TEKNILLINEN TIEDEKUNTA

Improvement of Steel Ladle Lid Circulation and Lifetime

Petri Lehtonen

PROSESSITEKNIIKAN KOULUTUSOHJELMA
Diplomityö
Toukokuu 2020

Abstract

Improvement of Steel Ladle Lid Circulation and Lifetime

Petri Lehtonen

University of Oulu, Process Metallurgy

Master's thesis 2020, 66 pp.

Supervisors at the university: Eetu-Pekka Heikkinen, Timo Fabritius

For an energy-intensive field of industry, such as steelmaking, temperature control in steel production is essential. As one of the methods to improve energy efficiency in SSAB Raahe's steel plant production, they introduced lids for their steel ladles to prevent heat losses during transportation. However, even though the lids have been in use for years, their actual properties have not been properly studied.

The aim of this work is to clarify current steel ladle lid lifetime, chart areas for development and improve condition monitoring methods. As a fundamental study, this thesis mainly presents the current situation and does not aim for major structural improvement. The essential part of this work is to develop methods to monitor the condition of steel ladle lids and record necessary information throughout lid lifetimes.

In the experimental part of this work, the condition of the lining was monitored to create a model of refractory wear for the steel ladle lids. Based on the observations during the trial and theoretical studies, the sources of the most common defects were investigated. The results show that the lids endure the process conditions decently but there is still room for improvement.

Keywords: refractories, steel, ladle, lid, monitoring, steelmaking, energy efficiency

Preword

This master's thesis was carried out at SSAB Raahe steelworks between August 2019 and April 2020. I want to thank SSAB for providing this opportunity and funding this thesis. For me, this thesis represented as great introduction to the world of refractory materials, which I am willing to learn more about in the future.

I would like to thank my instructors at SSAB, M.Sc. (Tech.) Heikki Pärkkä and M. Sc. (Tech) Miika Sihvonen, for all the instructions and advice they provided during the thesis process. Their trust in me helped me through this endeavor. I also want to thank my supervisors at the University of Oulu, D.Sc. (Tech) Eetu-Pekka Heikkinen and D.Sc. (Tech) Timo Fabritius, for supervising my work.

For me it was a pleasure to work as part of the Raahe steelworks process development team. Their positive attitude towards me and my work encouraged me to continue through the challenges that I faced. Special thanks to Harri Eskola for his contribution in creating the condition monitoring system. His efforts were essential for the success of this thesis. Also, I would like to thank the all the workers and collaborative parties that I worked with for their co-operation.

As my studies at University of Oulu come to the end, I would like to thank all of my fellow students and friends for being there for me. The last six years I spent studying has been the best part of my life so far and will always have its place in my memories. And lastly, I want to thank my family for all the support they gave throughout the years.

Raahe, 17.4.2020

Petri Lehtonen

TABLE OF CONTENT

1 INTRODUCTION

1.1 Background

Steel production has always been highly energy intensive and as such even minor improvements in efficiency might provide significant savings. It is known that steel ladles sometimes have to wait long times for sequent treatment, leading to high amounts of heat losses. Heat losses are usually compensated by overheating each charge. However, this procedure is not very sustainable because overheating requires even more resources and accelerates the rate of refractory wear. To reduce heat losses during transportation, the steel plant in Raahe developed lids to cover previously open ladles. Positive results made the lids permanent equipment in steel production.

Refractories are essential for steady and safe steel production but also are a significant expense. Longer campaign times can bring significant financial savings but on the other hand excessively worn out linings increase the risk of breakouts. By monitoring the condition of the lining as frequently as possible, risks can be observed in time and possibly repaired to lengthen the campaigns. However, this has not been the case for steel ladle lids. Due to their simple role in the steel production process, there has not been any recording of age or condition of each ladle lid.

1.2 The goals of the thesis

The first goal of this master’s thesis is to inspect current practices related to the steel ladle lids and map out areas for development. The inspection report aims to comprehensively describe the entire lifecycle and ways of handling the ladle lids which can then be used as a base for later studies. To reach this goal, it is necessary that a system of monitoring lid condition throughout the production cycle is developed and becomes a part of the operator’s normal routine. The goal of the experimental study is to detect various defect types in steel ladle lids and examine their sources.

In addition to the primary goals, smaller projects concerning the steel ladle lids are done with an aim to improve practices, to improve efficiency and thus bring financial savings. These practices include improvements around logistics, storing, safety and design but more detailed descriptions of these are not included in this thesis.

1.3 Structure of the thesis

The structure of the thesis can be divided into theoretical and practical parts. Theory provides background on which the practical studies are later based. Figure 1 presents each chapter of this work and their relation to others.

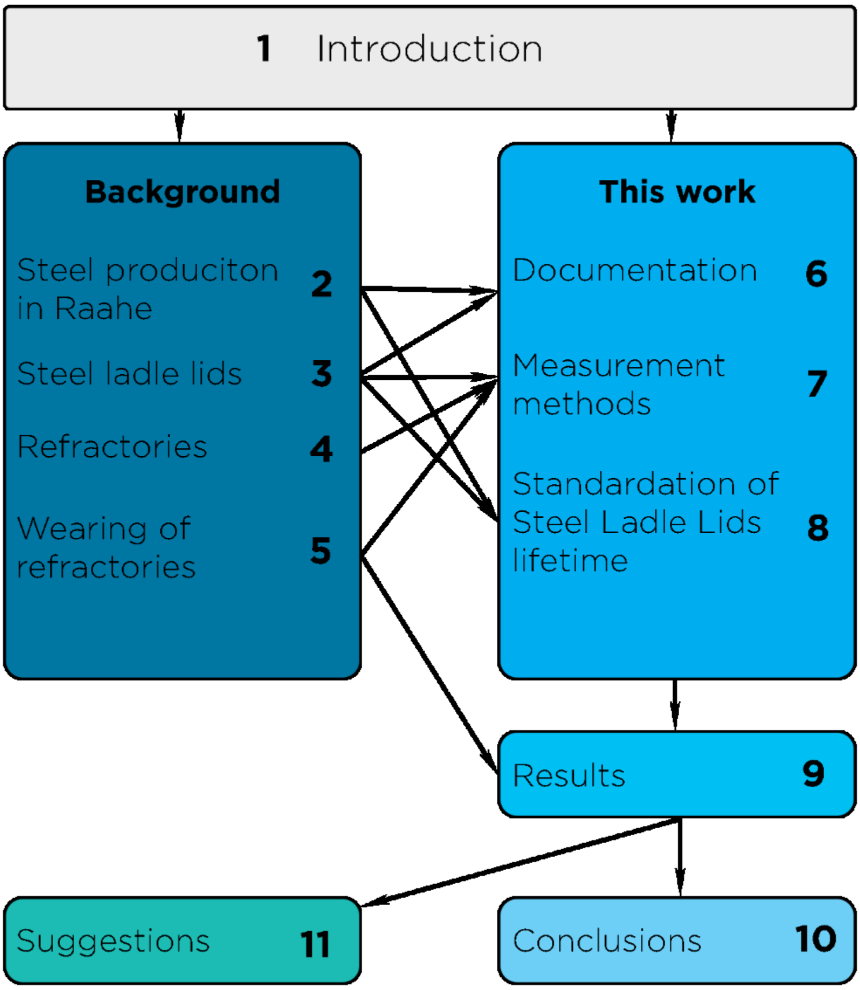


Figure 1. Structure of the thesis.

2 STEEL PRODUCTION IN RAAHE STEEL PLANT

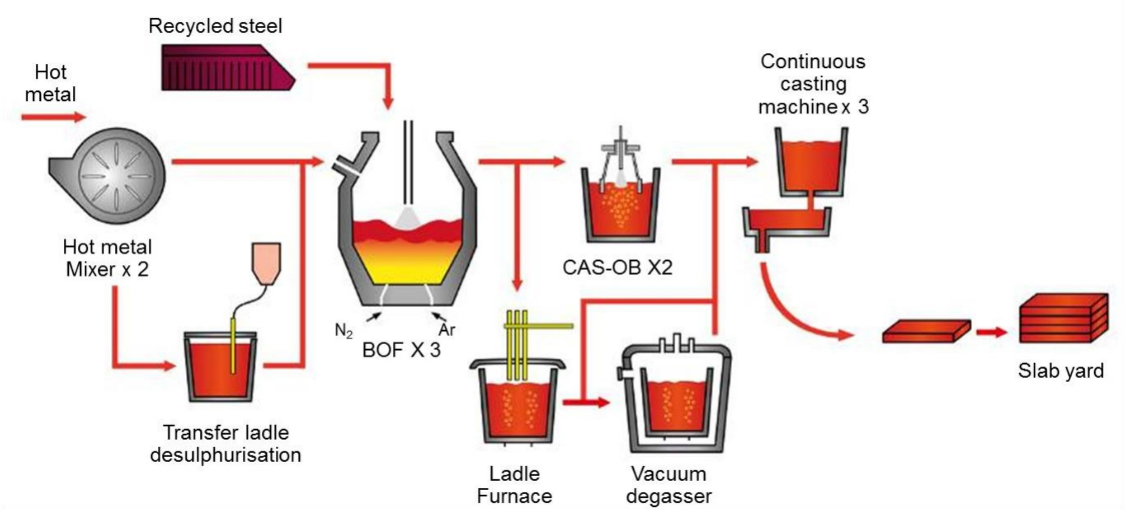


Figure 2. Schematic presentation of the steel production routes in SSAB Raahe (Ollila 2015) .

Raahe steel works is specialized in producing steel plates and strips from ore-based raw materials. The main process routes within the steel plant are presented in Figure 2. Currently, iron pellets are the main source of iron for the process chain that aims to refine them into high-quality steel products. Initially, iron oxides within the raw material need to be reduced into metallic iron. Even though SSAB is planning to get rid of all of the process steps that utilize fossil fuels, blast furnace is currently the leading method for ore-based hot metal production and is still used also in the Raahe steel plant. Blast furnaces are tall shaft furnaces that utilize coke to reduce and melt raw materials into hot metal. Even though the furnace is loaded and emptied in batches, the reactions within are ongoing continuously. Produced hot metal is poured into ladles and taken for primary desulphurization. Currently, there are two operating units on the Raahe site that provide hot metal for the needs of the steel plant.

After primary desulphurization, ladles filled with hot metal are brought on tracks to the steel plant for further processing. Crane operators skim off the sulfurous slag from the top of the hot metal and add slag formers to form a new protective layer. Hot metal is then stored in two large mixers which are simple storage units lined with refractories. Each of them can store up to 1300 tons of hot metal. Their main purpose is to dose charges for converters and act as buffers before steel production. At the same time, mixers homogenize the composition and temperature of the hot metal, which helps in production planning (Ollila, 2015).

Each of the process steps after the hot metal mixers are part of the refining process where resources are significantly more valuable. After ensuring sufficient capacity for sequent process steps, a designated converter orders a hot metal charge from the mixers. Batch size usually varies from 85 to 110 tons. Most of the charges are taken directly to the converters but some of the steel grades require very low sulphur content. These charges are taken to a secondary desulphurization station where excess sulphur is removed by injecting calcium carbide (CaC_2) into hot metal. Reagent is injected with pneumatic lance injection which creates flow that mixes the hot metal. Forming calcium sulphide rises into the slag which is later removed by skimming. After the treatment, the sulphur content is between 0.002 – 0.007 %. (Teräskirja; SSAB – Work instructions, 2019)

Hot metal is then charged into a LD-converter for refining (Figure 3). Raahe steel plant has three converters and the capacity of each unit is 125 tons. Main goal of the treatment is to produce molten crude steel for further refining. Essential parameters for measuring success are the composition and temperature of the crude steel which both are mainly controlled though oxygen blowing. LD-converters utilize a water-cooled lance to inject a jet of oxygen on the surface of the melt. The melt is stirred with inert gas fed through bottom purging. The carbon content is reduced to approximately 0.04 % depending on the steel grade. Decarburization provides a surplus of heat which may accelerate wearing of refractories. In the Raahe steel plant the excess heat is used to melt scrap metal which is inserted into a converter before the hot metal. Because a portion of the scrap is residue from later processes, this is an efficient method to improve steel plants' internal material efficiency. The target temperature of the crude steel varies between 1630 and 1750 °C. Rough alloying is also done during the converter process by controlling feed and oxidation of desired components. Depending on the oxidation rate of the alloying materials, feeding is done in different stages of the process. Refining also removes phosphorus and vanadium from the hot metal. After decarburization there is high amount of oxygen dissolved into the steel which would cause formation of carbon monoxide (CO) bubbles during casting and pores in slabs. Finished crude steel is poured though the tap hole into the steel ladle and "killed" with aluminum to remove excess oxygen (Ollila, 2012).

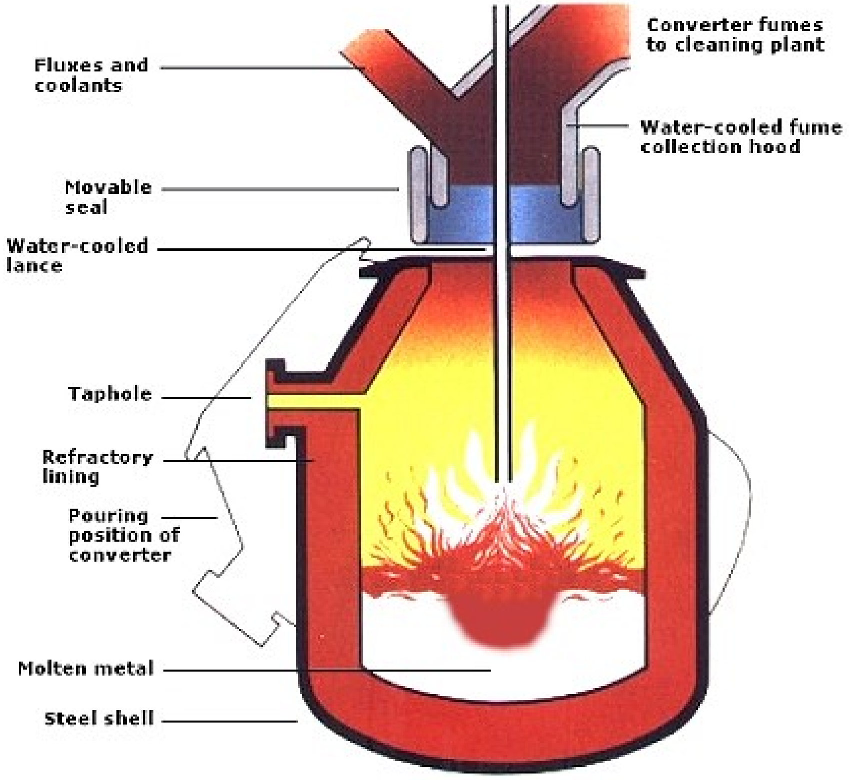


Figure 3. Schematic of LD-converter (Ollila, 2015).

After tapping, crude steel is stored within the steel ladle. Ladles are moved around the facility with both ladle cars and cranes. Desired steel grade determines into which production route and treatment the melt is taken. During each transportation, steel ladles are covered with lids to reduce heat losses. Lids are only removed for the duration of the treatment.

In secondary metallurgy the temperature control is one of the key elements in creating high quality steel. To reach alloying goal without excessive material losses temperature of the melt has to be within a certain range. Low temperatures also increase risk of early solidification and poor ladle free opening in the beginning of the casting. As a part of the temperature control steel ladle lids reduce the heat losses but do not remove the need for steel melt to be reheated. Secondary steelmaking in Raahe has two main routes that are divided by main method of heating.

First of them is CAS-OB ("composition adjustment by sealed argon bubbling and oxygen blowing") in which the crude steel is heated up chemically. During the treatment, argon is injected from the bottom of the ladle to create an open eye into the covering slag layer. To prevent undesired oxidation, the open eye is covered with a protective bell. Aluminum lump is fed through the bell and oxygen via lance into the molten steel where it oxidizes and provides heat. Needed alloying materials are fed through the bell. Twin stations at SSAB Raahe are capable to reach heating rate of 11 °C/min. Duration of the treatment varies from 20 to 40 minutes (Teräskirja, SSAB internal presentation, 2019).

Other route for secondary steelmaking usually starts with the ladle furnace, which can be used on its own or paired with the vacuum tank degasser. Ladle furnace utilizes electricity as a main source of heating. The unit at the Raahe steel plant is capable to heat 125 tons of steel at the rate of 4 °C/min. Alloying material can be fed as lumps or with cored wire feeding. Ladle furnace excels at temperature management, high inclusion cleanliness and lower tapping temperatures.

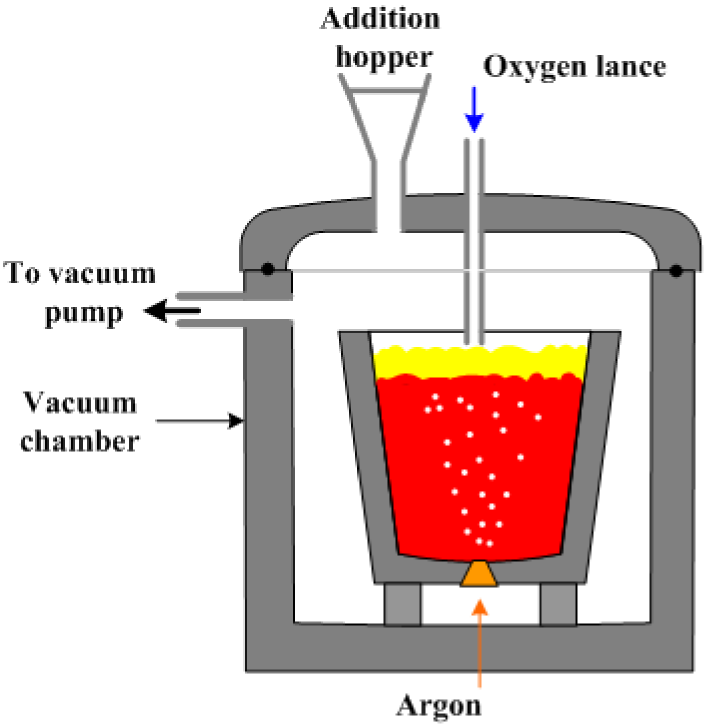


Figure 4. Schematic of vacuum tank degasser (Substech).

To create high-strength steel grades, SSAB Raahe uses a vacuum tank degasser (presented in Figure 4). The main goal is to clean steel from dissolved impurities such as hydrogen and nitrogen. If needed, the degasser can be also used to create low-carbon steel grades, however it requires dissolved oxygen in the melt. For the duration of the treatment, the ladle is sealed in an airtight container and set under a vacuum. Lowered pressure forces dissolved gases to vaporize and leave the melt. The conditions within the tank also favor the formation of carbon monoxide, which results in efficient decarburization of the steel.

The tank degasser can use both lumps and cored wire feed as a source of alloying material. Compared to other treatments, the tank degasser may also utilize cheaper carbon-rich materials which may bring significant financial savings. Other benefits of this treatment are high inclusion cleanliness with effective desulphurization and nitrogen removal. As a downside, the vacuum treatment accelerates ladle refractory wear and lowers steels temperature rapidly (Teräskirja).

After the refining, the liquid steel is transferred to continuous casting machines (CCM). During the casting steel starts to solidify and attains its slab dimensions. Continuous casting makes chaining of multiple heats possible and therefore improves production efficiency significantly. Raahe steel plant has three continuous casting machines, two of which are curved casting machines (no. 4 and 5) and one vertical bending casting machine (no. 6) (Figure 5). They are all single strand casters with adjustable strand width but have their own designated role. Twin casters 4 and 5 have a mold thickness of 210 mm and are mainly used for casting strip slabs. As a newer generation caster, the CCM 6 is a bit more versatile than CCMs 4 and 5. It has an adjustable mold size and uses soft reduction to prevent centerline segregation in the slabs. Its main function is to produce steel slabs for plate production but it may also stand in for other casters.

At the beginning of the casting, refined steel is drained from the ladle into a tundish, which acts as a reservoir before steel is poured into a mold. The tundish has an essential role in chaining multiple heats into a sequence and thus enabling continuous casting. By opening the stopper rod, steel flows into the mold where the primary solidification occurs. Cooling rate is controlled by creating a film between the strand and water-cooled mold surface. Components for the film come from casting powder, which is fed on top of the mold. The mold is then oscillated to improve flow of the casting powder and prevent steel from sticking onto the wall. After the steel shell has grown strong enough to support itself, the strand is guided through the rest of the casting machine by pulling the dummy bar. The steel strand is pulled through the machine where it is further cooled by spraying an air-mist through nozzles on the surface. The caster bends and straightens the strand as it goes through the machine. At the end of the casting the strand is cut into slabs and marked for later identification (SSAB internal presentation, 2019).

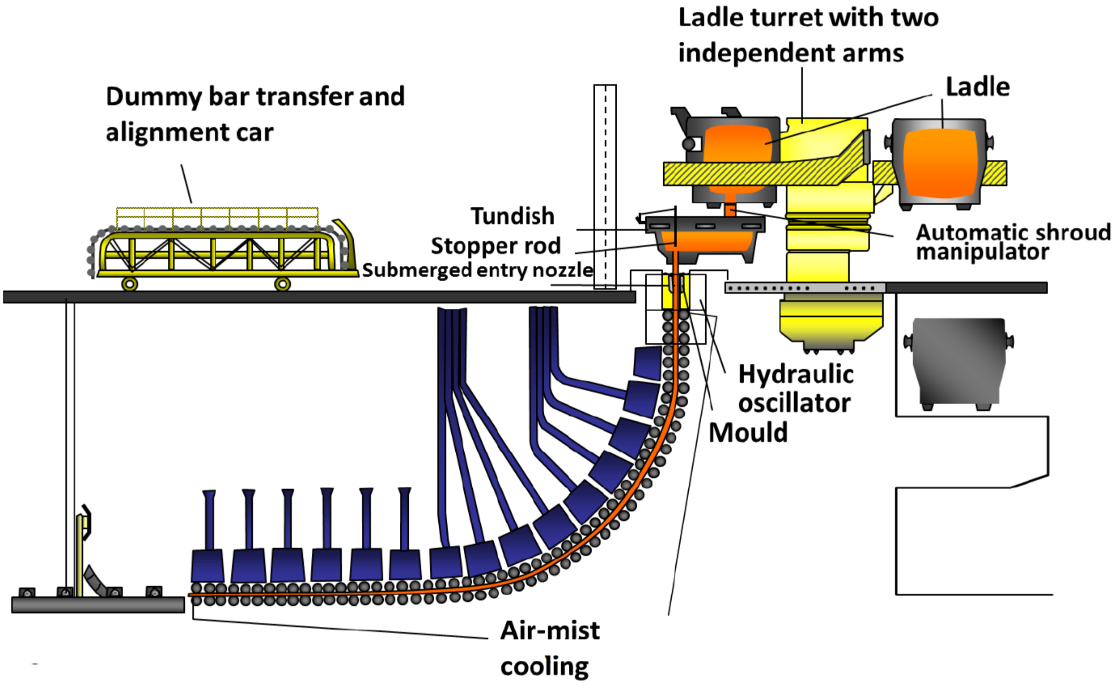


Figure 5. Schematic of continuous casting machine 6 (SSAB presentation – 2019).

3 STEEL LADLE LID

Steel ladle lids are objects used to cover the top of the steel ladle. They are mainly used to reduce heat losses during waiting and transportation but also provide additional protection for the molten steel. The main components of the lid are the refractory lining and steel framework. Like steel ladles, the lids are round shaped with a diameter of 3.6 meters. With the most recent design, total mass of the system is roughly 5800 kg.

3.1 Steel ladle lid design

Design of the steel ladle lid has been developed significantly over the year. The most significant change in the design has been the change from completely flat lining to the concave structure. Figure 6 represent a schematic presentation of the current design of the steel ladle lid.

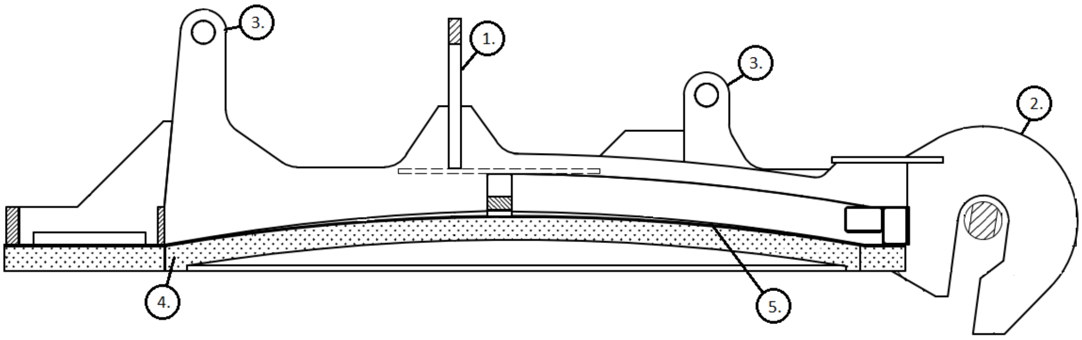


Figure 6. Schematic presentation of the steel ladle lid (Koivula, 2005).

3.1.1 Structure of the framework

The top part of the lid is generally called the framework. It is made from steel and it acts as a structure to which other components are attached. Over the years, the framework design has faced a couple of minor structural improvements, but functional components have remained unchanged. With a small amount of maintenance frameworks can be reused almost infinitely. Because the framework is the most durable component of the lid, they are individually labeled with identification numbers on both sides of the lid.

Within the steel plant, cranes are the most feasible method to move heavy objects. For this reason, lids are equipped with two lifting lugs (1 in Figure 6) which the cranes use to hook on to. The first lifting lug is in the center of the lid and it is used when the lid needs to be moved elsewhere. The second one is located in between the hinge plates (2 in Figure 6). The second lug is used if the lid needs to be in a vertical position or it needs to be flipped around.

The purpose of the hinge plates is to lock onto their counterpart at the back of the ladle. The lock mechanism is designed to be simple enough for shift attachment and detachment which are necessary in different process treatments. For most of the time lids rest on top of the ladles, but during slag pouring ladles need to be tilted. To avoid excessive maneuvers, hinge plates are made strong enough to support the weight of the lid which enables ladle tilting without the need for detaching. As seen in Figure 7, the lid can support its own weight while hanging on the ladle.

Figure 7. Lid remains attached to the ladle during slag pouring.

Lid frameworks are also equipped with three steel bearings (3 in Figure 6) which are used to store lids on racks. The bearings are distributed around the lid to make it as steady as possible during storing.

3.1.2 Design of the lining

Refractory lining (4 in Figure 6) is the part of the lid which faces most of the heat and corroding conditions. The current lining design is presented in Figure 8. An outline of the lining is made of refractory blocks which are attached to the framework with bolts. These blocks are designed to receive most of the mechanical stresses that the lid faces during normal conditions. Blocks are dried and reinforced with steel fibers to attain maximal strength and wear resistance. Currently, used blocks are 10 cm thick and have small grooves on the side that faces the center (Figure 9).

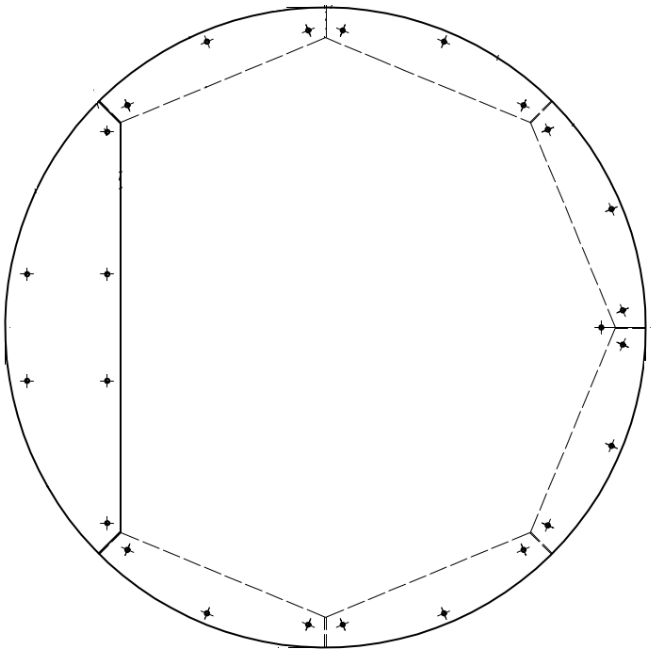


Figure 8. Schematic of the lid lining design (Based on Koivula 2005).

Surrounding blocks form an outline for the lid and are used to shape the monolithic centerpiece during casting. The lining is made with a single cast on top of the back plate and then compressed by vibrating the mold. The lid is then taken to a dryer where the excess moisture is removed. Metallic anchors welded (Figure 10) on the plate help the monolithic mass to stick on an otherwise flat surface. More information about anchoring and refractory materials is presented in Chapter 4.

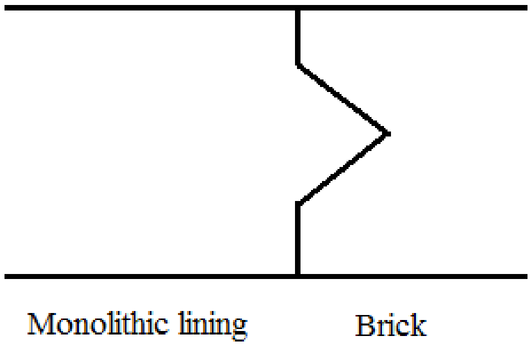


Figure 9. Cross-section schematic of the border between the brick and the lining.

Figure 10. Metal anchors welded on the back plate of the lid.

3.2 Role of the lids at steel plant

The steel plant uses mainly two types of ladles. The charging ladles are only used between the mixers and the converters. All the other process units use steel ladles for storing the steel. Figure 11 represents a process map of the Raahe steel plant where the units in which steel ladles are used are marked with red circles.

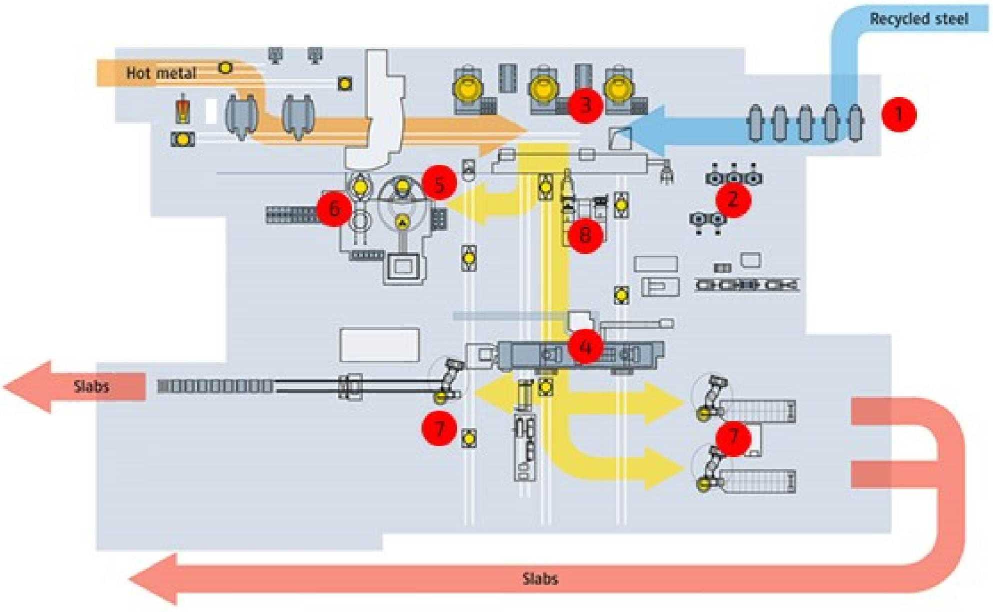


Figure 11. Material flow and process unit map of Raahe steel plant (Based on Ollila, 2015).

3.2.1 Logistics and lid circulation

New steel ladle lids are brought from the brick shop to the steel plant with a forklift. In most cases lids cannot be deployed into use directly, which means they need to be stored somewhere. Because currently there is no explicit place for storing ladle lids, they are taken to various locations. The northern part of the scrap hall (1 in Figure 11) is used as a common storage for various objects such as ladle lids. The hall provides adequate protection from the weather and is close to the steel production line and has therefore been considered as the best option for a storing location. However, in some occasions the end of the hall is too full and the lids are taken elsewhere.

During transportation and storing the lids' lining is facing upwards but before further utilization they need to be flipped around. However, there is no proper device for this procedure at the moment. Usually lids are flipped with cranes. The procedure is done by hoisting the lid into a vertical position and then slowly dragging it on the ground to turn the desired side upwards. Because wire needs to be attached onto the lug manually, some of the crane operators consider this procedure as excessive and laborious work which might be a partial reason for poor lid circulation. Flipping is usually done at the area near the ladle dryers (2 in Figure 11).

To ease these storing challenges, SSAB acquired a storing rack for steel ladle lids (presented in Figure 12). The rack is designed to hold up to three lids simultaneously but there are still a couple of challenges to overcome before it can be deployed into use. To store a lid on the rack, the lining has to be facing downwards. However, lids usually leave the brick shop with their lining facing upwards. To use the lid storing rack reasonably, the forklift requires aid from the cranes to flip the lid around. With current procedures, the benefits of the rack are considered smaller than the benefits it would provide.

Figure 12. Storing rack for steel ladle lids.

For the duration of different steel production processes, lids are separated from their ladles and stored on holders. There are two different types of holders at the Raahe steel plant. The first one, spike racks, are used at converters (3 in Figure 11) and CAS-OB stations (4 in Figure 11). Racks are located above the ladle car track and are designed to capture lids as the car drives under. As the ladle car approaches, the rack is lowered to catch lids by the rolls. Movement of the car makes the lid slide slowly further and eventually lock its position in notches at the end of the rack. Eventually the rack is lifted to its original position to prevent the lid from falling. An image of the storing system is presented in Figure 13. After the treatment the lid is attached back on top of the ladle in reverse order.

Figure 13. Lid stored on the rack near the converter (BOF).

Lid storing methods at the ladle furnace (5 in Figure 11) and vacuum degasser (6 in Figure 11) are different because these process treatments are not located on top of the ladle car tracks. At this area ladle traffic is mainly operated by cranes. For the duration of the ladle furnace treatments lids are stored on a rotary turret, which is presented in Figure 14. It is operated independently and can store up to two lids simultaneously. The turret uses hooks to grab and detach the lid from the top of the ladle. The vacuum degasser utilizes a similar storing method, but instead of a turret the hooks are attached to a sliding tray.

Figure 14. Lid storing system at ladle furnace.

Usually each lid is associated with one ladle until one of them is discarded. However, some of the shifts prefer operating the steel plant with a cycle one lid short. The reason for this arrangement is that they do not place the lid on top of the ladle between the ladle furnace and vacuum degasser. By removing one lid from the cycle, less maneuvers are needed and the hang time of the lid is slightly reduced. As a result, the ladle gets a different lid for sequent steps. On occasions of exceptionally large charges, the lid is removed before bringing them to the continuous casting machines (7 in Figure 11) to reduce total weight of the system.

Occasionally, a lid is temporarily taken out of the cycle. Because there is no specific location for storing these lids within the steel plant, they are placed lying on the ground. They are commonly found in the area between the ladle tracks or near ladle dryers but sometimes they are taken elsewhere. Without the ladle to provide heat, lids cool down to room temperature quite quickly. Because there is no device for preheating lids before introducing them back to the cycle, rapid heating causes additional stress to the lining.

3.2.2 Ladle in-line maintenance station

After each cycle the condition of steel ladles and their lids are evaluated at the line maintenance station (8 in Figure 11). Lids are evaluated visually by checking the degree of wearing in linings. According to the current station operators work instructions, lids must be discarded from the cycle when the lining has started to crumble, or the framework has been significantly damaged (SSAB – work instructions 2019). Condition of the lining is currently evaluated through a small gap between the ladle and the lid. Unfortunately, the narrow field of view and high thermal radiation makes it challenging to detect small cracks and defects in the lining. Because of the challenges in the direct evaluation, some of the operators prefer evaluating the condition indirectly. When the lining starts to wear out and crumble its capabilities to insulate decline. Cracks conduct heat onto the back plate which gradually starts to heat up. Around 500 °C, the steel surface starts glowing a dark shade of red and the brightness of the color corresponds with rising temperature. This phenomenon is called red heat and it can be used to estimate the temperature of ferrous metal with relative accuracy without measurement equipment. However, over time small amounts of dirt start to accumulate on top of the lid which makes minor changes in color easy to miss. As the temperature rises to around 700 °C, steel shines bright enough to be spotted regardless of dirt and lighting. However, to reach these temperatures the lining has to be almost entirely worn out. Exposed metal pieces heat up when the lids are being used but have enough time to cool down when stored on the racks. Hot and cold cycles weaken the steel and eventually make it lose its shape.

In most cases damaged lids remain in circulation for a duration of multiple heats, even after the defect has been observed. Additional heats increase severity of the defects and therefore makes repairing more difficult. Part of the problem is the uncertainty about the amount of the lids in the reservoir because currently there is no way to keep track of the location of the lids.

Unlike most of the refractories, the current condition of each individual lid is not recorded. Even though lids have been in use for over 20 years, there is not a target value or realistic estimate for one’s lifespan. Current estimates are based on the dates when the lid leaves and arrives back at the brick shop which also includes time spent in reservoir, on the ground or waiting for repair.

In the current refractory design, the weakest areas seem to be around the edges of the monolithic lining. Recently deployed lids usually stay in excellent condition for a long time, but it seems that the wearing rate accelerates after initial cracks occur on the surface. Worn out lining is also more prone to spalling which is harmful to steel production. Small refractory spalls have significantly poorer tolerance against the corrosive conditions within the melt and therefore partially dissolves. Even though most of the inclusions are caught in the tundish some of them passes the screening and decreases the grade of the steel.

During the process cycle the surface temperature of the lid lining varies significantly. Measured temperatures peaks around 1300°C when the lid covers full steel ladle just before cast initiation. As the lid preserves heat within the ladle, they protect each other from cool air. However, when the lid is stored on the racks, the fresh air rapidly cools down the lid. As the lid diverges from the ladle the temperature is around 1000°C but it will drop below 500 °C during tapping. The actual temperatures also depend heavily on the current production rate and number of ladles being used at the time. As there is no other heat source for the lids than the molten steel, temperature of the lids remains much lower when the production rate is lower than normal.

Over time, slag splashes form a layer of skull on top of the ladle. Uneven surface of skull prevents placing the lid on top of the ladle properly. Excess skull also restricts volume of the ladle which is why it is regularly removed at the deskulling station. For this process the ladle is set down lying on top of a rig which keeps the ladle stationary. The lid is then detached with a loader to get access to the interior of the ladle. Usually the lid is set leaning on a ladle nearby or stored on a lid holder. After that, the loader operator removes the skull with an anchor and attaches the lid back to the ladle. Various tools used for moving and storing the steel ladle are presented in Figure 15.

Figure 15. Devices at desculling station. Lid grabbing tool for a loader is hanging from the lid holder and deskulling anchor is on the ground.

3.2.3 Brick shop

The brick shop at Raahe steel plant supports steel production by providing and maintaining refractory products. One of their tasks is to assemble new and repair steel ladle lids. They have the capacity to work on two lids at a time in addition to the ones that are being dried.

Discarded lids are taken to the brick shop lining facing down and set lying on the floor. Initially, mechanics remove severely damaged pieces of the plate and cover the open areas by welding new pieces on top of them. After the framework has been restored, the lid needs to be flipped around with a crane. Possibly loose pieces of the lining are then removed by hand, and lost anchors are replaced. To improve the patches adhesion with the original lining, the glassy slag layer is occasionally shattered by chipping. After the preparations are finished, the holes in the lining are filled with patching material. The lid is then taken to the dryer to remove excess moisture. Refractory patches attain their final strength when they are deployed into use (SSAB internal document – Work instructions for mechanics at brick shop).

4 REFRACTORIES

Refractories are ceramic materials that are used in various high-temperature processes. By definition, refractories must withstand high temperatures without melting, breaking down or reacting with the surrounding substances over a necessary period of time. Generally, refractories have three main roles: act as container, provide protection to personnel and contain heat within the device (Poirier et al. 2017 [1]).

Refractories are scarcely used on their own. At low temperatures steel has far superior formability and strength compared to ceramics, which is why refractories are usually surrounded with a steel shell. A uniform shell protects the refractory lining from external impacts and holds the lining together. However, steel loses most of its mechanical properties at temperatures above 500 °C. Sufficient lining protects the shell against corroding substances and prevents the temperature from rising above critical levels.

Refractory materials consist of aggregates, binders, additives and pores (presented in Figure 16). Aggregates can be considered as the main component of the refractory product and they retain their mechanical strength and volume in designated process conditions. Binders are additives that hold refractory product together but are also considered as the weakest part of refractory. Different binders are effective only at certain stages of the products lifecycle and they have a tendency to volatilize, dehydrate or be sintered at higher temperatures. Bindings are usually divided in four groups: hydraulic, chemical, organic and ceramic bonds (Shestakov 2002). Hydraulic binders are generally used in green state (10 – 30 °C) of the product. Binder substance reacts with water and forms a solid matrix that is used to agglomerate other solid materials. Sometimes hydraulic binders can be considered as chemical ones but due to their popularity in industry they are considered here as their own group. Other common chemical binders are sodium silicate, potassium silicate and aluminum silicate. In the modern refractory industry organic binders are scarcely used but they might have some potential in replacing some of the hydraulic binders due to their smaller carbon footprint. Ceramic binding occurs at temperatures above 800 °C where particles are held together through sintering (Schacht C. et al. 2004). Role of the additives is to enhance properties or behavior of the refractories in a designated way. Some of them are utilized during preparations stages, for example to improve installations, enhance fluidic properties or speed up hardening. Other additives have impacts on the properties of the final product. Generally, they have some desired properties but would not withstand the process condition on their own. For example, carbon particles combusts at relatively low temperatures without a protective environment, but as a refractory additive they provide high thermal conductivity with low thermal expansion and high resistances towards thermal shock. Finally, pores are empty spots inside the materials. They are usually formed during the drying process and are essential in terms of thermal conductivity (Poirier et al. 2017 [1]).

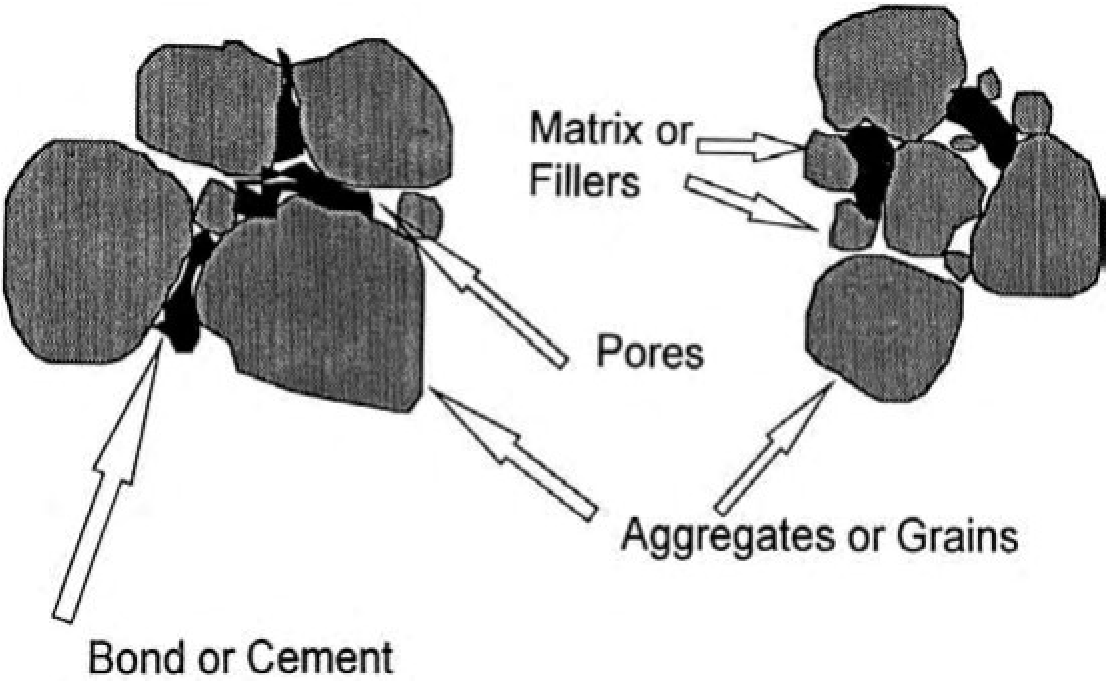


Figure 16. Schematic of refractories' textural elements (Landy R. 2004).

Refractory products can be divided into two categories: shaped and monolithic products. As the name implies, the shaped products are made into specific shapes and sizes. These bricks and elements are easy to apply into their designated place but are poorly adjustable for other occasions. In general, bricks are designed to attain maximum density and provide strength to the finished lining. Monolithic refractories include various kinds of products, for example ramming mixes, mortars, coatings, castables and gunning mixes. They are more versatile than their brick counterparts but are in general a bit weaker against mechanical stresses. They are applied directly to the designated location where they attain their final properties (Schacht C. et al. 2004).

4.1 Classification based on composition

Refractory types can be classified in numerous ways but in general they are classified by the chemical composition of the main component. One way to classify refractory products is presented in Table 1 in which products are divided into four main groups: high alumina, acidic, basic and special products.

Table 1. Classification of refractory product families according to ISO 1109 standard (Buhr A. et al. 2017).

Product family	Share of main component
High alumina, Group 1	Al_2O_3: ≥ 56 %
High alumina, Group 2	Al_2O_3: 45 % - 56 %
Fireclay/Chamotte	Al_2O_3: 30 % - 45 % SiO_2: 50% - 80%
Semi-silica	SiO_2: 85 % - 93 %
Silica	SiO_2: ≥ 93 %
Basic products:	
Magnesia	MgO ≥ 80 %
Magnesia chrome	55 % ≤ MgO < 80 %
Chrome magnesia	25 % ≤ MgO < 55 %
Chromite	Cr2O3 ≥ 25 %
Forsterite	MgO < 25%
Doloma	
Special products	Materials based on Carbon, Graphite, Zircon silicate, Zirconia, Carbides, Nitrides, Borides or Spinel Materials based on several Oxides Materials based on pure oxides High purity materials

4.2 Refractories' properties

Refractory properties are used to predict a product's performance in a designated application. They are usually classified into physical, thermal, chemical and ceramic properties. Each of these properties may vary in different environments which have led to standardization of measurement methods. In this chapter the key properties of the refractories according to ASTM standardization are listed in Table 2.

Table 2. ASTM standard test codes for refractory properties (Based on Banerjee S. 2004, Updates by ASTM).

Property	Type	Standard code
Bulk density and apparent porosity	Physical	ASTM C20 – 00(2015)
Cold compressive strength and modulus rupture	Physical	ASTM C133 – 97(2015)
Hot modulus of rupture	Physical	ASTM C583 – 15
Abrasion resistance	Physical	ASTM C704 – 15
Thermal expansion and creep	Strength	ASTM C832 – 00
Thermal shock and thermal cycling	Thermal	ASTM C1171 – 16
Thermal conductivity (refractory brick)	Thermal	ASTM C202 – 19
Thermal conductivity (refractories in general)	Thermal	ASTM C201 – 93
Rotary slag testing for refractory materials	Chemical	ASTM C874 – 11
Hydration resistance	Chemical	ASTM C465 – 18

Standardized physical properties for refractories are density, porosity, strength and abrasion. Other physical properties are often derived from measurements of these properties and are therefore used to select suitable refractories for specific applications. In general, high porosity leads to low density. This ratio can be used to predict properties like strength, abrasion and gas permeability. Due to thermal expansion, density is usually given at several temperatures. Refractories' strength is also given in cold and hot strengths. Cold strength describes the behavior of the refractories before and during the installation, whereas hot strength indicates performance at elevated temperatures. In general, shaped refractories are stronger than monolithic products as they develop strength during processing and possible firing. Whether the cold or the hot strength is more important depends on designated application, although in general hot strength is more important. Abrasion resistance describes how well a refractory surface endures abrasion from high velocity particles. It measures strength of the bonds between refractory particles. Good abrasion resistance is important in appliances that handle solid materials such as rotary kiln (Brosnan 2004).

Thermal properties indicate how refractories behave at elevated temperatures or during heating and cooling. Unlike many other materials, refractories usually do not have a specific melting point. Instead they have a softening point above which the bonding system starts to break causing the products to lose their structure and shape. Hence, the temperature within the designated application should not exceed the softening point of the given refractory material. However, physical properties of the refractories change even at lower temperatures. Because most of the refractory materials expand during heating, manufacturers provide thermal expansion values for their product. This measure describes permanent changes to the product when exposed to different temperatures and then cooled down. This phenomenon might cause tension between two objects and therefore accelerate refractory wear, but it can be also used to tighten gaps between loose bricks. Refractories that must withstand recurring heating and cooling usually benefit from low thermal expansion values. Alternating heating and cooling is generally called thermal shock. Thermal shock resistance is mainly defined by properties of the binder material. Hard and rigid systems are unable to recover from recurring expansion and shrinkage causing the material to crumble. Microstructural cracks and defects in matrix generally improve a material's thermal shock resistance. Refractories' thermal conductivity describes how well the material conducts heat from the hot to the cold face. Refractories' ability to insulate is often desirable feature in most of the appliances as it helps to save energy and protect other equipment from heat. Refractories can also receive and store heat from outer sources. Materials with high heat capacity are often used on applications where there are no constant heat sources (Brosnan 2004).

Refractories are heterogenic materials which means that their chemical properties can be examined in multiple ways. Usually the refractory particles are the most tolerant part of the material, whereas the binders tend to be significantly weaker. Therefore, chemical properties include chemical analyses of the refractory materials, bonding type and ability to resist a certain corrosive environment, all of which are mainly dictated by the chemical composition of the material. Materials' suitability for a certain environment is generally determined by basicity or acidity of the material. It is determined by the ratio between acid and basic components. In practice, a rough estimate from the nature of the material is estimated from the ratio of basic quicklime (CaO) and acidic silica (SiO_2). In the steel industry the term "v" or "c/s" ratio is often used to define the border between basic and acid chemistry which considers more components. The acid-basic classification for the refractory materials relevant to the steel industry are presented in Table 3. It is also applicable for estimating the nature of the slag (Brosnan 2004).

$$V = \frac{c}{s} = \frac{[CaO] + [MgO] + [FeO] + [MnO] + \cdots}{[SiO_2] + [P_2O_5] + [Al_2O_3] + [Fe_2O_3] + [Mn_2O_3] + \cdots}$$

Where V-values exceeding 1.0 are treated as basic materials and slags, whereas values below that are considered as acidic (Brosnan 2004).

Table 3. Classification of oxides by their acidity and basicity (Nivala M. 2015)

Material	Components	Nature
Silica	SiO_2	The most acid
Chamotte	$Al_2O_3 + SiO_2$	
Zirconium	$ZrO_2 + SiO_2$	
Zirconia	ZrO_2	
Graphite	C	Neutral
Corundum	Al_2O_3	
Forsterite	$2MgO + SiO_2$	
Spinel	$MgO + Al_2O_3$	
Magnesia-chromium	MgO + Cr	
Magnesia	MgO	
Dolomite	CaO + MgO	The most basic

Refractories that have similar acidity with the liquids they are in contact with are more resistant to chemical corrosion. Corrosion reactions can be seen as the system reaching for a balance between the material and the corroding substance, hence similar compositions have slower reactions. Because slag in steel refining is considerably basic, the working lining in the slag line of the ladles is made from basic materials. However, the lower part of the ladles' working lining is made from acidic materials because it better endures direct contact with steel (Brosnan 2004).

Weaknesses of each refractory product may be supplemented by creating a layered structure for the lining. The lining used in steel ladles at Raahe consist of three layers, which are the insulation, back and working lining. Insulation lining has a low thermal conductivity and therefore protects the shell of the ladle from the heat. However, it has poor chemical and mechanical resistances. The working lining is the part which is in contact with the molten substances. Essentially it has low solubility into the steel which results in lower amounts of impurities in the products. Working lining is easy to repair and patch but is relatively short-lived. The role of the back lining is to act as a barrier between these two layers as it endures brief contact with the melt. It enables mechanical removal of the working lining without damaging the insulating layer (Banerjee S. 2004).

4.3 Refractory materials in steel ladle lids

Currently, the design of the lining is a single-layered lining made from alumina-silica refractory products. A more specific composition of the material provided by the manufacturer is presented in Table 4.

Table 4. Material information for refractories used in steel ladle lids without steel fibers.

		Brick	Monolithic mass	Patching mass
Chemical analysis				
Al_2O_3	%	63	66	77.0
SiO_2	%	32	30	12.0
CaO	%	3	4	4.0
Fe_2O_3	%	<1	<1	<1
Physical properties				
Bulk density	g/m^3	2.20	2.3	2.7
Products density	g/m^3	2.24		
Recom. max temperature	°C	1300	1400	1400

Each of these products are further strengthened by adding steel fibers into the mixture. Fibers provide better mechanical strength although they might lower the softening temperature of the product. They also prevent partially loose pieces of lining from falling off.

Mineralogically, the main component of these refractory products is mullite. Formation paths and a rough estimate of the products' final composition can be derived from the alumina-silica binary phase equilibrium diagram presented in Figure 17. Mullite is formed as a reaction product when heating a mixture of alumina and silica. Composition of the pure mullite is 71.6 w-% and 28.4 w-%, noted as 'mullite ss' in Figure 17. It possesses excellent refractory properties for a compound exhibiting a melting point of 1850℃. By decreasing the amount of alumina, the excess SiO_2 exists as cristobalite and glassy phases. These phases melt at temperatures above 1595℃ and therefore have a significantly lower theoretical maximum application temperature. Above 72 w-% of Al_2O_3, the compounds have solidus located at 1840℃. Excess alumina appear as corundum, which has a melting point of 2050℃ (Brosnan 2004).

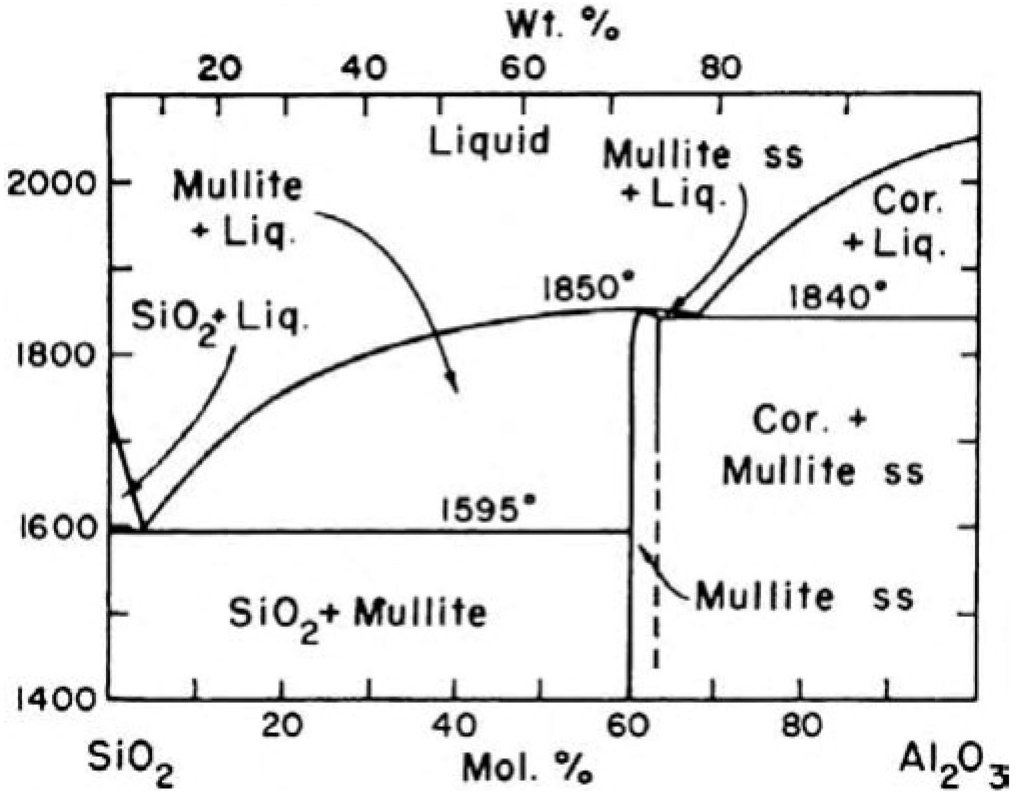


Figure 17. The alumina-silica phase equilibrium diagram (Brosnan D. A. 2004).

4.4 Anchoring for monolithic lining

When compared to brick, the use of monolithic lining has various advantages. They are applicable regardless of the shape of the vessel, form a seamless lining and generally provide faster installation time. However, on their own they stick poorly to even surfaces due to lack of adhesion to the vessel shell and inability to support themselves. These problems can be fixed with anchors. Anchors are metallic or ceramic devices attached on the surface of the vessel which prevent refractory material from falling off. The development of anchoring methods has been essential in the growing popularity of monolithic linings.

Because metallic anchors are significantly cheaper than ceramic ones they are generally used in all appliances where temperature remains below 1100 °C. They are welded directly into the surface of the vessel and are then covered with monolithic refractory material. One example of a typical metallic anchor is presented in Figure 18. Because anchors' properties are far different than the surrounding refractories, it is essential that they are the right size. Recommended anchor size is just below 80 % of the thickness of the lining (Harbison-Walker 2005). Oversizing the anchoring may create unnecessary pressure towards lining due to insufficient thermal insulation. When exposed to high temperatures the metals in general expand significantly more than the surrounding refractory material. In a sealed environment the stress caused by the expanding material is directed into the lining. Repeated expanding and shrinking may cause cracks in the lining. On the other hand, an undersized anchor will not provide enough adhesion during casting causing challenges in placing them (Goulart C. A. et al. 2015).

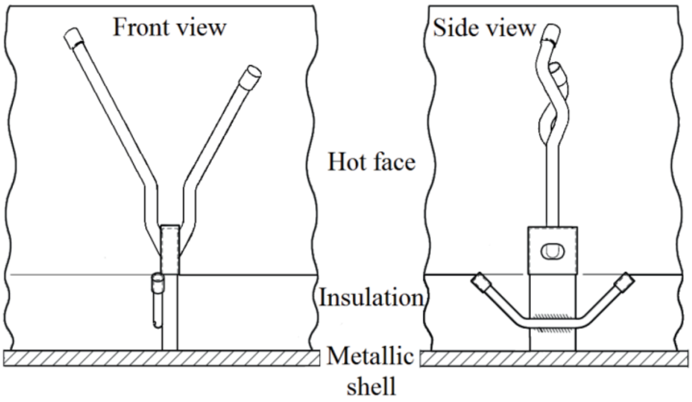


Figure 18. Example of metallic anchoring (Goulart C. A. et al. 2015).

When the application temperature exceeds 1100 °C the use of ceramic anchors becomes more feasible than metallic ones. Ceramic anchors are basically small refractory bricks that have some attachment mechanism on the appliance surface. Their surface is rough and grooved to maximize adhesion between them and the monolithic mass. One example of a typical ceramic anchor is presented in Figure 19. The composition of the ceramic anchors is often chosen to correspond with the surrounding lining, thus exhibiting similar properties at elevated temperatures. Because of similar behavior, the anchors do not need an insulating cover against the heat and are therefore sized to match the thickness of the lining (Harvison-Walker 2005).

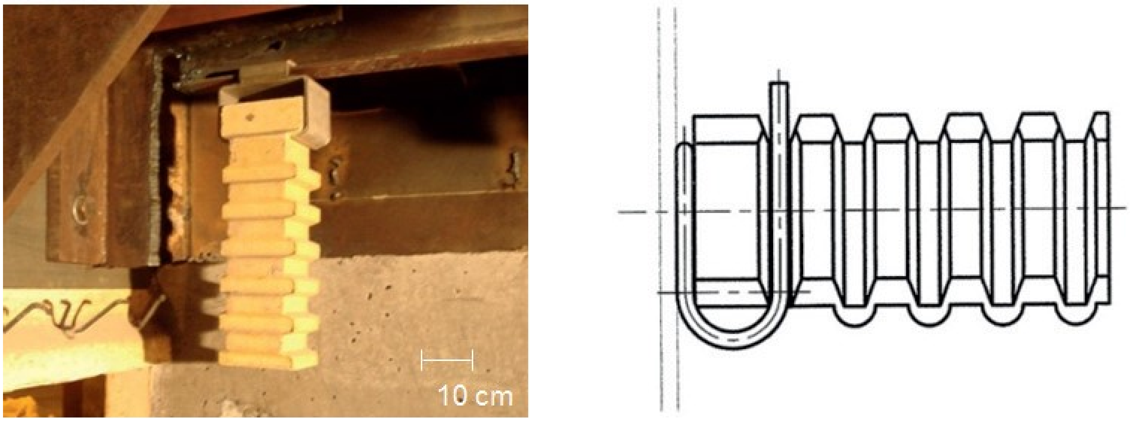


Figure 19. Photo and schematic of a typical ceramic anchor before installation (Goulart C. A. et al. 2015).

Alongside the anchor size and the material, placement patterns and spacing play significant roles in the endurance of the final product. Dense placing creates unwanted irregularities in the monolithic lining and therefore increases the risk of defects. Infrequent placing, however, lacks sufficient adhesion. Currently, the spacing is mostly determined based on the previous experiences but mathematical models are being developed. The appropriate spacing is related to the placing patterns of the anchoring. Systematic patterns provide an even distribution of the burden, therefore enhancing the properties of the lining. Common examples of these patterns are presented in Figure 20 (Goulart C. A. et al. 2015).

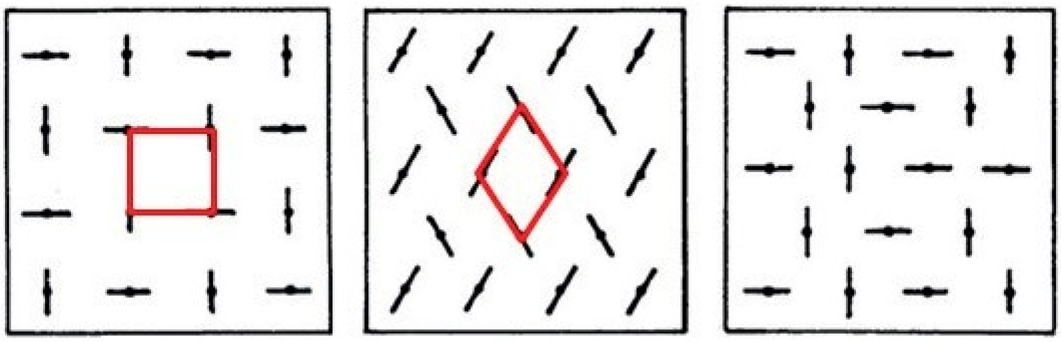


Figure 20. Usual anchoring patterns for metal anchors (Goulart C. A. et al. 2015).

5 WEARING OF REFRACTORIES

Even though refractories are designed to endure a corrosive environment at elevated temperatures, they do eventually wear out. Insufficient lining can cause severe safety issues and reduce their efficiency during operations. Refractories are usually used in reactors which contain molten phases that have chemical reactions with the refractory material resulting in consumption or wear of the refractories. Unlike most refractories used in steel production, steel ladle lids are not designed to be in direct contact with these substances but are still exposed to molten slag splashes regularly. In addition to chemical wear, the material may face other sources of stress which accelerates these reactions or breaks the structure of the material on its own. In this chapter the basic wearing mechanisms are presented and their relevance to the steel ladle lids is estimated (Poirier et al. 2017 [1]).

Like refractory properties, their wearing mechanisms are also divided into three groups: mechanical, thermal and chemical wearing (Figure 21). Albeit these mechanisms are presented on separately, the real refractory wear is often combination of these.

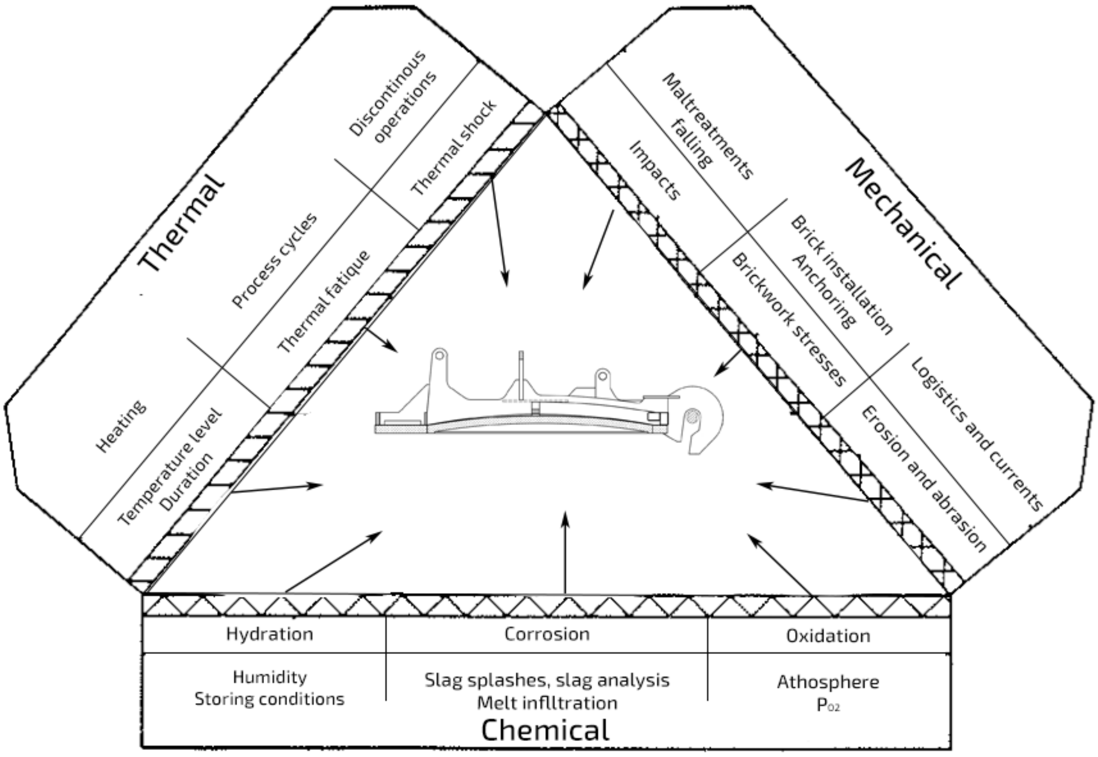


Figure 21. Wear stress on the refractory lining of steel ladle lid (modified from Helelä 1986).

5.1 Chemical wear

Chemical wear is caused by the reactions between refractory lining and the fluids the material is in contact with. Commonly, these substances are molten metals, liquid slags or surrounding atmosphere. Because of the heterogenous structure of the refractories, the reactions may occur with the refractory particles themselves or with the binder material. Chemically dissolved refractory material may cause impurities in the melt.

Reactions between the refractory material and metallic substances are commonly reduction-oxidation reactions (redox). In these reactions the oxidation states of certain elements change resulting in new compounds. All these reactions are driven by thermodynamics. The reaction causes the most unstable oxide compound to dissolve from the lining into the molten metal. A substance’s tendency to oxidize can be determined by calculating the Gibbs free energies at a designated temperature. The Ellingham diagram (Figure 22) presents plotting of Gibbs free energy as a function of temperature for pure substances. Substances that are lower on the diagram have a higher tendency to oxidize and thus remain in oxide form (Poirier et al.2017 [2]).

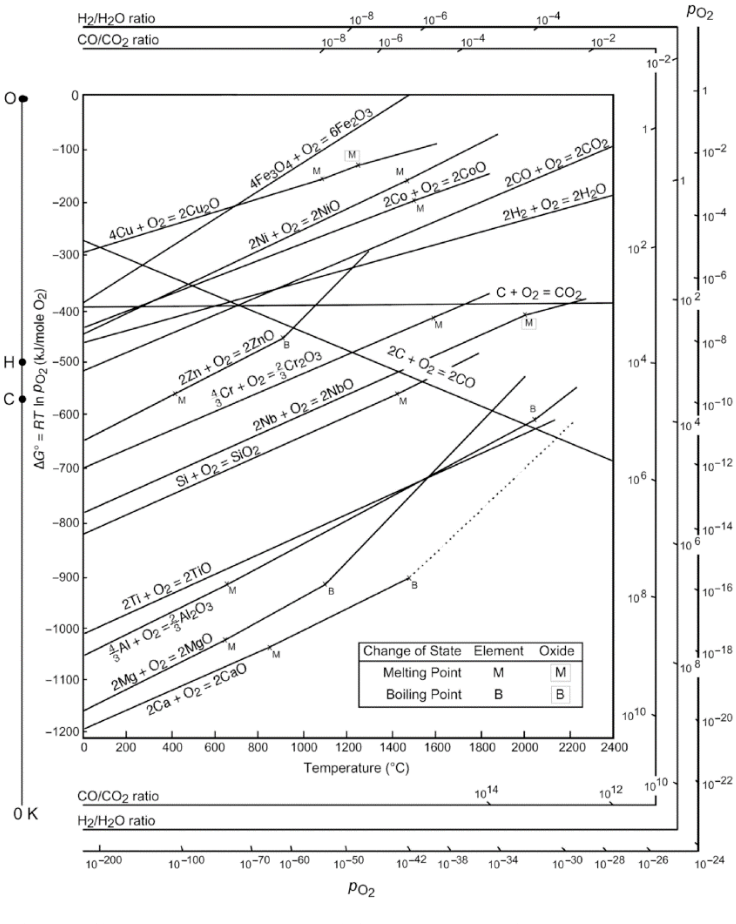


Figure 22. Ellingham diagram for pure oxide compounds (Meier G.H. 2014).

As seen in Figure 22, the main components of the refractory materials (alumina, silica, magnesia, etc.) have a high tendency to remain in the oxidized form at elevated temperatures in the presence of most metals. However, the properties of the refractory material can be enhanced with other components such as carbon. Free carbon particles have a high tendency to oxidize when coming in contact with FeO, which is one of the main components of the slag.

Because both slag and the refractory material consist mostly of oxide compounds, the role of the redox reactions in refractory corrosion is relatively small. The corrosive reactions between these two phases are mainly defined by the differences in acidity and basicity of the compounds. In general, the reactions try to find balance in the system which is why substances with similar composition have very low reactivity with each other. Respectively, significantly different substances have high reactivity with each other and consume the lining rapidly (Poirier et al. 2017 [3]).

Even in otherwise favorable conditions the reactants need to be in contact with each other for reactions to occur. Corrosive reactions can be significantly hindered by reducing the amount of the reaction area defined by the characteristics of the refractory material and wettability of the contained melt. In general, porous materials have a larger surface area for potential reactions compared to dense materials but depending on the type of the liquid, the entire area may not be fully utilized. Wetting describes liquids' ability to maintain contact with a solid surface. Figure 23 represents different types of wetting. Scaling goes from 0° to 180° where low contact angles indicate good wetting capabilities for the liquid (Poirier et al. 2017 [4]).

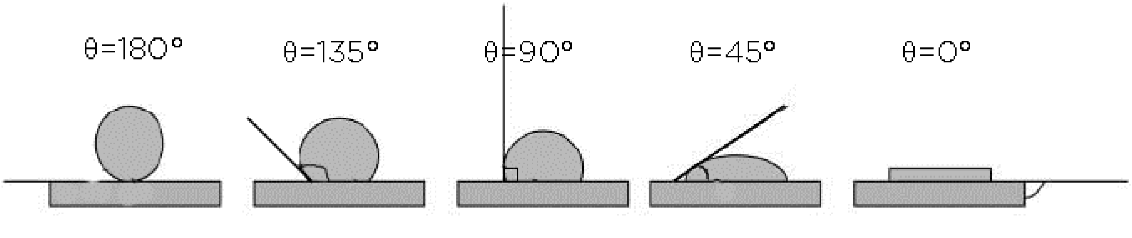


Figure 23. Different degrees of wetting (Garai R.M. et al. 2005).

Because the surface of the refractory material has some roughness on a microstructural level, the liquids with poor wettability (θ>>90°) can only attain a limited amount of contact points with the solid resulting in a small surface area on which reactions may occur. The liquids that have contact angles below 90° can infiltrate pores on the surface spontaneously. Size of the pores determines how well and deep the liquid can reach (Poirier et al. 2017 [4]).

The chemical wear of the refractories may not always be imminent. The wearing may be a result of multiple reactions in which new phases are being formed and these interphases replace the original structure, eventually breaking it. As the lining wears out, the slag has more opportunities to infiltrate the lining, thus accelerating the wearing rate even further. Mechanical cracks and other defects in the surface help the liquid penetrate the matrix and accelerate the wearing rate significantly. An example of the refractory slag interface is presented in Figure 24 (Brosnan 2004).

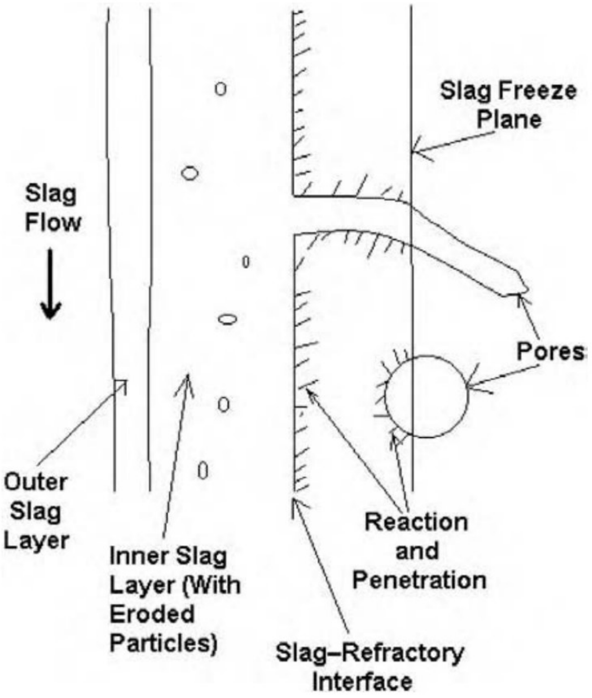


Figure 24. Cross section of the interface between slag and refractory (Brosnan 2004).

Even though the refractory materials reactions with the atmosphere in normal conditions are negligible, occasionally it has a significant impact on refractory wear. During vacuum treatment, the air surrounding the ladle is drained which sets suitable conditions for steel refining. However, the vacuum increases the slag's capability to infiltrate the pores of the lining therefore wearing it significantly faster when compared to other treatments (Guo M. et al. 2007).

5.2 Thermal wear

Thermal wear of the refractory material is caused by the elevated temperature level or its changes. The wear can be observed as cracks and thermal stresses within the material. Severity and the location of the stresses are affected by the structure of the material, its properties, heating/cooling rate and current temperature.

The highest theoretical application temperature for refractories is usually determined by the softening point of the material, above which it loses most of its strength leaving it more vulnerable against other stresses. The softening point of each material is determined by its mineralogical and chemical structure. In practice, the recommended application temperature for refractory material is significantly below the actual softening point because changes in the structure may occur even at lower temperatures.

Most of the materials refractories expand slightly as the temperature rises. Minor expansion is generally considered as beneficial because small gaps are sealed between the bricks. However, tight brickwork and uneven heat distribution causes stresses in the lining which eventually causes micro-cracks in the materials structure. After the initial cracks have formed, their growing rate usually accelerates. When material is cooled, it starts to shrink. Refractories' property to recover its original condition is described as thermal shock resistance. Once heated up to process conditions it is advisable to avoid unnecessary cooling of the refractory material if possible. Even the most thermal shock-resistant materials cannot recover from multiple heating cycles.

One of the most damaging sources of thermal stress is rapid changes in temperature. Unevenly expanding material causes severe stresses between the particles and breaks the binding structure. Materials with high thermal conductivity endure these stresses better because they can distribute the heat within the material more evenly (Poirier et al. 2005 [2]).

5.3 Mechanical wear

Refractories' mechanical wear is a result of static or dynamic load that the lining must face. Wear can often be observed as fractures which weaken the strength of the refractory and accelerate chemical wear rate by increasing surface area for reactions. Refractories tend to be fragile against mechanical stresses especially at lower temperatures, but attain more plastic properties during heating. Although plasticity improves strength of the material, it hinders its ability to recover (Banerjee et al. 2004).

Dynamic load consists of sudden impacts towards the refractory lining. Although some of the impacts might be necessary for the process itself (such as charging of the burden materials), most of them are the result of maltreatment or other abbreviation. Steel ladle lids face these stresses at least during two occasions: flipping and as a result of falling. With current flipping procedures the weight of the lid is briefly on the tip of the brick causing stresses towards it. Similarly, if the lid falls off it may cause bending of the hull and shatters the structure of the lining resulting in imminent discarding of the lid.

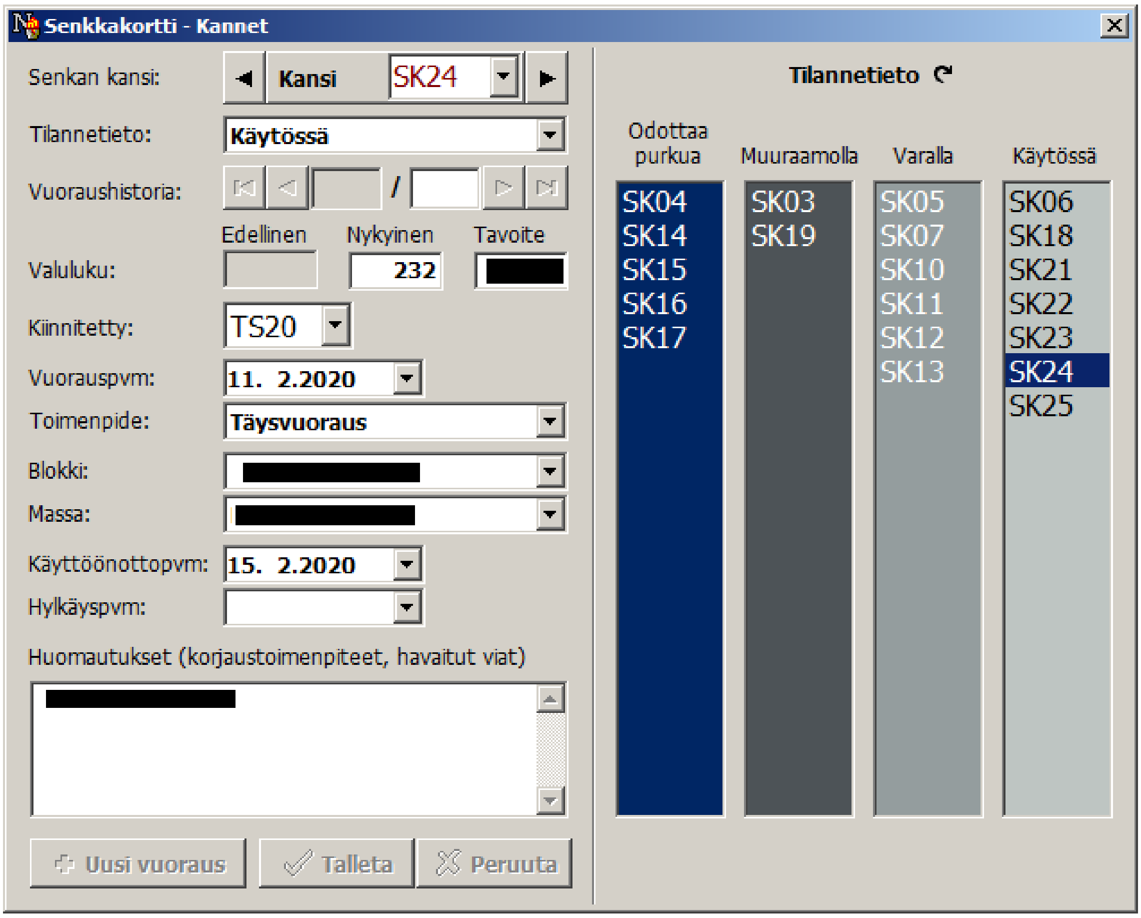
Static stresses occur within the lining and during contact with other materials. They are often relatively small but can add up and become more significant. For instance, refractory materials at the bottom of the vessel support all the burden of the material above in addition to their own weight. Also, as the temperature rises, the material starts to expand and tighten the seams between the bricks. Stresses between the bricks are designed to be well below the strength threshold of the material, but even minor stresses can change the properties of the materials in certain conditions. A phenomenon called creep occurs when a material's structure changes irreversibly as a result of constant stresses and elevated temperature.

Refractories face erosive forces when in contact with moving liquids and solids. In addition to abrasion, the movement of the liquids also accelerates chemical wear. During steelmaking, various injections and jets are used to homogenize the melt by creating currents into the melt. Optimization of the process conditions is often a compromise between optimal treatment conditions and refractory wear. By increasing the jet and making the current more turbulent, the mixing of the batch is improved but it also accelerates eroding forces.

6 DOCUMENTATION

The steel ladle lids have been developed significantly over the years, however due to the lack of documentation it is hard to quantify the significance of these changes. One of the main goals for this thesis was to develop means to reliably store information about the lids and set the groundwork for future studies. In this chapter, the basic functions of the 'steel ladle lid' card, which was created as a tool for storing and browsing data on the steel ladle lids, are presented.

The card was created on the SSAB Raahe steel plant's internal data management system (NEUVO) which has a key role for most of the operations. The card's design was based on multiple other tools within the system and developed with a user interface from which all the necessary information concerning the lids can be seen at once. Layout of the steel ladle lid card is presented in Figure 25.



Senkan kansi: Kansi SK24
Tilannetieto: Käytössä
Vuoraushistoria: /
Valuluku: Edellinen: — Nykyinen: 232 Tavoite: [redacted]
Kiinnitetty: TS20
Vuorauspvm: 11. 2.2020
Toimenpide: Täysvuoraus
Blokki: [redacted]
Massa: [redacted]
Käyttöönottopvm: 15. 2.2020
Hylkäyspvm:
Huomautukset (korjaustoimenpiteet, havaitut viat): [redacted]

Tilannetieto

Odottaa purkua	Muuraamolla	Varalla	Käytössä
SK04	SK03	SK05	SK06
SK14	SK19	SK07	SK18
SK15		SK10	SK21
SK16		SK11	SK22
SK17		SK12	SK23
		SK13	SK24
			SK25

Figure 25. Main view of steel ladle lid card.

6.1 Steel ladle lids’ lifetime recording

The first part of the card is designed to record and display information about individual lids. A lid’s cycle is set to reset at the brick shop where a new data sheet is created and the previous one is saved on the history database. Workers at the brick shop select the refractory material and define the procedures done to the lid. Based on these features, the card displays the target amount of heats for that lid. The card automatically saves the dates of casting, deployment and discarding based on the change of status.

After the lid is defined as ‘Deployed’ it is possible to attach it to a ladle. An individual lid’s heat count is based on use of the ladle they are attached to, as each heat has its own designated ladle. Validity of the attachments is checked as the ladle arrives to the ladle in line maintenance station and when ladle or lid is discarded. Possible observations and special arrangements around the lid can be typed in the free text zone of each lid.

6.2 Lids status and reservoir

The other half of the card is designated to give a real-time view of the current location of the lids. The goal was to attain real-time estimates of workload and reservoirs in different places. Possible locations of the lids were heavily simplified as the exact location of the lid is not that important. The possible statuses are ‘Deployed’, ‘Discarded’, ‘Being repaired’ and ‘In reserve’. A typical cycle is presented in Figure 26. Changes in the status are made manually by the operators at the ladle in line maintenance station or by the workers at the brick shop where the ‘In reserve’ and ‘Discarded’ statuses are set.

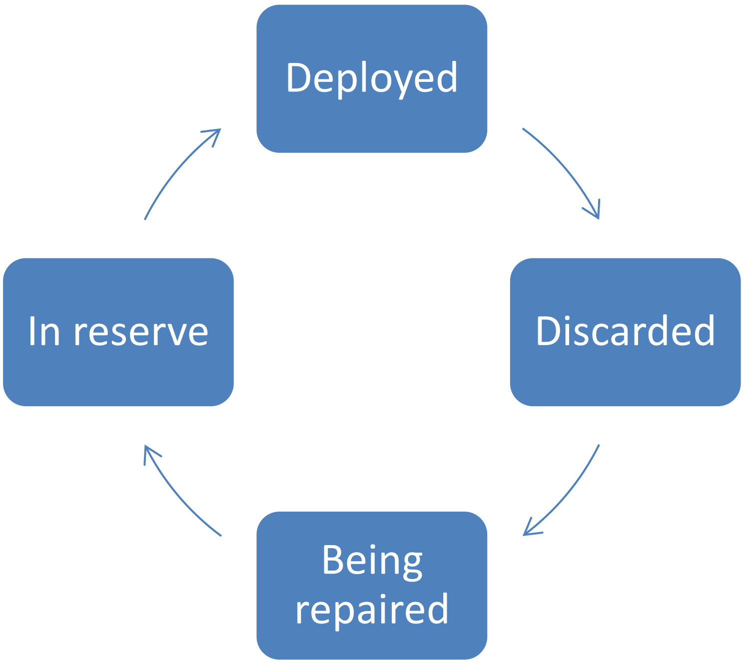


Figure 26. Common status cycle for the steel ladle lids.

Lids that are in use at the steel plant or standing by within immediate reach are defined as deployed. As a rough generalization, as long as the lid remains within the steel plant, it is defined with this status. To prevent accidental misuse, the ‘Deployed’ status prevents creation of a new sheet for that lid. After the lid has been taken out of the cycle, excluding temporary removals, its status is changed to ‘Discarded’. They have no designated location but are usually taken to the yard near the brick shop. ‘Being repaired’ status indicates that the lid is currently at the brick shop. After the lining has dried, the workers at the brick shop change the status to ‘In reserve’. These lids are either finished at the brick shop or taken to the end of the scrap hall.

7 MEASURING METHODS FOR LID CONDITION

The measuring of lids' lining conditions is essential in terms of efficiency and safety in the long run. By measuring and monitoring the condition of the lining, the lids can be used efficiently as long as they remain in excellent condition and can be discarded in time. Detecting the abnormalities in the lining in time can bring significant savings in material losses, workload and therefore financial savings are also realized.

Lack of systematic measurements causes overuse and therefore excessively worn out lids. Severe defects in the lining acts as a channel for heat to escape from the ladle resulting in significant heat losses. Because proactive temperature control is essential for steelmaking, unpredicted heat losses increases the risk of missing the target temperature and composition. Crumbling refractory material also causes inclusions into the melt which in large quantities downgrade steel quality.

Ideally, steel ladle lids require direct measurement of the thickness of the lining which would give data from local refractory wear. However, these changes would require large investments in changing the process devices and measuring equipment, which has led to consideration of indirect measuring methods.

7.1 Currently used methods

Visual estimation is currently the only way the condition of the steel ladle lids is evaluated. The condition of the lid is usually checked when the ladle is taken to the ladle in line maintenance station. Operators are instructed to check the surface of the lining through a gap between the lid and ladle for clearly visible defects.

As part of visual examinations, the color changes on the backplate of the lid has been a convenient method to detect possible defects. The phenomenon is based on thermal electromagnetic radiation emitted by the heated object, which in this case is the steel plate. According to Planck's law, after a certain point the color of any heated material is solely determined by its temperature (Tomokazy K 2007). Depending on its temperature, solid steel can attain colors from dark red to yellowish white. Different color shades represent certain temperatures which are presented in Figure 27.

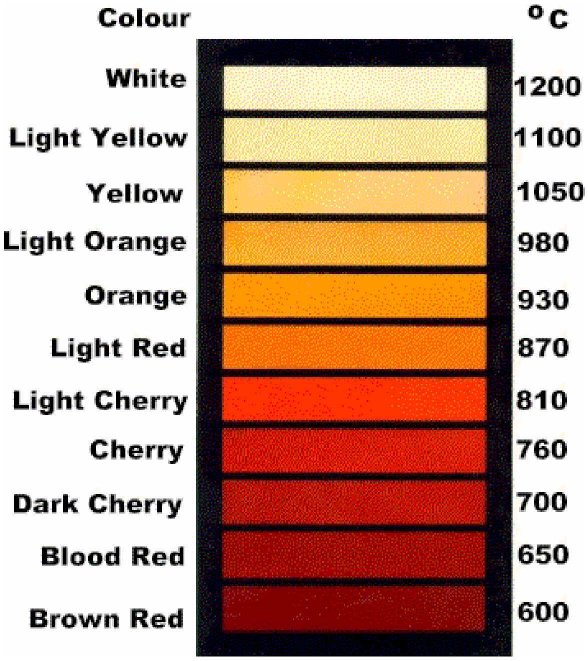


Figure 27. Color chart for solid steel at various temperatures (Tharwa Valley Forge 2020).

The changes in color indirectly indicate severity of the defects in the lining, but without recorded data there is no certain knowledge of the severity of the defect at each stage. Initial changes in color are also so faint that they are easy to miss in production conditions. A glowing area may be on time or a wider area depending on the type of the defects in the lining.

7.2 Experimental methods

7.2.1 Indirect measuring methods

As the name suggests, the indirect measuring does measure the condition of the lining through some other measurements. As seen in the current procedures, the temperature of the backplate is a decent indicator for the condition of the lining but is not currently robust enough. The defects become visible at relatively high temperatures and the observations are not unambiguous enough for being a reliable source.

However, the heated-up material emits radiation beyond the visible range. Observation range can be increased beyond visible wavelengths with relatively simple equipment. Infrared thermometers and cameras are one of the most common temperature measurement methods. By measuring the radiation energies at different wavelengths, they can define the surface temperature of the observed material. Where the thermometer detects the singular value of a singular spot, the thermal camera can measure a wider area at that time. Based on the gathered data, the camera can build a visual representation of thermal distribution. Figure 28 represents spectral energy densities as a function of wavelengths. Typically, the human eye can detect wavelengths between 380 to 740 nm. As seen from Figure 28, visible range misses the highest energy densities especially at low temperatures. The vast majority of the radiation is emitted at infrared frequencies, especially at low temperatures which is why the measurements should be based on it (Adkins C.J. 1983).

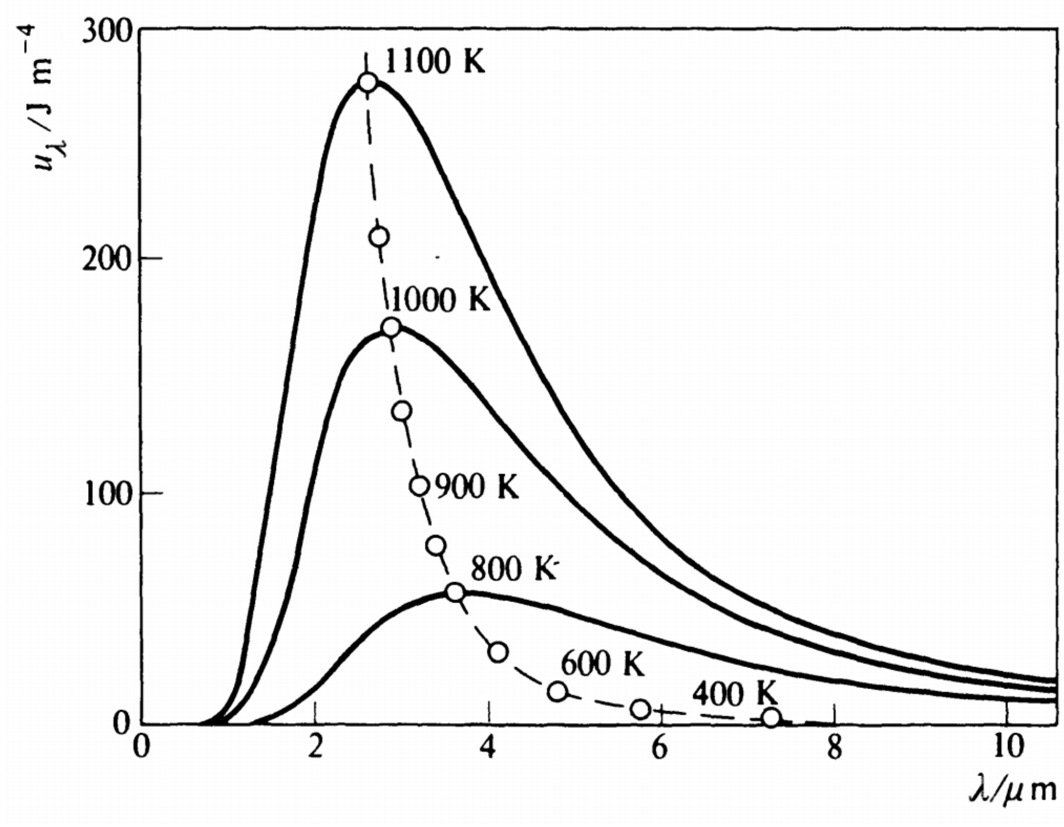


Figure 28. Spectral energy distribution as a function of wavelength. White dots indicate peaks of energy densities at certain temperatures. Visible wavelengths are roughly between 0.3 and 0,7 λ/µm (Adkins 1983).

Even though temperature can be measured in multiple ways, most of them are not easily applicable to the industrial environment. Some of the methods are based on the thermal expansion of certain substances or differences between two joint metal pieces. They are often used to measure temperature of the environment and therefore cannot provide a comprehensive view of the condition of the lining.

During this study, some measurement methods were tested preliminarily. Due to its short preparation time and comprehensive measurements, the thermal imaging seemed the most feasible option to go forward with. Types of cameras and parameters used during the measurement are presented in Table 5.

Table 5. Used parameters for the thermal camera.

Setting	Value
Camera Model	Fluke Ti400
Background temperature	22.0 °C
Emissivity	0.80
Transmission	1.00
Calibration range	From -20.00 °C to 1200.00 °C
IR Sensor Size	320 x 240

7.2.2 Direct measurements

Laser measurement is currently the leading method for scanning the thickness of the lining in most industrial appliances. Modern equipment can provide detailed models from the inspected object relatively quickly, which makes condition evaluation easy (example presented in Figure 29). The equipment consists of a transmitter and a receiver. The transmitter sends laser pulses towards the target surface at various angles. Pulses reflect from the surface and head into the receiver. The equipment then calculates the distances based on the time delay between the sending and the receiving of the laser pulse (Lamm, 2013).

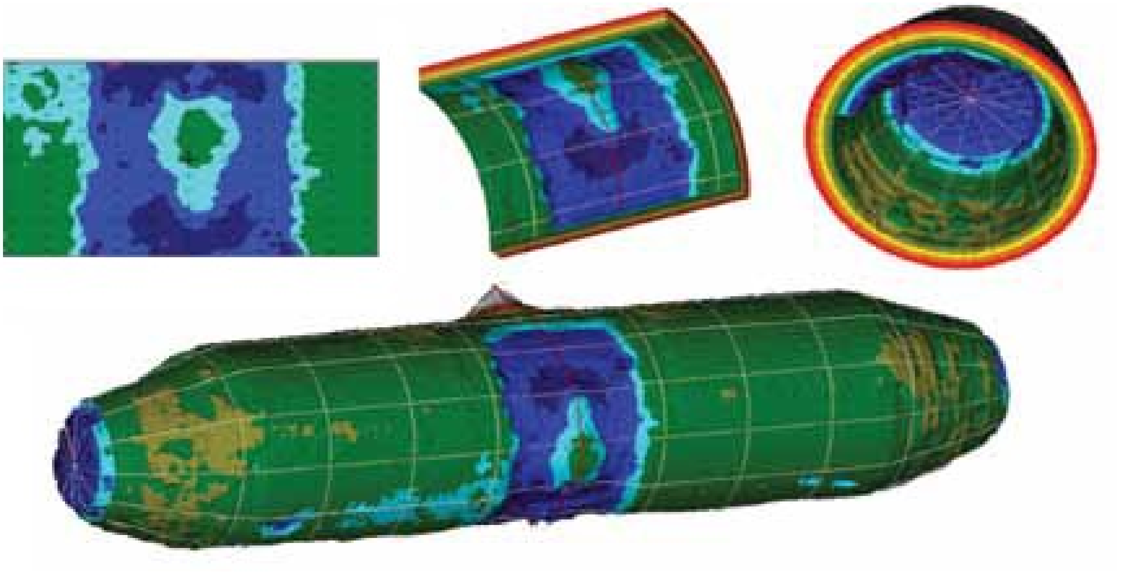


Figure 29. Examples of laser measurements from the torpedo ladle (Lamm, 2013).

Another considered direct measurement method was photogrammetry, where the object is modeled based on multiple photographs. Because singular images lack three dimensional aspects and are often a bit distorted, they cannot be used as an accurate source of measurements. By combining multiple images, the photogrammetry programs can create a 3d-model of the photographed object with realistic scaling (Schenk T. 2005).

When comparing the laser measurements to the photogrammetry, they both have their own advantages. Laser measurements require high-end equipment and a stable location. However, after the set up the measurements are relatively quick and provide accurate data with low risk of error. Photogrammetry, on the other hand, requires a regular camera and is not tied to any location. However, the modeling takes more time and is more prone to errors during the modeling phase. Despite the risks of low-quality models, the low investment costs and simplicity ere of greater significance in executing this work. Therefore, during the trial period, the photogrammetry was used as a method of direct measurement.

8 STANDARDIZATION FOR STEEL LADLE LID LIFETIME

8.1 Goals and arrangements

The main goal of the trials was to determine current lifetime for steel ladle lids and introduce continuous condition monitoring as a permanent procedure at the Raahe steel plant. The trials aim to set base values for the following studies and experimental lid designs. Observations during the trials aimed to identify different types of defects in steel ladle lids, their source and map out means to prevent them. The secondary goal was to create a model for refractory wear based on the gathered data which can be used to estimate lids' conditions based on the number of heats.

The trials were conducted over a two-month period. As a preparation, a system that would keep track of number of heats for each ladle lid was deployed as a part of daily operations. Each ladle lid used during the test period was included in the test population. The condition of each lid was evaluated before deployment and was classified correspondingly as new or repaired. The condition of each lid was evaluated weekly with visual inspection and thermal camera imaging. The main goal of thermal imaging was to predict upcoming defects and chart out new criteria for discarding. Additional inspections for the lids were done if its condition changed significantly between scheduled inspections. Assessments were made during the normal steelmaking process cycle to minimize interference of the steel production.

Because there was no previous record of steel ladle lids' ages, the initial amount of heats for the lids used at the time was estimated. Estimation was based on deployment date, number of ladles used in circulation and production rate. The number of heats for the lids deployed after the trial initiation was naturally set to zero. Condition evaluations became regular after the steel ladle lid card was deployed, which made determining lids' ages more feasible. Operators were taught to use the steel ladle lid card at the beginning of the trial period. Their responsibility was to make sure that the lid was attached to the right ladle in the database.

8.2 Measurements

In most cases the hull and the lining were evaluated separately. Condition of the back plate was checked and visualized with thermal camera at the ladle in the line maintenance station between the heats. Notable observations were also photographed and sketched on paper. Checkups at the station also included an approximation of the lining condition through a slightly opened gap between the lid and the ladle.

However, most of the lining evaluations were made when the lids were stored on the racks near the BOF or CAS-OB. If possible, the observations were made while the lining was still glowing as this highlighted the defects on the surface. Criteria for the grading are listed in Table 6.

Table 6. Steel ladle lid condition grading.

Grade	Criteria
5	Excellent lining condition: no visible cracks Hull is entirely intact. Previously added patches are allowed Repaired areas cover previous defects entirely
4	Minor flaws observed on the surface of the lining: small amount of corrosion or cracks. Hull is entirely intact. Excess repair mass is crumbling revealing the original lining
3	Lining has clearly visible flaws: Metal anchoring has been exposed, large cracks or severe defect on the refractory blocks. Some degree of scaling is observable on the surface of the back plate, hot spots are detectable with thermal camera. Clear border visible between repair mass and original lining.
2	Pieces of refractory are loose from the monolithic lining. Cracks seem to go through the lining, but the metal plate is not exposed. Back plate is glowing red
1	Lining has partially worn out exposing the back plate Plate has been ruptured or is glowing bright Lid has taken impact from external source

After the lid had been discarded it was taken to a field near the brick shop to cool down. There, most of the lids were inspected one last time before taking them in for a repair. The purpose of these inspections was to examine the defects in proximity.

The amount of refractory loss development of defects was modeled with the image-based Autodesk ReCap CAD-program. One example of these models is presented in Figure 30. Lids were photographed and modeled after the initial cast a couple of times during use and after lids were discarded. Models were compared with each other to give defect size estimates.

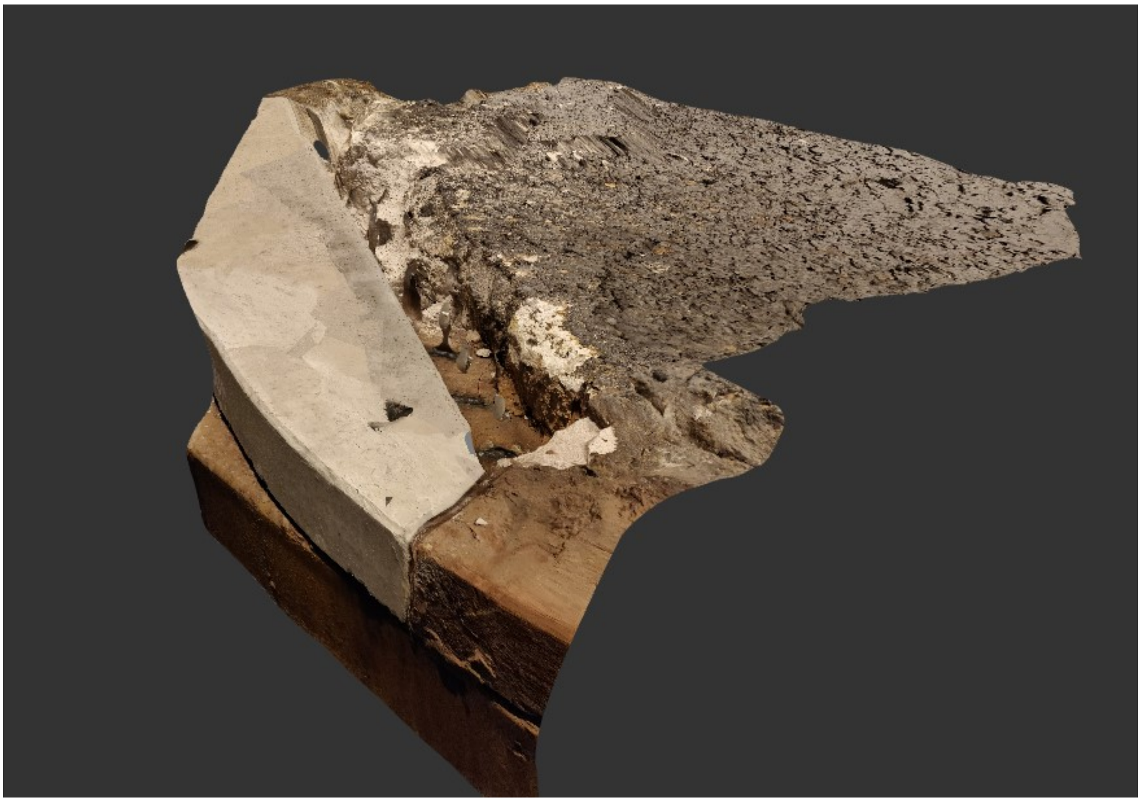


Figure 30. Example of lid modelization with ReCap.

8.3 Challenges and sources of error

The beginning of the trial was challenging for this test period. One of the main goals of this thesis was to inspect lid behavior in normal conditions which was not the case at the time. At the beginning of the test period, slow production rate and the holiday season changed the normal cycle of the lids by giving them more time to cool down. Differences can be seen in the thermal images where the surface temperature of the lids at the beginning is significantly lower than during the rest of the trial. Frequent and large changes in temperature tend to accelerate the refractory wear rate which might have affected lid lifetime measurements during this trial.

One of the main sources of error is the new work instructions for the operators at the ladle in the line maintenance station. Due to lack of guidance and change resistance some of the operators occasionally neglected to keep the lid card up to date which might have led to a faulty amount of heats. Information on the card was updated as soon as a flaw was noted. However, as the trials proceeded, less neglects were observed.

9 RESULTS

Even though the two-month trial faced some challenges (cf. chapter 8.3), the inspections were carried out without major problems. The main problem was shortage of intact steel ladle lids which prevented damaged lids to be discarded at the right time. Excessive use caused unnecessary damage to the existing lining and the hull. The shortage was mainly a result of sudden acceleration of the production rate, poor initial condition of the lids and a couple incidences of unfortunate mishandling of the lids. Lids that should have been already discarded were excluded from the lifetime evaluation alongside with the lids that were dropped or otherwise mechanically damaged.

The lining wear rate was meant to be measured with image-based CAD modelling. However, these measurements were ceased at the midpoint of the trial period due to poor results and irrelevance to the main goal. Because defects developed much faster than anticipated, the initial measurement pace was too irregular. Combined with a couple of bad models caused by user error, the results were hard to analyze.

Without previous data on endurance of the steel ladle lids, there is no reliable reference to which results can be compared. These results are meant to directionally describe the current lid situation and set a basis for further studies. Results were analyzed with Microsoft Excel 2010 and Minitab 19 Statistical software.

9.1 Lifespan of the steel ladle lids

As explained in chapter 8.2, the grading of the lining goes from 1 to 5 where the higher points represent better condition of the lid. Requirements for each grade are listed in Table 6. Grades above 3 are considered as excellent condition, whereas values below it indicate that the lid should be discarded as soon as possible.

The lids were classified by their condition during the deployment. At the beginning of the trial there were two lids that had not been repaired yet which were classified as “New”. Over the trial period, five lids were suitable for this classification. Out of these five lids, two were discarded during the inspections: one due to natural weariness and the other as a result of unfortunate external impact.

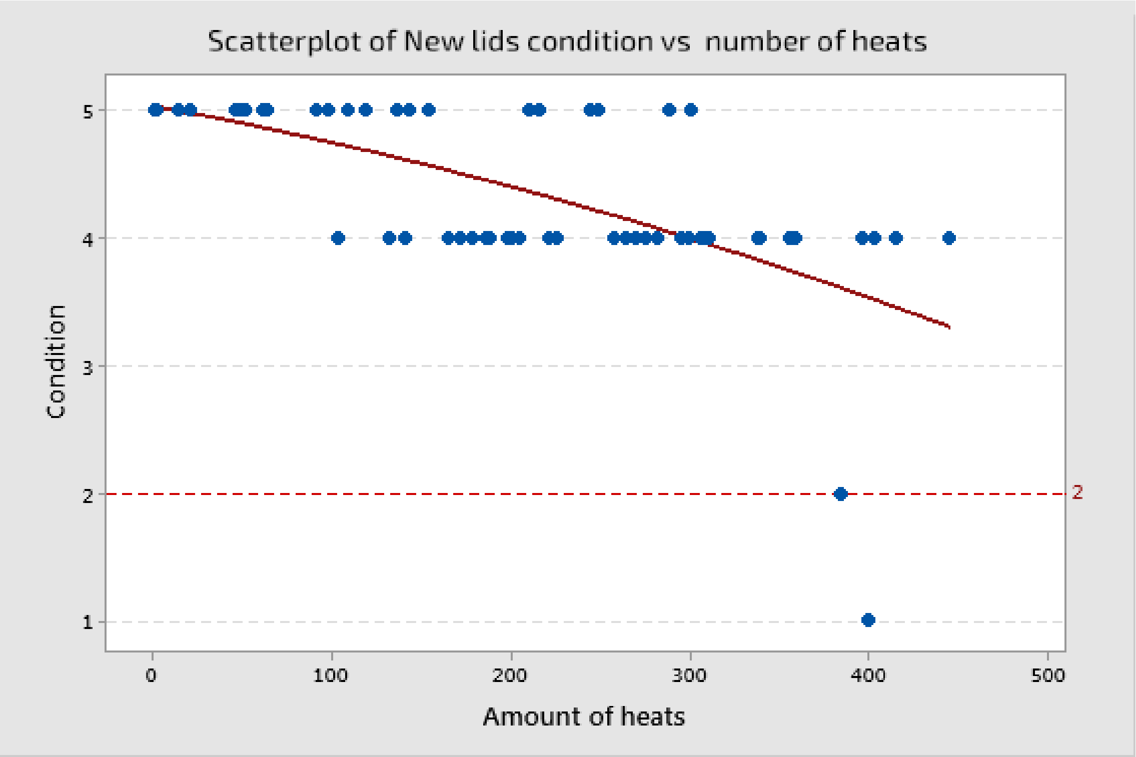


Figure 31. Condition of the new lining over the amount of heats.

Figure 31 shows the condition of the new steel ladle lids over the amount of heats. As seen in the figure, the condition of the new lids remains in almost perfect condition over a hundred heats. At this point, typical defects of the new lids become visible, but they do not have a significant impact on the overall condition. These kinds of defects are described in more detail in chapter 9.2. Regardless of the small defects, the condition of the lining seems to remain in excellent shape for the duration of hundreds of heats. At an average production rate, 200 heats for a lid takes roughly a month. Because only one of these lids were naturally discarded during the trial period, it is hard to analyze wearing rate further. However, it is worth mentioning that once the first severe defects in the lining were observed, the condition of the lid plummeted.

The rest of the lids were classified as ‘Repaired’ lids. Even though the magnitude of the repairing varied from minor procedures to partial replacement of elements, they were studied as one group. During the trial period a total of 17 campaigns using repaired lids were monitored.

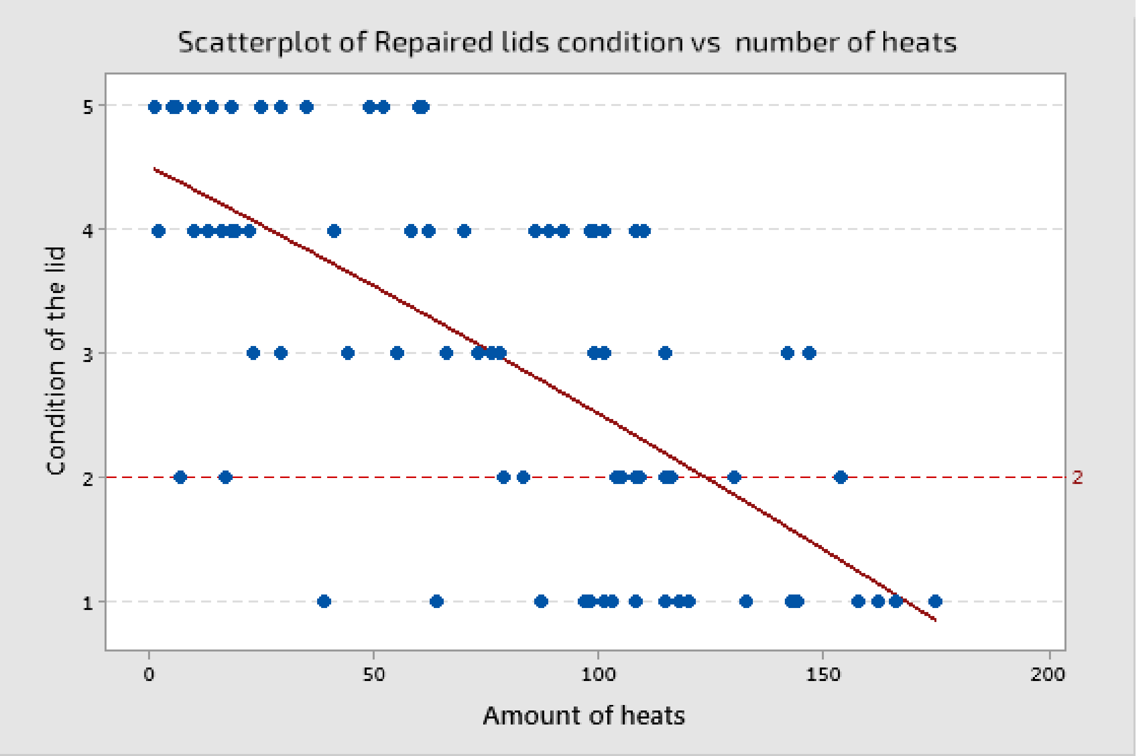


Figure 32. Condition of the repaired lids over the amount of heats.

Figure 32 represent the condition of the repaired lids through their campaign in the steel plant. As seen in the figure, the condition of the lining decreases significantly faster in comparison to new linings. The weakest ones were those that had been patched with an excessive amount of mass. These patches were not capable of enduring small impacts that the lid inevitably faces during the normal process cycle. Otherwise, the amount of patching material had no notable difference in lid lifetime. Frugally patched lids stayed in use the same amount of time as those averagely patched.

The grading values below 3 indicate that the lid should be discarded from the cycle. As seen from the regression curve in Figure 32 indicating the average lid condition after a certain amount of heats, it can be estimated that a repaired lid lasts for 130 heats above decent condition.

9.2 Observed defects and their origin

9.2.1 Defects on the hull

Most of the observed defects on the hull were the result of some degree of misuse. In ideal conditions the hull should not receive any burden and be recyclable without repair.

Defects presented in figures from 33 to 35 represent different degrees of plate exposure to heat. The main reason for these defects is insufficient lining and lids delayed discarding time. As seen in Figure 33 the heat causes the plate to rapidly oxidize leaving charred flakes on the surface of the plate. Continuing exposure to the hot atmosphere weakens the steel significantly, making the surface wavy as seen in Figure 34. Eventually the steel loses all of its strength, rupturing the surface (Figure 35).

Figure 33. Large area has been exposed to the heat for a relatively short duration.

Figure 34. Repeating exposure to the heat makes metal structure to lose its shape and strength.

Figure 35. Continuous exposure to heat causes plate to lose its shape and rupture.

These defects are repaired by removing the damaged area and welding pieces of metal to cover the hole. A small amount of scaling does not necessarily require restoration if the inner surface is still intact. However even a small amount of scales prevents new anchors from being welded and therefore requires repair. An example of the inner surface can be seen in Figure36.

Figure 36. Heat has corroded most of the anchors and severely damaged the plate.

Although in practice these defects are near inevitable, they can be avoided by discarding lids from the cycle in time. Work instructions implemented during this thesis should help in diminishing the severity of these defects and reducing their frequency.

Sometimes the lid faces significant impact as a result of human error or some other anomaly. As a result, pieces of the hull can be bent leading to fractures in the lining. Figures from 37 to 39 present examples of these defects. The most common source of impact is a lid falling from the rack hinges ahead causing them to bend (seen in Figure 38). Because the abnormalities on the hull are one of the main reasons for the lid getting stuck on the rig, it is important that the lids are examined carefully before taking them back into the process cycle. In Figure 37, a guard rail has bent over the bearing preventing them from rolling properly.

Figure 37. Protective guardrail of the bearing has bent as a result of impact.

Figure 38. Hinges are usually bent if a lid falls off a rack.

Figure 39. Lid has been crooked as a result of continuous maltreatment.

9.2.2 Defects on the lining

Although it was difficult to estimate the wearing rate of the lining directly, certain patterns in defect development were observed.

Most of the new lids stayed in excellent condition over a hundred heats. After reaching a certain age, some degree of corroding was observed at the inner edge of the peak brick for all of the new lids. Defects remained relatively shallow as it did not exceed the wedge of the monolithic lining (Figure 9 Chapter 3.1.2.). The monolithic lining seems to remain unaffected, indicating that the material of the brick has something to do with the corrosion. Because slag splashes can be seen on all of the bricks, it does not seem that the slag is excessively corrosive to the brick. The corroded area is the only portion of the bricks that is not directly in contact with the walls of the ladle. The walls protect the bricks of the lid from hot fluid in the vessel. Both the monolithic center and the bricks are high alumina products with similar properties, but the amount of steel fibers used in the bricks is significantly higher. High metal content might lower the thermal resistance of the brick resulting in partial melting. Eventually, slag splashes cover the lid forming a protective layer on top of the lining. An example of this corrosion is presented in Figure 40.

Figure 40. Condition of the peak brick after 200 heats.

Over time, the monolithic lining has a tendency to start crumbling. This phenomenon can be seen in Figure 41 where the surface of the monolithic lining is covered with small cracks. Most of them seem to appear at random locations, but one uniform crack can be seen circulating at the edge of the lining. These cracks are formed in the area where the casting mold leaves its marks and where the outermost anchors are attached. After becoming visible, the cracks start growing at an accelerating rate. The center of the lining presented in Figure 42 is still in decent condition, but the border area is visibly crumbling. As the fractures grow, they divide the monolithic lining into smaller pieces which become loose and eventually fall off.

Figure 41. Minor cracks can be seen circling near the edge of the monolithic lining after 200 heats.

Figure 42. Fractures become deeper as time goes on.

There was some variation in defect development from this point onward. Sometimes crumbling occurred only on the surface of the lining which made defect monitoring and predicting the date of discarding possible. The metal plate on the crumbling areas gradually heats up, which makes it possible to detect these defects with a thermal camera. However, in most cases the cracks grew gradually larger and loosened large pieces. As seen in Figure 43, the surrounding material remains relatively intact even when large pieces of refractory are missing.

Figure 43. Large piece of refractory has fallen off exposing the metal cover.

Occasionally, cracks grew on their own without significant losses in refractory material. As seen in Figure 44, the steel plate has a linear cut on the surface but there is no visible damage from the heat on the surrounding area. The lining of the lid seen in Figure 45 seems typical for its age without major defects. The images are taken during the same cycle of the lid.

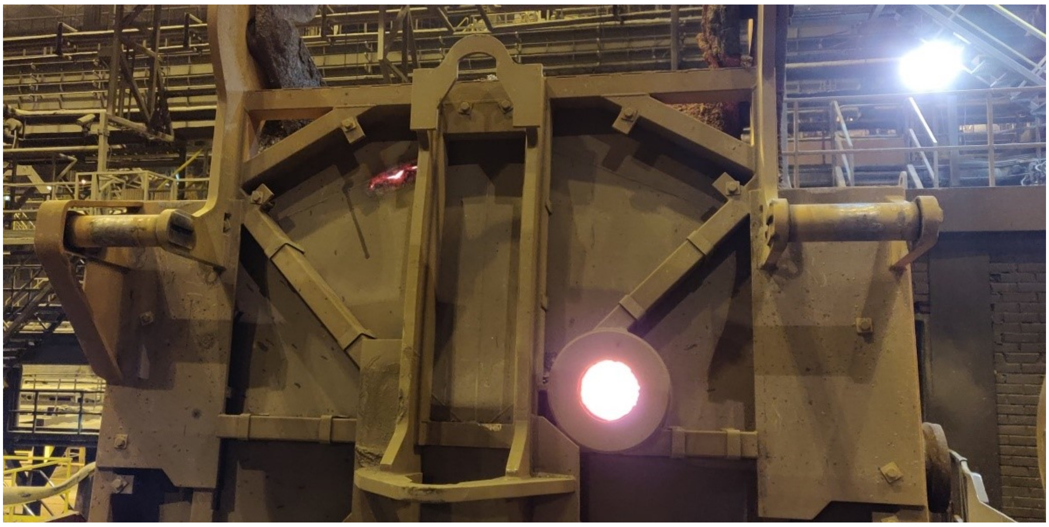


Figure 44. Backplate has burst open.

Figure 45. The lining of the lid seems to be in decent shape.

There were notable differences in the way in which differently repaired lids lasted in the cycle. The poorest performance was noted on the lids that were repaired with an excessive amount of patching material. Lids inevitably face small impacts during their cycle throughout the process which cause excessive patching material to fall off. Without proper attachment, the excess layer fell off after initial heats. As seen in Figure 46, the excess patching material rapidly falls off after a couple of heats. Falling material also loosens the patch itself causing those lids to be discarded early.

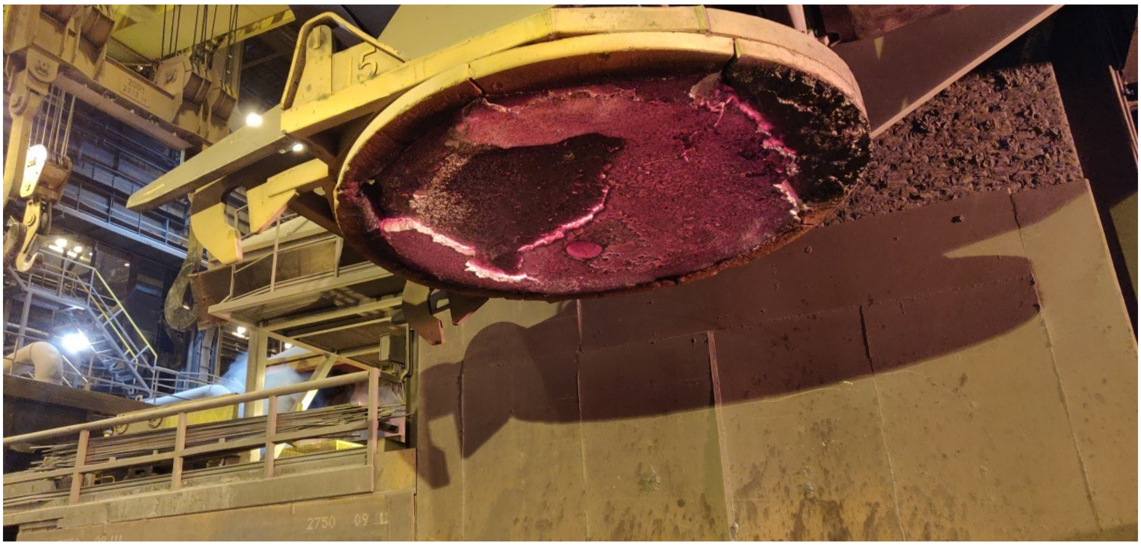


Figure 46. Repaired lid with excessive amount of repair material after two heats.

9.3 Thermal inspections

The goal of the thermal camera inspections was to create a model which compares thickness of the lining with surface temperature of the plate. However, it was noted at the beginning of the trial that the arrangements for the trial were not sufficient for creating coherent measurements. Some of the lids had more time to cool down before arriving to the measurement station, which hampered measurements' comparability with each other. Combined with inaccurate measurement for the thickness of the lining, results remained superficial. Later thermal inspections were used to predict occurrence of defects, in which it excelled. Thermal scanning detected fractures and other flaws much earlier than visual inspections.

With a sufficient layer of the lining, the surface temperature of the back plate should remain under 400℃ in all occasions. As the heat finds its way through the lining, the back plate starts to partially heat up. Figures 47 and 49 represent lids that were visually in decent condition and passed the field evaluation at the time. However, a quick glance at the thermal images (figures 48 and 50) indicates that there are notable hot areas indicating poor condition of the lining.

Figure 47. Visually, the backplate seems to be in decent condition.

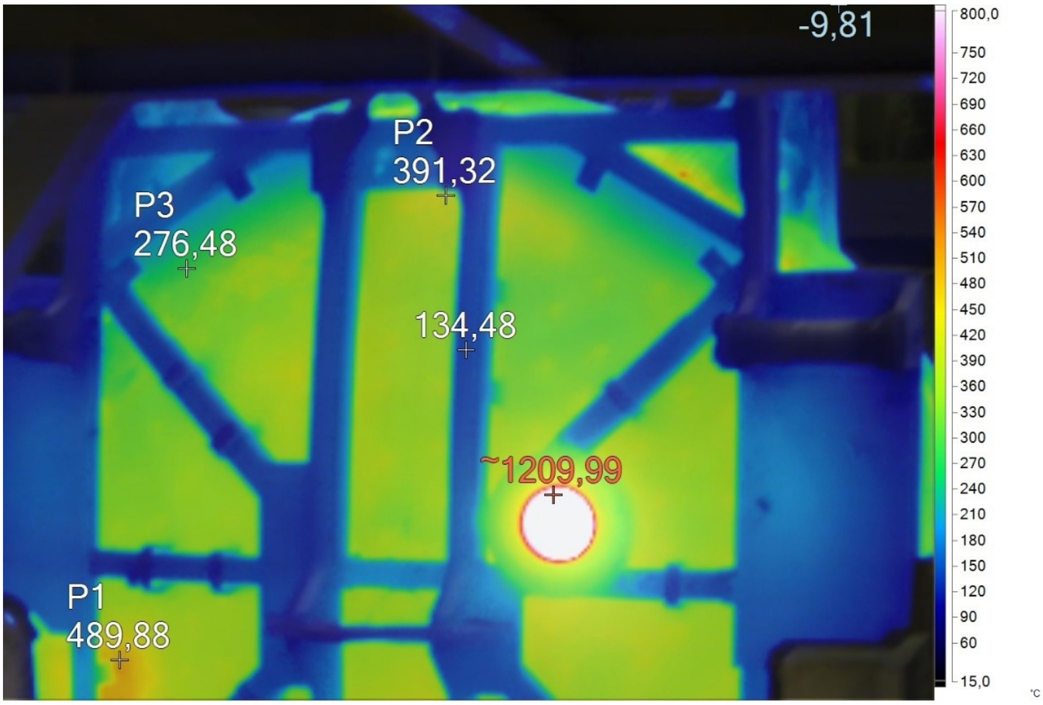


Figure 48. Thermal imaging reveals several hot areas.

As seen in Figure 48 there are two significantly hotter areas noticeable on the thermal image. Although the lining has worn out a bit from the whole surface area of the lid, there are two distinguishable defects seen on the back of the plate. Whereas P3 (fig. 47) indicates a typical surface temperature at the border of the monolithic lining and the bricks, P1 and P2 (fig. 48) indicate clearly distinguishable defects in the lining. Severity of the defects can be directly estimated from the size and temperature level of the measured area.

Figure 49. No visible defects observed on the backplate.

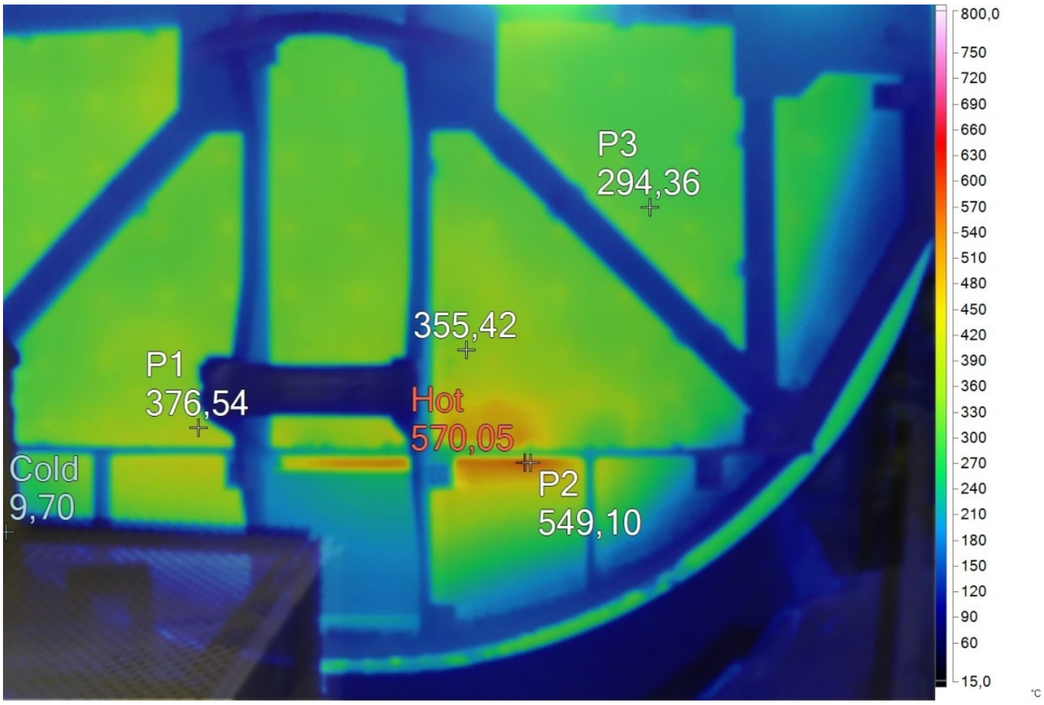


Figure 50. Narrow area has heated up significantly in comparison to the rest of the lid.

A narrow region of locally heated area is presented in Figure 50. These narrow defects at the border between the peak brick and the monolithic lining are a result of chemical corrosion that has advanced to late stages. Although these defects are easy to notice when checking the condition of the lining directly, they often remain unseen during routine visual inspections of the back plate. These defects, like the one presented in Figure 50, are located close to lid reinforcing structures which may partially block view during visual inspections. Similar thermal imaging problems become increasingly less likely as the heat conducts to a bit wider area than the defect itself.

10 CONCLUSIONS

10.1 Condition monitoring

Condition monitoring for steel ladle lids has significantly improved during this thesis. After the trial period the steel ladle lid card has been used as a permanent tool for keeping track of lid circulation. As time goes on, the recorded data should provide more information about the estimated lifetime and possible areas for development. With reliable reference data, the possible experiments have more reliability.

Thermal imaging proved to be an efficient tool for detecting possible defects earlier than visual inspection and therefore reduced the amount of labor during repair. Because the temperature of the back plate gradually rises as the defect becomes more severe, its temperature could be used as an unambiguous criterion for discarding. Photogrammetry, on the other hand, requires significantly more processing and is still quite unreliable, which is why it should not be used on its own. With proper set up it can provide additional data but should not be used otherwise.

10.2 Refractory wear

Based on the observations the different refractories in the steel ladle lids wear out in different ways. Typical weak areas are presented in Figure 51. The main source of wear in the monolithic part of the lining seems to be a combination of thermal and mechanical stresses. Initially, the repeating temperature changes start to weaken the structure of the lining by creating microscopical fractures. As the lining’s capability to insulate weakens, the anchoring receives more heat than it should and starts to expand. Pressure towards the lining creates cracks which eventually start to spread out. Fractures follow the anchoring line and occasionally branch even further into the lining as seen in Figure 52. As pieces of refractory become loose, they fall off exposing the back plate entirely.

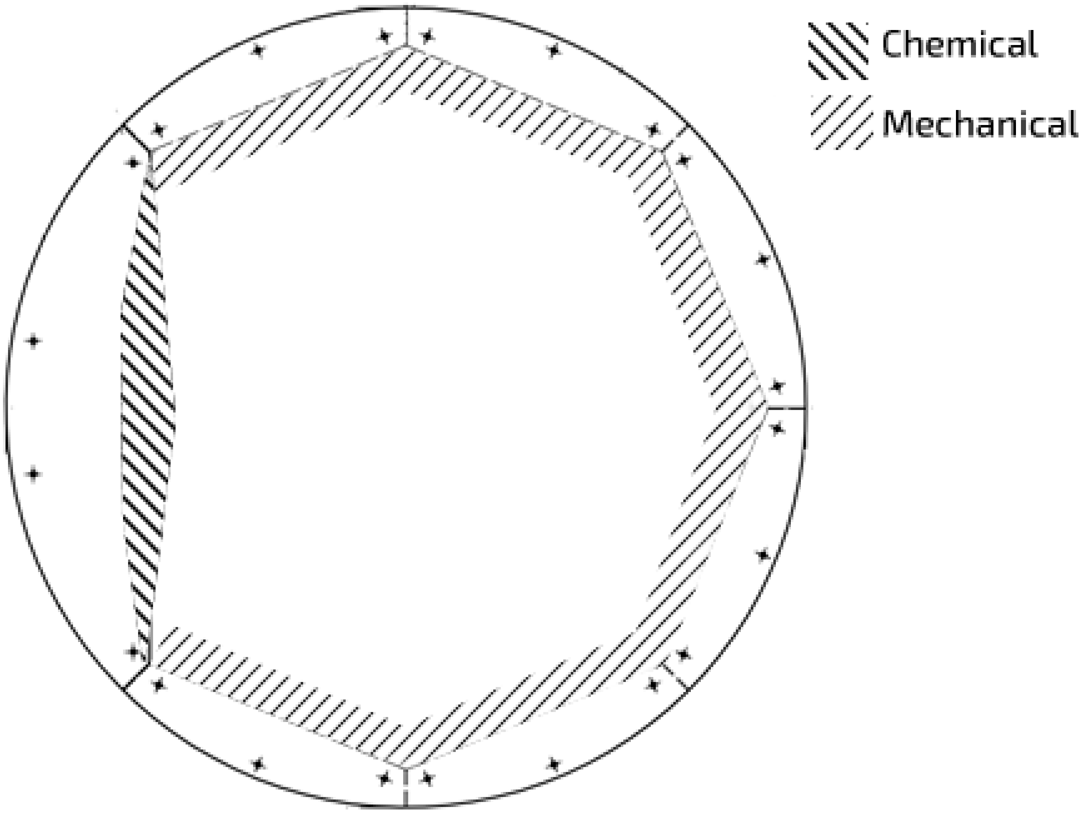


Figure 51. Typical refractory wear areas on the steel ladle lid lining.

Figure 52. Metal anchoring seems to be in the focuses of the cracks.

As presented in Figure 51, the refractory blocks endure thermal changes and mechanical stresses better than the monolithic part, however they seem to be more prone to chemical wear. Although most of the elements are beyond the reach of the slag, the splashes eventually cover the entire lining. The corroding rate of the bricks seem to vary a bit. It seems that a thick slag layer protects the bricks more than it corrodes, whereas a thin layer consumes the material relatively quickly.

Even before the trial period it was known that the average lifetime of the repaired lid was significantly shorter than for a new lid. Nevertheless, the actual endurance during the trial period came as somewhat of a surprise. Despite additional anchoring, the patching material seem to get loose relatively easily and then fall off. As the current repair procedures seem to be quite inefficient, they should be revised as soon as possible.

11 SUGGESTIONS FOR IMPROVEMENT AND FURTHER RESEARCH

11.1 Suggestions for improvement

The current anchoring seems to be a bit too tall and thick. According to Harbison-Walker (2005), thin metal anchoring should cover 80 % of the thickness of the lining at maximum. Smaller and lighter anchors might provide enough adhesion without causing fractures in the lining.

Chemical wear of the bricks could be decreased with small changes in the design. Size of the peak brick was previously increased as an attempt to reduce refractory wear, however there is no certainty of how the changes effected refractory lifetime. As the results of this thesis show, the current brick design is more prone to chemical wear than the monolithic lining. It could be worth trying to revert the peak brick to the original size. Also, the composition of the brick could be reconsidered to increase corrosion resistance.

As most of the defects seem to accumulate at the border between the monolithic center and the bricks, there was an idea to create an entire lining with a single cast. Entirely monolithic lining should endure mechanical and thermal wear better and with proper composition there should not be problems with chemical wear either. At the end of the thesis one of these experimental lids was casted and deployed into use. An image of the monolithic lid is presented in Figure 53.

Figure 53. Experimental lining made with single cast.

With improved condition monitoring and capability to detect defects in advance, some methods for hot-repair could be implemented to improve lid lifetime without removing them from the cycle. However, these changes would require significant changes in current operator procedures.

11.2 Topics for further research

As it is well known, the lining and the refractory material are a significant financial expense. The current design in the lining is relatively thick for refractories that face relatively little corrosion. By thinning the lid lining slightly, the amount of needed refractory mass would be reduced significantly without affecting the lid's capability to insulate or length of its lifetime. With more accurate monitoring of refractory wear, this would not represent considerable risk to the operation.

Because current repair procedures do not extend lid lifetime enough to be considered financially efficient, new methods should be developed. As the casting of a new lid requires a lot of unused materials, longer campaigns for the repaired lids would be crucial for sustainable lid circulation. Anchoring would be one of the easiest ways to prevent patches from falling, but also other methods should be considered. Current patching material endures the process conditions both thermally and chemically so material tests should not be periodized.

REFERENCES

Adkins C. J. 1983 – “Equilibrium thermodynamics – 3rd edition”, Cambridge University Press, Reprinted 1988, pages 152 – 153. ISBN: 0524-25445-0

Banerjee S. 2004 - "Properties of Refractories" available at "Refractories handbook". Marcel Dekker, Inc. on pages 1-10 - ISBN: 0-8247-5654-1

Buhr A. et al. 2017 - "Basics on Chemical and Mineralogical Composition of Refractory Material and Slag" - Presented in a seminar: Refractory Technology, Refractory Materials and Slags in Metallurgy, November 2017, Cologne, Germany

Brosnan D. A. 2004 - "Alumina-Silica Brick" available at "Refractories handbook". Marcel Dekker, Inc. on pages 79-107 - ISBN: 0-8247-5654-1

Garai R. M., Tereja-Garcia R. Sánchez I.C., Rodriguez-Valverde M.A. 2005 – “Study on Effect of Raw Material Composition on Water-Repellent Capacity of Paraffin Wax Emulsions on Wood”, Journal of Dispersion Science and Technology 26(1) p. 9-18

Goulart C. A. , Braulio M. A. L., Teider B. H. ,Pandolfelli V. C. 2015 - "A Critical Analysis of Anchor Spacing in Refractory Lining Design" - Refractories worldforum 1/2016 pages 92-107

Guo M., Parada S., Jones P.T., Van Dyck J., Boydens E., Durinck D., Blanpain B., Wollats P. 2007 - “Degradation mechanisms of magnesia-carbon refractories by high-alumina stainless steel slags under vacuum” – Ceramics International, Volume 33, Issue 6 2007, pages 1007-1018

Harbison-Walker – Handbook of Refractory Practice 2005, Section 7 “Installation References” Pages IR 63-82

Helelä, K. (1986). Tiilet korkealämpötilaprosesseissa. Tiilipäivät (pp. 1-65). Metallurgian kannatusyhdistys Ry

Koivula 2005 – SSAB internal document – Steel ladle lid measurements

Landy R.A. 2004 – “Magnesia Refractories” – Refractories handbook". Marcel Dekker, Inc. on pages 109-145. ISBN: 0-8247-5654-1

Meier G.H. 2014 – ”University of Pittsburgh – Summary of basic thermodynamic concepts” – Cambridge University Press, Pages 1-39 Available on: https://doi.org/10.1017/CBO9781139047029.002 (19.3.2020)

Nivala M. 2015 – “Optimizing the lining life of steel ladles with gunning and laser measurement” – Thesis work – Aalto University

Ollila, S. (2012). *HUT, BOF short presentation*

Ollila, S. (2015). *Steel production 2015 SSAB Eng*

Poirier j., Smith J., Jung I-H., Kang Y-B,. Eustathopoulos N., Blond É., Rigaud M. 2017 - "Corrosion of Refractories: The Fundamentals" F.I.R.E Compendium Series. ISBN 978-3-87264-006-2

[1] Features of refractory corrosion	Pages 1-38
[2] Thermodynamics	Pages 43-114
[3] Kinetics	Pages 121-180
[4] Wetting and infiltration of refractories	Pages 187-226

Shestakov 2002 - "An Introduction to Refractory Binders" AZO Network UK Ltd. Available on: https://www.azom.com/article.aspx?ArticleID=1409 (20.1.2020)

Schacht C. et al. 2004. "Refractories handbook". Marcel Dekker, Inc. - ISBN: 0-8247-5654-1

Schenk T. 2005. “Introduction to Photogrammetry” – Department of Civil and Environmental Engineering and Geodetic Science, The Ohio State University

SSAB – Steel production in Raahe (2019)

SSAB - Work instructions (2019), Ladle in line maintenance operator

SSAB - Work instructions (2019), Mixer operator

Substach – Ladle refining. Available on: https://www.substech.com/dokuwiki/doku.php?id=ladle_refining (31.3.2020)

Teräskirja, 9. edition (2014). Metallinjalostajat ry, ISBN 978-952-238-121-7

Tharwa Valley Forge – temperature charts for blacksmithing 2020 Available on: https://www.tharwavalleyforge.com/articles/reference/14-temperature-charts (23.3.2020)

Tomokazy K. & Kam-Ching L. 2007 – “The Astrophysics of Emission-Line Stars” – Spinger Science+Business Media, LLC, page 41