working casting powder. Other grades in Table 12 could not be linked to casting powder-related problems.

Table 12. Reported breakouts during the reference period.

Heat number	Slab grade	Date
54690	0891	23.6.2020
77105	0891	10.7.2021
77426	0566	16.7.2021
77813	0782	23.7.2021

The Sapsol system, in other words the breakout inhibition system, tracks the temperatures of thermocouples in the mould. It is based on the known behaviour of thermocouples when breakouts are about to happen. Generally, before breakouts upper and lower thermocouple temperature curves start to approach each other. When the system detects this kind of behaviour, it slows down the casting speed to give the strand more time to cool and form a thicker shell.

On many occasions, the reasons for uneven or insufficient shell thickness, which lead to triggering of the sticking alarm, can be traced to insufficient lubrication or too low heat transfer. Both are greatly affected by casting powder as presented in the literature review part of this thesis. For each steel grade, the percentage of heats with sticking alarms on machines 4 & 5 are presented in Figure 8. Similar results for heats casted in machine 6 are presented in Figure 9. In general, sticking alarms are not that common and to mitigate the effect of singular bad heats, data was collected from the long time period of 1.1.2020 – 30.9.2021.

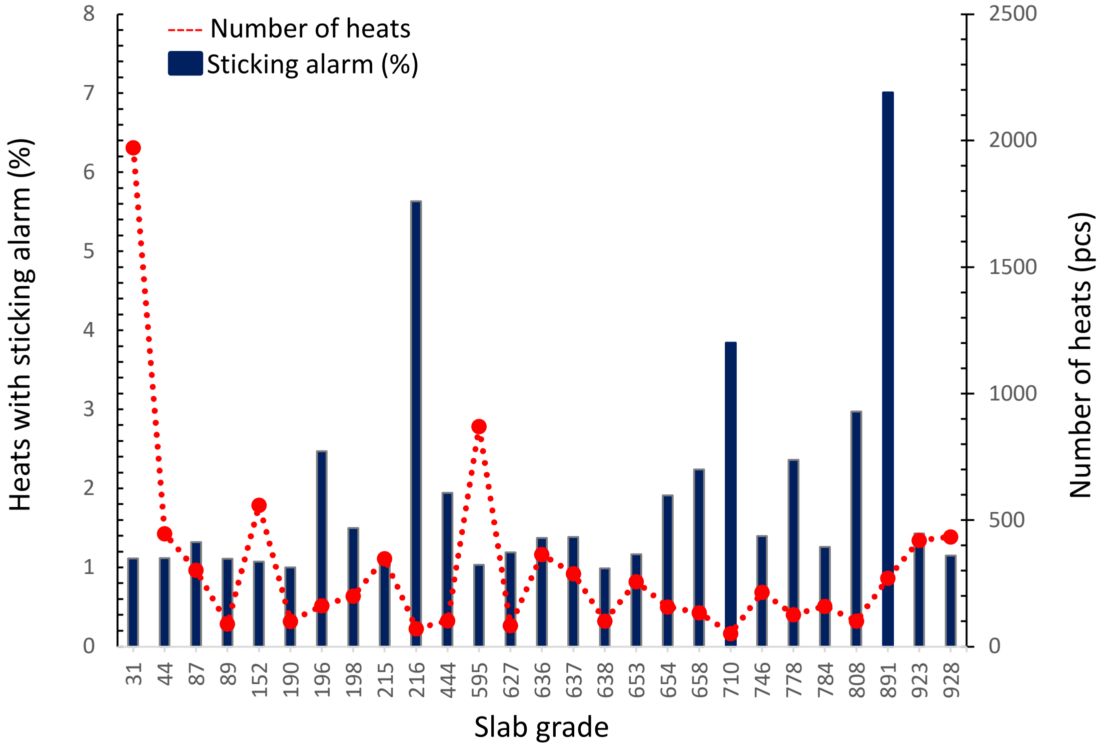

Figure 8. Heats with sticking alarms CCM 4 & 5.

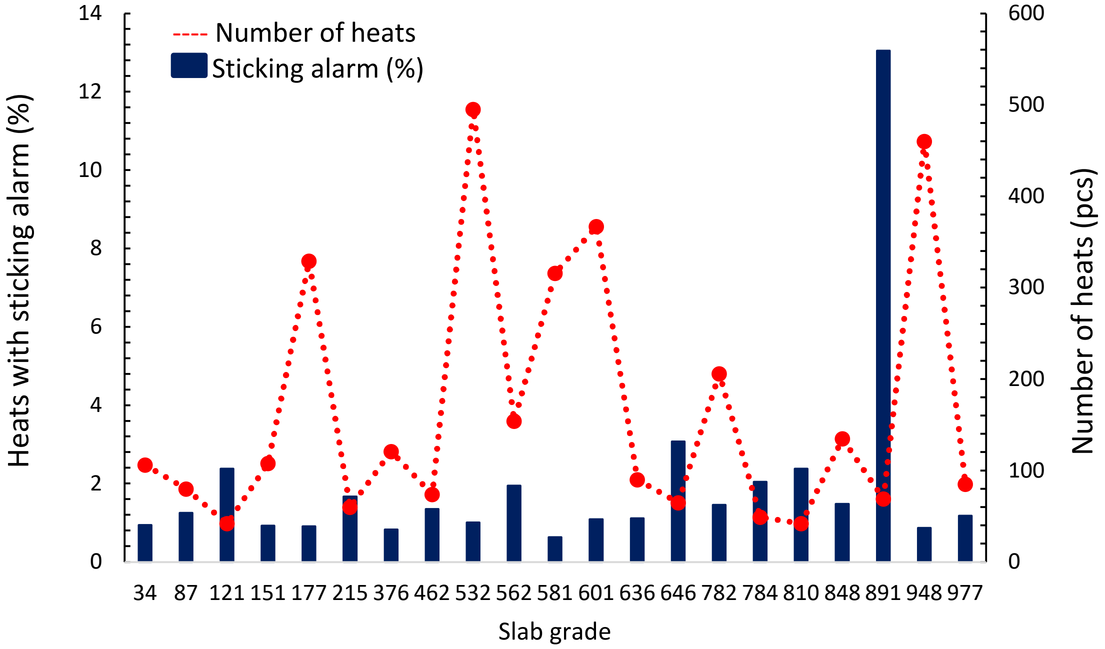

Figure 9. Heats with sticking alarms CCM 6.

5.1.2 Defect analysis

Defect analyses were originally performed for both plate and strip grades separately to get a reference point and information about how many defects were reported and how many corresponding plate defects were present. For plate grades, the reporting system works well and inspections are done for all slabs, so the data is reliable. Unfortunately, the same cannot be said for strip grades and thus the strip grade analysis was excluded from the results.

Historical data was gathered from the database for defect data analysis from the term 1.1.2020 – 1.10.2021. The results of these analyses are presented in Figures 10 – 13. A common way to present defect amounts in the Raahe Works is to calculate what proportion of product has defects and then calculate the percentage portion per tonne of casted steel. This method was used in all historical defect data analyses carried out in this thesis. Basically, this requires the following steps. Getting historical data about all casted heats from the reference period, which includes in these cases several different data retrievals. Basic information about every heat is retrieved including heat number, serial number, casting width, casting thickness and several more attributes. Based on these, the total weight, number of casted heats and number of casted slabs can be calculated. After this, with the help of reported defects and historical data, the percentage of the total production containing defects was calculated for each considered slab grade.

5.1.3 Analysis of transverse cracks and lag defects in slabs

The link between transverse crack and unsuitable casting powders was discussed in chapter 4. Figures 10 and 11 present the defected amount of steel in tonne-% per casted amount of steel in the previously introduced reference period. The blue columns present the scrapped amount and red dotted line presents the number of heats for each slab grade to give a proportioning point. Figures 12 and 13 present the amount of slag defects and corresponding plate defect in the same way. Slab grades presented in these Figures were taken for further inspection. These analyses are used later in chapter 6 to assist in choosing of slab grades for the test period.

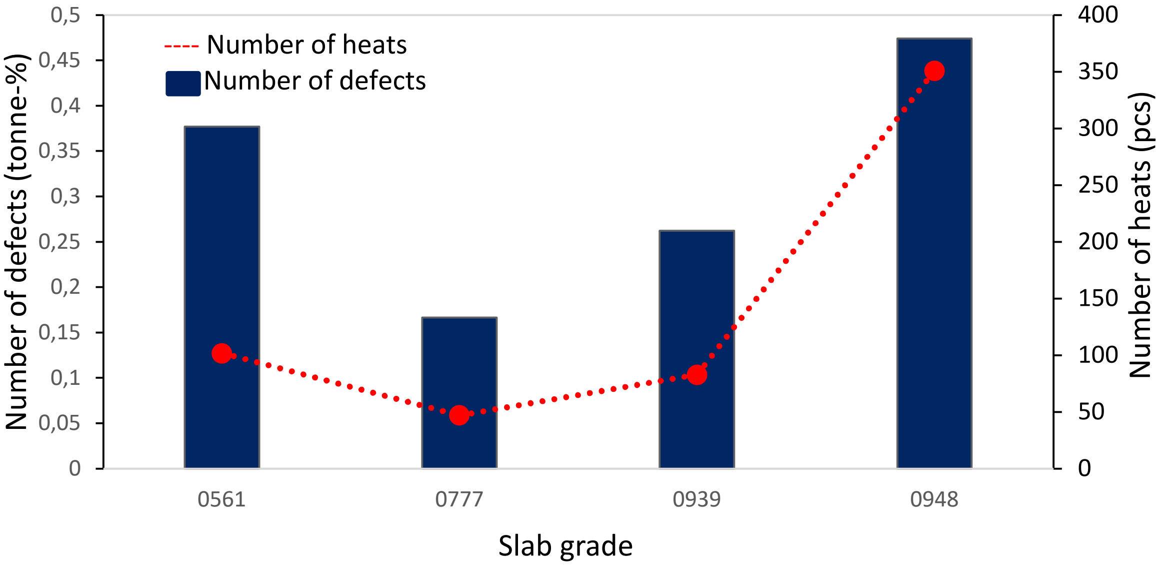

Figure 10. Transverse cracks in slabs and transversal crack defect in plates per casted tonne of steel for casting thickness 210 mm.

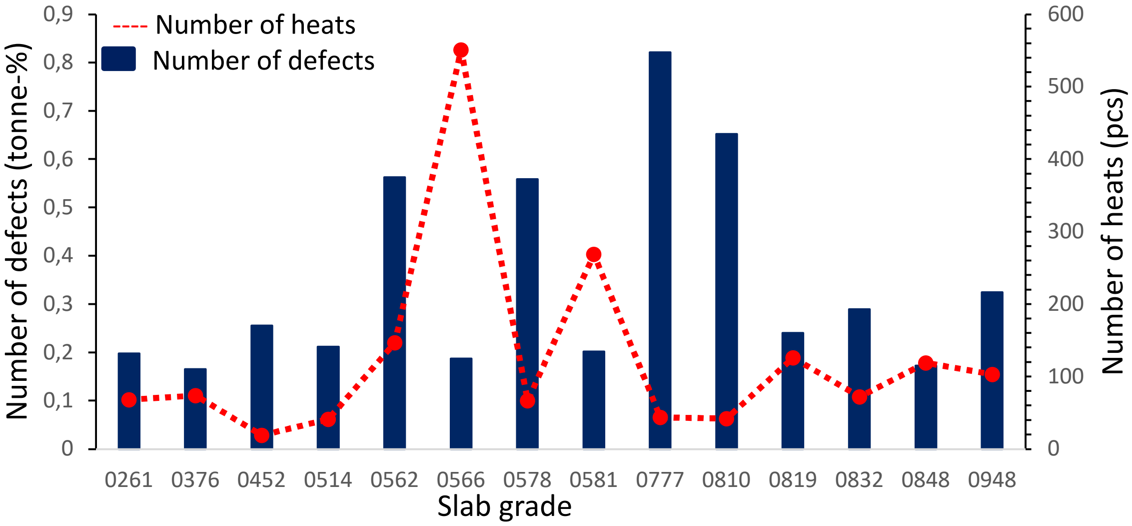

Figure 11. Transverse cracks in slabs and transversal crack defect in plates per casted tonne of steel for casting thickness 270 mm.

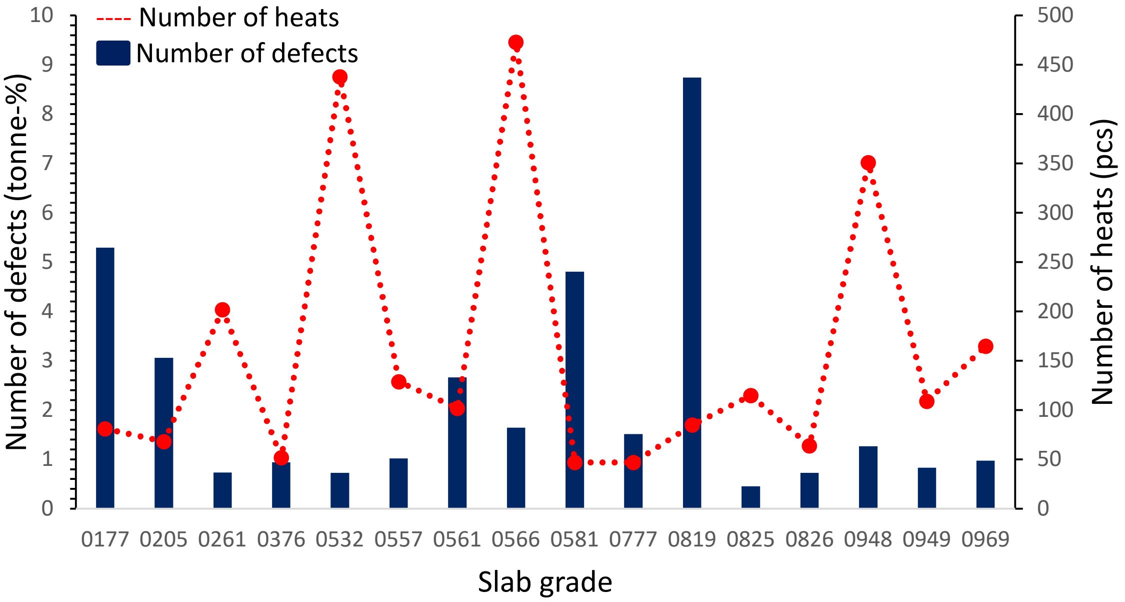

Figure 12. Slag defects in slabs and slivers in plates per casted tonne of steel for casting thickness 210 mm.

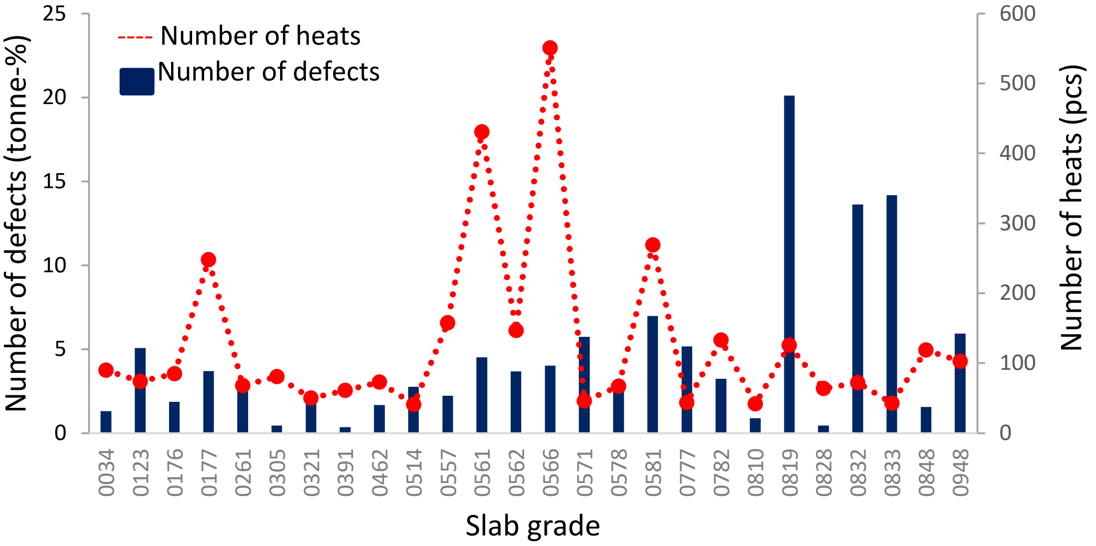

Figure 13. Slag defects in slabs and sliver in plates per casted tonne of steel for casting thickness 270 mm.

Slab grades 0193 and 0627 are special in that some of the customers are particularly demanding with regard to product quality. This resulted in the need to inspect the coils more precisely than normal. This data was analysed and is presented in Figure 14. Defects that could indicate casting powder malfunctioning are represented by red columns and blue columns represent the total amount of coils inspected. The data shows that the product might have a high number of casting powder-related defects. Still, it is important to keep in mind that these coils were subjected to close inspection, where also harmless defects were reported among the crucial ones.

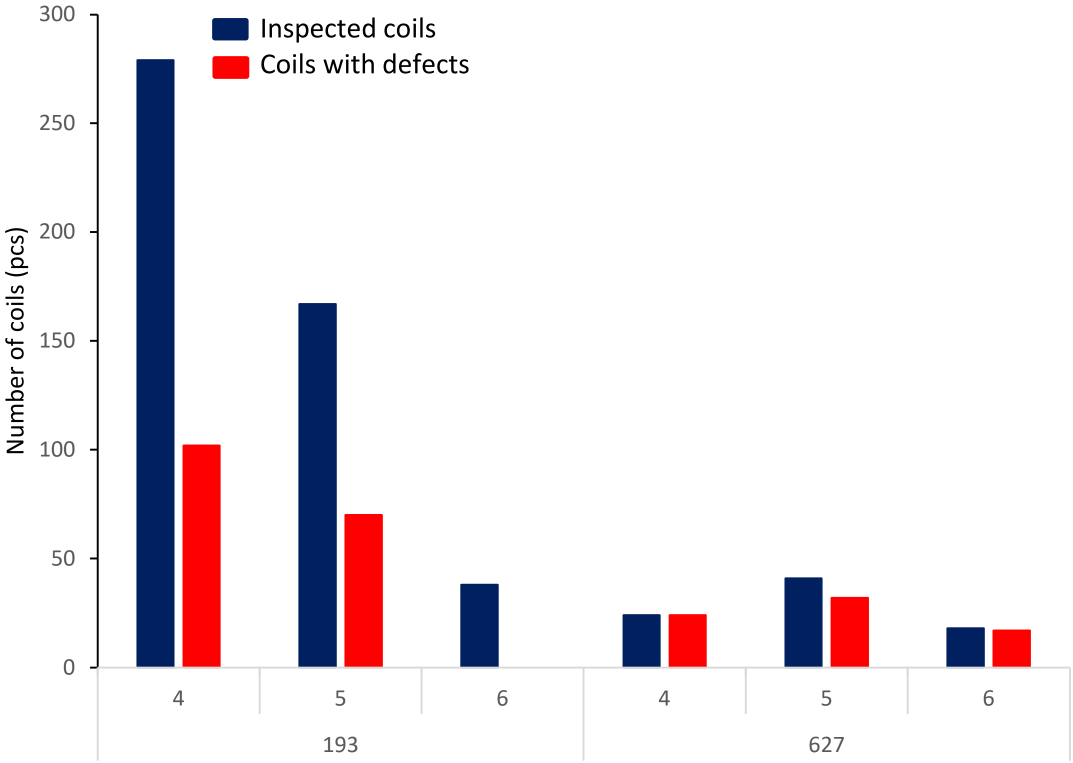

Figure 14. Slag and sliver defects in inspected strips.

5.1.4 Calculation of CP and FP values for all slab grades

CP and FP values are strongly linked since calculating FP first requires calculating CP. FP calculation is used as the main rule for casting powder selection in Luleå and as a minor part in Oxelösund. In addition, the literature widely recommends FP to be used when classifying slab grades as peritectic and non-peritectic as presented in chapter 3.

Many different equations have been proposed for calculation of CP and FP values. Three equations with slight differences were used in the calculation of CP and FP values for all of Raahe steel mill's slab grades in this thesis. Results of the calculated values with alternative methods are really close to each other and resulted in almost identical classification of slab grades.

As presented in chapter 2, alloying elements undoubtedly impact steel solidification and CP and FP are used in some of SSAB’s other steel mills. Thus, the decision was made to classify slab grades in casting powder tests based on FP. More precisely, Equation 14 presented in chapter 3 will be used to support this classification.

5.1.5 Required powder consumption and required T_{br} calculations

As presented in chapter 3.5.1 it is at least theoretically possible to choose a casting powder by calculating its required powder consumption and required powder properties. To be able to use this method, data that contains all necessary input variables were gathered from the time period 1.1.2021 – 1.10.2021. After the data was formatted, Equations 13 – 18 were used to get the classification values for slab grades. The first major problem with this method was the number of possible combinations (2639) and thus the system would be complex. Second, a more severe problem is inaccuracy of equations, which resulted in inaccurate T_{br} values for the casting powders. As a result, this method was only used in backing up the FP methods and giving guidelines for generally suitable Tbr values.

5.2 Comparison between different rules for casting powder selection

All four steel mills have their own way of choosing the right casting powder for the slab grade. The most basic way of just going with the suppliers’ recommendations and running testing period is used in all the steel mills reviewed in this thesis. This is a common practice when a new casting powder is needed due new slab grade specifications, environmental reasons, or work safety reasons.

When comparing Raahe’s casting powder selection rules to the literature and the company’s other factories rule sets, CP and FP calculation show the most potential to for use in testing and developing casting powder rules. These calculations are in use at Luleå and partially used in Oxelösund. In addition, the literature widely backed the usage of FP and CP calculations. Other differences when comparing Raahe’s rules to other steel mills and literature were extensive testing, little movements of the iron-carbon phase diagram reference values and comparing the casting parameters to existing slab grades. Extensive testing would probably result in selection of the best casting powder, but costs and time limitation would not allow that. In addition, idea of this work was to get clear rules, not randomly test things. Comparison between new and old slab grade casting parameters and components could lead to moderate results, but the rule system would become more complex, and this kind of method would result in many exceptions and really complicate the rule system, which is not desirable.

6 CASTING POWDER TESTS

To ensure that ferritic potential and carbon potential calculations can be used in casting powder selection in Raahe, some tests were done during the test period 16.11.2021 – 17.1.2022. The main purpose of these industrial tests is to provide a basis for future testing and development.

6.1 Casting tests

In this study, the actual test castings were performed in CCM4, CCM5 and CCM6, when allowed by normal production scheduling. The main purpose in the tests was to find if better slab quality could be achieved by using different rules for casting powder selection. Changes in the starting and main casting powders for selected slab grades were applied by changing the used powders in the NEUVO information system. The test period started 16.11.2021 and was ended 17.1.2022. Monitoring the test sequences was necessary to ensure that slab quality would not decrease, and process problems would not emerge.

CP and FP calculations discussed in 3.4.3 and 3.4.4 were chosen to be used in re-classifying slab grades. These values were calculated for all strip and plate grades. Most grades ended up with the same classification as before, but those with different classifications were chosen for further inspections.

The slab grades were selected for tests according to certain conditions. The first condition was that a specific grade should have process disturbances or slab defects in a significant number of heats. The other conditions were: FP calculation would indicate that an alternative casting powder would be better or Luleå carbon limits would result in different classification, historical production amounts are large enough (at least 24 heats per year), slab grade does not require a special casting powder due to its composition or the composition is not a known reason for defect or process problems. Slab grades 0825, 0826 and 0969 were chosen for testing, even though no major problems were detected before the tests. This was done to get more test heats and better proof of the method’s suitability. The tests carried out are presented in Tables 13 and 14.

Table 13. Casting powders tests for CCM 4 & 5.

Grade	FP	Reason for the change	Thickness (mm)	Original starting powder	Test starting powder	Original main powder	Test main powder
0216	0.985	FP	210	RA1	RA2	RA4	RA5
0627	0.985	FP	210	RA1	RA2	RA4	RA5
0628	0.978	FP	210	RA1	RA2	RA4	RA5
0891	1.23	FP	210	RA2	RA1	RA5	RA4

Table 14. Casting powders tests for CCM 6.

Grade	FP	Reason for the change	Thickness (mm)	Original starting powder	Test starting powder	Original main powder	Test main powder
0177	0.875	FP	210	RA2	RA1	RA5	RA7
0825	0.89	FP	210	RA2	RA1	RA5	RA7
0826	0.87	FP	210	RA2	RA1	RA5	RA7
0969	0.78	FP	210	RA2	RA1	RA5	RA7
0891	1.23	FP	210	RA2	RA1	RA5	RA7

Along with the tests in Tables 13 and 14, starting powder tests were planned for slab grades 0832 and 0833. The need for these tests exists because both grades have a significant amount of slag defects and corresponding plate defects as can be seen from Figure 13 in Chapter 5. FP calculation also supports the usage of a peritectic starting powder. Defects found in these specific grades are usually found in the first two slabs and only the main casting powder RA6 is suitable for a thickness of 270 mm. So, no changes to the main casting powder were made. Normally RA1 and RA6 powders are never used together but according to their data sheet values and T_{br} calculations these powders should be compatible. The starting powder tests are given in Table 15.

Table 15. Starting powder tests for CCM 6.

Grade	FP	Thickness (mm)	Original starting powder	Test starting powder	Main powder
0832	1.014	270	RA1	RA2	RA6
0833	1.024	270	RA1	RA2	RA6

7 RESULTS AND DISCUSSION

In this chapter, the results of the test period are presented and discussed. The results are presented first in section 7.1 and discussed in the context of three categories: defects, process disturbances and process data analysis.

7.1 Results

The testing period results are presented and reviewed in this chapter. Table 16 presents important process values for casting powder tests. The number of heats is quite low for most grades. On the other hand, relatively few slabs had casting powder-related defects.

Table 16. Production and observed defects during the test period.

Grade	Type	Casting widths (mm)	Casting speeds (m/min)	Heats	Slabs	Slab defects	Plate defects	Reclamation
0177	K	1850	1.02–1.14	8	42	1	8	0
0216	N	1250–1425	1.6–	3	17	N/A	N/A	0
0627	N	1300–1550	1.23–1.6	33	160	N/A	N/A	2
0628	N	1400–1625	1.34–1.56	8	53	N/A	N/A	0
0825	K	1850	1.12–1.19	14	61	1	0	0
0826	K	1850	1.12–1.19	17	70	0	0	0
0832	K	1975	0.85	3	6	1	5	0
0833	K	1975	0.85	2	4	1	0	0
0891	N	1275–1875	1.24–1.7	53	268	N/A	N/A	0
0969	K	1825–1875	1.13–1.19	25	96	0	0	0

K = plate grade, N = strip grade

Table 17 presents casting disturbance analysis results. In this table, disturbances 40, 96, 97 and 98 are presented for the testing and reference periods. Disturbance 40 is important because it gives information about uneven or malfunctioning lubrication, but in some cases the NEUVO information system does not record it due to other previous disturbances. Thus, disturbance data for disturbance 40 was collected manually from the DNA database to make sure the data was correct. Disturbances 96, 97 and 98 are correct in the NEUVO information system and not as important as in 40. So, they can be analysed together.

Dynamic surface-level fluctuation (casting disturbance 97) is defined in automation as at least four surface-level fluctuations of over 5 mm in CCM5 and CCM6 or at least four surface-level fluctuations of over 7 mm for CCM6 within 120 s. Dynamic surface-level fluctuation is linked to insufficient lubrication, which causes changing of friction in the mould and therefore can cause this disturbance.

Spontaneous opening of the SEN (casting disturbance 96) is defined in the automation system as a 4 – 29.9 mm change of mould level within 2 s time, while automatic control of the mould level is on and casting disturbance 97 is not detected. From the casting powder performance viewpoint, this disturbance is useful because it indicates if the mould level is not constant and therefore the possible defects are not caused by the casting powder.

Extra cooling water activation by the operator triggers casting disturbance 98. Extra cooling waters are generally applied if the mould level fluctuates for an extended period. Since this disturbance is activated only if the operator manually applies extra cooling, it only indicates that something is clearly wrong. No exact reason is available, and in practice the need for extra cooling depends strongly on operator opinion. Still when this disturbance is recorded, it gives valuable information for visual inspections of casting parameters.

Table 17. Fractions of heats having casting disturbances in reference and test periods. All numbers are in percentages.

Grade	Casting disturbance							
	40	40*	97	97*	96	96*	98	98*
0177	0.91	0	1.23	37.5	8.64	75.0	0	0
0216	5.63	33.3	28.17	66.66	1.40	33.33	0	0
0627	2.43	0	26.2	18.18	3.57	3.03	2.4	0
0628	0	0	20.51	25	5.12	0	0	0
0825	0	0	0	0	1.73	14.28	0	0
0826	0	0	0	11.76	0	11.76	0	0
0832	0	0	0	0	2.77	0	0	0
0833	0	0	0	0	0	0	0	0
0891	5.58	0	20.18	16.98	21.76	15.09	0	0
0969	0	0	0	0	0.57	0	0	0

* Test period value

The percentage amount of casting powder-related defects per casted tonne of steel in the test period and reference period are presented in Table 18. In this table, the defect amounts are presented only for the K type test slab grades, where the columns labelled 1 to 6 are the defect types in the following order: transverse cracks in slabs and transversal crack defect in plates for casting thickness 210 mm (1), transverse cracks in slabs and transversal crack defect in plates for casting thickness 270 mm (2), slag defects in slabs and slivers in plates for casting thickness 210 mm (3), slag defects in slabs and slivers in plates for casting thickness 270 mm (4), longitudinal cracks and plate crack 210 mm (5) and longitudinal cracks and plate crack 270 mm (6).

Table 18. Fractions of heats having casting powder-related defects in reference and test periods. All numbers are in percentages.

Grade	Defect											
	1	1*	2	2*	3	3*	4	4*	5	5*	6	6*
0177	0.13	0.74	0	0	5.29	2.56	0		0	0	0	0
0832	0	0	0.28	0	0	0	13.62	6.87	0	0	1.20	0
0833	0	0	0	0	0	0	14.16	12.35	0	0	1.51	0
0825	0.05	0	0	0	0.45	0	0	0	0	0.17	0	0
0826	0	0	0	0	0.72	0	0	0	0	0	0	0
0969	0	0	0	0	0.97	0	0	0	0	0	0	0

* Test period value

7.2 Process variable analysis

Process variable analysis is divided into a visual and calculative part. in visual part parameters were plotted with Aspen software. Figure 15 presents the observed process variables as a function of time. Figure 16 presents the used scaling for the thermocouples used in visual examination. Visual examinations were performed for all test heats but only example pictures are presented in these results due to the large total amount of heats. The used time was 2 h 30 min for every picture. Appendix 3 has larger pictures of these example cases to improve clarity.

The main process variables in Figure 15 are heat transfer, stopper rod position, and mould level. Heat transfer is the red curve. It shows the amount of heat transferred from the mould to the cooling water. Heat transfer depends on casting speed, steel temperature and used type of casting powder. Stopper rod position is the light blue curve. This process variable simply shows in percentages the position of the rod. The dark blue curve is the mould level. Variations in mould level influence the lubrication. This is due to the bulging phenomena happening when mould levels vary. It is also not desired to have changes in mould level in a short time period. Visual analysis aims to find out if the observed deviation in variables increase or decrease due to the casting powder changes. Other variables in Figures 15 are the width of the mould (black), casting speed (green) and casted length of the heat (grey). Mould width and casting speed are used in visual analysis to explain unexpected variations in chosen key process variables. They also are used to find the right spot for calculating values. In addition, casted length of the heat is only used to find specific heat or slab from a sequence.

Thermocouple values are plotted in Figure 16. Thermocouples are located horizontally in the upper and lower rows in the mould. When analysing the curves visually in a similar sense as with other variables, the standard deviation for each thermocouple should be low but also the upper and lower thermocouples should not approach each other because it is a clear indicator of possible sticking of steel due to insufficient lubrication. In general, their difference should stay the same if no changes in other parameters are made. Especially the upper row indicates how the lubrication is working. If the value of adjacent couples is close together and no quick changes in their values can be noticed, the lubrication is working well. Other variables are the same as in Figure 15.

In the calculative part of process parameter analysis, the average and standard deviation (SD) were calculated to heat transfer (HT), stopper rod position (SP), mould surface level (ML) and thermocouple elements (TC) for all test period heats and selected reference period heats. The usefulness of these values is questionable due to changes in casting speed and steel temperature. Thus, most attention is focused on the defected slabs of the test period.

To evaluate the possibilities of linking defects to casting parameters, calculations were done in five parts. First, values for parameters were calculated for the defected slabs. Second, the same calculation was done for the slab casted just before the defected slab. The third step was to calculate parameters for good casting with the new powder and lastly for the reference slab casted with the old powder. To keep these values comparable, the values are calculated for each case in a way that casting speed, width and steel temperature are approximately the same, if possible.

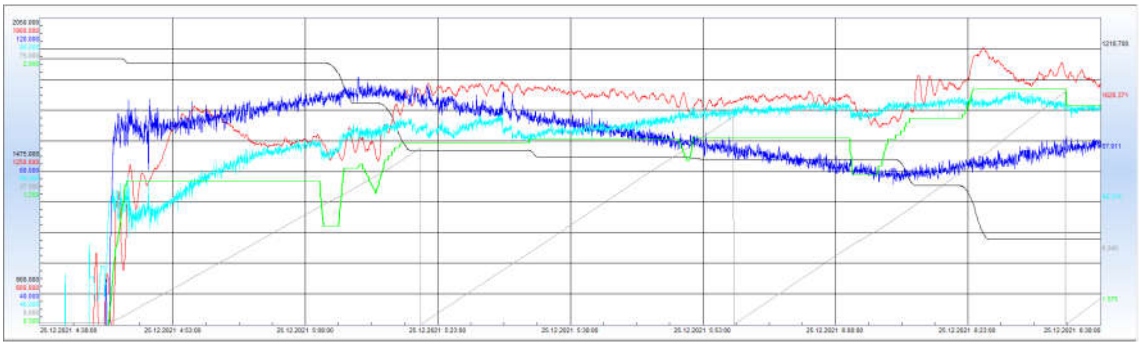

Figure 15. Aspen process variables example CCM 6 (slab grade 0891 heats 87370, 87374 and 87375).

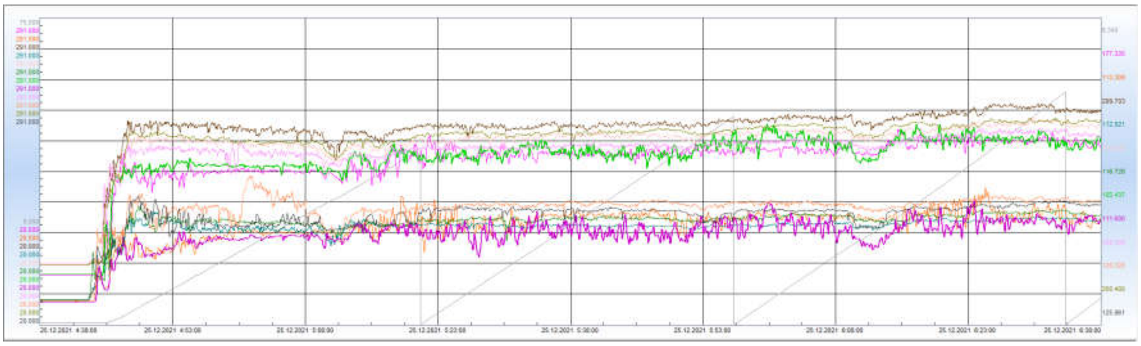

Figure 16. Aspen thermocouple example CCM 6 slab grade 0891 heats 87370, 87374 and 87375).

7.3 Discussion of results

All results are reviewed separately below but in the same way with the expectation that no defect data is available for strip-type slab grades (N). First, the defects' percentages, which are the most important results, are discussed in general. All test sequences were analysed visually and based on the process variable values calculated. The calculative values for each process variable are presented in Appendix 1. If the casting process proceeds ideally, the deviation in the process variable is low and their values are quite close to each other. To get information from a possible link between the process parameters and casting powder-related defects, the parameters were calculated for all detected defects. To get a reference point, the calculations were made for five different sections, which are whole heat, defected slab, slab before defect (RP1), slab from other heat with new powder (RP2) and slab from old heat with original powder (RP3). The aim was to see if any correlation between defects and parameters can be found and to see whether these calculations are suitable for casting powder evaluation.

7.3.1 Grade 0177 (K)

As presented in Table 14, slab grade 0177's starting powder and main casting powder were changed from peritectic to non-peritectic for the testing period. The grade fulfilled the chosen requirements to be tested due to the following reasons: it had a different classification according to Luleå's selection rules, production volume in the reference period (81 heats), relatively large amounts of casting disruptions (see Table 17), transversal cracks and relatively common slag defects (Table 18). In the actual testing period, 8 heats were cast in sequences (88007, 88265 and 88538).

The test period had a 0.6 percentage point increase in transversal cracking per casted tonne of steel but a decrease of 2.7 percentage points of slag defects in the first two casted slabs. Disruptions increased markedly as can been seen from Table 17. Sequence 88265 was the only one without any disruptions. On the other hand, sequences 88007 and 88538 had several disruptions.

Visual analysis of process parameter graphs reveals a quite large fluctuation in SP and ML for the whole sequence 88007, when compared to the reference period's graphs. HT had a relatively stable graph during the parts of the sequence where no changes to CS were made. TC graphs indicated more variation, but no approaching of TC pairs could be detected. Fluctuation can be explained for this sequence by problems in secondary metallurgy, which resulted increased waiting time in CCM6 and required changes to CS. In addition, both ladles had to be lanced open and the first one twice. Sequence 88265 had no major problems in any casting parameters and all graphs looked relatively good. Sequence 88538 had variation in SP and ML in the last three heats but no clear reason for these fluctuations could be tracked. Casting disturbance 96 was active during the last three heats, so it is quite likely that some problems with the stopper rod were present.

Casting powder change increased the average value of HT about 100 kW/m^2 and standard deviation doubled when compared to only good reference sequences. Standard deviation values of SP and ML increased slightly. Calculated average temperatures increased for all TCs but the increase was larger for the upper than lower rings. Calculated standard deviation for TC elements increased in the test period.

CASE 1.1

The first defect of heat 87786 was slag defect and was found on the first slab of the heat. According to composition analysis, the amount of Al was slightly high but otherwise composition was at the correct level. There were no disturbances during the heat and the casting parameter graphs looked normal. CS was increased during casting of the first slab, which causes fluctuations in HT. Steel temperature was 16 degrees over the suggested value. Figure 17 shows the values and standard deviations of the chosen indication parameters. Defect columns have higher SDs than the reference points for HT, SP ML and TC. As a conclusion for case 1.1, several factors are clearly affecting slag defect formation, but these kinds of defects are typically found in the first and second slabs of the first heat and no singular variable is causing this defect.

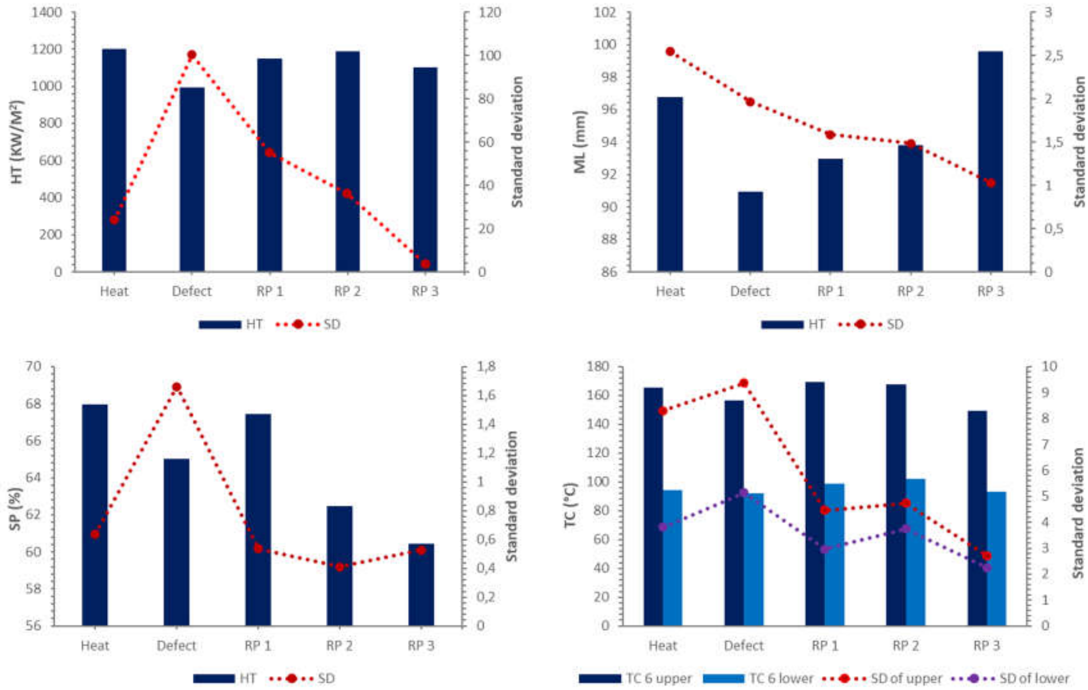

Figure 17. HT, SP, ML and TC 6 and their standard deviation. Slag defect case (1.1) in heat 87786.

CASE 1.2

The second defect of heat 87786 was a sliver defect found on a rolled plate from the fourth slab of the heat. The heat had only one disturbance, disturbance 96 in the fifth slab. Process parameter graphs had significant fluctuations on all chosen indicator parameters. To make thing even worse, the CS was decreased during casting of the slab, which causes fluctuations to increase even more. Steel temperature was 16 °C over the target value. Figures for the indicator parameters are presented in Appendix 2. They show that the SD of the chosen indication parameters gets high values for all the parameters other than ML. As a conclusion for case 1.2, the sliver happened due to over-temperature, the grade's relatively high amount of Nb and quick change in CS and malfunctioning of the casting powder.

CASE 1.3

The first defect of heat 87790 was a sliver found on a milled plate from the third slab of the heat. According to composition analysis, the amount of Al was slightly high but otherwise composition was at the correct level. The slab had several disruptions (96). Figures for the indicator parameters are presented in Appendix 2. Indicator parameters unexpectedly showed lowering of the SD for all parameters. Simultaneously, the actual values stayed in the right area. Steels temperature was 11 degrees over the guide value. As a conclusion for case 1.3, several factors are clearly affecting sliver formation and casting powder is one of them.

Conclusion for grade 0177

When considering all the information concluded in chapter 7.2.1 it is obvious that the casting powder change was not beneficial for this grade and caused more defects and de-stabilized the casting process. Casting powders should be changed back to the former ones. Still, change could be retried, with changes in oscillation and cooling practices.

7.3.2 Grade 0216 (N)

Slab grade 0216's starting powder and main casting powder were changed from non-peritectic to peritectic for the testing period (Table 13). The grade fulfilled the requirements to be chosen for testing due to the following reasons: it is a peritectic slab grade according FP calculation, production volume during the reference period of 71 heats and relatively many casting disruptions 40, 96, 97 (Table 17). In the actual testing period only 3 heats were cast in sequence 88376, this means that the results for this grade are only indicative and further inspections are required to form any trustworthy conclusions.

Disruptions values presented in Table 17 seem extremely high, but these disruptions are not active for very long. The low number of heats also quickly increases the percentage values and no quick conclusions should be made based on these results.

Visual analysis of the only test sequence for this slab grade indicated the expected lower HT and lower temperatures in all TC. SP and ML both have fluctuations in the test period and reference period, but the intensity stays the same. Larger fluctuations in the process parameters were caused by reductions of mould width and slowing CS. In addition, no clear indications of the mould powder's poor performance are present.

Casting powder change decreased the average values of HT and standard deviation lowered slightly when comparing only good reference sequences. Standard deviation values of SP and ML increased slightly. Calculated average temperatures decreased for all TCs. Calculated standard deviation for TC elements stayed about the same.

Conclusion for grade 0216

Results indicated that more testing should be done for slab grade 0216, due to the following: only one sequence was casted in the test period; visual and calculative analysis showed that peritectic casting powder would probably work for the grade.

7.3.3 Grade 0627 (N)

Slab grade 0627's starting powder and main casting powder were changed from non-peritectic to peritectic for the testing period (Table 13). Slab grade 0627 was chosen due to it is peritectic qualities according to FP calculation, production volume in reference period is high enough (84 heats) and relatively large amounts of casting disruptions 40, 96, 97 and 98 are present during the reference period (Table 17). In the actual testing period, 33 heats were cast in sequence (87838, 87966, 88034, 88376, 88504, 88604, 88613, 88627, 88629 and 88712).

It can be seen from Table 17 that the amount of casting disruptions present for slab grade 0627 have decreased significantly, when comparing reference and test periods values. The most positive result is that disturbance 40 has not occurred even once during the test period.

In general, visual analysis of the process parameter graphs showed expected lowering of HT and simultaneously temperatures measured for TCs were lower than in the reference. Fluctuation in SP and ML were in most cases less than in the reference. No clear indicators of separation of adjacent TCs could be detected.

Process parameter graphs of test series 87966, 88034 and 88376 indicated that the casting process had problems. Sequences for 87966 had relatively high fluctuations in the ML curve and slightly more fluctuations in SP than other test sequences. The TC graphs still looked normal, and the sequence only had one reported problem, which was waiting for the ladle. This caused a need for slowing down the CS, but the intensity of SP fluctuation did not change. Most likely the problems with this sequence are related to the stopper rod itself and not caused by the casting powder. Sequence 88034 had fluctuations in ML and SP for first ladle and especially at the beginning. The shapes of TC graphs do not indicate any casting powder-related problems. SP values drop twice as fast compared to normal. The sequence used tested the stopper rod, which explains partially the fluctuations. The last sequence that had noticeable deviation in process parameter curves was 88376. ML had a significant variance in the beginning of the first ladle and simultaneously the TC curves started to approach each other. Steel temperatures were a little low for the sequence but its unlikely that these caused this kind of problem. No certain reason could be determined for fluctuations.

Casting powder change decreased the average values of HT and standard deviation lowered when comparing only good reference sequences. Standard deviation values of SP decreased during the test period. ML’s calculated standard deviation values stayed approximately the same. Calculated average temperatures decreased for all TCs and standard deviation for TC elements lowered slightly.

CASE 5.1

The first reclamation for slab grade 0627 was due to a crack in the coil. The corresponding slab from which the coil was made is the first slab of heats 87684. Composition of the heat was correct according to the analysis and temperature was at the correct level if measuring error is considered. Figures for the indicator parameters are presented in Appendix 2. SDs of indicator parameters are low and their actual values are at a good level. HT and ML curves are stable during casting, while SP values have fluctuations. TC curves also are quite stable. The sequence used to test the stopper rod and Ar gas flow was not stable or at the correct level. Narrowing of the steel strand and change of CS is done during casting of defected slabs. Defect occurrence is explained by the test stopper rod. Casting powder change did not affect this defect formation.

CASE 5.2

The second reclamation for slab grade 0627 was also a crack in the coil. The corresponding slab from which the coil was made was the first slab of heat 88121. Composition of the heat was correct according to the analysis. Temperature was 12 degrees over the target value, which resulted in lowering of CS for the slab casted before the defected. Figures for the indicator parameters are presented in Appendix 2. These graphs show that the SD of indicators is low and their actual values are at a good level. The HT curve in the visual analysis of the Aspen graphs shows a spike during casting of the defected slab. Other indicator curves had a good shape. Defects occurring is explained by Ar gas flow values, which indicate minor blockage in SEN. Casting powder change did not affect this defect formation.

Conclusion for grade 0627

Results indicated that peritectic casting powder is suitable for grade 0627, due to the following: significant decrease in all disruptions; calculative analysis showed lowering of SD for all indicator parameters; visual analysis showed a positive change in indicator parameter curves.

7.3.4 Grade 0628 (N)

Slab grades 0628 starting powder and main casting powder were changed from non-peritectic to peritectic for the testing period (Table 13). Slab grade 0628 was chosen due to it is peritectic slab grade according FP calculation, production volume in reference period is high enough (78 heats), relatively high amounts of casting disruptions (96 and 97; Table 17). In the actual testing period, 8 heats were cast in sequences 87956, 88466, 88545.

Results in Table 17 indicate that the amount of casting disturbance 96 for slab grade 0628 has decreased, but the amount of disturbance 97 had increased slightly, when comparing reference and test period values.

In general, visual analysis of the process parameter graphs showed expected lowering of HT and simultaneously temperatures measured from upper thermal elements were lower than in the reference. Fluctuations in SP and ML were in most cases at the same level as in the reference. No clear indicators about separation of adjacent TCs could be detected and the general shape of TC curves looked fine. ML had fluctuations in the beginning of each sequence, but this is quite typical for this slab grade when compared to the reference sequences. The only sequence with clear increases in variance was 87956. Fluctuations in ML start at the beginning of casting. Normally these fluctuations tune down halfway through the first heat, but this does not happen in this sequence. No exact reason could be tracked for this.

Casting powder change lowered the average values of HT and standard deviation lowered when comparing only to good reference sequences. ML's calculated standard deviation values increased slightly. Standard deviation values of SP decreased slightly during the test period. Calculated average values of TCs decreased for all TCs and standard deviation for TC elements stayed at the same level.

Conclusion for grade 0628

Results indicated that peritectic casting powder is suitable for grade 0628 due to the following: Total number of disruptions lowered; calculative analysis showed lowering of SD for most indicator parameters; visual analysis showed positive change in process parameter curves.

7.3.5 Grade 0825 (K)

As presented in Table 14, slab grade 0825's starting powder and main casting powder were changed from peritectic to non-peritectic for the testing period. Grade fulfilled the testing requirements due to the following reasons: it had production volume of 115 heats in reference period; different classification according Luleå's selection rules; transversal cracks and slag defects occur (Table 18). In the actual testing period, 14 heats were cast in sequences 88011, 88243, 88259, 88371 and 88590. This means that the results for this grade are only indicative and further inspections are required.

No transversal cracking or slag defects were detected during the test period. A very small amount of longitudinal cracking was detected during the test period. Only 0.2% of the whole production of this grade during the test period had longitudinal cracking. Only processes disturbance 96 is present in reference and test period. The percentage number of heats with disturbance 96 is quite high but it is active only for three slabs.

The process parameter values appeared normal in the graphs for all sequences when compared to the references sequences. Minor fluctuations were present in the last heats of sequences 88243 and 88259 for SP and ML.

Casting powder change increased calculated average values of HT and its SD slightly increased but it became more constant between sequences. SD for casting parameter SP and ML are low in both reference sequences and in the actual testing sequences. Minor increases in both values can still be observed. Values for TC are increased in the testing period, but SD stays about the same.

CASE 2.1

The only defect reported during the test period for the slab grade 0825 was a crack on plate 11, which was milled from the fourth slab of heat 86900. Alloying of the heat was successful according to composition analysis and the temperature of the steel was inside the margin of error. Casting disturbance 96 was present during casting the second and third slabs of the sequence. Visual analysis of process parameters showed significant increase in SP and ML fluctuation at the end of the sequence. Figures for indicator parameters are presented in Appendix 2. SD values for all indicator parameters have a clear spike at the point where the slab with defects is casted. The root cause of the found defect in the plate was tracked to longitudinal cracking in the slab. The lowering of HT and the fluctuation in process parameters are most likely the reasons for the defect. Additionally, the slab was also the last slab of the sequence and the defects are more likely to occur in first and last slabs of sequences.

Conclusion for grade 0825

Defect amounts decreased during testing of the slab grade. On the other hand, the number of disruptions increased but they were present in the heat. If the slabs with huge amounts of disruptions are excluded, disturbance amounts remain the same as in the reference. Results indicated that using non-peritectic powders for grade 0825 could be beneficial.

7.3.6 Grade 0826 (K)

As presented in Table 14, slab grade 0826's starting powder and main casting powder were changed from peritectic to non-peritectic for the testing period. Grade fulfilled the requirements to testing due to the following reasons: it had a production volume during the reference period of 64 heats, a different classification according Luleå's selection rules and slag defects occur (Table 18). In the actual testing period, 17 heats were cast for sequences 88011, 88243, 88259, 88371 and 88590.

Slag defect amount decreased from 0.7% to 0% during the test period, but the amount of defected steel was quite low even before the testing period. Process disruptions 96 and 97 increased by 11.8% during the test period. The disturbance 96 is present only for the ending of longer casting sequences if three or more heats were cast. Each time a disturbance occurred in the test sequences, first variation of SP starts to increase slowly and then MV starts to also become unstable. This indicates poor performance of the stopper rod, which will lead to mould level fluctuations in longer sequences.

Visual analysis showed the expected increase of HT in all sequences. The general behaviour of ML and SP was quite like the references process parameter graphs. In the ending of test sequences 88223, 88238 and 88620, more fluctuations happened in ML and SP. Still, this happened only for the end of the last heat in longer casting sequences and is not present in shorter sequences like 87964, whose graphs were clearly better than the reference graphs. This indicates that slab grade 0826 is not suitable for longer casting sequences.

Casting powder change increased calculated average values of HT. SDs for casting parameters SP and ML are low in both reference sequences and in the actual testing sequences. Values of TC are increased during the testing period, but their SD stays about the same.

Conclusion for grade 0826

Defect amounts decreased during testing for the slab grade, but only slightly. On the other hand, the number of disruptions increased but they were present only for the last slabs of the sequences. Calculated indicator values did not indicate incompatibility of the casting powder either. As a result, a casting powder tests should be continued and re-evaluated when more test sequences have been cast.

7.3.7 Grade 0832 (K)

As presented in Table 14, slab grade 0832's starting powder was changed from non-peritectic to peritectic for the testing period. Grade fulfilled the requirements to be chosen for the testing grade due to the following reasons: FP calculation indicates that grade is strongly peritectic and therefore lower heat transfer powder would be beneficial, production volume in the reference period of 72 heats, relatively high amounts of casting disturbance 96 (Table 17) and slag defects relatively common for the first two slabs of the sequence (Table 18). In the actual testing period, 8 heats were casted in sequences 88074, 88496 and 88813, but because the starting powder is used only for first heat of each sequence and generally it affects only the first two slabs of the beginning of each sequence, evaluations of test sequences consider only the first and second slabs of the first heat.

The amount of slag defect decreased in the first two slabs of the sequence from 13.6% in the reference period to 6.9% in the test period and no transversal cracking or longitudinal cracking happened during test period. Disturbance 96 occurrence decreased from the reference periods 2.7% to 0%.

In visual analysis of process parameters, graphs for parameters SP and ML had slightly less deviation and stabilized more quickly. No significant difference in TC graphs could be detected in visual analysis. HT curve had an unusual drop in sequence 88496 at the point where the starting powder should be completely consumed and only the main casting powder should affect the HT. Other sequences did not have this drop.

Casting powder change lowered the average values of HT slightly, but as expected, the effects were small due to the starting powders' relatively short period of influence. Standard deviation of calculated values for casting parameters stayed at the same level when comparing only the good sequences. No major changes could be observed from these results.

CASE 3.1

The first defect of heat 88633 was slag defect found in the first slab. Additionally, plate 16 made from the first slab had slivers, which were caused by slag defect in the slab. Alloying of the heat was successful according to composition analysis and the temperature of the steel was at the correct level. No casting disruptions occurred during casting of the corresponding slab. Visual analysis of process parameter graphs showed typical fluctuations for all the inspected variables. The main difference when comparing to the reference was the lower HT during casting the first two slabs, which is caused by the starting powder change. Figures for indicator parameters are presented in Appendix 2. These figures indicate that the actual values of HT, SP and ML drop slightly, and SD increases for the slab that had defects. TC values stayed almost same but a slight increase occurred in their SD. Slag defects have been common for this grade and the reason for the occurrence of these defects is the grade's target composition combined with the effect of the casting starting.

CASE 3.2

Two slivers were found on plates 14 and 15 rolled from the second slab of heat 88633. Alloying of the heat was successful according to composition analysis and the temperature of the steel was at the correct level. No casting disruptions were present during casting of the corresponding slab. Visual analysis of process parameter graphs showed slightly more fluctuation for ML and SP and other parameter curves looked normal for inspected variables. Figures for indicator parameters are presented in Appendix 2. Only HT has significant differences; its SD is significantly higher than in the reference. Slag defects have been common for this grade and the reason for these defects occurring is the grade's target composition combined with the effect of the casting starting.

CASE 3.3

Sliver was found on plate 11 milled from the first slab of heat 87638. Alloying of the heat was successful according to composition analysis and the temperature of the steel was at the correct level, when taking the measurement error range into account. Several casting disruptions were present for the first and second slab. Process parameter graphs looked normal for all parameters except HT. HT had an unexpected drop during casting the slab.

Figures for indicator parameters are presented in the Appendix 2. These figures show an increase of SD for all the indicator parameters. The main reason for this defect was still traced to opening the ladle by lance. Additionally, slag defects and their corresponding plate defect are common for this grade.

CASE 3.4

The last defect found during the test period for slab grade 0832 was sliver in the plate 12 from the first slab of the heat 86313. Alloying of the heat was successful according to composition analysis but the temperature of the steel was 10 °C over target. No casting disruptions were present during casting of the corresponding slab. Visual analysis of the process parameter graphs indicated that nothing unusual happened. Figures for indicator parameters are presented in Appendix 2. SD values are high for all indicator parameters when comparing to the reference. As mentioned previously, slag defects have been common for this grade and the reason for occurrence of these defects is the grade's target composition combined with the effect of the casting starting.

Conclusion for grade 0832

Results indicated that using peritectic starting powder does reduce the amount of defect in total and no immediate problems arise from changing the starting powder. Still, it is important to note that the test period consisted of only 8 heats and 3 of these were the first of the sequences. More testing is needed to get the information necessary to make a conclusion. In light of the already obtained result, the casting powder change had no negative impact on total quality.

7.3.8 Grade 0833 (K)

Slab grade 0833's starting powder was changed from non-peritectic to peritectic for the testing period. This grade was chosen to be a test grade due to the following reasons: FP calculations indicated that the grade is strongly peritectic and therefore lower heat transfer powder would be beneficial, production volume in reference period was 43 heats, slag defects were relatively common for the two first slabs of the sequence (Table 18). In the actual testing period, 4 heats were casted (sequences 88493 and 88809). For the same reason as mentioned for slab grade 0832 only the first two slabs of the first heats were considered.

The amount of slag defect decreased in the first two slabs of the sequence from 14.2% in the reference period to 12.4% in the test period. In addition, no longitudinal cracking or transversal cracking occurred in the test period. Slab grade 0833 had no process disruptions, which was a notable result of this thesis.

In visual analysis of process parameters' graphs, parameters SP and ML behaved in a similar way as during the reference period. The HT curve did not increase as fast as in the reference and made the curve more stable looking. TC graphs had slightly less deviation in the beginning and the TC curves for lower elements were in a tighter group. Other process parameter looked very similar compared to references.

Casting powder change had a minor effect on the average values of HT, but as expected these changes were small due to the starting powders' relatively short period of influence. Standard deviation of HT for slab grade 0833 had huge deviations between heats in the reference and test periods. Commonly, the first heat's SD is much greater for all process parameters than the second ones. When considering the previous information, there is no clear change in calculated SD values happening due to the casting powder change.

CASE 4.1

The only defect reported during the test period for slab grade 0833 was slag defect in the first slab of heat 87630. Alloying of the heat was successful according to composition analysis, but the temperature of the steel was 9 °C over target. No casting disruptions were present during casting of the corresponding slab. Visual analysis of process parameters showed an unexpended drop of HT during casting of the corresponding slab. Figures for indicator parameters are presented in Appendix 2. SD values for all indicator parameters have a clear spike in the point where a slab with defects is casted. Composition of grade 0833 is really close to 0832 and it has also been typical for it to have slag defects in a similar sense. The root cause of the defect is composition and additionally start of casting also increases the probability of slag defect formation.

Conclusion for grade 0833

Results indicated that using a peritectic starting powder does reduce slightly the amount of defect. Still, it is important to notice that the test period consisted of only 4 heats and 2 of them were the first of the sequences. More testing is needed to get the information necessary to make conclusions. After the analysis, additional defect information was obtained and it shifted the defect amount back to a normal level. Starting powder change does not provide any benefit for this steel grade because slag defect still occur.

7.3.9 Grade 0891 (N)

As presented in Tables 13 & 14, slab grade 0891's starting powder and main casting powder were changed from peritectic to non-peritectic for the testing period. The test period for this grade had already started before this thesis, but the analysis part of the test was left to this work. Still, grade fulfilled the set requirements to be chosen for testing due to the following reasons: it had a production volume of 317 heats in the reference period, different classification according Luleå's selection rules and multiple sticker breakouts in a relatively short time window. In the actual testing period, 53 heats were cast consisting of sequences 85835, 886351, 86529, 86762, 87910, 88403, 88406 at CCM 6 and 86111, 86133, 86311, 86198, 86665, 86917, 87188, 87240, 87430, 87561, 87853, 88133 at CCM4 and CCM 5. Unlike other tests, tests regarding slab grade 0891 were done in all casting machines.

Slab grade 0891 had 2 breakouts in the reference period and 0 in the test period, which is a huge improvement. Casting disruptions 40, 96 and 97 were all quite common for the slab grade in the reference period. In the test period, percentage amount of casting with disturbance 40 was 0 and disruptions 96 and 97 were less common.

Visual analysis showed the expected increase of HT in all sequences. Simultaneously, the values of TCs increased. ML and SP behaviours are quite similar in the reference period and test period. In points where ML and SP clearly have a more unstable curve, the explanation is either a change in CS or MW. The largest fluctuations in TC curves happen when CS or MW are changed. It can still clearly be seen that the temperatures are more unstable.

Casting powder change increased the calculated average values of HT. SD values for slab grade 0891 are dispersed in both the reference and testing period for HT. SDs for casting parameters SP and ML are low in actual testing sequences and reference sequences. Values of TC are increased in the testing period, but their SDs are slightly less on average.

Conclusion for grade 0891

After casting powder change, no breakouts happened while casting slab grade 0891. Number of disruptions lowered significantly in the test period. Most importantly, disturbance 40 did not happen even once. Casting powder change has been beneficial for slab grade 0891.

7.3.10 Grade 0969 (K)

As presented in Table 14, slab grades 0969 starting powder and main casting powder were changed from peritectic to non-peritectic for the testing period. Grade was chosen for testing due to the following reasons: it had a production volume of 175 heats in the reference period, different classification according to Luleå's selection rules and slag defects present (Table 18). In the testing period, 25 heats were cast in sequences 87842, 88013, 88113, 88236, 88255, 88601, 88618, 88625 and 88732.

None of the 25 test heats contained any of the considered process disruptions, which means a lowering of 0.57 percentage points in occurrence of disturbance 96. Disruptions are and have been quite rare for this grade, which means that the testing sequence consisting of 25 heats is not likely enough to tell the whole truth. The amount of slag defect reduced from 0.9% of the total casted amount of steel in the reference to 0% in the test. These defect and disturbance amount results indicated that casting powder change improved the quality of the casted product.

On behalf of ML and SP, no noticeable difference could be detected in process parameter graphs. Generally, reference period graphs have very little variance, when excluding the beginning and ending of sequences. The same is also true for test period graphs. As expected, HT is increased due to casting powder change to non-peritectic powder. TC values also increased in all sequences. The fluctuations are at the same level in tests and references after the starting powder's effects fade away. Measured temperatures between TCs had greater differences in same ring at the beginning of heat than in reference.

Calculated values for indicator parameters show no increase in SD values. Major differences between test and reference periods are increased average values of TCs and increased value of HT.

Conclusion for grade 0969

Casting powder change improved slightly the quality of production. No defects happened during the testing period and no considered process disturbances were present. The amount of tests was not large enough, but results so far indicate improvement.

7.4 Sources of error

In any study it is important to track possible error factors and their causes and minimize them if possible. Factors that could cause errors in the results are considered separately for each different analysis type below.

Defects are registered to the system manually by operators working in the slab hall and rolling mill. According to the methods, every side of every slab should be inspected during transportation from the slab hall to the rolling mill. This data is quite trustworthy for plate slabs since they have a much more demanding quality vector in the quality modelling system. Therefore, these slabs are more likely to have a more strict refurbished class than strip slabs. It is still possible that not all defects are found or that the inspector inputs the wrong defect in the system.

The analysis performed for strip grades 0193 and 0627 has several problems. The analysis was based on inspection reports from the strip mill, which were instructed to be done with extreme precision. This resulted in a situation where even the smallest defect would place the coil in the defected category. Also, these inspections were done by several people and only for specific customers' coils. This resulted in a situation where the inspection did not cover all production and fluctuation in the severity rating of defects.

Process variable analysis was divided into two parts. The first part consists of visual analysis of deviation and a general shape of variable graphs in Aspen software. In this part, the main idea was to find clearly problematic parts of casting sequences by comparing test sequence graphs to reference period graphs. The second part consisted of a case type study of average values and variances of variables compared to reference period successful castings. Case type analyses were done for the defected heats only. In both process variable analysis parts, the selection of reference affects the conclusions. To mitigate the possible error caused by a poorly selected reference, several sequences were used as a reference and clearly bad sequences were left out from the reference. This way, the possible error will not happen in a positive direction.

Process parameters are generally collected with 1 Hz frequency and linear interpolation is used to fill the gaps between measurements or calculated values. The frequency is more than enough to keep data accurate and linear interpolation should not affect the results greatly, even though linear interpolation causes inaccuracy.

8 CONCLUSIONS AND FUTHER DEVELOPMENT

Casting powders have a key role in continuous casting of steel by affecting several mould phenomena and casting variables. Heat transfers and lubrication are most affected by casting powder and their optimal value is linked to the solidification route of the steel and thus on the chemical composition of the slab grade. Additionally, casting speed oscillation and dimensions of casted strand are important as well.

Casting powder selection rules in Raahe are strongly based on the iron-carbon phase diagram presented in chapter 2. Generally, this method works well when slab grades do not contain much alloying materials. Demand for special steels is rising and thus driving increasing production toward micro alloyed steels. This change, which began before this thesis, has been partially countered by using limit values for micro alloying. This way the change in solidification routes and low ductility zones was partially compensated.

Literature review recommended the possibility of using ferritic potential to classify steel grades in peritectic and non-peritectic grades, which is a common way of dividing steel grades. Survey research on casting powder selection rules and usage in other SSAB factories also indicated the same. Differences in casting powder selection are quite big between different sources, but ferritic potential calculation is commonly used in one form or another. Due to these facts, ferritic potential calculation was used in the tests to classify the slab grades as well as minor changes in carbon limit values.

Before tests, a present-state evaluation was necessary to find slab grades that could have casting powder-related defects or process disturbance. Data was gathered from SSAB's database, and based on the defect amounts and process disturbance, slab grades were chosen for further inspection. In these inspections, if the grade was classified differently according to test rules and none of the trim factors were met, grade was chosen for the test period. In total, 10 slab grades were chosen for the test period.

Table 19. Summarized results of the test period.

Grade	Type	Change	Disturbances total	Defects total	Result
0177	K	PER →NP	↑	↑	Negative
0216	N	NP →PER	↑	N/A	More tests*
0627	N	NP →PER	↓	N/A	Positive
0628	N	NP →PER	→	N/A	Positive*
0825	K	PER →NP	↑	↓	Positive*
0826	K	PER →NP	↑	↓	Positive*
0832	K	NP →PER	↓	↓	No change*
0833	K	NP →PER	→	↓	No change*
0891	N	PER →NP	↓	N/A	Positive
0969	K	PER →NP	↓	↓	Positive

* = indicative, K = plate, N = strip, PER = peritectic, NP = non-peritectic

Results in Table 19 support that new slab grade classification methods work for 7 grades. Two slab grades had no major change and for grade 0177 the test had to be ended due to the rising number of defects and process disturbances. In general, these results are promising but it is important to notice the low amount of production during the test period for grades 0216, 0628, 0832, 0833, 0825 and 0826. For the N-type slab grades the defect amounts are unknow and slab inspections should be done in the future before and after testing to get more precise defect information.

For further continuation of the tests, constant supervision of the tests left in production should be continued. The number of defects per casted tonne of steel and the number of disturbances during casting should be inspected regularly. Casting powder suitability is confirmed in the literature and at other SSAB locations, mostly based on the defect amounts. Defect amount clearly gives the best way to see if the casting powder is suitable or not. Problems with this include the relatively slow response and possibility of error due to incorrect judgement by the operator. Process variables and process disturbances give real time information about how the casting powder is working. Average values and standard deviation were calculated for each heat during the test period and the curves of the parameters were observed with the help of Aspen software. Process variable curves give a quick and good overview of the casting process and deviation can easily be seen there. In future tests it is recommended to constantly check the general shape of the curves for the test grades. Calculative values generally tell the same story, which can be seen from process variable graphs. Although the main difference is that the actual values are now accessible and in theory comparisons should be easy between different heats. Usage of these values is still quite challenging due to the change of other parameters and thus finding heat that has similar casting parameters is time-consuming and sometimes impossible. Still, the calculative work showed clearly that the standard deviation increases for the key variables for defected parts of the strand. Additionally, change in heat transfer and thermocouple temperature values before and during the test was expected and happened in the expected direction depending on the change of casting powder to peritectic or non-peritectic.

In future casting powder-related tests, it would be beneficial to optimize casting powder-related process parameters such as oscillation, casting speed and cooling simultaneously to get the best possible results while doing casting powder tests. During this work it was noticed that the most useful parameters for evaluating casting powder tests are defect data, process disturbance and process variable graphs and thus these are recommended to be used in the future. Additionally, better evaluation of N-type slab grade defects would add valuable information to casting powder testing, or at least slab inspections should be performed before and during future casting powder tests.

9 SUMMARY

The main objective of this study was to investigate casting powder selection rules in the literature and inside SSAB. During these investigations, a comprehensive image of the casting powders’ design, usage and selection has been formed.

There are many ways to select a casting powder for certain slab grades presented in the literature and many of these are in use at SSAB. Commonly, casting powder selection is based on the carbon-iron solidification diagram, carbon potential, ferrite potential or alloying amounts. These methods all attempt to classify slab grades as peritectic or non-peritectic. It is important to note that special grades are excluded from these rules. From the viewpoint of Raahe’s casting powder selection rules and possibility to improve them, FP calculation had the most potential.

The evaluation of casting powder tests is a complex task and multiple practices have been in use at Raahe and other steel mills. The experimental part of this study comprised defect analysis, process disturbance analysis and process parameter analysis. Process parameter analysis was composed of two parts: process parameter graph analyses and the calculation part.

Lastly, overall the objective of this study was achieved. The main objective of the literature review of this study was to provide a good overall picture of the importance of casting powders. Further their importance about their effect on the casting process was explained and it was proven that casting powders are suitable for certain slab grades in combination with known process parameters. The experimental part of this thesis has two major parts: the present state evaluation and process experiments. Multiple slab grades that had problems, potentially related to casting powder, were identified in the first part of the experimental study and 10 process tests were done in the second part. Even though all results were not positive, most of the tests showed positive improvements. Still, it must be kept in mind that most of the test grades had relatively few heats. Nine of ten tests continued to be used following completion of this thesis.

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APPENDIX 1

Table 1. Calculated values SP, ML, HT, TC 06 upper and TC 06 lower for slab grade 0177.

Heat	Width	HT	HT (SD)	SP	SP (SD)	ML	ML (SD)	TC 6	TC 6 (SD)	TC 6	TC 6 (SD)
81574	1850	1053.4	52.9	60.6	0.8	97.0	2.5	148.9	9.3	91.3	2.4
81577	1850	1096.4	5.3	61.6	0.4	90.3	2.4	151.5	7.3	91.0	2.8
81578	1850	1079.6	8.5	61.3	0.3	82.4	2.4	152.0	5.4	89.0	2.6
81579	1850	1083.1	8.6	61.4	1.6	97.7	2.5	144.3	8.3	86.6	2.7
86092	1850	1162.8	23.3	73.5	2.9	96.1	4.2	166.8	54.4	93.3	4.4
86094	1850	1181.0	12.2	65.8	1.1	91.6	2.3	164.0	31.9	87.4	3.1
86916	1850	1207.1	22.6	62.5	0.6	96.8	2.4	165.3	37.9	97.0	5.6
86917	1850	1188.1	23.6	61.9	0.6	91.2	2.3	165.8	55.1	91.6	6.3
87786	1850	1201.8	24.0	67.9	0.6	96.7	2.5	165.4	69.0	94.4	3.8
87788	1850	1146.2	11.4	67.1	1.7	91.2	2.4	158.2	40.8	88.2	3.7
87789	1850	1153.7	8.8	67.9	1.1	80.8	2.1	170.5	33.4	87.9	3.5
87790	1850	1182.9	20.3	68.2	1.3	92.6	5.5	155.2	61.3	89.6	4.4

Table 2. Calculated values SP, ML, HT, TC 05 upper and TC 05 lower for slab grade 0216.

Heat	Width	HT	HT (SD)	SP	SP (SD)	ML	ML (SD)	TC 5	TC 5 (SD)	TC 5	TC 5 (SD)
65822	1350	1682.2	53.1	67.8	0.6	98.5	2.5	204.5	3.9	142.2	2.8
65825	1325	1624.9	35.1	68.3	0.5	94.9	3.0	203.8	2.6	139.6	1.5
65826	1250	1509.3	22.0	69.2	0.7	77.9	1.3	192.8	2.6	142.4	0.9
65827	1225	1564.8	21.5	70.4	1.1	95.5	3.7	203.3	2.4	138.3	1.8
67546	1350	1630.0	47.0	66.1	1.2	98.9	2.5	211.0	4.2	145.1	3.3
67547	1250	1619.1	40.3	70.3	0.9	91.8	4.2	210.2	4.0	147.2	2.4
68831	1425	1658.8	60.7	70.8	0.9	98.9	2.6	178.5	2.5	130.2	3.3
68832	1175	1616.5	43.1	74.3	1.5	90.7	4.6	183.6	2.6	130.7	2.1
70151	1325	1661.6	58.0	64.3	1.4	98.7	2.9	185.2	2.3	128.1	3.8
70152	1275	1549.1	22.9	68.0	1.0	92.7	3.8	183.7	1.4	130.3	2.1
71947	1275	1692.7	46.5	74.2	0.9	99.0	3.0	179.6	2.4	130.5	2.9
71948	1175	1526.2	67.2	77.4	0.7	90.0	4.7	182.5	3.2	130.5	3.1

Table 3. Calculated values SP, ML, HT, TC 05 upper and TC 05 lower for slab grade 0627 (CCM 4).

Heat	Width	HT	HT (SD)	SP	SP (SD)	ML	ML (SD)	TC 5	TC 5 (SD)	TC 5	TC 5 (SD)
84955	1325	1427.6	184.3	70.3	2.1	99.5	3.0	178.8	14.3	126.7	11.0
84957	1325	1552.9	15.6	70.8	0.5	90.3	3.5	193.5	1.9	136.9	1.6
84958	1325	1494.0	15.3	70.9	0.2	78.9	1.6	190.1	1.9	140.1	0.8
84961	1325	1494.9	18.4	70.8	0.5	98.8	2.6	182.2	2.9	131.5	2.2
84962	1325	1295.5	236.2	55.4	26.1	94.2	6.7	169.8	19.3	119.3	14.7
84963	1325	1465.7	19.7	65.0	0.2	101.7	1.2	185.5	1.2	127.6	3.0
84967	1325	1624.4	79.9	61.0	2.5	98.6	3.1	189.4	4.9	134.3	3.6
84969	1325	1517.0	25.5	55.4	0.5	92.9	3.6	184.2	1.0	134.1	1.8
84970	1325	1416.2	21.0	51.4	0.7	78.3	1.0	181.9	1.6	128.8	1.6
84973	1325	1428.4	15.6	45.1	1.4	97.3	2.9	183.3	2.2	124.9	2.1
85542	1525	1316.1	27.3	53.9	0.3	99.1	2.7	171.4	4.0	126.0	1.3
86189	1325	1486.0	56.5	53.7	1.4	99.2	2.5	187.1	4.0	128.4	4.1
86194	1325	1371.7	9.2	49.4	0.3	93.0	3.3	181.1	1.9	128.4	5.0
86195	1325	1296.9	105.9	47.1	1.9	78.5	1.2	181.2	10.9	128.1	5.7
86196	1325	1408.3	18.5	42.7	0.6	98.3	2.6	179.6	3.0	129.8	3.3
88118	1325	1446.7	44.1	57.9	0.8	99.1	2.7	178.4	5.7	130.0	3.3
88120	1325	1395.5	14.0	53.2	0.5	93.0	3.1	177.5	2.0	133.0	1.6
88121	1325	1363.3	25.3	48.5	0.9	78.2	0.9	183.0	1.6	132.7	4.3
88123	1325	1343.1	12.4	43.1	1.0	97.1	3.0	172.2	2.3	123.4	4.3

Table 4. Calculated values SP, ML, HT, TC 05 upper and TC 05 lower for slab grade 0627 (CCM 5).

Heat	Width	HT	HT (SD)	SP	SP (SD)	ML	ML (SD)	TC 5	TC 5 (SD)	TC 5	TC 5 (SD)
85968	1325	1482.1	35.4	62.5	1.0	98.7	3.1	174.3	5.5	120.1	2.8
85973	1325	1506.1	21.9	59.0	0.7	93.5	3.7	174.0	1.2	120.8	1.5
85974	1325	1376.9	32.5	51.6	1.2	78.5	1.9	170.5	2.9	114.7	5.0
85975	1325	1434.2	15.3	47.2	0.7	98.2	3.1	165.7	1.6	110.9	6.5
87683	1550	1349.7	28.0	65.7	0.5	98.2	2.9	165.0	7.4	120.3	4.7
87684	1450	1400.3	12.0	63.8	0.3	93.9	3.2	168.8	2.6	120.7	6.1
87685	1325	1368.6	13.4	62.9	0.2	78.1	0.9	176.8	1.4	120.2	3.7
87687	1300	1399.6	11.5	61.0	0.3	97.2	3.0	168.2	2.0	118.4	2.2
88016	1325	1542.6	52.9	62.2	1.2	98.2	2.8	180.9	5.4	121.9	3.8
88018	1325	1447.8	24.1	58.3	0.6	94.1	3.2	174.5	2.5	122.1	1.9
88019	1325	1383.6	14.2	55.5	0.4	78.1	0.8	180.1	1.7	121.7	4.1
88021	1325	1376.8	14.9	53.5	0.2	96.2	3.0	170.1	2.6	120.4	3.2
88050	1325	1595.7	52.2	60.2	0.7	98.4	2.9	178.6	2.9	121.3	5.5
88052	1325	1434.8	21.8	57.7	0.3	93.2	3.5	172.6	1.8	121.8	2.0
88053	1325	1373.6	38.0	55.6	0.6	78.3	1.1	177.4	6.0	120.5	6.0
88057	1325	1416.9	18.4	54.3	0.3	97.6	2.8	168.1	3.3	119.0	3.6
88110	1325	1513.7	48.0	58.0	0.5	98.9	2.8	174.2	8.4	122.0	2.2
88112	1325	1330.9	18.3	55.1	0.3	90.5	4.4	165.9	4.0	114.6	2.5
88113	1325	1381.3	19.7	51.9	0.5	80.4	2.4	173.6	1.7	120.2	3.0
88115	1325	1404.4	16.7	47.8	0.5	101.0	1.6	165.1	2.2	116.4	2.8
88357	1325	1593.5	48.5	63.3	0.9	98.5	2.6	155.6	3.5	129.1	3.0
88358	1325	1480.1	27.2	60.7	0.2	94.4	3.0	147.6	2.6	124.4	5.2
88360	1325	1325.7	13.4	56.7	0.6	78.2	0.9	142.4	3.4	121.7	3.7
88361	1325	1437.5	16.6	55.4	0.6	97.4	2.9	144.6	1.5	125.5	3.3
85968	1325	1482.1	35.4	62.5	1.0	98.7	3.1	174.3	5.5	120.1	2.8

Table 5. Calculated values SP, ML, HT, TC 05 upper and TC 05 lower for slab grade 0628 (CCM4).

Heat	Width	HT	HT (SD)	SP	SP (SD)	ML	ML (SD)	TC 5	TC 5 (SD)	TC 5	TC 5 (SD)
83251	1625	1473.2	16.2	98.6	2.6	97.0	2.5	201.3	2.5	98.6	2.6
83252	1625	1262.9	12.7	93.1	3.8	90.3	2.4	188.1	1.3	93.1	3.8
83253	1625	1338.2	6.5	78.3	1.0	82.4	2.4	198.1	0.9	78.3	1.0
85549	1525	1390.5	63.7	92.6	3.3	97.7	2.5	176.2	7.0	92.6	3.3
85550	1350	1335.3	23.6	78.1	0.9	96.1	4.2	177.3	1.6	78.1	0.9
85551	1350	1370.2	14.8	96.5	2.8	91.6	2.3	171.0	1.2	96.5	2.8
87819	1625	1272.2	14.4	94.3	2.9	96.8	2.4	167.2	1.9	94.3	2.9
87818	1625	1320.2	25.0	98.9	2.5	91.2	2.3	173.7	6.7	98.9	2.5

Table 6. Calculated values SP, ML, HT, TC 05 upper and TC 05 lower for slab grade 0628 (CCM5).

Heat	Width	HT	HT (SD)	SP	SP (SD)	ML	ML (SD)	TC 5	TC 5 (SD)	TC 5	TC 5 (SD)
80548	1350	1537.4	8.8	56.3	0.3	94.7	3.1	184.9	1.2	122.7	1.4
83664	1400	1649.7	55.9	66.2	1.1	98.2	2.6	206.1	5.6	130.1	4.1
83665	1400	1540.2	25.0	61.7	0.5	95.7	2.9	201.9	3.3	126.9	2.8
83669	1400	1630.7	12.9	57.2	0.8	78.0	1.1	214.5	1.8	135.7	0.8
85941	1625	1222.9	18.2	60.8	0.5	90.8	3.8	157.2	2.0	110.4	4.1
85942	1625	1226.8	42.4	58.7	0.9	79.0	2.0	165.7	4.9	111.8	5.6
85936	1625	1184.7	14.5	63.4	0.8	99.1	3.2	154.9	4.8	105.6	1.6
85943	1400	1365.5	7.6	56.7	0.7	99.0	2.7	166.5	2.7	116.9	5.5
87552	1625	1395.1	23.6	57.3	0.5	98.2	2.7	168.0	4.3	115.0	2.1
87553	1625	1336.4	47.4	56.6	0.7	93.9	3.7	158.8	4.4	115.0	3.9

Table 7. Calculated values SP, ML, HT, TC 06 upper and TC 06 lower for slab grade 0825 (CCM6).

Heat	Width	HT	HT (SD)	SP	SP (SD)	ML	ML (SD)	TC 6	TC 6 (SD)	TC 6	TC 6 (SD)
84139	1850	1266.2	43.7	62.6	0.8	95.3	1.8	161.7	2.1	105.3	2.5
84140	1850	1329.2	7.7	64.7	0.3	95.0	1.4	159.8	1.2	106.1	2.2
84141	1850	1306.5	13.4	66.2	0.4	83.4	1.4	163.9	1.4	106.7	2.6
84428	1850	1223.7	49.9	59.3	0.4	95.2	1.8	160.3	1.8	99.7	2.6
84431	1850	1119.4	66.7	59.4	1.5	94.8	1.6	150.9	7.8	103.8	5.0
84435	1850	1271.6	7.2	59.3	0.3	83.0	1.5	164.0	1.6	103.1	2.2
84727	1850	1211.3	52.1	61.7	1.3	95.3	1.8	163.4	2.1	97.6	3.6
84730	1850	1329.9	12.4	65.2	0.5	94.8	1.4	163.6	2.1	108.6	4.0
84731	1850	1392.0	10.4	65.8	0.5	83.7	1.3	170.3	2.9	110.6	2.0
86104	1850	1397.9	35.6	59.1	0.6	95.3	1.8	177.4	2.5	108.9	2.9
86107	1850	1191.9	108.9	57.5	0.8	93.9	2.0	165.3	6.2	94.4	4.6
86109	1850	1369.5	29.6	59.4	0.3	81.1	1.5	183.9	5.9	102.0	4.8
86846	1850	1417.8	20.0	65.0	0.5	95.6	1.7	176.5	2.7	112.7	3.3
86848	1850	1341.6	24.8	65.6	0.2	94.8	1.3	177.4	3.1	107.6	4.0
86850	1850	1336.8	15.5	67.8	1.2	82.9	1.7	185.4	3.3	102.4	5.2
86897	1850	1229.7	147.0	60.3	1.6	96.0	1.9	168.4	9.5	101.8	5.3
86898	1850	1416.7	28.6	62.8	0.4	94.1	1.5	178.5	2.4	99.9	4.1
86900	1850	1288.8	12.7	63.3	1.3	82.7	2.0	171.8	5.8	99.4	3.1
87264	1850	1400.3	36.6	56.9	0.8	95.2	1.9	176.3	3.3	106.6	3.9
87266	1850	1156.6	63.8	56.6	0.4	94.3	1.7	157.5	3.7	99.8	3.1
87267	1850	1296.8	21.3	59.8	0.6	82.0	1.5	180.0	4.8	99.0	3.4
87973	1850	1440.0	29.8	70.4	0.4	95.7	1.8	177.8	9.6	114.9	7.6

Table 8. Calculated values SP, ML, HT, TC 06 upper and TC 06 lower for slab grade 0826 (CCM6).

Heat	Width	HT	HT (SD)	SP	SP (SD)	ML	ML (SD)	TC 6	TC 6 (SD)	TC 6	TC 6 (SD)
83206	1850	1269.3	33.0	62.5	1.7	95.3	1.7	157.4	1.9	102.1	3.2
83207	1850	1169.1	75.3	64.8	0.7	94.1	1.7	143.5	4.3	98.7	2.3
83208	1850	1345.3	7.6	64.6	0.2	82.1	1.3	162.2	1.5	102.4	1.5
84162	1850	1244.0	57.6	62.8	0.5	95.2	1.9	165.5	2.1	100.4	3.0
84166	1850	1365.9	10.0	62.8	0.3	95.6	1.3	163.1	1.4	107.7	2.0
84167	1850	1436.6	9.7	64.7	0.5	85.0	1.7	174.4	1.8	107.3	1.2
84915	1850	1283.4	39.4	61.1	0.6	95.6	1.9	167.8	3.6	102.4	3.8
84921	1850	1297.5	13.8	64.2	0.7	94.2	1.6	167.3	2.0	104.2	0.9
84922	1850	1274.2	7.1	63.7	0.5	82.4	1.7	169.4	2.8	102.8	1.5
85244	1850	1457.7	35.6	60.1	0.7	95.5	1.9	179.1	3.8	112.7	4.9
85249	1850	1325.6	65.5	59.9	0.7	94.3	1.6	160.8	9.5	104.2	6.2
85250	1850	1280.0	26.1	60.9	1.2	81.9	1.7	176.2	5.2	99.1	4.7
85964	1850	1308.9	27.4	67.1	0.4	95.7	1.9	172.5	2.4	98.8	3.0
85969	1850	1383.0	14.4	66.4	0.3	94.5	1.5	179.3	3.9	106.4	4.2
86787	1850	1432.3	21.6	54.8	1.0	95.3	1.7	179.0	3.8	110.3	3.4
86788	1850	1382.0	23.7	56.0	0.3	94.9	1.6	178.4	1.8	98.4	2.1
86790	1850	1247.2	20.8	59.6	1.5	82.4	2.0	165.6	6.9	100.0	3.9
86831	1850	1410.2	27.6	59.7	0.6	95.3	1.9	177.2	2.8	111.1	3.1
86834	1850	1387.1	12.9	59.4	0.3	95.3	1.5	177.0	1.9	99.7	2.9
86835	1850	1273.4	15.6	61.1	1.3	83.2	1.7	169.2	6.2	100.8	3.6
87506	1850	1431.2	17.6	70.9	0.4	95.1	1.6	180.7	3.8	110.0	3.9
87509	1850	1391.1	24.4	72.8	0.6	95.4	1.5	179.1	2.1	99.0	2.7
87510	1850	1308.5	23.2	75.6	1.0	84.0	1.6	167.1	7.8	103.7	4.5
88091	1850	1388.2	68.8	67.8	1.1	95.5	2.0	177.9	10.2	110.8	8.0
88092	1850	1225.2	70.7	71.2	0.9	93.8	1.6	168.7	11.2	98.6	6.7
88093	1850	1346.2	31.4	73.6	0.4	81.5	1.4	187.7	5.5	108.2	8.9

Table 9. Calculated values SP, ML, HT, TC 06 upper and TC 06 lower for slab grade 0832 (CCM6).

Heat	Width	HT	HT (SD)	SP	SP (SD)	ML	ML (SD)	TC 6	TC 6 (SD)	TC 6	TC 6 (SD)
82240	1975	1155.6	28.5	66.4	0.6	95.4	1.8	153.9	2.4	100.5	4.1
82242	1975	1007.5	8.2	67.6	0.3	95.0	1.3	148.2	1.4	90.8	2.4
83303	1975	1073.8	38.5	65.0	0.5	95.7	1.7	149.6	2.6	97.1	3.8
83305	1975	1028.0	4.9	66.6	0.3	94.5	1.4	149.0	1.5	90.5	2.5
83306	1975	896.4	66.0	66.7	0.6	81.9	1.7	141.1	4.6	85.0	3.7
83307	1975	969.3	11.8	68.7	0.2	88.0	1.3	148.5	1.6	90.0	2.7
84985	1975	1084.3	36.9	60.4	0.8	95.6	1.7	149.1	2.2	96.7	3.1
84987	1975	1016.1	5.8	63.4	0.4	94.5	1.4	147.8	1.1	91.8	2.1
84989	1975	983.8	6.7	64.1	0.3	82.7	1.4	149.7	1.3	92.5	1.9
86313	1975	1007.6	27.6	66.7	2.3	95.5	1.8	149.2	2.6	90.1	2.2
86315	1975	906.7	83.0	70.7	0.6	93.0	2.0	136.5	5.9	85.1	5.3
86316	1975	1002.5	8.9	72.2	0.4	80.3	1.3	151.4	1.9	94.9	3.7
87638	1975	934.7	68.9	69.0	1.1	95.9	2.0	135.8	4.8	86.6	4.8
87639	1975	1050.6	6.7	70.1	0.4	93.7	1.5	139.0	1.7	96.9	2.8
87640	1975	995.1	14.2	68.8	0.3	82.0	1.4	140.9	2.1	89.4	2.3
88633	1975	982.9	18.6	65.8	0.7	95.4	1.6	142.6	2.1	89.5	3.8
88634	1975	1001.1	7.1	68.0	0.4	95.1	1.4	138.8	2.0	89.8	5.0

Table 10. Calculated values SP, ML, HT, TC 06 upper and TC 06 lower for slab grade 0833 (CCM6).

Heat	Width	HT	HT (SD)	SP	SP (SD)	ML	ML (SD)	TC 6	TC 6 (SD)	TC 6	TC 6 (SD)
80188	1975	1145.3	61.4	66.9	0.5	95.7	1.8	152.1	4.1	89.8	4.4
80189	1975	979.1	7.7	67.5	0.2	94.4	1.5	146.5	1.6	87.3	1.6
83880	1975	1123.1	45.7	67.9	0.6	95.4	1.8	151.4	3.5	95.5	5.7
83883	1975	1032.0	8.9	68.6	0.3	94.9	1.4	147.3	1.2	94.4	1.1
87630	1975	1041.4	34.1	63.6	1.7	95.2	1.7	141.9	1.9	92.7	2.9
87632	1975	1042.1	8.4	68.0	0.3	94.9	1.3	137.4	1.2	86.3	2.8
88621	1975	1034.3	23.2	67.7	0.5	95.5	1.7	143.9	2.1	94.4	2.9
88622	1975	1031.1	8.2	68.5	0.3	95.1	1.3	139.7	1.5	88.3	2.3

Table 11. Calculated values SP, ML, HT, TC 05 upper and TC 05 lower for slab grade 0891 (CCM 4).

Heat	Width	HT	HT (SD)	SP	SP (SD)	ML	ML (SD)	TC 5	TC 5 (SD)	TC 5	TC 5 (SD)
75179	1550	1363.3	36.8	60.7	1.2	98.6	2.5	197.4	2.1	135.2	2.2
75183	1525	1243.9	15.7	63.6	0.5	94.9	2.7	197.8	2.2	126.6	1.9
75185	1525	1229.7	7.1	64.6	0.6	78.0	1.3	178.9	3.7	130.3	1.7
75186	1525	1243.1	9.9	65.6	1.0	92.4	3.3	193.9	2.2	126.3	4.2
75404	1550	1369.6	44.2	60.8	0.9	98.7	2.5	191.8	1.8	130.7	0.9
75409	1425	1212.5	18.2	60.2	0.4	92.6	3.9	193.5	3.6	126.8	5.1
75411	1275	1273.6	115.0	59.5	1.6	80.2	3.2	188.5	14.7	136.9	9.6
78013	1225	1425.1	145.2	63.5	1.4	100.0	2.9	172.5	8.3	121.8	10.0
78015	1225	1369.6	10.2	63.9	0.4	87.3	3.8	180.5	1.8	122.9	1.0
78016	1375	1441.5	10.6	64.7	0.4	80.0	1.8	183.3	1.6	126.1	1.1
78017	1525	1419.1	9.8	64.6	0.4	99.2	2.2	171.2	1.6	120.1	1.6
79839	1525	1606.7	64.2	70.7	0.8	98.3	2.5	199.9	2.2	144.1	3.4
79840	1525	1416.9	35.1	71.9	0.7	95.2	2.8	199.4	3.8	141.2	2.8
81499	1275	1579.4	68.4	70.3	0.5	98.9	2.6	188.8	3.2	129.8	3.3
81502	1275	1396.5	16.4	72.6	1.7	91.3	4.4	187.3	2.3	126.3	0.9
82294	1575	1359.2	139.3	65.5	1.6	98.6	2.6	176.9	6.9	121.2	6.5
82295	1575	1305.4	7.8	63.1	2.1	93.8	3.7	183.1	1.3	124.5	1.0
86502	1525	1518.3	54.8	65.8	0.4	98.9	2.3	183.7	2.8	133.6	2.8
86503	1525	1329.3	82.4	65.5	0.9	93.6	3.4	182.2	5.5	130.0	4.7
86505	1525	1453.2	12.8	64.8	0.9	78.2	1.2	197.4	1.1	140.0	0.8

Table 12. Calculated values SP, ML, HT, TC 05 upper and TC 05 lower for slab grade 0891 (CCM 5).

Heat	Width	HT	HT (SD)	SP	SP (SD)	ML	ML (SD)	TC 5	TC 5 (SD)	TC 5	TC 5 (SD)
77159	1525	1340.1	19.6	68.6	0.9	94.9	3.1	168.4	2.8	95.7	0.5
77160	1275	1348.9	25.5	69.1	0.8	78.0	1.1	181.5	2.3	100.0	1.3
78395	1550	1477.3	61.3	70.8	1.3	97.6	2.7	184.0	4.5	108.1	5.7
78396	1525	1317.6	33.8	67.5	1.0	95.6	3.0	184.8	2.6	97.0	2.9
78397	1525	1299.5	13.7	64.5	0.7	78.0	1.3	190.1	1.9	98.1	3.0
78400	1425	1326.1	69.6	63.4	1.3	93.5	4.2	181.8	2.3	97.1	5.5
79919	1550	1552.7	64.4	64.4	0.7	99.0	2.4	188.1	3.0	109.9	3.4
79922	1525	1377.2	10.5	66.0	0.5	94.8	2.6	187.0	1.5	102.9	4.0
79923	1525	1432.8	9.1	65.8	0.4	77.9	1.0	194.8	1.5	108.8	1.8
79925	1525	1405.7	7.7	65.5	0.5	92.2	3.2	192.8	3.0	108.7	2.7
80392	1575	1593.5	64.5	74.5	0.8	98.3	2.6	183.5	4.7	124.2	12.1
80393	1525	1405.6	7.3	74.7	0.3	95.6	2.6	181.3	1.2	118.6	4.0
80394	1525	1419.7	10.2	74.9	0.3	78.1	0.9	187.1	1.4	121.9	1.8
80395	1425	1432.8	23.1	72.8	0.4	93.6	4.0	184.7	2.3	119.2	3.8
80960	1225	1572.3	56.7	70.0	1.3	99.5	2.9	202.8	3.6	115.2	2.0
80961	1325	1410.7	39.0	69.8	1.0	91.2	3.3	200.1	2.3	112.5	5.6
80962	1525	1407.3	14.3	70.8	1.0	77.9	1.6	204.7	1.5	120.5	5.2
80963	1525	1242.2	106.6	63.8	1.2	96.3	3.8	183.7	6.0	104.6	7.8
83235	1525	1574.8	51.7	65.8	0.8	98.1	2.6	200.9	3.9	116.1	4.4
83239	1525	1437.2	15.6	67.9	0.4	95.4	2.7	204.6	2.1	114.0	3.2
83240	1525	1488.1	19.6	69.1	0.5	78.0	1.0	211.9	1.9	121.5	2.7
83416	1525	1571.3	58.3	69.1	1.1	97.9	2.6	194.1	4.6	111.0	3.8
83419	1525	1436.9	22.2	72.5	1.7	93.5	4.5	203.4	2.5	109.7	3.0
84011	1525	1346.1	193.4	66.9	0.6	99.3	3.0	182.8	12.3	104.5	15.5
84013	1525	1443.5	18.3	71.5	1.9	90.8	3.1	201.3	2.2	113.4	2.1
84014	1525	1432.8	30.6	74.5	2.8	78.5	2.4	209.3	2.5	114.2	2.8
84432	1525	1565.0	53.9	72.8	1.0	97.6	2.5	176.7	5.1	113.1	3.1
84438	1525	1406.3	13.1	75.0	1.1	96.8	2.3	182.4	6.3	109.7	4.6
84439	1525	1427.7	11.5	73.9	1.0	78.3	1.6	135.3	5.6	114.5	3.4
85597	1550	1576.9	50.6	66.0	1.0	98.4	2.7	183.8	6.4	115.2	6.1
85600	1550	1431.0	9.2	68.9	0.7	94.3	3.2	173.2	9.9	112.8	2.0
85601	1300	1478.5	10.6	70.5	1.7	77.9	1.3	135.9	2.7	119.0	1.8

Table 13. Calculated values SP, ML, HT, TC 06 upper and TC 06 lower for slab grade 0891 (CCM 6).

Heat	Width	HT	HT (SD)	SP	SP (SD)	ML	ML (SD)	TC 6	TC 6 (SD)	TC 6	TC 6 (SD)
75003	1525	1456.5	1046.7	67.5	1.8	90.6	3.3	140.5	3.1	91.7	2.4
75005	1525	1553.5	1279.2	68.7	1.2	83.4	2.9	161.4	1.5	104.5	2.2
75009	1225	1072.2	1348.0	63.5	1.6	98.8	2.2	154.8	1.7	102.1	3.3
75863	1875	1404.1	1313.3	74.6	1.3	96.0	2.3	151.3	3.0	102.7	3.4
75864	1550	1465.8	1287.4	77.0	1.1	82.2	2.8	159.4	1.7	105.8	1.4
75868	1525	1361.2	1247.0	77.4	1.0	89.2	2.8	154.0	1.4	101.2	1.8
76273	1550	1312.9	1506.3	70.1	1.5	96.1	2.4	156.2	3.7	110.2	3.6
76278	1525	1496.8	1351.2	69.7	0.7	92.2	2.2	156.9	1.7	118.9	3.5
76279	1525	1302.1	1096.1	64.6	1.5	82.3	3.0	145.6	8.5	95.1	5.3
76280	1300	1333.0	1378.2	62.1	1.0	98.2	2.4	154.9	1.9	106.3	3.0
77145	1525	1481.8	1443.5	63.5	1.2	96.2	2.1	151.9	4.2	107.4	4.3
77148	1525	1446.3	1283.6	66.5	0.5	92.3	2.2	153.3	2.3	109.5	4.9
77149	1525	1320.9	1163.3	63.8	0.9	80.5	1.9	151.8	2.0	98.8	2.4
78677	1875	1192.4	1543.6	73.0	1.3	96.1	2.5	173.9	5.1	111.4	2.9
78679	1525	1323.1	1525.1	73.4	0.9	92.1	2.6	177.4	1.7	112.0	1.2
80514	1875	1462.8	1548.8	74.5	1.1	96.4	2.8	179.0	4.6	115.0	3.9
80515	1700	1451.9	1576.8	75.9	0.2	91.8	1.9	184.8	1.2	112.8	0.8
80518	1525	1371.7	1670.1	77.1	0.3	80.3	1.3	197.4	1.4	120.7	0.9
80520	1300	1461.1	1616.8	77.2	0.6	94.0	2.6	185.7	2.2	116.0	0.7
81050	1875	1225.2	1534.7	70.5	1.4	95.9	2.6	182.4	4.6	118.6	3.1
81791	1525	1354.9	1694.9	75.2	1.9	96.4	3.3	186.2	5.0	121.1	6.6
81794	1525	1515.0	1725.0	72.9	2.2	91.3	3.3	193.9	3.0	120.1	1.8
85795	1525	1252.1	1646.1	60.0	1.3	96.6	2.5	190.4	3.0	114.9	4.4
85796	1275	1304.4	1585.1	64.5	0.8	89.7	2.9	196.2	2.4	113.6	3.5
87370	1875	1557.1	1416.4	61.3	2.0	95.9	2.4	179.5	3.6	109.7	2.6
87374	1550	1484.7	1586.1	65.4	0.6	92.4	2.0	187.1	1.8	113.3	1.3
87375	1525	1408.6	1555.8	68.5	0.6	80.4	1.3	190.2	3.7	114.7	2.3
87376	1225	1514.2	1662.3	68.1	0.4	93.7	2.6	191.7	2.9	116.3	1.7
87381	1875	1211.2	1593.9	66.5	1.2	96.3	2.7	185.2	5.2	120.0	10.0
87383	1525	1293.9	1598.0	72.8	0.7	92.2	2.0	186.5	1.2	115.2	1.0
87386	1525	1620.4	1604.5	69.6	0.5	80.3	1.6	192.3	2.2	116.7	1.7

Table 14. Calculated values SP, ML, HT, TC 06 upper and TC 06 lower for slab grade 0961 (CCM 6).

Heat	Width	HT	HT (SD)	SP	SP (SD)	ML	ML (SD)	TC 6	TC 6 (SD)	TC 6	TC 6 (SD)
84784	1850	1456.5	7.0	71.9	0.3	84.4	1.2	178.1	1.2	113.9	0.8
84789	1850	1553.5	29.5	64.8	0.4	95.2	1.7	172.9	2.5	109.8	4.3
84792	1850	1072.2	83.1	61.5	0.4	94.2	2.0	140.9	5.4	90.8	4.4
84793	1850	1404.1	11.7	65.6	0.4	81.5	1.7	177.2	1.0	113.9	0.8
84912	1850	1465.8	37.1	62.8	0.5	95.8	1.8	174.4	3.6	102.3	2.1
84913	1850	1361.2	48.7	63.6	0.6	94.0	1.6	170.5	1.9	103.9	1.0
84914	1850	1312.9	13.7	63.0	0.2	82.0	1.4	173.9	1.2	99.0	0.9
85561	1875	1496.8	36.2	57.0	2.4	95.1	1.6	173.8	1.9	105.1	2.9
85564	1875	1302.1	74.6	60.6	0.7	94.2	1.5	165.2	3.7	102.2	1.0
85565	1875	1333.0	10.6	61.7	0.2	81.8	1.5	177.3	1.9	103.3	0.2
86111	1850	1481.8	27.5	57.1	0.5	95.1	1.7	181.5	2.4	107.4	3.8
86114	1850	1446.3	13.6	60.0	0.3	95.4	1.4	174.8	1.1	104.7	0.5
86115	1850	1320.9	13.0	60.9	0.2	83.9	1.4	175.4	1.6	103.3	1.4
86445	1850	1426.7	81.8	59.3	0.6	95.3	1.7	174.4	1.5	102.9	3.0
86446	1850	1192.4	119.7	64.0	0.8	94.4	1.9	161.6	8.2	95.1	9.2
86448	1850	1323.1	19.9	61.9	0.5	82.3	1.5	180.5	1.1	101.2	1.2
86824	1850	1462.8	56.3	60.1	0.6	95.5	1.7	172.6	2.0	100.7	3.9
86827	1850	1451.9	15.4	61.3	0.2	94.8	1.3	171.8	1.9	106.8	1.2
86828	1850	1371.7	14.1	62.6	0.5	83.2	1.4	175.0	1.3	99.7	0.7
86885	1850	1461.1	44.9	60.6	0.6	95.1	1.8	172.5	3.1	105.2	4.2
86886	1850	1225.2	69.4	67.1	0.4	95.1	1.6	164.4	3.3	98.5	3.4
86888	1850	1354.9	13.0	63.9	0.4	83.5	1.5	173.7	1.4	99.9	2.9
88002	1850	1515.0	47.3	60.6	0.7	95.3	1.8	172.9	4.3	106.9	5.3
88005	1850	1252.1	39.8	62.0	0.9	94.2	1.7	161.2	4.2	95.5	1.8
88006	1850	1304.4	10.4	63.1	0.4	81.5	1.5	173.6	1.2	99.7	0.3
88075	1850	1557.1	60.2	63.6	0.9	94.9	1.8	180.4	2.5	107.9	2.8
88076	1850	1484.7	15.1	66.8	0.3	95.9	1.2	175.1	1.1	104.7	0.6
88079	1850	1408.6	17.6	68.0	0.4	84.6	1.5	178.3	1.8	102.5	1.6
88105	1850	1514.2	78.0	63.0	0.6	95.4	1.5	178.6	1.8	106.4	2.8
88107	1850	1211.2	74.1	66.9	0.4	93.8	1.8	165.9	4.3	101.4	2.7
88109	1850	1293.9	14.5	66.1	0.2	81.1	1.3	177.8	1.1	102.7	0.9
88410	1875	1620.4	90.3	70.4	1.5	95.0	1.6	164.0	1.7	106.7	4.0

APPENDIX 2

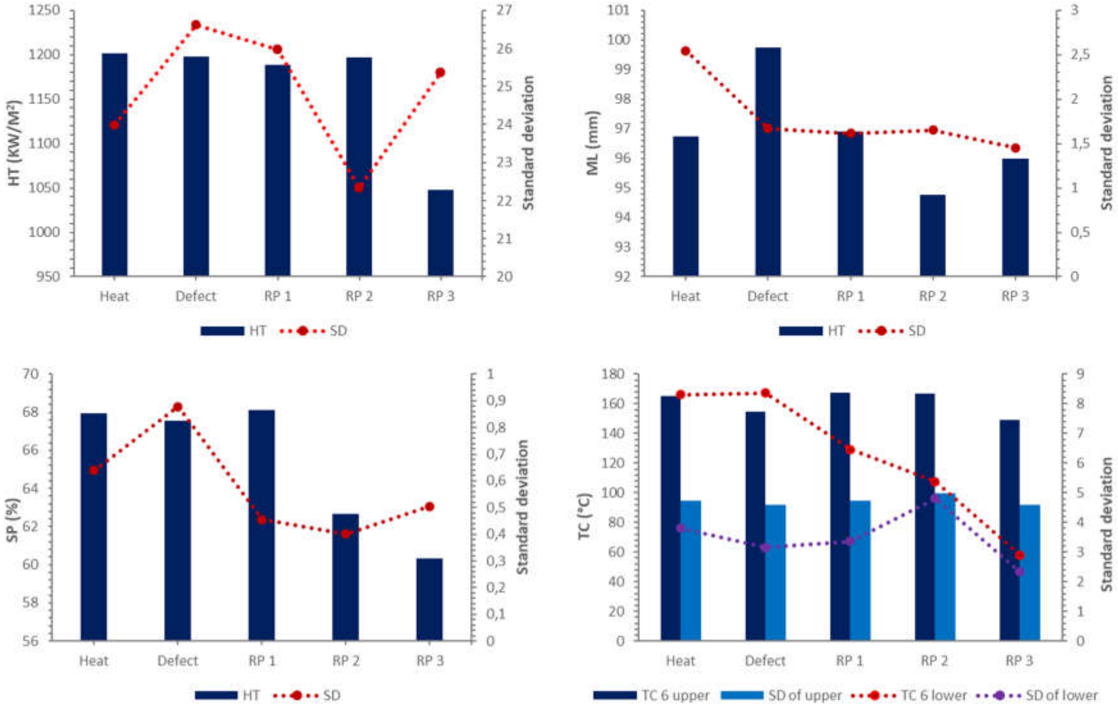

Figure 1. HT, SP, ML and TC 6 and their standard deviation. Sliver defect case (1.2) in heat 87786.

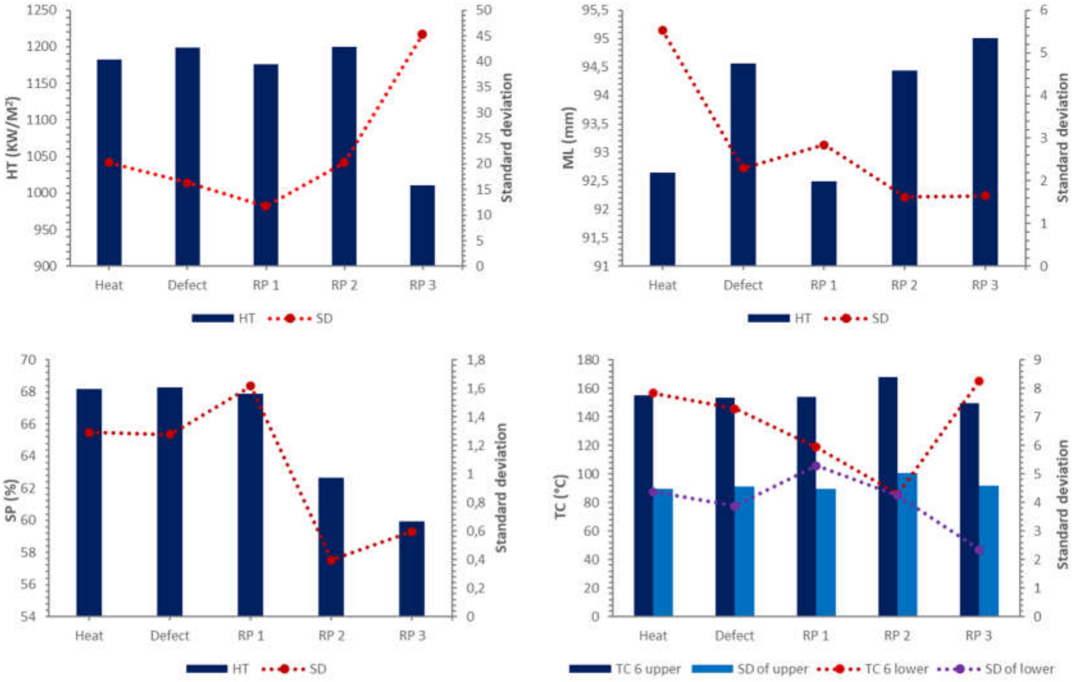

Figure 2. HT, SP, ML and TC 6 and their standard deviation. Sliver defect case (1.3) in heat 87790.

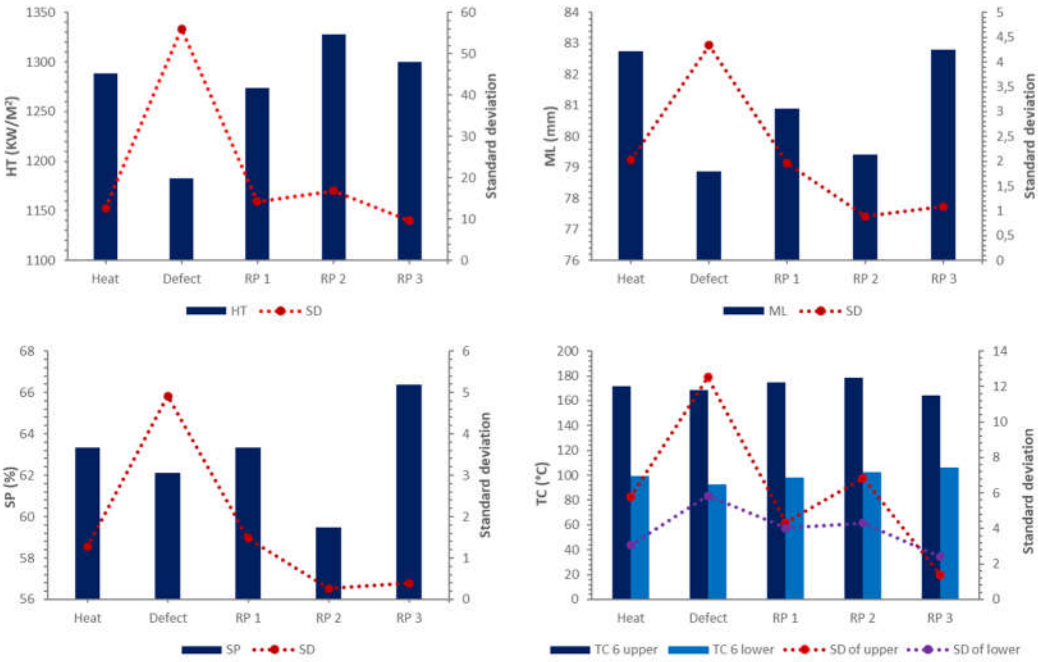

Figure 3. HT, SP, ML and TC 6 and their standard deviation. Crack defect case (2.1) in heat 86900.

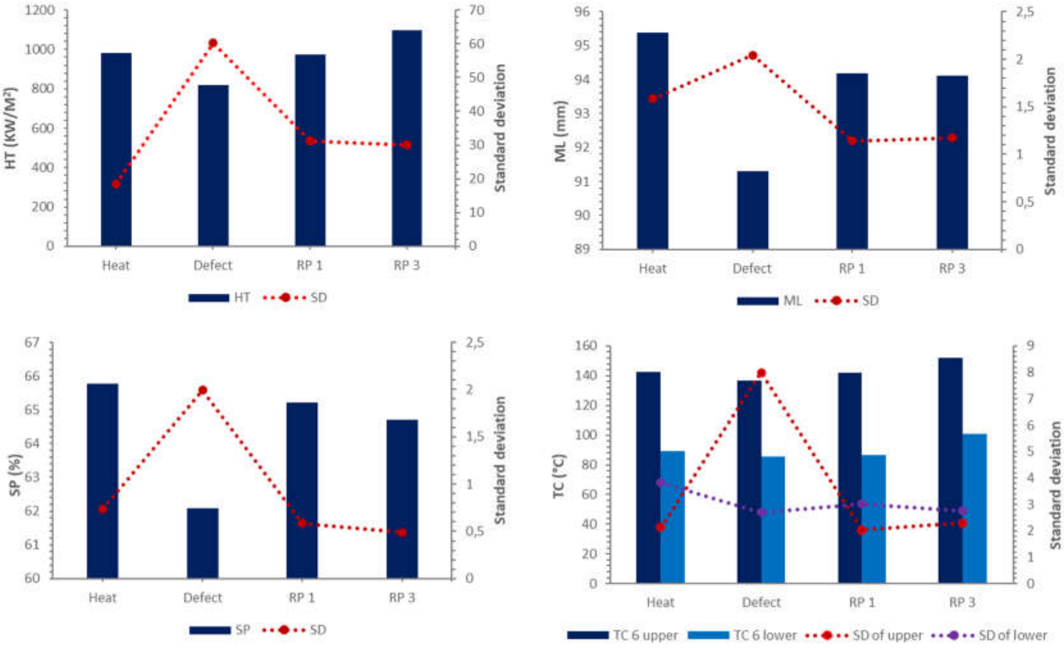

Figure 4. HT, SP, ML and TC 6 and their standard deviation. Slag defect case (3.1) in heat 88633.

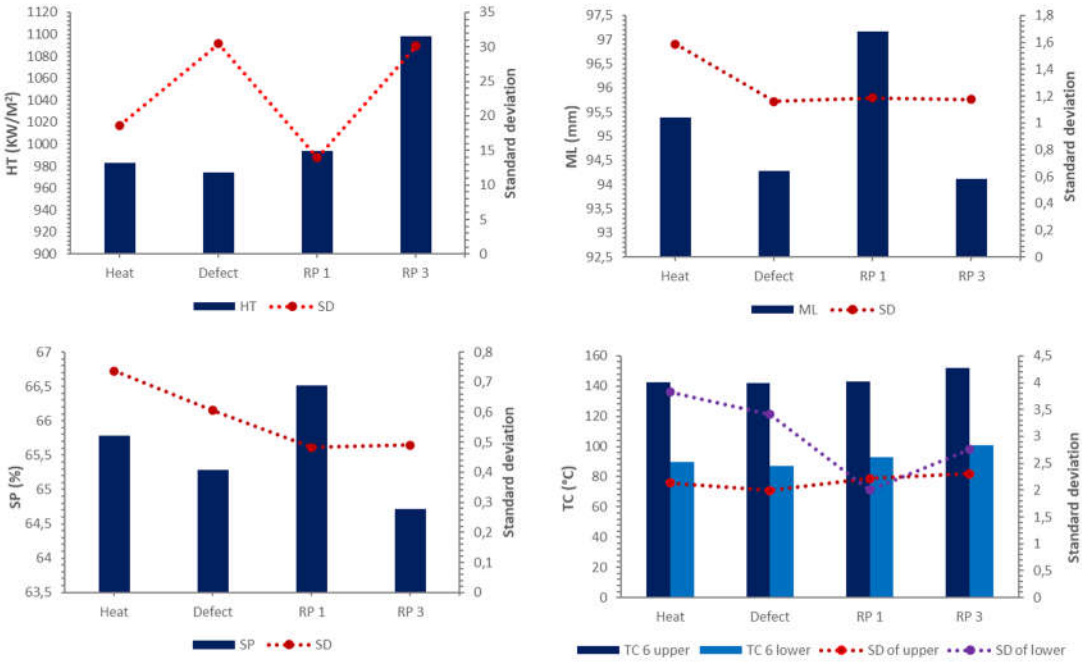

Figure 5. HT, SP, ML and TC 6 and their standard deviation. Sliver defect case (3.2) in heat 88633.

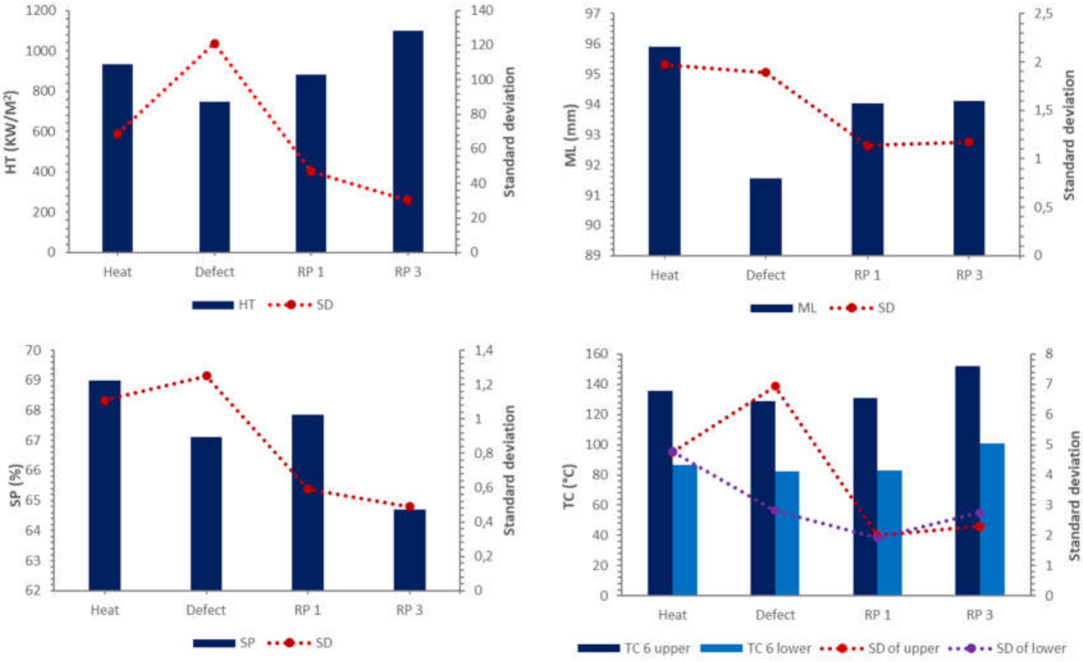

Figure 6. HT, SP, ML and TC 6 and their standard deviation. Sliver defects case (3.3) in heat 87638.

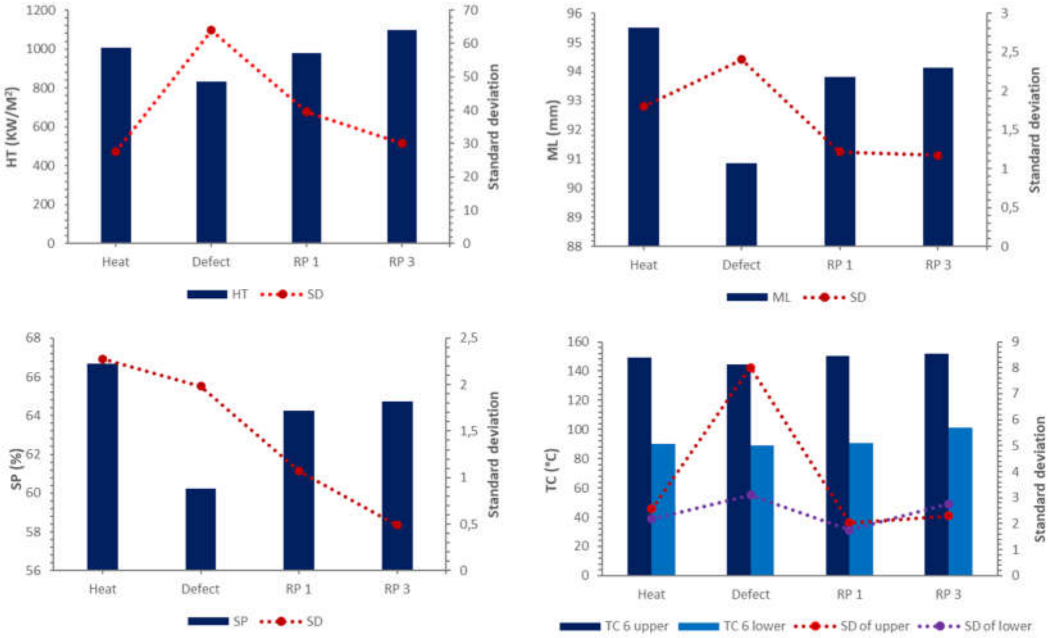

Figure 7. HT, SP, ML and TC 6 and their standard deviation. Sliver defect case (3.4) in heat 86313.

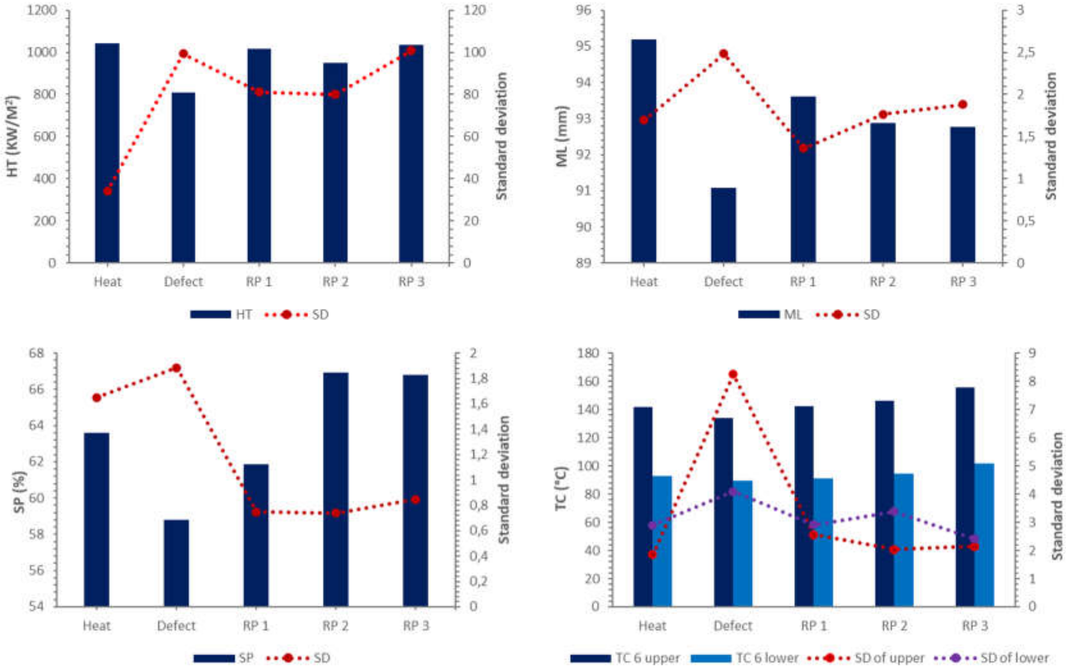

Figure 8. HT, SP, ML and TC 6 and their standard deviation. Slag defect case (4.1) in heat 87630.

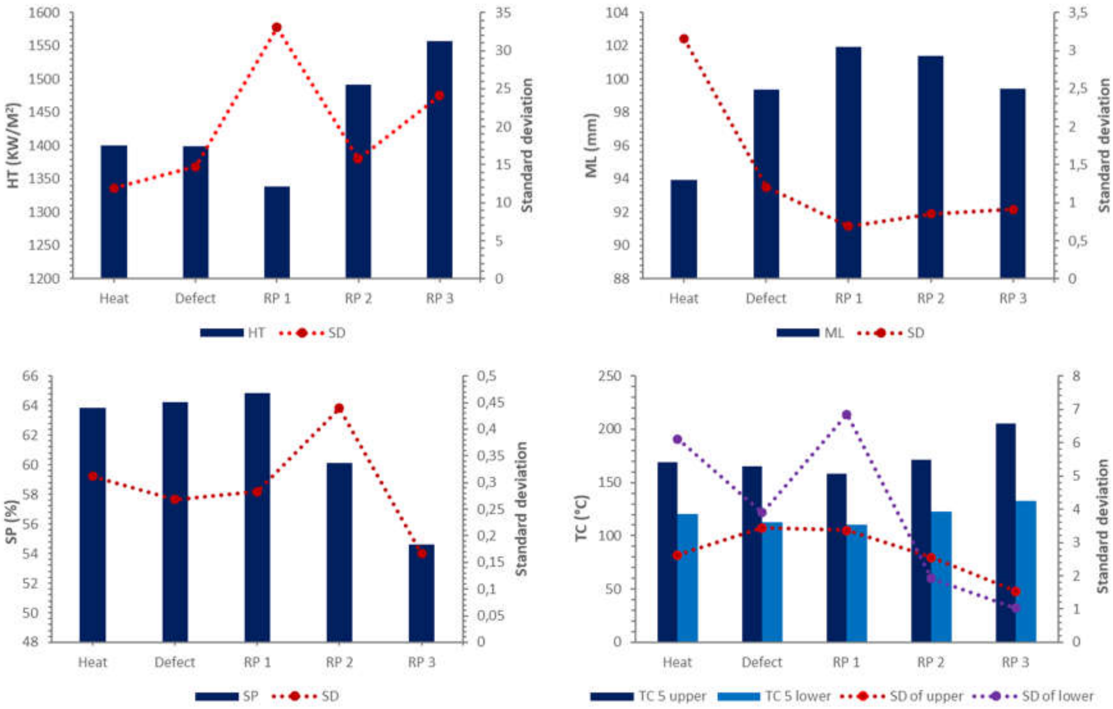

Figure 9. HT, SP, ML and TC 5 and their standard deviation. Crack defect in coil case (5.1) in heat 87684.

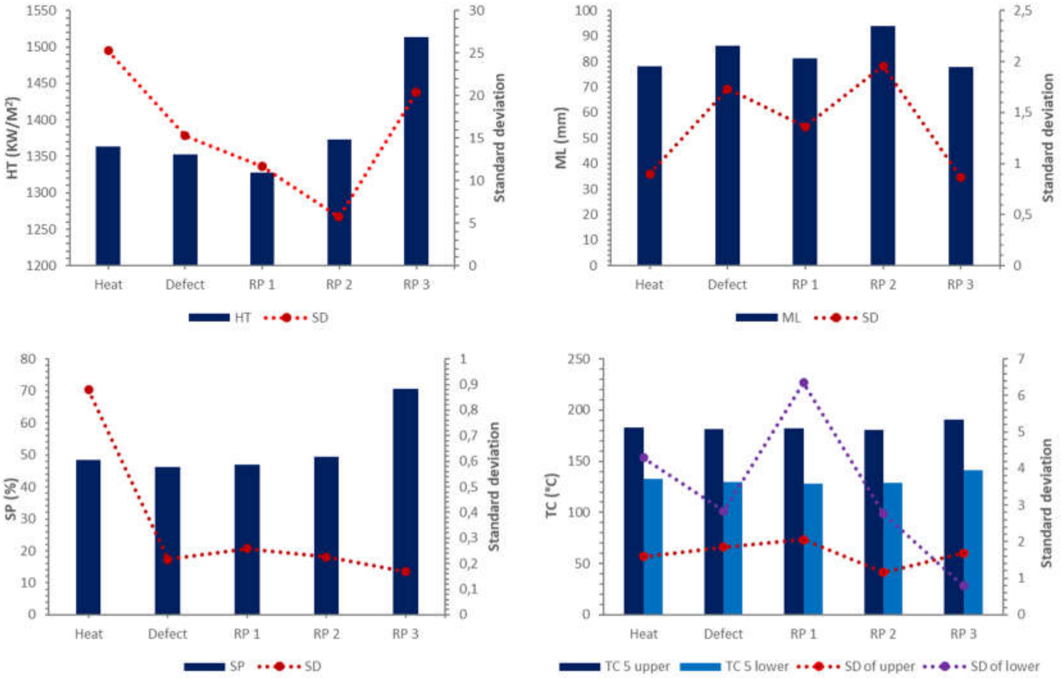

Figure 10. HT, SP, ML and TC 5 and their standard deviation. Crack defect in coil case (5.2) in heat 88121.

APPENDIX 3

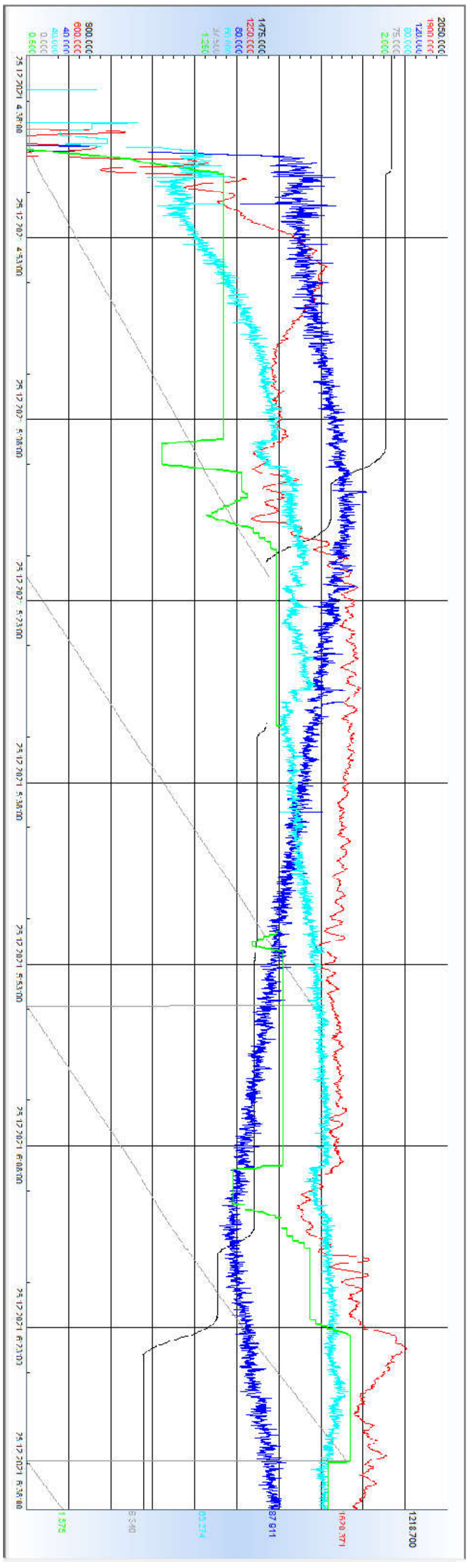

Figure 1. Aspen Process variables example CCM 6 (slab grade 0891 heats 87370, 87374 and 87375).

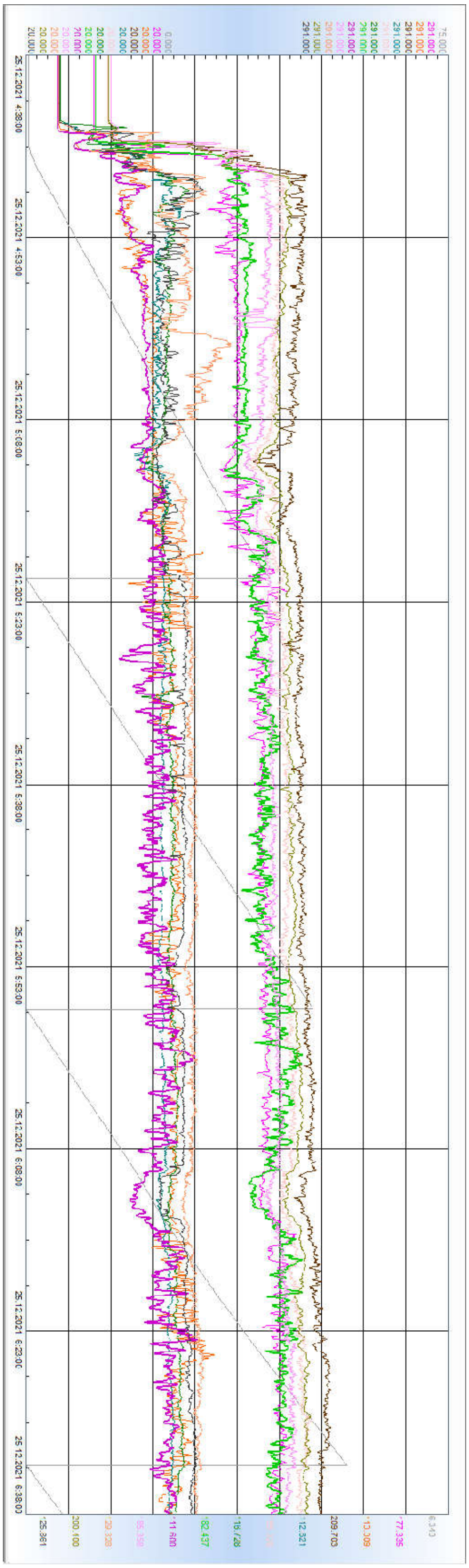

Figure 2. Aspen thermocouple example CCM 6 slab grade 0891 heats 87370, 87374 and 87375.