The Journal of Refractory Innovations

bulletin

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RHI MAGNESITA

bulletin

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Cover picture: The photo shows a converter with bottom purging plugs for steelmaking. Scrap as an iron source and cooling medium is charged with pig iron in the converter and in combination with other materials, refined into steel using the basic oxygen process. A higher level of product sophistication (e.g., clean steel, high-purity and low-carbon steel grades) and the fluctuating quality of input materials (e.g., raw material availability and volatile prices) require an optimized converter process with effective bottom purging. An effective bottom purging system leads to an increase in output and improved metallurgical results, providing for effective and efficient oxygen steel production at low cost. Advantages include high-quality and economical steel production, minimum tap-to-tap times, reduction of re-blowing rates, and improved process control. Customized converter lining concepts and purging systems (type, arrangement, number and flow volume of plugs, gas control units) are designed and produced by RHI MAGNESITA and delivered to our globally operating customers.

RHI Magnesita Worldwide news

India

New Casting Record at JSPL Angul

A new casting record, of 6854 tons in 31 hours with 30 heats through a single tundish without a tube changing device has been set at JSPL Angul. RHI Magnesita (RHIM) has been associated with JSPL Angul, since the commissioning of the Phase One - 6 million tons plant located at Angul, Orissa in India which follows a process route of: NEOF/ EAF OR BOF (250 MT capacity) →LF →VD (based on grade) →CASTER. RHIM supply the complete refractory for 1x1 Slab Caster Tundish on Management Contract basis. To set this Asia record, there was a clear objective with customer to increase the yield and caster availability and to reduce tundish consumption. All products used were supplied from the production unit in Bhiwadi, India. The joint efforts from the customer and the RHIM team has led to direct and indirect cost savings, in terms of productivity, refractory consumption, and yield. (RHIM) is focused with its esteemed customer for further scope of improvements to stabilize the performance and achieve further record-breaking results.

Europe

RHI Magnesita Drives the Refractory 4.0 by Participating in the METEC 2019

The METEC in Düsseldorf, Germany only takes place every four years and is the largest international trade fair for metallurgy, steel casting, and steel production. The fair covers subjects such as machinery, plants and products for the steel industry, environmental and resource preservation, and energy efficiency.

METEC offers the unique opportunity to meet international buyers, users, experts, and decision makers from the metallurgy, heat technology, and foundry industries. The exhibition provides the ideal ground to establish new and maintain existing business contacts, because approximately 17000 people frequent the METEC and the side events to the fair, such as panel discussions and conferences. RHI Magnesita will be present with four interactive hypeboxes strung alongside a LED Wall to provide visitors information on the lifecycle of products from mining to solution—Refractory 4.0. The stand includes interactive touch tables which provide interested parties with e-folders and business presentations. Visit us at our booth and share your METEC experience on Social Media. Don't forget to tag #rhimagnesita in your pictures!

China

Strategic Partners for China Cement

Since 2008 the China Cement team began a cooperation with Tongda, which became a strategic partner in 2014. Since that time Tongda has worked as a purchasing platform for refractory materials for Jidong-Jinyu cement group (approximately 70 kilns) and for overseas projects, RHI Magnesita (RHIM) cooperated with Tongda on FLS. The tonnage has increased each year despite a shrinking market. RHIM not only supply Tongda with products, but also provide technical support and rapid troubleshooting through which Tongda expanded their market in Jidong group. It is a very stable and successful long-term strategic partnership which contributed 12781 t to the business in 2018.

Another outstanding strategic partner for the China Cement group is Chongqing Liangyou. They have warehouses in Chongqing, Guangxi Nanning, and Yunnan Kunming, which helps to reduce lead time and ensure quick delivery to customers. With the enhanced flexibility of urgent delivery, this partnership ensures potential sales to 30kt and improve the price position due to SCM/ logistic saving. With this partner, RHIM achieved 25000t in 2018.

RHI Magnesita Worldwide news (continued)

Brazil

Innovative Modification Increases Magnesite Processing Plant Productivity by 20% Brumado

The RHI Magnesita production facility located in Brumado (Brazil) is one of the most important high purity DBM producers worldwide. The site relies on magnesite mines, flotation plant, calcination furnace, briquetting stage, and sintering shaft kiln. The flotation plant is the responsible for removing the ore impurities (silicates), increasing the MgO content, hence, the DBM refractoriness. This stage was identified as the process bottleneck, more specifically the grinding circuit. An innovative process solution was studied by the mineral processing R&D team in laboratory scale, pilot plant, and implemented industrially. The concept adopted is the combination of staged grinding circuit with high frequency screener. Formerly, the four ball mills present in the plant worked in closed circuit with hydrocyclones. The new approach changed the process route, with three ball mills working in open circuit, the product feeds the high frequency screener and only the screener oversize feeds the fourth ball mill. This modification (start up last September) led to a more efficient energy use for comminution, allowing the plant to increase its productivity by 20%, without increasing grinding equipment. Recently, the project was recognized by a specialized mining journal in Brazil (Minérios e Minerales), being one of the projects awarded by the 21st Mining Excellence Prize.

Worldwide

RHI Magnesita—100% Safe@Work

RHI Magnesita's (RHIM) focus to be the driving force of the refractory industry is relevant with the ongoing focus and commitment to the health and safety of all team members, clients, and the contractors who support our successes. Notwithstanding the challenges of a newly merged organization, RHIM was able to achieve results better than any in our history. The lost time injury frequency (LTIF) in 2018 was 0.43, a significant improvement over the 2017 amalgamated result of 1.06. Reflecting on what drove these results, we focused on the importance of reporting near misses and unsafe situations, ensuring quality reports, but more importantly, the actions taken. By focusing on the near misses and unsafe situations, we are preventing more serious incidents.

The Golden Rules for Safety were also reintroduced, aligning all members of the organization on the basic expectations to keep themselves and team members safe. The POST (workplace safety observation program) has been introduced to most operations. POST will be introduced to all remaining operations as well as to non — operations. These two programs truly drive the behaviour of our people.

Striving to build on the success of 2018, and ensuring continued improvement in 2019, a fatality prevention program will be introduced. A program to measure the level of implementation of key prevention programs that are most impactful for occupational safety, lockout/tagout, working at heights, elevated loads, internal traffic, and confined spaces, will be implemented. This will identify the gaps and aid in developing the necessary programs and implementation at each site. For the locations that have struggled, and continue to struggle, there will be a heavy emphasis placed on leadership training for those facilities. It is critical that these key personnel understand what is expected, but also providing the necessary tools to execute the key role.

There will also be a focus on aligning the safety program for all units of the organization, ensuring the team members providing services, installing materials, or any other RHIM colleague in the field has the same information as counterparts in operations. The success in 2018 would not have been possible without the commitment of management. We look forward to continuous improvement in 2019 and to celebrating many more successes in the years ahead.

Vietnam

HOA PHAT DUNG QUAT Signs Two Contracts with RHI Magnesita

RHI Magnesita (RHIM) has been awarded two contracts that comprises refractory deliveries and installation services for the new DUNG QUAT greenfield project. A three year contract was signed for the BOF and the steel casting ladle refractories. A five year contract was signed for the ladle slide gate and the tundish refractories. For both contracts RHIM provides installation services and machinery.

Hoa Phat Group is the largest local steel producer in Vietnam, a stock listed company and a long-time customer of RHIM since 2003. Hoa Phat Dung Quat´s integrated steel complex will have an annual capacity of 4 million tons of steel. The first phase will produce approximately 2 million tons per year of predominatly long products and is scheduled for commissioning in June 2019. The second phase of the project will add another 2 million tons per year of flat products. It is expected that the entire project will be completed by the middle of 2020.

Worldwide

RHI Magnesita joins UN Global Compact

Since October 2018, RHI Magnesita has been one of the first global players in the refractory industry to join the UN Global Compact, the worldwide biggest initiative for corporate sustainability. According to Stefan Borgas, this is a huge milestone on the company's path to sustainability: "Joining the Global Compact will not only help us to create long-term values for our business, but also for our communities and our environment". More than 12000 members from more than 160 countries have already signed the Global Compact and are therefore obliged to align their corporate strategies and principles with the universal principles of the human rights, job norms, environmentalism, and the fight against corruption. The members are under obligation to raise awareness and to promote measures within their company to globally reach the UN goals for sustainable development until 2030. The Global Compact is a leadership-platform for the development, implementation and disclosure of responsible corporate practices that was founded in 2000. For more information, please visit www.unglobalcompact.org.

Worldwide

PFD (Plug Function Device) Assisting Optimal Plug Cleaning

Proper oxygen cleaning of ladle purging plugs is of decisive importance for a correct function of the ladle gas purging equipment. Insufficient oxygen cleaning may result in reduced opening rates as well as low gas flow rates whereas excessive oxygen cleaning will damage the purging plugs and lead to reduced life times. Premature wear of the plugs caused by such excessive oxygen cleaning may also present a major safety concern. Accurate oxygen cleaning requires educated and experienced personnel at the ladle repair stand. In order to assist the operators for this important task RHI Magnesita has developed a device called PFD which informs the operators optically and acoustically by a horn when the plug has been cleaned successfully and full flow rate has been achieved again. A very user-friendly navigation allows quick implementation into existing processes. Several steel plants in Europe, India, and North America have tested the PFD successfully and have implemented the PFD into their oxygen cleaning process. Based on their very positive feedback the global market roll-out for the PFD will take place in 2019.

Worldwide

RHI Magnesita on Social Media

Today's communication world is shifting towards digital and social media. Therefore, order to increase our reach and build our reputation. You can find RHI Magnesita on LinkedIn, Facebook, and Instagram. Like the company pages, share the postings, and get the latest news about the leader of the refractory industry!

RHI Magnesita Worldwide news (continued)

Worldwide

Trade Fair Highlights 2019

RHI Magnesita (RHIM) participates in approximately 35 trade fairs, exhibitions, and conferences, spread all around the globe all over the year. These events each evolve around one of the areas RHIM is driving business in: steel, glass, nonferrous metals, raw material, lime, cement, EEC (environment — energy — chemistry) and foundry.

The METEC trade fair in June in Düsseldorf, Germany is one of the most significant exhibitions this year, RHIM was also present at numerous other fairs and conferences, such as CEMENTTECH in March in Anhui, China. The world's largest exhibition for the cement industry, AISTech 2019—steel's premier technology event—in Pittsburgh, USA in May, and almost simultaneously at China Glass, the biggest glass industrial technical exhibition in Asia in Peking, China. In July interested parties can meet RHIM in Shanghai, China at ALUMINIUM CHINA.

The 10th International Copper Conference 2019 will take place from 18th—21st August in Vancouver, Canada, where RHIM is participating, presenting technical papers, and also represented with a booth (#15&17) during the exhibition. In October, RHIM can be visited at UNITECR— a conference to contribute to the progress and exchange of industrial knowledge and technologies concerning refractories in Yokohama, Japan. The Metal-Expo in November in Russia can also not be imagined without the participation of RHIM. Last but not least, RHIM is closing the year 2019 with attendance at the 23rd Middle East Iron & Steel Conference in Dubai, UAE in December.

Worldwide

Cold Crushing Strength of MgO-C Bricks

For many steel plants, the CCS is a standard value that is used as an indication of the refractory brick quality, even though the value is not directly related to refractoriness. Unfortunately there are different methods and standards (ASTM, ISO, GOST,...) which are used to measure CCS worldwide. Even the ISO standard offers two ways to measure the CCS, one with and one without cardboard inlay (ISO 10059-1 and ISO 10059-2). Previous research has shown that this can have a significant influence on the measured values, but now an in-depth study has been completed by R&D Leoben. A detailed comparison of the main influence of sample preparation and measurement process has been developed.
By recognising these influences, a better communication between RHI Magnesita and customers can be achieved. This knowledge enables a faster and more flexible reaction to customer complaints and wishes on CCS measurements. This is a big step towards the direct comparison of measurements from one standard to another and helps to understand and explain differences or deviations of CCS measurements.

Europe

Technology News Flow Control

The erosion and corrosion resistance of stopper nose materials has a critical influence on the continuous casting process of several aggressive steel grades, such as ferritic and austenitic stainless steels. RHI Magnesita has successfully tested the newly developed high-performance stopper nose material DELTEK M090 at a European stainless steel producer. This new material is hydraulically pressed and assembled with the ISO-body of the stopper using the new screw-on concept. Under tough conditions a new lifetime record of 15 heats has been achieved. Based on the initial test results of DELTEK M090 the wear could be rated as exceptionally low in comparison with other common stopper nose materials. The potential of this new magnesia based material grade will be further evaluated under aggressive casting conditions.


RHI MAGNESITA
The
global leader
in refractories

A letter from our editor

Welcome to the 2019 special edition of the Bulletin, published to coincide with the METEC 2019 trade fair and 4th European Steel Technology and Application Days. These events provide an exciting opportunity to showcase the new global leader in refractories and how RHI Magnesita is setting the pace of innovation in the industry to deliver the best products and services for its customers.

The first paper provides an example of how multiple systems and know-how can be combined to achieve highly efficient, cost-effective hot metal desulphurization in the ladle. With a focus on safety and stability, the multifaceted approach results in unique tailored solutions that optimize production while reducing operational expenditure. Since 2017, Agellis® has been a RHI Magnesita brand and this strategic expansion of the product range incorporates more than 30 years of experience in molten metal level measurement, detection, and monitoring. VISIR—a vision and infrared platform for critical process monitoring—is highlighted in the second article describing how this technology can be incorporated into a dynamic maintenance system to monitor the ladle fleet. The objective ladle status measurements increase safety in the steelmaking operation whilst optimizing fleet usage. In the next paper a slag modelling approach is described that when introduced at a customer sustainably decreased refractory mix consumption in the EAF and increased productivity due to lower maintenance requirements. This is followed by a further example of the significant production benefits that can be achieved through a close cooperation between the steel plant and RHI Magnesita. Focused on the BOF, a partnership contract resulted in a 108% higher campaign life, 100% bottom stirring availability, as well as decreased refractory consumption and maintenance.

To enhance the Ladle-to-Mould portfolio, RHI Magnesita is working synergistically with Prosimet, a continuous casting technology expert. As a result of introducing the patented PROIL in the open casting process of a US billet producer, multiple benefits were achieved including improved quality and safety as well as the possibility to cast new steel grades. The subsequent papers in this flow control section describe the safety, automation, and cost advantages of the high-performance INTERSTOP® S ladle gate series; ladle shroud design optimization using numerical modelling; and the GYRONOZZLE development for improved flow conditions in billet and bloom moulds, including CFD and physical investigations examining the interaction with electromagnetic stirrers.

A new water soluble binder for the foundry industry, developed in collaboration with the Österreichisches Giesserei Institut, is presented in the next article. It not only shows significant potential regarding easy mould and core removal but also has eco-friendly features. This is followed by the description of how a sequentially coupled modelling approach was used to develop a novel roof panel brick suspension system. The iterative numerical simulations avoided costly practical experiments prior to the trial that is now running in a nonferrous EAF. The final paper exemplifies the role of postmortem investigations and thermochemical calculations to understand how customer practices can contribute to refractory wear and thereby enables RHI Magnesita to provide tailored lining recommendations for specific requirements.

In closing, I would like to express my sincere thanks to all the authors and Bulletin editorial team for their hard work and dedication behind this 2019 METEC edition.

Yours sincerely

Stefan Schriebl
Corporate Research and Development
RHI Magnesita

"To enhance the Ladle-to-Mould portfolio, RHI Magnesita is working synergistically with Prosimet, a continuous casting technology expert. As a result of introducing the patented PROIL in the open casting process of a US billet producer, multiple benefits were achieved including improved quality and safety as well as the possibility to cast new steel grades."


RHI MAGNESITA
And we take
leadership
seriously

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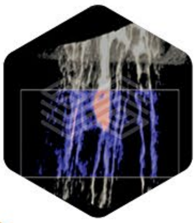

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Andreas Viertauer, Kevin Christmann, Jürgen Schütz, Markus Gruber, Bernhard Spiess and Patrik Bloemer

Efficient Hot Metal Desulphurisation Ladle

This paper provides an overview of technical solutions for a highly efficient hot metal desulphurisation ladle. It focuses on refractory design, economic aspects of steel production as well as process stability and safety. In this regard, convenient bottom gas stirring during deslagging after evaluation of the optimal location for the purging plugs, holistic monitoring of the deslagging process and of undesired remaining sulphur-rich slag, iron losses, and general ladle shell temperature distribution during deslagging will be addressed.

Introduction

Hot metal desulphurisation is currently state-of-the-art and mostly done in the hot metal ladle [1, 2]. To match the requirements of modern steel production, a high lifetime with respect to availability of the hot metal ladles is required. Simultaneously increasing cost pressure raises the demand for cost effective solutions. The lining configuration therefore has to be chosen adequately. Temperature losses are minimized and hot spot formation at the steel shell is avoided by tailor-made lining configurations.

In the steel production process, typically the hot metal ladle is placed in the desulphurisation stand, where desulphurisation agents such as magnesium, calcium-carbide, and/or lime, or a combination of these materials are injected into the hot metal. The reagents bind the dissolved sulphur for example as MgS and CaS in the hot metal and form a sulphur-rich slag, after floating to the bath surface. This slag is removed by a skimmer plate after the injection. The desulphurisation and deslagging has to be done very quickly in order to save valuable process time, which is supported by bottom gas stirring in some plants. Therefore high purging availability, achieved by using a suitable plug type, and a proper gas flow control unit, is essential. For the evaluation of the optimal plug location, a computational fluid dynamics (CFD) simulation is a useful tool [3]. The demand for high ladle lifetimes increases the need for safety. The **s**afety **o**ptimized **c**losing system with **h**inged door (SOC-H) for purge plug is effectively contributing to process safety and stability. Furthermore, infrared (IR) detection is an appropriate tool to monitor the deslagging process itself, helping to minimise metal losses as well as the remaining sulphur-rich slag. Additionally, it enables the visualisation of the ladle shell temperature at the control room and alerts the operator if the shell temperature is above a defined limit.

Lining Configuration

Several different lining concepts for hot metal ladles can be found. Depending on the operating conditions and considering economic, environmental, local, and other aspects, the optimum lining concept for each customer has to be developed individually. With regards to those factors the refractory selection is strongly dependent on the main raw materials. Table I provides an overview of the typical

Table I.
Typical wear areas, wear mechanism, and refractory countermeasures for hot metal ladles.

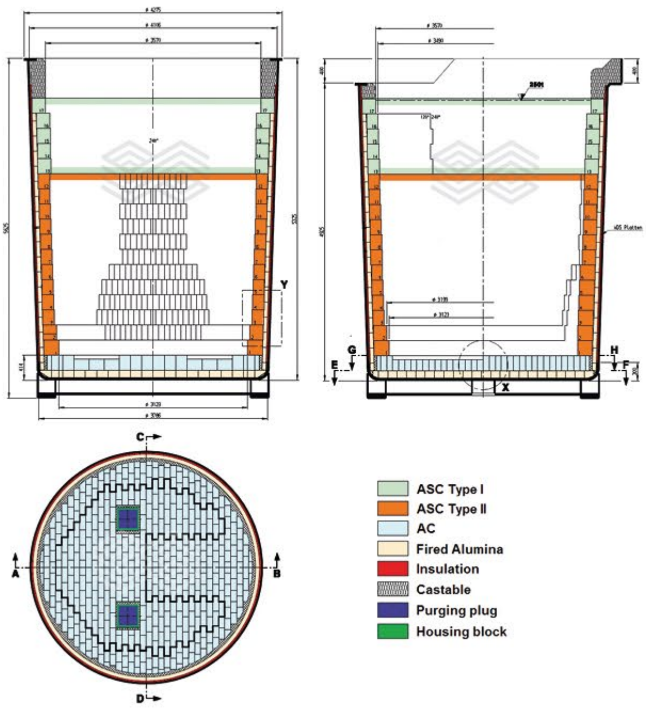
Area	Type of attack on refractory	Wear mechanism	Required properties for refractory
Spout	Chemical; physical	Abrasion during BOF charging; deslagging; Spout cleaning; downtimes (oxidation); slag contact; thermal cycling; thermo mechanical stress	CCS; TSR; AR; CR; OR
Slag Line	Chemical; physical	Deslagging; downtimes (oxidation); slag contact; bath movement due to bottom stirring; thermal cycling; thermo mechanical stress	CCS; TSR; AR; CR; OR; LW
Barrel	Chemical; physical	Downtimes (oxidation); slag contact (if bath level is low or due to strong bath stirring); thermal cycling; abrasion and thermal shock (if there is an wall impact during hot metal charging); thermo mechanical stress	CCS; TSR; CR; OR
Bottom	Physical	Downtimes (oxidation); thermal shock during hot metal charging; Abrasion due to bottom purging; thermo mechanical stress	CCS; TSR; AR; OR
Impact pad	Physical	Downtimes (oxidation); abrasion and thermal shock during hot metal charging; abrasion due to bottom stirring; thermo mechanical stress	CCS; TSR; AR; OR
Permanent lining	Physical	Abrasion during wrecking; thermal shock; thermo mechanical stress	CCS; TSR; AR; RuL; HMR; RC
CCS = cold crushing strength; TSR = thermal shock resistance; AR = abrasion resistance; CR = resistance to chemical attack; OR = oxidation resistance; LW = low wettability; RuL = refractoriness under load; HMR = hot modulus of rupture; RC = creep resistance			

wear areas of an hot metal ladle and shows the most important type of attack on the refractory, as well as necessary properties for the refractory to counter.

Usually, bricked hot metal ladles are lined either with fired, ceramic bonded, high alumina bricks (based on bauxite and andalusite), tempered resin bonded high alumina bricks with graphite content (alumina, carbon (AC) bricks) or with additional SiC content (alumina, silicon carbide, carbon (ASC) bricks) [3, 4]. Figure 1 shows an example for a high performance hot metal ladle. This ladle is equipped with two bottom stirring plugs. Bottom and barrel have an impact area. The slag line bricks are reinforced.

The high alumina castable in the spout of the hot metal ladle is needed to provide the following properties to achieve high lifetimes: high cold crushing strength, high thermal shock resistance, high abrasion resistance, and very good chemical resistance.

Figure 1.
High performance hot metal ladle.



Furthermore, this ladle is equipped with high grade tempered ASC bricks, based on high purity brown fused alumina (BFA), in the slag line. High density and abrasion resistance, good thermal shock resistance as well as a high resistance against chemical corrosion make BFA a good choice for the slag line, especially when desulphurisation is part of the metallurgy. The SiC content in ASC bricks further improves the thermal shock resistance and increases the abrasion resistance. Carbon addition in AC and ASC bricks counters slag and metal infiltration.

Also in the barrel of the ladle, ASC bricks are installed. These bricks are based on high alumina containing bauxite and BFA, which is the best economical solution (cost – performance compromise). Both ASC grades in the slag line and barrel are equipped with antioxidants, which provide oxidation resistance accompanied by a volume increase, enhanced density, and reduction of porosity.

In the ladle bottom a high grade andalusite based AC brick is installed. At temperatures above approximately 1270 °C andalusite transforms to mullite, which is accompanied by a volume increase. Therefore andalusite is beneficial for example in the impact area, where joints need to be sealed to prevent slag and metal infiltration. Furthermore, the andalusite provides excellent physical properties in terms of creep resistance, refractoriness under load, thermal shock resistance, hot modulus of rupture, and hot strength, which make it a perfect choice for the hot metal ladle bottom.

The safety lining is made of andalusite and bauxite based fired alumina bricks, providing a high refractoriness under load, abrasion resistance, thermal shock resistance, and shape stability. The permanent lining is also equipped with a layer of insulating ceramic fibres in order to control the shell temperature of the hot metal ladle. Table II shows technical data of the selected materials.

The following steady state thermal calculations show the effect of wear on the shell temperature in the selected hot

Table II.
Physical and chemical properties of the selected materials for the high performance hot metal ladle.

Type	Al_2O_3 [%]	SiO_2 [%]	SiC [%]	Fe_2O_3 [%]	C [%]	BD [g/cm³]	AP [vol. %]	CCS [N/mm²]	AOX	Bonding	Raw material
ASC I	85.0	1.5	7.0		6.0	3.28	6	60	yes	Resin	Brown fused alumina, graphite, silicon carbide
ASC II	83.0	4.0	7.0	1.0	6.0	3.00	7	55	yes	Resin	Bauxite, brown fused alumina; graphite, silicon carbide
AC	70.0	27.0		0.5	7.0	2.83	7	50	no	Resin	Andalusite, graphite
Fired alumina	66.0	30.0		1.3		2.70	15	60	no	Ceramic	Andalusite, bauxite
Insulation	46.0	54.0				0.435			no	Organic-chemical-ceramic	Ceramic fibre
Castable	98.5	1.0		0.1		3.05		65	no	Sol- bonding	Sintered alumina

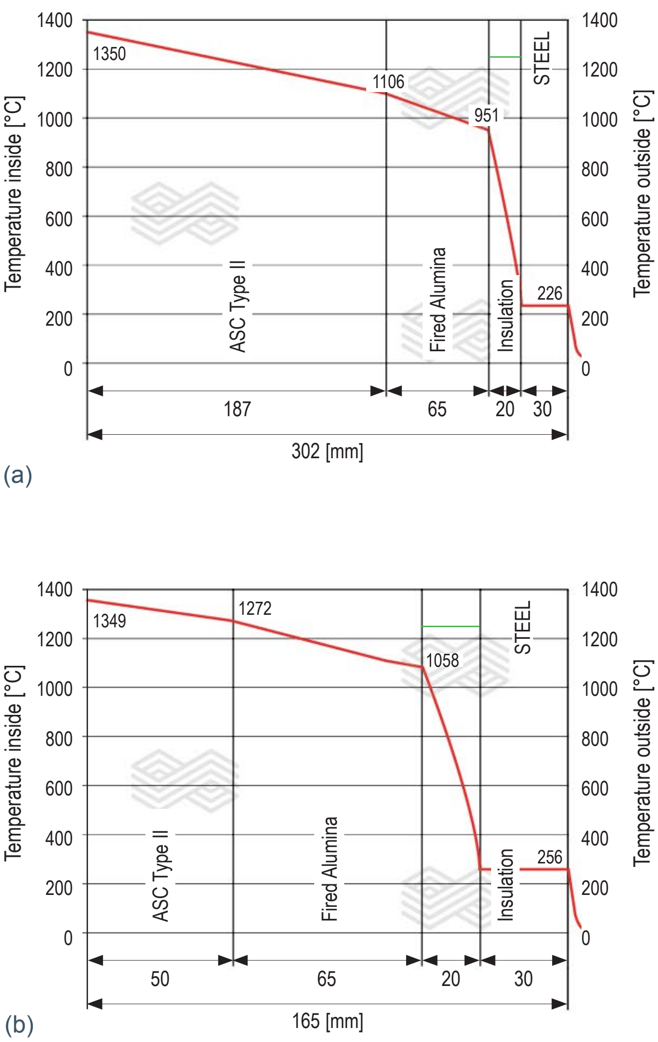
BD = bulk density; AP = apparent porosity; CCS = cold crushing strength; AOX = antioxidants metal ladle design. In this case the working lining setup has a minimum thickness of 187 mm in the barrel. Therefore the thermal conductivity will be calculated at that point. Figure 2 (a) shows the temperature profile with 100% of the wear lining thickness intact. Figure 2 (b) presents the same setup with a remaining wear lining thickness of 50 mm at the end of the campaign.

The comparison of Figure 2 (a) and (b) reveals that even a strong decrease in the wear lining thickness will not lead to an excessive temperature increase on the steel shell. In total the shell temperature of the chosen setup will increase by 30 K at the end of the hot metal ladle campaign, which is acceptable.

The presented hot metal ladle utilizes high performance focused materials in the working and safety lining. These materials are in use at different customer locations and under various process conditions. The known wear behaviour of the presented material selection enables estimated expected lifetime of the high-performance hot metal ladle to be at 1000 to 1100 heats without repairs. If repairs are made, for example in the ladle bottom, the lifetime can be further increased by 400–500 heats.

Figure 2.

Temperature profile showing (a) 187 mm and (b) 50 mm wear lining thickness.



As an alternative to bricked concepts, partial and full monolithic linings can be used [5]. However, monolithic ladle linings may cause certain additional investments (template for sidewall lining, mixing equipment, programmable pre-heater, etc.). As the refractory consumption in the hot metal ladles is rather low, these investments are usually only economic, if a monolithic lining is also used in the steel teeming ladle – where the consumption is much higher – and the equipment can be used for both ladle types.

Desulphurisation Optimisation Using CFD Modelling

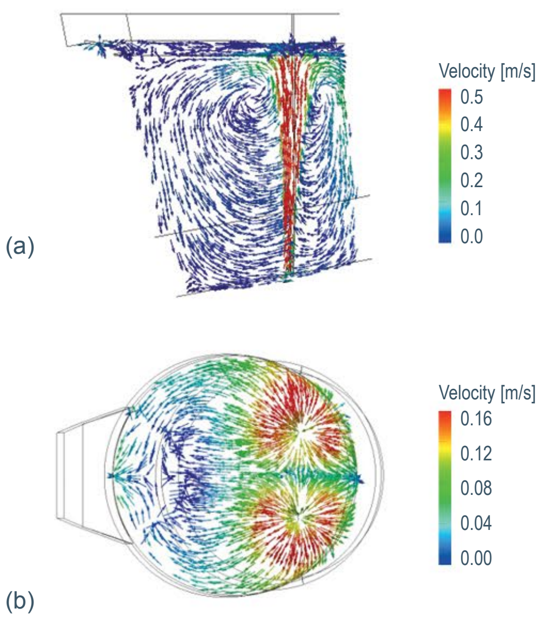
To provide an efficient deslagging process in hot metal ladles, it is useful to install purging plugs in the ladle bottom for gas stirring. Whereby the slag is moved towards the spout. To achieve the desired effect, the location of plugs is important. To determine the optimum plug position, a computational fluid dynamics (CFD) model can be used, providing the opportunity to gain detailed information about the flow behaviour during the purging process. In order to depict the interaction of steel, slag, and air, a 3D multiphase approach was chosen. The gas stirring is calculated using a discrete phase model (DPM) [6].

It was possible to simulate the purge plug induced movement of hot metal with the appropriate material properties for hot metal, slag, and air. The forming of the open eye, and subsequent movement of the slag towards the spout which supports the deslagging process with the skimmer plate was simulated.

The CFD simulation in the present case was carried out for a 290 t hot metal ladle using two purging plugs with a purging rate of 38 Nm^3/h per plug. By investigating different possible plug positions, it was found that in this case, the optimum plug location was close to the horizontal ladle axis (Figure 3).

Figure 3.

CFD simulation, showing (a) cross section and (b) top view.



The stirring gas will rise vertically without touching the wall and so the plume can grow. The slag flow is orientated towards the centreline of the ladle and will be pushed to the spout, this helps to improve the efficiency of deslagging. A further benefit is that the gas will not flow along the wall, which leads to:

- A better momentum at the steel-slag interface.
- Minimized flow along the wall.
- Less erosion of the wear lining.

Purging Plugs for Ladles

Different types of purging plugs can be used to support the deslagging process (Table III). Usually nitrogen gas is used as medium to create the open eye formation on the surface. The flow rate is mainly influenced by the heat size and can go up to approximately 40 Nm^3/h per plug. Generally porous plugs with random porosity or multi component plugs are the optimum design for this application. Due to the low viscosity of hot metal monolithic single component plugs have a higher risk for hot metal infiltration which may result in a subsequent blockage of the plug. Therefore single component plugs are not favoured for hot metal application [7, 8].

Safety Closing System for Purging Plugs

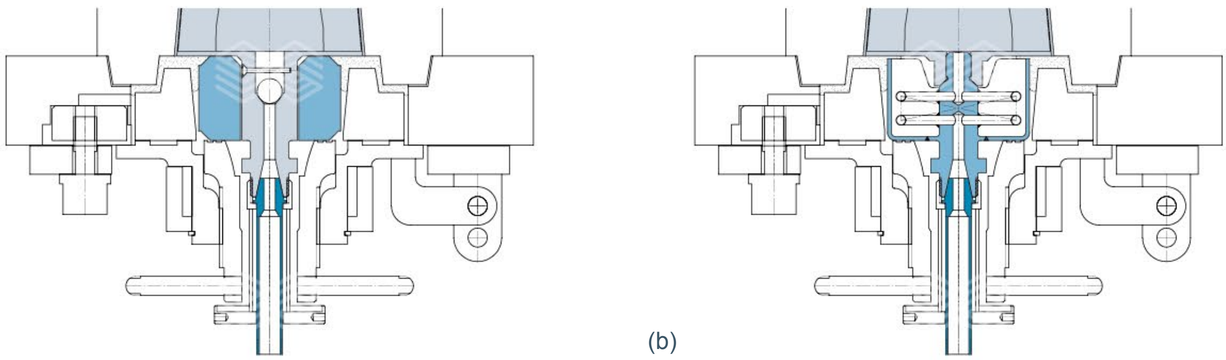
Hot metal has a very low viscosity and is very critical for operational safety. To limit this risk, the so called SOC-H is used as a safety closing system for the purge plug. This system provides safe handling and in the event of hot metal penetration through the plug, the hot metal will freeze in the ball chamber of the integrated non return valve due to the high thermal conductivity of the surrounding steel (Figure 4a). An alternative is the use of a reusable copper spiral (Figure 4b). For maximal reliability the simple but innovative solution of an integrated non return valve is recommended (Figure 4a). In addition to the safety features, the SOC-H system allows an easy and quick exchange of the purging plug, increasing high availability. If the plug is worn down, or a plug failure is observed, the affected plugs can be replaced by a new one without taking the ladle out of hot cycle operation [8, 9].

Not only the best suitable purging plug is essential for the purging availability, the gas flow regulation equipment also has a significant influence (Figure 5) [10]. The gas connection is usually made with an auto coupling system when the ladle is in the desulphurisation stand. The purging started when the ladle is turned into the inclined deslagging position and stopped after deslagging is finished.

Table III.
Different purging plug configurations.

Multi component plugs			Single component plugs	
Segment plug	Hybrid plug [15]	Porous plug	Slot plug	Star plug
				
Random and direct pore structure		Random pore structure	Direct pore structure	
High porosity and planar parallel slots	High porosity and surrounding slots	High porosity	Separate slots	Continuous slots
Pressed and cast		Pressed	Cast	

Figure 4.
Showing (a) closing mechanism [15] with integrated non return valve, and (b) with copper spiral.



(a) (b)

Deslagging Process

Once the ladle is tilted into the deslagging position, the slag will be removed by a movable arm with skimmer plate. The amount of slag to be removed can be up to approx. 20 kg/t hot metal [11]. This amount is influenced by the number and type of desulphurisation agent, heat size, and amount of carry-over slag from the torpedo ladle. The deslagging continues for approximately 5 to 7 minutes and is influenced by multiple factors, such as operational skills, size of the skimmer plate, speed of the rocker beam, amount and viscosity of the slag, and bottom purging. Never the less during the deslagging process the losses of liquid iron should be minimized in a cost- process relevant way. To fulfil these requirements infrared (IR) systems are used in some plants as shown in Figures 6 and 7 [12].

Some steel plants measure the ladle steel shell temperature as part of condition monitoring with respect to preventive maintenance actions.

At any adequate position on the process route the ladle shell and even the bottom are detected by several fixed installed IR based systems [12]. The ladle steel shell monitoring starts when the ladle is placed at the desulphurisation station and the current status is displayed directly at the control room. The system displays the temperature distribution over the steel shell from each view angle as well as trend curves for selected areas, providing operators “heads-up” information on an eventual problem area. Eventual hot spots are automatically detected and an alarm is displayed to operators. An example is shown in Figure 8. Each measurement sequence is stored in the system server for data trend analysis and status reports are possible.

Summary

Over the past decades the function of the hot metal ladle has been transformed from a simple transport vessel to a treatment unit to obtain a more consistent, standardized product with lower specific costs even for the further treatment steps. Refractory concepts have to be chosen specifically for each customer’s expectations. Depending on the treatment steps, processes, and conditioning agents as well as the chosen refractory concept and maintenance strategy, the lifetime of the hot metal wear lining can be up to 2000 heats whereby safety and ecological aspects have to be considered.

Desulphurisation and deslagging has to be done as quickly as possible. Therefore a proper gas stirring has to be provided. CFD simulation is a useful tool to find the best position for the purging plug within the hot metal ladle. The simulation revealed that the best position in this case was close to the centreline of the ladle. The specific plug type chosen and the gas stirring facility are key factors. The SOC-H is an appropriate system to provide safety for the gas purging installation, as well as easy reliable handling.

IR vision system is a possibility to optimize the deslagging process by minimising hot metal losses and visualisation of remaining slag. In addition, the steel shell temperature can be monitored and displayed at the control room by IR imaging when the ladle is seated in the desulphurisation stand. If the shell temperature is slightly above a clearly defined temperature range an alarm will be generated. All relevant data for process optimisation and safety will be automatically stored for further data processing with respect to condition monitoring and life time prognosis [14].

Figure 6.
IR system monitoring the deslagging.

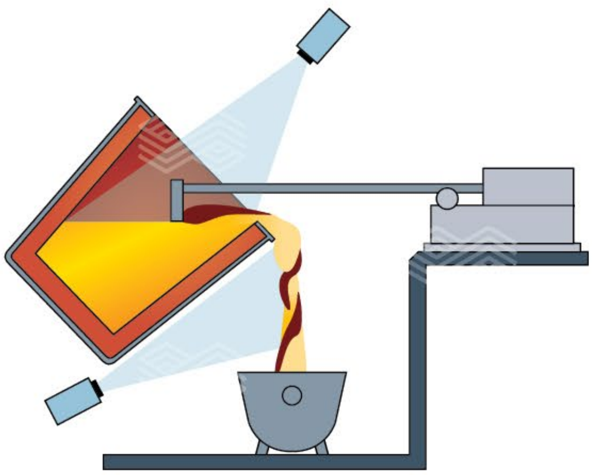
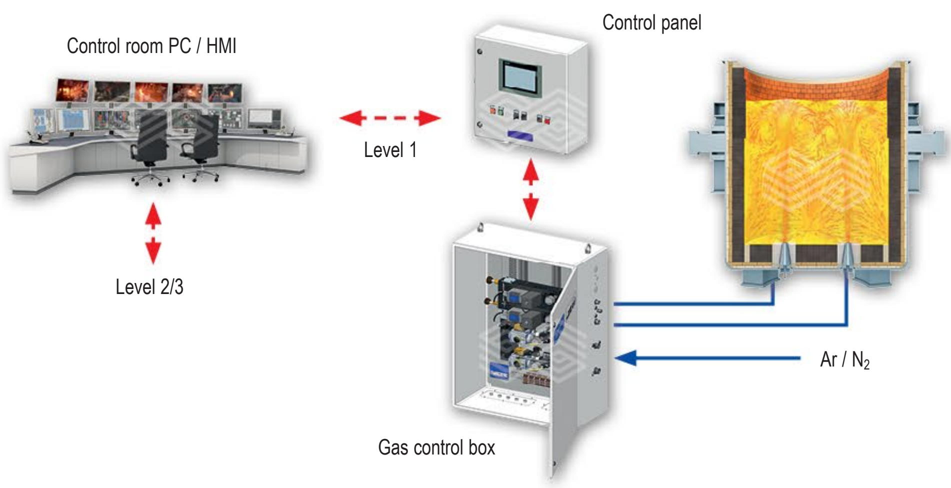


Figure 5.
Layout and instrumentation of a purging system.



Conclusions

The increasing demands for product quality require specific tailor-made solutions. However, developments in technology integration and unique solutions can provide opportunities for improvement. The continuing research into the adaption of technology (IR), modelling (plug location) and safety (SOC-H), demonstrates the commitment of RHIM to the creation of individual solutions for customers. These developments provide opportunities for customers to optimise production, while reducing the operational expenditure (OPEX).

Figure 8.

IR image from a hot metal ladle [13].

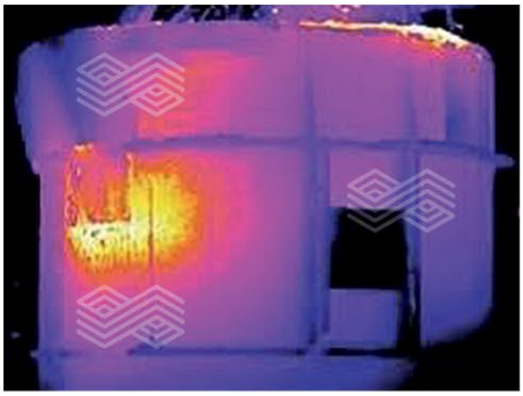
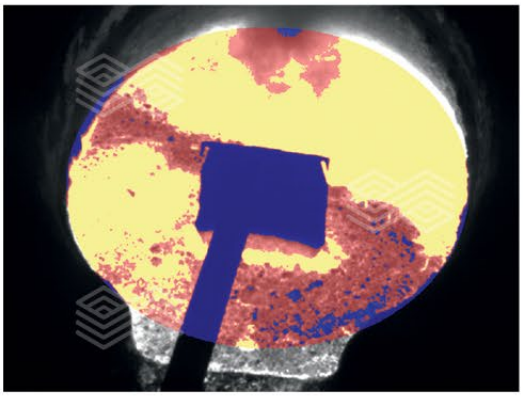


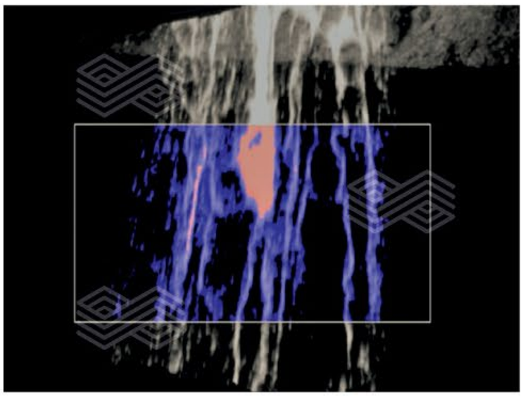
Figure 7.

Showing (a) IR cameras monitoring deslagging and (b) hot metal losses during deslagging.

(a)



(b)



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Magnus Persson, Jan-Peter Nilsson, Karl Adolfsson, Ann Sjöstedt and Matthias Höck

Ladle Fleet Monitoring for Safety and Lifetime Evaluation

This article discusses the implementation of vision and infrared systems (VISIR) to monitor the entire ladle fleet in operation efficiently, making sure each ladle is objectively safe to be used. Additionally, it highlights the use of empirical measurement data as a decisive input to help maximise the refractory use, applying a dynamic maintenance schedule while keeping safety a priority. These processes must be performed without impacting the operations resources, eliminating subjectivity, and without slowing the process.

Introduction

Safety for the personnel and the operations is the most important factor when introducing a ladle fleet integrity monitoring system. Ensuring each ladle shell is safe, goes hand in hand with operational excellence, as unplanned production problems results in higher production costs.

Prolonging refractory lifetime when possible and thereby reducing the maintenance costs is also a factor that cannot be undermined. Following up refractory performances objectively and in a coherent matter allows for adaptive maintenance practices and optimisation of the ladle fleet utilisation. The collection of relevant data for each unit in the process and in real time is a prerequisite for the adaption of Industry 4.0 and the linked applications.

Problem Description

In many plants, ladles are considered of secondary importance compared with other processes and more complex installations. The ladles have a certain life cycle which is considered equal between the units, given they are circulated in the same process. There are however an infinite number of factors that affect the ladle shell integrity and the refractories.

Some pre-exposure factors, such as heating practices, are crucial to avoid thermal shock issues in the refractory, while in-use factors such as steel exposure time have a direct impact on the refractory wear. For the permanent lining and ladle steel shell itself, the operation outside of the thermal scope typically shortens the lifetime. It is well understood that all factors cannot be considered when analysing a ladle life cycle and in practice the number of heats is considered the most significant.

The typical ladle "life cycle" is based on judgements throughout the processes and on prior agreed practices. In the best cases, the judgements are made conservatively and safety of operation can be achieved at a certain expense.

However, from time to time and unexpectedly, a ladle breakout can occur even with use of conservative, observational practices. There may be seemingly no noticeable process deviations or indications leading to the prediction of such an event. These rare and unexpected breakouts have a huge impact on production performances and can have disastrous safety consequences.

Common Methods

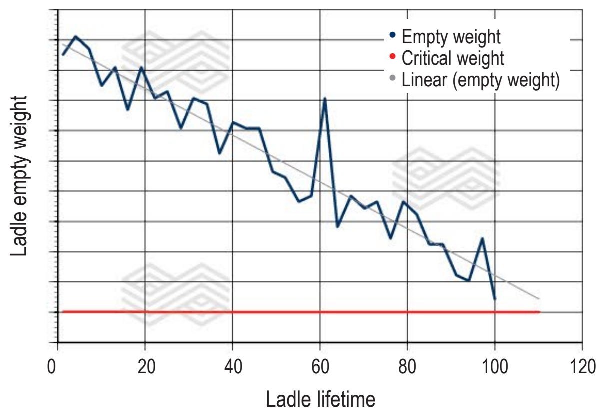
The processes and common methods applied today are very often based on historically learned practices, individual knowledge, and experience.

Before each heat a visual inspection is carried out to ensure no obvious problems have occurred during preparation and heating. During the heat itself, the ladle shell is visually observed by operators to potentially detect any overheated and "red glowing" areas that can occur when the ladle integrity has been compromised. After a certain number of heats, the specific unit is taken out of service to be partially or entirely relined.

Some steel plants measure and plot the weight of the empty ladle after slag tilting. With reduced thickness of the refractory material, the weight decreases until it reaches a critical level and the ladle is removed from operation. This critical level is determined from experience in combination with data from other methods. The greatest disadvantage is, that this method provides no warning if there is localized wear in a small area. Even if the wear is uniform, a strong scatter of the weight from heat to heat due to slag skulls or gunning repairs makes interpretation difficult as shown in Figure 1. It can only provide a rough estimation of expected ladle lifetime.

Figure 1.

Showing the plotted weight of the empty lades between heats.



Additionally, in some operations, a laser based residual refractory thickness measurement is performed at set intervals to track the wear of the refractories. This additional measurement helps determine whether the refractories are following the predicted wear rate. At a certain level, the refractories are considered too thin to efficiently contain steel and the ladle is taken out of service. This type of laser-based measurement is very helpful to record and monitor the ladle internal wear changes in order to add an objective value to the subjectivity of a visual inspection. However, it is very important to perform visual inspections as some states, such as cracks, are difficult to detect by a laser-based measurement.

In practice, most methods are fully dependent on an experience based visual inspection leading to decision making. In order to objectively support in this decision, Agellis® offers the VISIR-LadleSafe system.

VISIR System Description

The VISIR platform is the base for several types of systems delivered by Agellis® aimed at monitoring and supporting different aspects of the steelmaking process. The different systems have varying purposes, such as process stability, traceability, steel loss avoidance, and safety of operation [1,2]. The VISIR-LadleSafe system, precisely targets the monitoring of the entire ladle fleet, in order to bring safety of operation, support maintenance practices, and optimise the fleet usage.

Each LadleSafe system handles up to six IR camera units in order to allow a relevant coverage of the ladle including all sides and bottom. The system software is able to handle up to nine flexible analysis areas per camera view. The purpose of using differentiated analysis areas in each camera view is to allow the pinpointing of critical areas on the ladle and consider them uniquely from the remaining areas on the ladle shell. For example, the status grading criteria for porous plug areas and lifting areas can be set differently in order to adapt the system to the specific circumstances found in the operation.

Additionally, the LadleSafe system includes an industrial I/O interface module which handles the exchange of communication with external devices, operator panels, and the plant Level 2 system. For example, trigger warning systems or receive start and stop signals to perform measurements without the need for operator interaction. All critical data related to measurements are logged in the database for statistics and status follow up. As a result of the data collected for each ladle unit, a more thorough analysis of the refractory performances can be performed.

IR Camera Technology

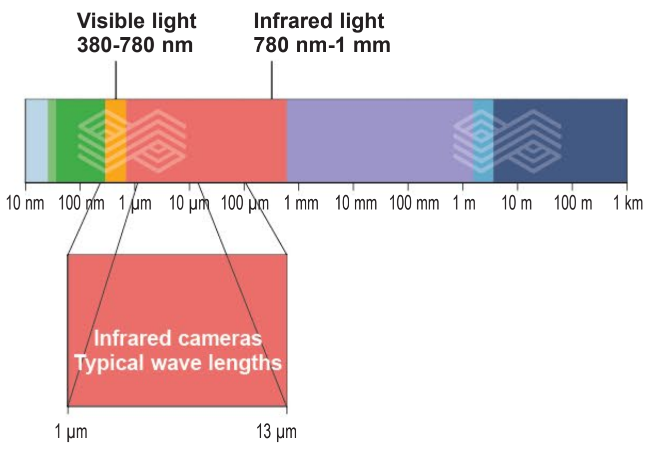
IR cameras for thermal imaging detect light emitted from the target objects themselves, known *as thermal emission (or black body radiation)*. The spectral power distribution of the emitted light shows a strong temperature dependency, and the photodetector arrays used in a thermal imaging system are chosen to be sensitive in a spectral region where the target objects emits thermal radiation [3]. In practice, there are additional constraints relating to the choice of the thermal imaging system. The cost of equipment, physical robustness, and practicality of the instrument are some important factors. The spectral penetration characteristics in the intended working environment can also have an impact on the usefulness of the imaging system.

It is therefore essential to select a camera in a wavelength range with suitable spectral properties for the intended application. Most IR cameras are sensitive in the range between 1 µm to 14 µm (Figure 2). The VISIR-LadleSafe system normally uses microbolometer based thermal cameras, which is a common type of IR camera and is sensitive in the long wavelength infrared (LWIR, 7–14 µm). This type of camera can provide reliable relative temperature distribution images from below 0 °C to over 2000 °C.

Regardless of thermal camera type, the signal detected is related to the temperature and can be used to form an image of the relative temperature distribution. The absolute temperature distribution, where the signal is converted into a temperature value, can be approximated but has limited precision as the emitted energy from an object also depends on its emissivity and this may vary over different regions in the field of view [4].

Figure 2.

Illustrates the spectral range where most IR cameras are sensitive.



Calibration to Environment

The thermal optical response may vary substantially between different target surfaces and because of this, each installation/situation must be calibrated. There are several factors that influence the apparent temperature distribution, as perceived by the camera, and the most prominent include emissivity, surface roughness/smoothness in combination with competing radiation sources, and the distance from the camera to the target surface.

The emissivity describes how effectively a surface emits radiation at a specific temperature compared to a black body. This property is highly material dependent and may therefore vary considerably between targets. The emissivity may even vary over the field-of-view due to compositional differences in the mechanical/structural features of the target, although this is normally taken into consideration when choosing camera placement.

The surface roughness/smoothness determines the angular dependency of the apparent temperature distribution. A rough surface is preferable over a smooth surface as it is less susceptible to specular reflections from competing radiation sources and minimizes the angular dependency of the thermal radiation from the surface. Typically, the smoother the surface the more critical the camera placement becomes.

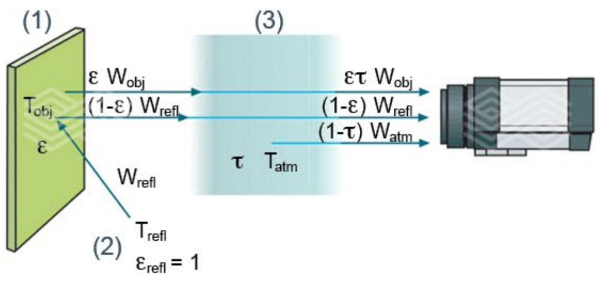
The free space distance between the camera and the target surface may distort the thermal signal due to the presence of smoke or flames, and to a lesser extent by atmospheric absorption. Figure 3 depicts the relation between the apparent relative temperature distribution and influencing factors such as the object emissivity, reflected sources and atmospheric absorption. In most cases, the influence of the variables mentioned above can be minimised or completely removed, by carefully choosing camera position, calibrating the IR camera hardware, or with adjustments in the VISIR software.

Typical Work Flow

Although each plant implements their own specific work flow, many have similar demands and the work flow described below in Figure 4 is representative of a standard installation.

Figure 3.

Showing the major factors influencing the apparent relative temperature distribution: (1) emissivity, (2) surface reflectivity, and (3) atmospheric attenuation.



The crane operator lifts the ladle to bring it to the caster. On the way, the ladle passes the area equipped and monitored by the LadleSafe system. As seen in the illustration in Figure 5 the ladle is monitored from all sides, by up to 6 camera units.

By positioning the ladle in the measurement area, the operator is able to perform a status measurement for each specific ladle. Once the measurement is initiated, the LadleSafe analyses the unit and presents a status result within a couple of seconds.

The status of the unit is presented as colours, text (OK, Warm, Hot, Danger), and as a grading between 1–10. The operator is then asked to approve or disapprove the ladle unit based on the measurement result.

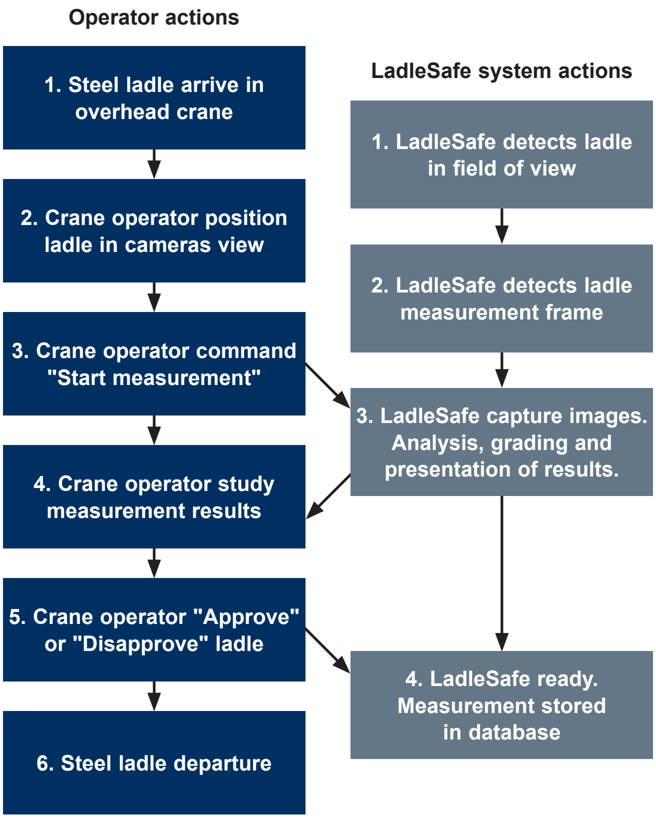
If the ladle is approved, it is released towards the caster and is logged as approved in the database. The entire monitoring procedure take less than 15 seconds and can be presented immediately to the operator as shown in Figure 6.

Placement of the System in the Process

As safety is the main focus, the measurement acquisition must be positioned in the best way possible to limit the risk of breakout and exposure to the personnel and critical equipment. Whereas the visual inspection processes in use, ensures the ladle is safe to be used before it enters the production, there are very few instances in the process itself that will efficiently control and verify that the ladle integrity remaines intact during the entire heat.

Figure 4.

LadleSafe system and interaction with operator.



There are only a few positions in the steelmaking process that, either expose the ladles to more stress and excessive wear or are production critical enough to be closely monitored.

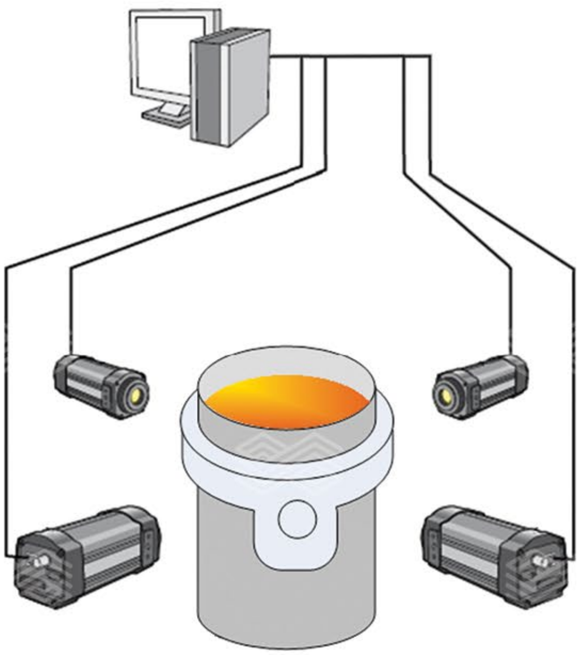
Tapping the ladle will expose the refractories to additional thermal stress and mechanical wear due to turbulences and additive practices. In this first step of the heat, the ladle is rapidly exposed to the process thermal load as well as different types of alloys added to the ladle. The additional thermal stress can create cracks if the ladle is not properly heated. The additions may mechanically damage the refractories if they are made in an inappropriate way. The position of the ladle during tapping is in most cases safe. The ladle can be observed both from a distance and by the tapping operators.

Secondary metallurgy processes can expose the ladle slag line to excessive wear due to stirring practices, slag volume, and overheating. In this position the ladle is surrounded by equipment and personnel. It is therefore vitally important to monitor the ladle in order to potentially detect a breach in the refractory integrity, as the damage to personnel and equipment is potentially high. For this specific location in the process Agellis® developed the VISIR-FurnaceSafe system. This system is unique as it provides a continuous measurement of the ladle shell, for example during ladle furnace process.

During casting, the ladle is usually not exposed to process related wear and the thermal losses are kept to a minimum by applying a ladle lid. However, the position of the ladle on top of the caster is critical in terms of safety as it exposes the personnel and the entire caster equipment to an imminent risk. It is therefore recommended to have a VISIR-LadleSafe station prior to the casting area.

Figure 5.

Illustrates the VISIR-system arrangement in relation to a target ladle.



In order to achieve an efficient monitoring of each ladle, a position must be found that allows an all-around view, including bottom, of the unit without adding essential process time or laborious procedures. This position is often easiest to be found somewhere along the route, when the ladle is travelling from the secondary metallurgy process toward the caster. Typically, when the ladle is lifted by the crane a 15 second stop at a predetermined position will be sufficient to perform the measurement and automatically obtain a ladle status based on objective criteria.

The measurement is carried out when the thermal load on the shell is close to the maximum, which is an important factor as the data should serve a dual purpose; support in the decision to keep or remove the ladle from circulation after a particular heat, and indicate whether a particular unit can be safely sent to the caster.

Implementing a measurement session for each unit sent to the caster collects the necessary data to assess the performances and will additionally ensure that dangerous ladles never reach the caster.

Safety as Focus and Maximal Utilisation as Target

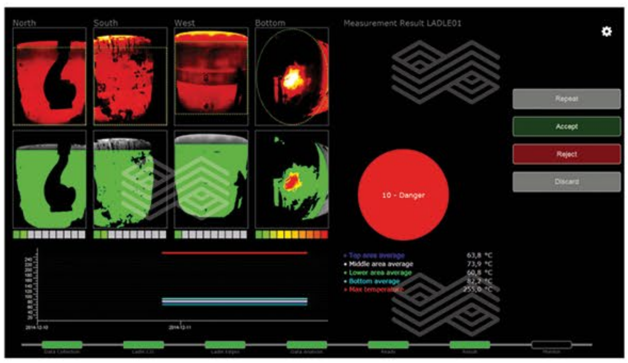
Through the implementation of a LadleSafe system, the operation will ensure dangerous ladles are detected well in advance of a breakout, allowing time to treat the defective unit accordingly. Implementing this additional measurement is primarily driven by the safety aspect.

When conducting visual inspections, the decision, whether a ladle should be kept in circulation or not is usually based on either detected defects, the number of heats conduced or the ladle residual weight. The maintenance personnel may find the ladle to be in good conditions but the critical number of heats has been reached, a conservative approach would direct the decision towards a circulation exit. Without additional information and proof of performance, it would be very difficult to argue for a continued circulation.

There are many factors affecting ladle integrity and refractory wear. Obviously, each ladle unit has a different exposure depending on the individual process variations. For example, a ladle may have been exposed to steel for a longer period than another despite having less heats.

Figure 6.

Shows a typical operator HMI and status analysis result.



These variations have a significant impact on refractory performances. A few percent of additional utilisation can result in substantial savings.

As each ladle unit is measured for integrity during each single heat, the VISIR database allows the maintenance personnel to obtain a summary, including a proof of integrity, at the highest thermal load. This additional and objective information can be utilised to prolong the circulation for a specific unit. Basing the withdrawal from circulation on objective in-process values will optimise the usage of the entire fleet.

Dynamic Maintenance and Safety Criteria

The dynamic maintenance concept uses the empirical data of each unit to determine the state of usage. To avoid breakouts in the steelmaking process, it may be necessary to remove some units before the planned maintenance schedule, and thereby shortening the expected lifetime. The same principle helps to determine units that have a potential to outperform the expected lifetime while maintaining the same safety criteria.

With safety as a specific criterion and being the decisive factor for maintenance, each ladle unit is taken out of circulation to perform refractory maintenance at the ideal moment. Additionally, the VISIR system can be used to assess the status of the permanent lining and insulating material.

Good insulators like fibre blankets or microporous plates usually have low application temperatures and/or low strength. When such insulating material breaks down, it must be replaced after the campaign. With the conventional methods, it is very difficult to evaluate if such a breakdown has occurred, often resulting in the use of ladles with insufficient insulation.

Using temperature distribution calculations models [6–8] as shown in Figure 7 and measurement results obtained with the VISIR system the performance of the insulation can be monitored and a dynamic maintenance advice can be obtained for each ladle unit.

The criteria for each customer will vary, as both the ladle and refractory design, system installation, and processes vary greatly. Each customer will find a unique set of criteria over time. More importantly, the judgement process for rating a ladle within the set criteria is identical for each unit and independent of who performs the measurement.

Ladle Designs and Implications

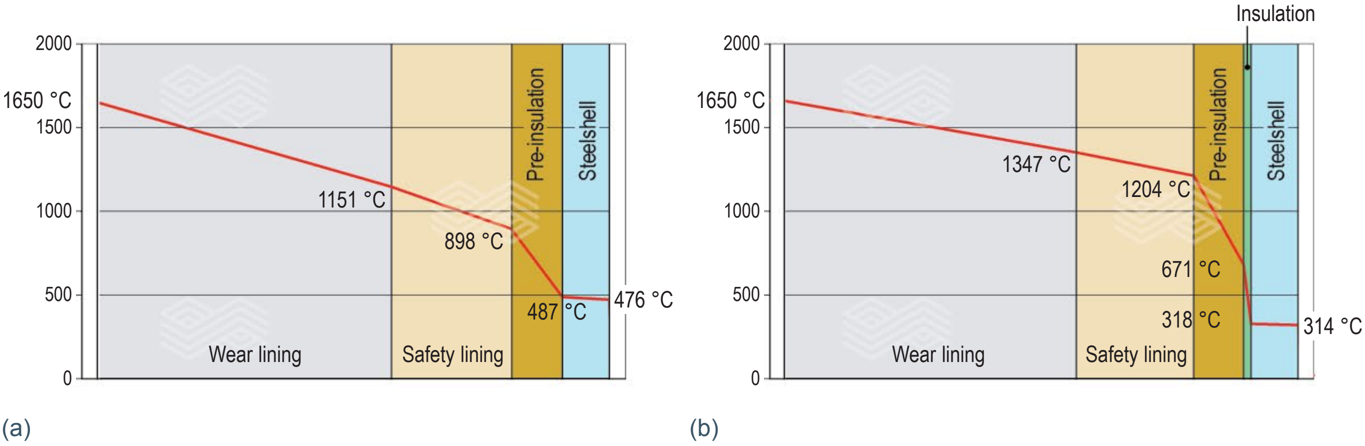
Ladles are designed by a wide range of suppliers with the mechanical proprieties and function in focus. The designs seldom consider the potential for breakouts and the typical areas where they may occur. A typical area is the slag line in general, and in particular, the area situated above a purging plug. Modern ladles often have a ring/cage around the top of the barrel in order to reinforce the mechanical strength and prevent deformations. Other designs include boxes and reinforcements around the trunions.

Using IR measurement units to detect a refractory integrity breach based on temperature differentiation demands that one understands the basics of emissivity-based measurements. As previously discussed, the position of the measured surface in relation to the measurement device, the smoothness of material, and angles all have an effect on the result of the measurement. Therefore, it is essential to measure and compare a ladle unit in the same way and from the same angle, each time. Ladle characteristics such as welded plates or boxed areas must be handled accordingly as the thermal response and emissivity will not be the same as other parts of the ladle body.

A LadleSafe system is able to isolate and analyses different parts of the object in order to efficiently detect any changes that may indicate a safety problem. Additionally, some areas of the object may have a unique set of criteria, such as bottom porous plugs, the sliding gate area, or the surroundings of the lifting devices.

Figure 7.

Showing the substantial difference in shell temperature distribution between (a) a lining without insulation and (b) a lining with insulation.



The use of Handheld Devices

Once the nature and limitations of the IR based measurement is understood, it is obvious that measurements provided out of context, such as with a handheld device will not be sufficient to provide operational safety.

Handheld devices, randomly scanning the ladle surface from different positions will provide different readings. The readings are not comparable with each other and local variations will result in meaningless values. Furthermore, the use of a handheld device requires the operators to process the readings immediately and make a judgement of the results based on too few criteria. It is also likely that the decision will not be documented and almost certain that the basis for the decision is not recorded.

In practice, the only criterion relevant from a handheld device is maximum shell temperature. Such a criterion is meaningless, when considering the complexity of the ladle shell structure. Additionally, the interpretation is operator dependent.

Refractory Performance Evaluation

Refractory performance evaluations can be made using different methods and references. There are often variations in the results of laboratory tests when compared to actual plant use. These are assumed to be the cumulative effect of various small “real world” issues, such as process variations or unexpected delays.

The VISIR database stores objective ladle status measurements. The system is equipped with an industrial I/O interface enabling relevant external signals to be logged to the relevant ladle unit in order to enhance the evaluation of the refractories in use.

The number of heats per ladle is an industry standard that does not consider individual process variations which, in some cases significantly affects the performances. The VISIR-LadleSafe system helps to achieve the most out of the entire ladle fleet refractories, as the specific ladle status determines the ladle lifetime of each specific unit.

Additionally, by integrating external data such as total steel exposure time, time at LF, time at caster, ladle weight after slag tilting, etc. a more precise and reliable evaluation can be made, potentially supporting advanced prediction models.

Conclusion

In conclusion, this article has discussed how to achieve an increase of safety into a steelmaking operation by removing the unpredicted and unexpected event of breakouts, while introducing a dynamic maintenance model based on the objective ladle status measured by a VISIR-LadleSafe system of each single ladle unit.

The article has briefly described the environment where the LadleSafe system is implemented and the purpose of the system. Described in the article, is a working knowledge of LadleSafe and the components, including environmental factors associated with IR technology.

The functionality and scientific basis of the system and the variables that should be considered for a successful implementation were outlined as were the clear benefits of the implementation of the LadleSafe system.

The concept allows for an extension of the number of heats while the primary focus remains on safety as it supports objectively the critical decision of whether a ladle is safe or if it should be removed from production, at the best possible moment.

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Francisco López, Alcides Farrando, Luciano Disante and Mark Loeffelholz

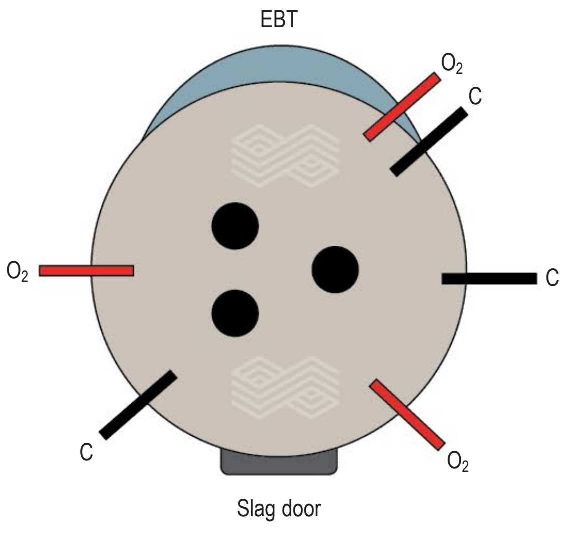
Slag Modelling for Optimising the Use of Fluxes in a DRI Based Steelmaking Operation

The use of phase diagrams for simulating and understanding steelmaking slags is both possible and feasible, enabling computer programming for the creation of a usuer-friendly interface to the operations engineer, in order to simulate with real plant data, the evolution of slag formation during the melting process in the electric arc furnace (EAF), especially with regards to the requirements of fluxes for foaming and saturation purposes. However, slag modelling for the EAF can be difficult. A lot of research and effort has been done, and continues to be done, in order to better understand the slag formation mechanism in the EAF and create a model, which accurately reflects what is occurring during the melting process, using thermodynamic tools, which would enable better control and a more predictive outcome. This paper describes the real case application of such a tool for a steelmaking plant in Argentina, which led to a meaningful and sustainable decrease of refractory mixes of the electric arc furnace and ensuring process safety.

Introduction

The development of the foamy mass balance (FoamyMB) by Eugene Pretorius at the end of 1990´s has come as an important contribution towards the effort to understand and control the slag formation process in the EAF and the impact on the refractory lining. Many papers have been published [1–4]. This tool has been used with success in some steelmaking plants where it is incorporated into the Level II – Supervisory Control.

Figure 1.
Layout of carbon and oxygen injection.



Slag modelling of the EAF was initiated in August 2014 at ArcelorMittal – Villa Constitución (AM-VC), Argentina, using the FoamyMB. The main goal was to reduce the specific consumption of basic monolithic refractory mixes used on the banks and bottom of the EAF. This paper shows that it is not always necessary to improve bricks or mixes quality to reduce refractory consumption and extend lifetime operation of the EAF. Correctly addressing issues within the process can also lead to savings.

Description of the Plant Facilities

AM-VC is a direct reduced iron (DRI)-based silicon-killed (SK) steel mill located in Villa Constitución, province of Santa Fe, centre east Argentina. It produces 1.4 Mt of steel per year with the following equipment:

- 1x125 Mtpa Midland-Ross Direct Reduction (MIDREX) plant.
- 2x130 t EAF.
- 2 ladle furnaces (LF).
- 2x6 strands billet continuous casting machines (CCM).

Description of the EAF Operation

The EAF is 6.8 m in diameter and is coupled with a 120 MVA transformer, using 24 inch electrodes, a power factor of 0.85 and an average active power of 89 MW, the maximum active power during flat bath is 102 MW. The pitch circle diameter is 1.2 m. The melting phase is aided by a chemical package consisting of 3 coherent jet (COJET) lances (O_2 injection and burner mode) located in the cold spots and 3 points of carbon injection, able to provide 18 MW of additional power [5] Figure 1.

Some relevant production data is shown on Table I.

Table I.
EAF operational data.

Parameter	Unit	Value
DRI usage	%	51–69
Scrap usage	%	31–49
Lime usage	kg/t	36–57
Tap-to-tap time	Minutes	60–65
Power-on time	Minutes	40
Specific energy consumption	kWh/t	530–576
Oxygen usage	Nm^3/t	26–30
DRI metallization	%	92–95
C in DRI	%	1.85–2.23
Tapping temperature	°C	1640–1657

The graphical DRI feeding operation is shown in Figure 2, and consists on the following steps. One or two buckets of scrap, depending on steel grade and quality, is charged and the scrap is then processed until 70% molten charge is reached. In the next step, the DRI is fed through the roof. Initially at a low rate (60 t/h), to create a liquid pool and in order to quickly obtain a foamy slag. The rate of addition is then gradually increased until 150 t/h. The maximum feeding rate is 230 t/h, however the ideal rate is between 140 and 180 t/h, depending on the amount of scrap charged, when the flat bath temperature is maintained at approximately 1580 °C. The rate of DRI feeding is reduced towards the end of the process, in order to complete the process at the desired tapping temperature and minimise refining time [6]. Blended lime (75% lime and 25% doloma) is continuously fed through the roof. This blend was used for logistical reason, as the plant was not equipped to handle the lime and doloma separately.

Table II.
Charges for modelling the slag at the EAF in kg/t.

Charge	Value
DRI	570
Scrap	335
Injected-C	9
Blended lime	51
Liquid heel	115
Remaining slag	15

Description of the Problem

From August 2014 onwards began a trend of increased refractory consumption in the banks, from an average of 2.22 kg/t to 2.98, as shown on Figure 3. It was necessary to address this issue, although this is a historic problem, the method by which it was addressed is still relevant and the practicality of slag models to identify solutions.

Initial Approach to the Problem

The initial approach was to model the whole slag formation process using the program FoamyMB and an approximate metallic mix of 60/40 DRI/scrap. The charges are shown in Table II (kg/t) and the chemistry is shown in Table III.

Figure 3.
Trend of banks usage in 2014

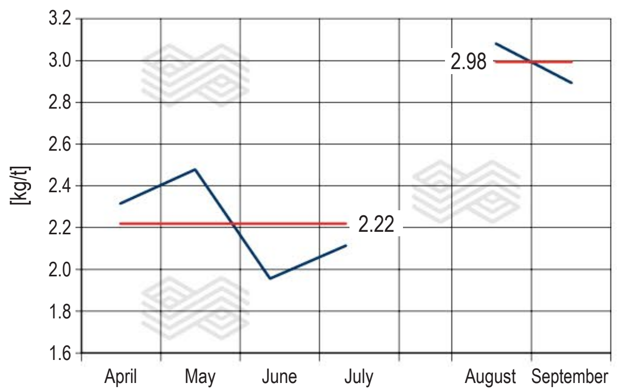
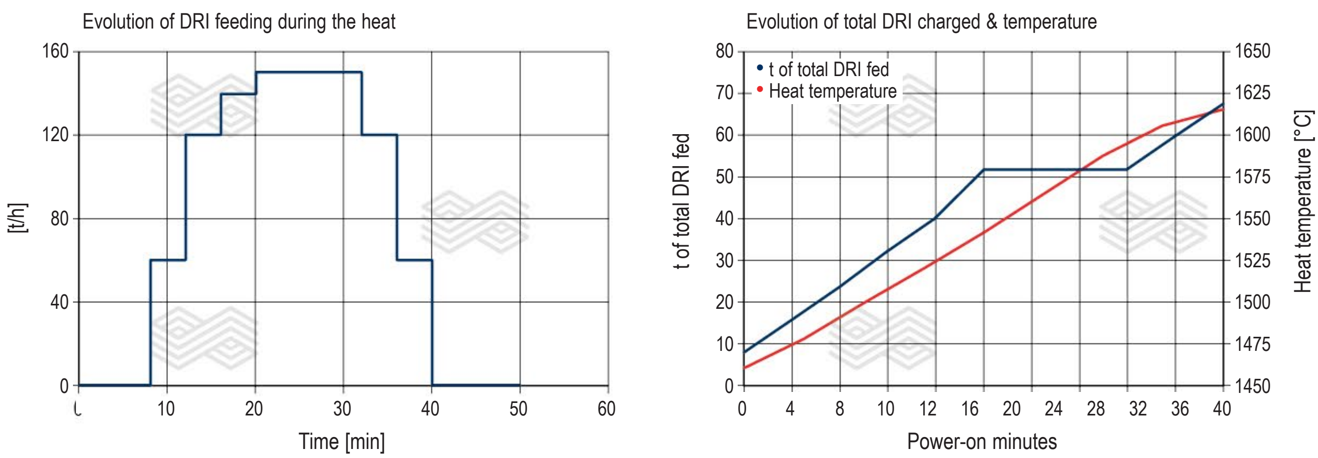


Table III.
Chemistry used on the FoamyMB.

	MgO [%]	CaO [%]	FeO [%]	Al_2O_3 [%]	SiO_2 [%]	MnO [%]	Cr_2O_3 [%]	TiO_2 [%]	P_2O_5 [%]	S [%]
Slag	11.03	35.69	28.10	4.58	16.96	1.95	0.40	0.40	0.23	0.40
DRI	0.70	1.10	8.00	0.65	1.90					
Blended lime	22.50	70.00	2.00		2.00					

Figure 2.
Graphical representation of the DRI feeding process.



The DRI analyses correspond to the gangue. For the injected carbon a fixed value of 98.7% and an ash content of 0.98% was considered

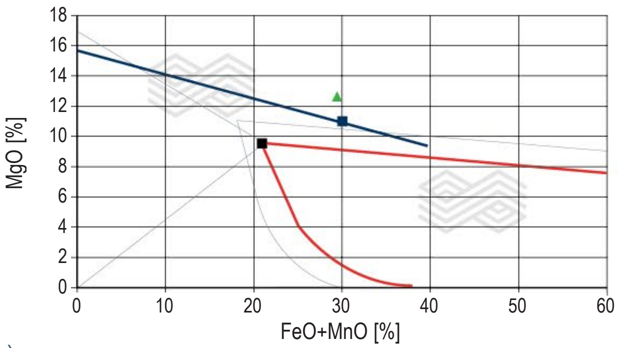
To generate the initial isothermal stability diagram (ISD) at 1600 °C it was assumed that the blowing pattern of oxygen was maintained, assuming the mass of FeO + MnO does not change. The ISD, both the existing state and the target values are shown in Figure 4 and the associated data in Table IV.

When analysed, these diagrams provided significant insight into potential areas of concern. In the diagram of the existing situations, the square shows the actual slag composition, while the triangle shows the calculated slag, on the basis of the additions. The variation between the calculated and analysed composition could be explained in 3 ways. Either some blended lime was lost in the exhaust system, which could be estimated through the analysis of the dust of the bag house. Alternatively, the blended lime may have had a lower wt.% MgO than reported, or there is a lack of homogeneity within the slag. The position of both are above the liquidus line, indicating an oversaturation of MgO, both for slag foaming and refractory protection.

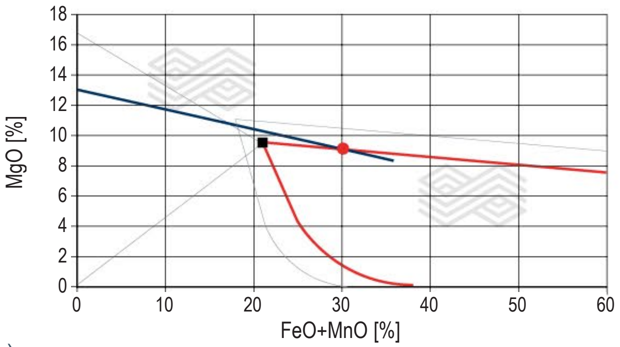
The total slag mass was between 16000 and 18000 kg/heat. Based on these results and making a reverse calculation for the scrap composition, it was estimated and input of dirt, (nonmetallic charge included in the scrap) of 1000 kg/heat.

Figure 4.

Showing the ISD of (a) the existing situation and (b) the target situation.



(a)



(b)

Table IV.

Data associated with the ISD.

Oxide	Unit	Analyzed	Calculated	Target
MgO	%	11.03	12.67	9.14
CaO	%	35.69	35.03	36.83
FeO	%	28.10	27.58	28.03
Al_2O_3	%	4.58	4.50	4.75
SiO_2	%	16.96	16.65	17.43
MnO	%	1.95	1.91	2.02
Cr_2O_3	%	0.40	0.39	0.41
TiO_2	%	0.40	0.39	0.41
P_2O_5	%	0.23	0.23	0.27
S	%	0.02	0.02	0.03
XOy	%	0.64	0.63	0.66
Total	%	100.00	100.00	100.00
B_3		1.63	1.63	1.63
FeO+MnO	%	30.05	29.50	30.05
Other oxides	%	1.29	1.27	1.38
Slag mass	kg	17242	17566	16704

Table V.

Step by step simulation of the feeding process.

Addition	Unit	Flux staging – Step										Total
		1	2	3	4	5	6	7	8	9	10	
Scrap	kg/heat	43600	0	0	0	0	0	0	0	0	0	43600
Blended lime	kg/heat	0	734	735	734	735	734	734	734	734	734	6608
DRI/HBI	kg/heat	0	4670	8000	9330	10000	10000	10000	10000	8000	4670	74670
Remaining slag	kg/heat	2000	0	0	0	0	0	0	0	0	0	2000
Injected carbon	kg/heat	0	135	136	136	136	136	136	136	136	136	1223
Hot heel	kg/heat	15000	0	0	0	0	0	0	0	0	0	15000
Dirt	kg/heat	1000	0	0	0	0	0	0	0	0	0	1000
FeO generated	kg/heat	0	329	330	329	330	329	330	329	330	330	2966
Expected temperature	°C	1500	1520	1530	1540	1550	1550	1550	1550	1600	1650	

For the conditions of

$$B_3 = 1.63 \left(\frac{CaO}{SiO_2+Al_2O_3}\right)$$

and temperature a MgO% of 9.14 would be sufficient for the slag to be at the liquidus line.

The results raised the question, if the slag is oversaturated with MgO, what was causing the increased consumption of the banks and bottom of the refractory lining?

Understanding the Wear Mechanism of Banks and Bottom Lining

The FoamyMB has the capacity to make step by step simulations of the process. In this case the process was divided into 10 steps of 4 minutes, for a total power-on time of 40 minutes during the feeding process, to replicate as close as possible the evolution of the heat, as shown of Table V. The assumptions were, that the charge of scrap, hot heel, remaining slag, and dirt, were considered to occur at Step 1, and the charge of DRI, blended lime, injected C and FeO formation begins at Step 2.

The evolution of the slag during the feeding process is shown in Figure 5. It can be seen that the initial slag composition is approximately 1% MgO (blue square) and then enters the liquid zone, shown by the red dots. As the process continues there is a convergence of the slag towards the liquidus line, which eventually leads to oversaturation. The initial values are in a very acidic zone, and as the process proceeds, the slag attacks the banks in a quest for saturation. The oversaturated state at the conclusion of the process, is the result of both the MgO consumed from the banks and the continuous feeding of blended lime. The evolution of B_3 and MgO during the feeding process is shown on Figure 6.

Proposal for Change

The proposal for change called for the charge of a bulk amount of blended lime at the start of the process (with the scrap charge), in order to create a buffer for the acidic oxides that form when the DRI feeding begins, as shown on Table VI.

Figure 5.
Evolution of the slag during the DRI feeding process.

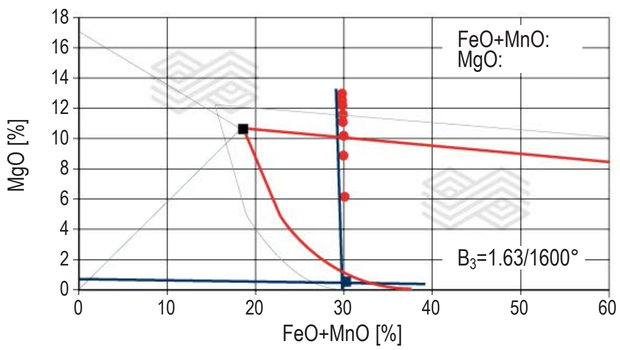


Figure 6.
Evolution of B_3 and MgO during the heat.

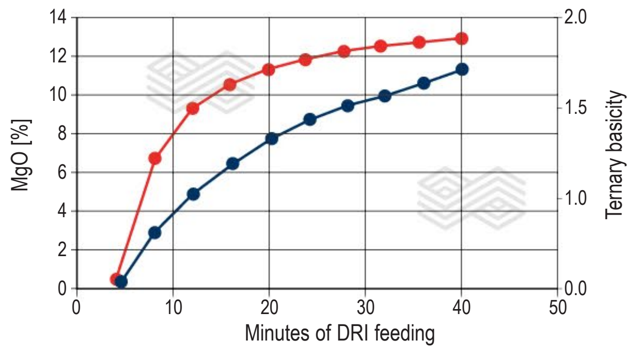


Table VI.
Proposed schedule of flux feeding.

Addition	Unit	Flux staging – Adjusted										Total
		1	2	3	4	5	6	7	8	9	10	
Scrap	kg/heat	43600	0	0	0	0	0	0	0	0	0	43600
Blended lime	kg/heat	2500	500	500	500	500	500	500	0	0	0	5500
DRI/HBI	kg/heat	0	4670	8000	9330	10000	10000	10000	10000	8000	4670	74670
Remaining slag	kg/heat	2000	0	0	0	0	0	0	0	0	0	2000
Injected carbon	kg/heat	0	135	136	136	136	136	136	136	136	136	1223
Hot heel	kg/heat	15000	0	0	0	0	0	0	0	0	0	15000
Dirt	kg/heat	1000	0	0	0	0	0	0	0	0	0	1000
FeO generated	kg/heat	0	329	330	329	330	329	330	329	330	330	2966
Expected temperature	°C	1500	1520	1530	1540	1550	1550	1550	1550	1600	1650	

With this proposal would be possible to stop feeding of blended lime 12 minutes prior to the end of DRI feeding, and it would be possible to decrease the total amount of blended lime by 1000 kg in order to finish on the liquidus line. The expected ISD and evolution of B_3 & MgO is shown in Figure 7 and the evolution of feeding of blended lime would follow the path shown on Figure 8

Results

Various changes were enacted in order to address the issues of the original process, such as increasing the amount of doloma in the blended lime and the refractory consumption was decreased on average from 2.5 kg/t to levels lower than 2 kg/t (Figure 9).

Conclusions

The FoamyMB model has proven to be a useful tool to simulate the heat process at the EAF for any type of metallic charge. This type of approach aids the operators in process safety, extending the refractory life without any risk.

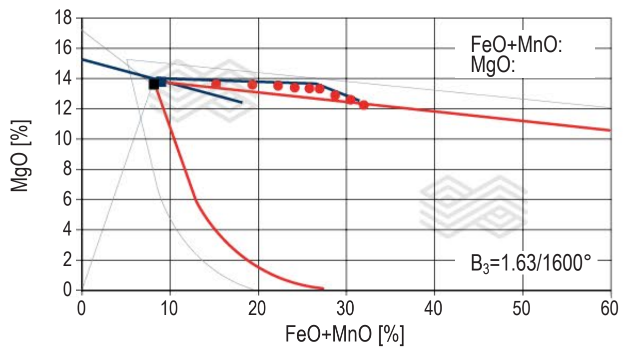
Although the recommendations were implemented with many limitations, such as logistics and DRI quality variation, the results obtained since the change are very encouraging. The use of separate sources of CaO and MgO, instead of a blended lime would allow for a better control of the process and flexibility to develop different scenarios to achieve saturation (B_3 and MgO). The lower refractory consumption in the banks results in an extended lifetime for the EAF and an increase in productivity due to the lower maintenance requirements.

Outlook

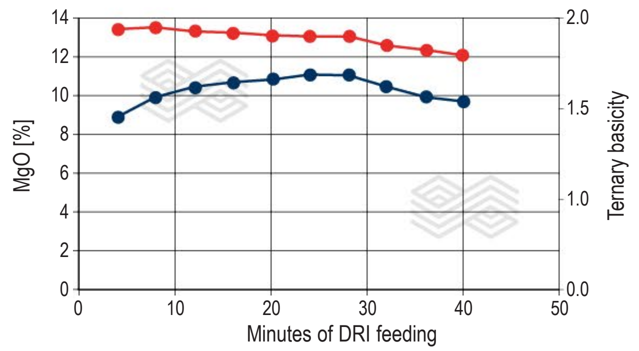
The search for a proper tool for understanding, controlling, and predicting slag formation in the EAF continues. The FoamyMB has been proven as a very thorough and accurate tool for this purpose, incorporating thermodynamic considerations and published slag phase diagrams. The regular use at some steel mills is a story of success and the application described in this paper demonstrates, that understanding the specifics of various stages of the heat process can assist steel mills to reduce the costs, both in the volume of material used (fluxes) and in extending refractory life.

Figure 7.

Expected ISD and evolution of B_3 & MgO with the proposed feeding of fluxes.



(a)



(b)

Figure 8.

Evolution of blended lime feeding current (red line) and proposal (blue line).

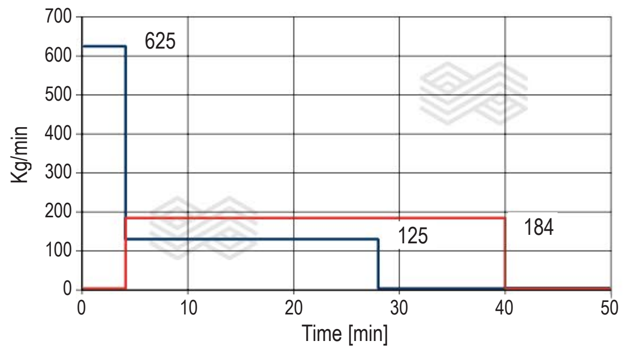
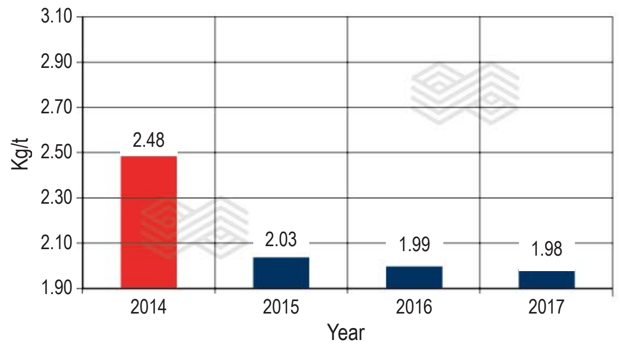


Figure 9.

Evolution of banks refractory consumption.



Acknowledgments

The authors would like to thank Eugene Pretorius, who was the precursor of this type of approach in South America in the mid-nineties.

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Amit Sarkar, Harsh Joshi, Andreas Schretter, Gerald Gutschier and Thomas Mitterer

Efficient Value Added Steel Production with low mix Maintenance Level at JSW Steel in India

JSW Steel (JSW) in Toranagallu, India is the fastest growing steel plant in the country. Currently operating three steel melting shops in Toranagallu with an annual production of approximately 12 MT of steel. In 2013 a partnership contract between JSW and RHI Magnesita started in SMS2 to increase the BOF campaign life and lower refractory consumption, reduce downtime for gunning and patching maintenance. Furthermore, the bottom purging system must be available until the end of campaign to ensure a value-added steel production throughout the full BOF campaign. At the start of this partnership contract the lining life was on average 2390 heats/campaign with a purging life of 1780 heats. In 2018 the average life was 4970 heats/campaign with 100% bottom stirring availability. The best campaign achieved a record life in SMS2 (November 2018) of 6057 heats with all eight bottom purging elements functional until the end of campaign.

Introduction

Today, the production of value-added steel has become more important for steel producers to ensure competitiveness on the global market. Furthermore, a steady increase of productivity is one of the most important targets and shutdowns of primary melting units like the BOF or EAF must coincide with other maintenance work in the steel melting shops.

On one hand a proper vessel relining and maintenance schedule during the entire campaign has to be planned, executed, and controlled, in order to avoid premature shutdowns of the melting vessels due to unforeseen refractory failures. On the other hand, the refractory consumption has to be reduced to decrease the specific cost levels and the condition of the lining including the bottom purging elements must be operational for the full lining life with lowest maintenance efforts to ensure a broad variety of steel grades can be produced with high productivity. Therefore, following preconditions are necessary to meet the required targets:

- Steady developed lining pattern with high quality bricks and appropriate repair mix selection.
- Training classes for steel shop employees.
- Basic maintenance planning for the campaign.
- Daily control of maintenance and slag work parameters, as well as operation and productivity conditions.
- Close cooperation between operation department, refractory engineering department and refractory supplier.
- Development of bottom purging patterns.
- Online scanning control of lining conditions.
- Lessons learned for improvements in subsequent campaigns.
- Continuous, ongoing and long-term partnership approach between steel plant and refractory supplier.

Process Strategy

The applied process strategy and converter technology depends on a successful combination of bottom gas purging technology with slag maintenance strategies for maximum purging efficiency at minimum refractory cost and consumption levels [1]. In the case of JSW the consumption for BOF refractory in 2013 was approximately 1.5 kg/tls and decreased to an average value of approximately 0.70 kg/tls in 2018. As the brick length and lining weight did not decrease during that period the improvements were achieved by strongly reduced mix maintenance and a high level of controlled BOF production with CaO and MgO saturated slags. With this combination a higher productivity with regard to the number of heats per day as well as generally longer campaigns were achieved which reduced the nonproductive days per year due to relining and the downtime for online repair i.e., gunning and patching application. Furthermore, the bottom stirring technology plays an important role as there are better conditions for blow end whilst protecting the lining with more suitable slags.

Operation Conditions

JSW operates in SMS2 four BOF with an average tap weight of approximately 180 tonnes per heat. After ladle furnace and partly RH degassing treatments, 5 continuous casters produce approximately 6.5 MT steel/pa (Financial year 2017/18). The hot metal has a quite broad variety of Si and Mn content due to the local and national iron ore supply. The challenge to operate a lining to a high average life depends upon a rapid response to changing input conditions in order to make adequate slag maintenance practice possible. This was done with Level2 system in accordance with process parameters and online scanning results to check the efficiency of slag conditioning during and slag maintenance after blow.

Lining Control

For every converter a fixed laser scanning system was available and the number of scans was approximately 140–180 scans per campaign. An onsite team and foreign refractory and process experts provided by RHI Magnesita were available for 24/7 assistance during the relining stage and operational phase of the converter in order to control lining conditions and slag maintenance performance. On a daily basis, meetings took place for maintenance planning with respect to the lining conditions and production planning, as well as a short review of the previous day in terms of fulfilling the daily targets. Together with the scanning results a daily report was produced which provided an overview of the lining development, necessary maintenance measures for the next 24 hours, and a dynamic online maintenance plan for the running BOF campaign.

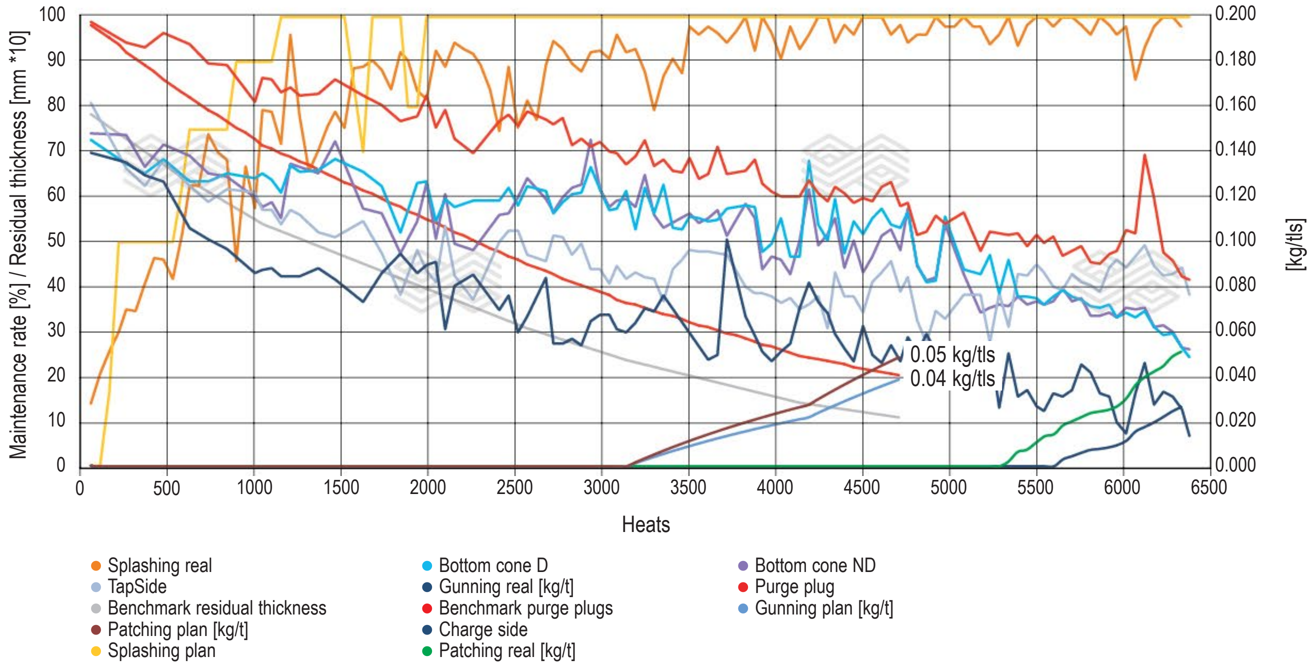
In the dynamic maintenance plan the lining conditions were compared with the existing maintenance measures, such as slag splashing, slag rocking, gunning, and hot patch application (Figure 1). All critical prewear areas were observed and maintained accordingly to achieve balanced conditions with highest efficiency, number of heats per day and highest safety level for the lining. Since different areas in the BOF can be maintained with different slag care methods and schemes, a precise observation of the individual wear areas is necessary in order to ensure (achieve) optimised care. On one hand the lining including bottom purging elements must be available for a 100% safe operation but on the other hand, excessive maintenance will have a negative influence on BOF productivity and a proper functionality of the bottom purging system.

Slag Conditioning and Slag Splashing

For an adequate slag work operation, the required input of fluxes during blow with respect to the input conditions must be provided, so that after tapping the slag splashing can begin without any further conditioning of the slag. This is the optimised scenario, as the splashing procedure can be started immediately after tapping without time loss for the addition of a MgO carrier and mixing with the slag. The slag has to be observed visually during tapping and then the information was forwarded to the operator whether the viscosity of the slag was acceptable for a direct splashing or if further additions were required for a sustainable slag coating. With various splashing patterns, different areas of the furnace could be reached. These areas as mentioned previously were defined in the dynamic maintenance plan along with a seamless visual lining monitoring.

In addition to a CaO/SiO_2 balanced slag the MgO saturation plays a major role in achieving a sustainable coating on the lining. Lime rich slags tend to stick well on the lining, but an additional MgO enriched slag will ensure a better protection of the lining. Figure 2 shows that the amount of saturated slags during blow was approximately 97% for all heats throughout the whole campaign. Even in the first half of the campaign it was at a level of 95%, so once the BOF reached the required volume with respect to the melt size at around 1000 heats, the wear speed was drastically reduced and ensured that a lifetime of more than 6000 heats was possible. Additionally, the number of slag splashing operations could be increased after the volume was reached and no excess bottom build up was visible. Nevertheless, the slag viscosity was the most influencing factor, as dry slags do not reach the concerned areas but cause unwanted build up and liquid slags does not provide the required protection coating.

Figure 1.
Dynamic maintenance plan for the record campaign Nr. 15.



Slag Maintenance and Bottom Purging Efficiency

Preconditions for optimised bottom purging conditions:

- Design of the purging plug.
- Plug installation and leak test procedure [1].
- Gas supply and control with stable flow at low and high rates and quick gas switch over [1].
- Low response time for set point change.
- Mass flow controlled supply systems for avoiding clogging tendency at low gas flow rates.
- Customised purging pattern. Controlled bottom slag layer on top of the plugs.
- [C]x[O] product measurement and monitoring.
- Visual monitoring of plug conditions during tapping and after slag maintenance.
- Standardised operating practice (SOPs) rules for slag maintenance [1].
- Evaluation of laser scans vs. maintenance practice vs. purging patterns [1].
- Flux monitoring vs. wear speed vs. bottom build up.

Figure 3 shows the changes in the bottom build-up. over the campaign. Figure 3a, shows the initial situation after the first heat, where there is no slag protection provided for the bottom purging element. Figure 3b shows the optimum conditions, where there is a slight slag coating over the plugs, but they are fully visible. This coating allows both the penetration of the purging gas into the melt for the proper mixing effect and protection of the purging element from the slag layer. Figure 3c shows the situation when the bottom build-up was too high and did not allow penetration of the inert gas into the melt in a controlled manner. In this case the [C]x[O] product will rise and a[O] will be higher at equivalent [C] level leading to the requirement of further deoxidation agents and higher costs.

Figure 2.
MgO saturation distribution

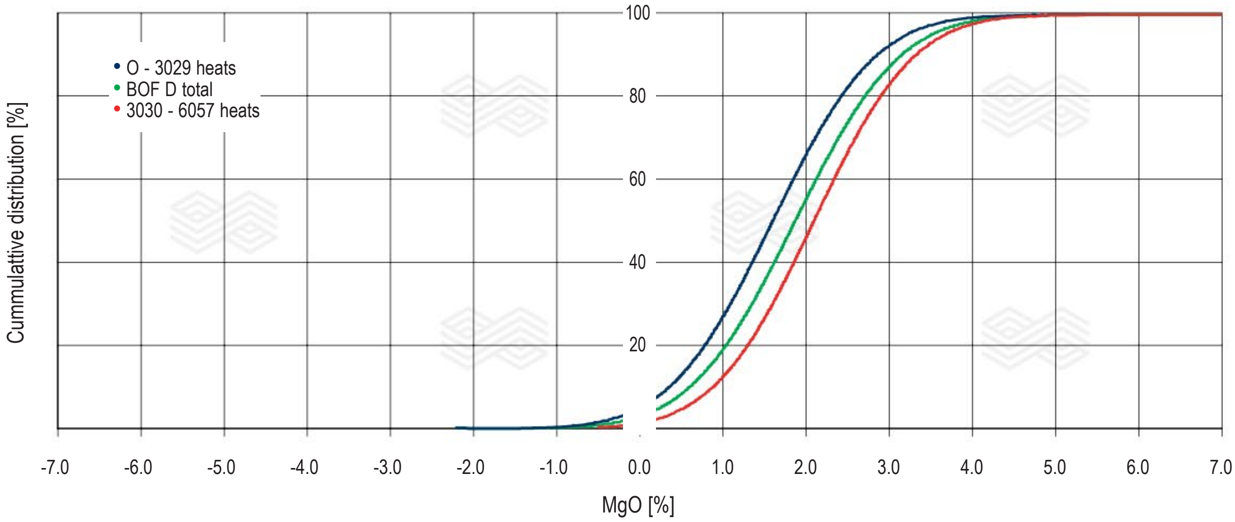
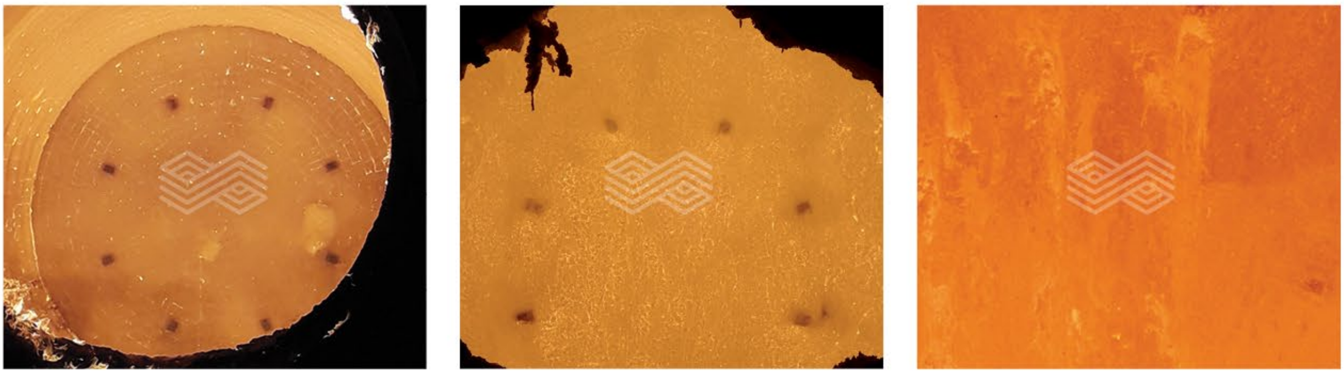


Figure 3.
Showing the conditions (a) after the first heat, (b) under optimum operating conditions, and (c) when the bottom build up is too high.



(a) (b) (c)

The major benefits of the functional bottom stirring until the end of campaign are:

- Lower FeO level at lower [C] level.
- Yield improvements.
- Lower a[O] level at same [C] level.
- De-oxidation agent savings–Al.
- Decrease of reblow rate after blow.
- Improved dephosphorisation conditions.
- Flux addition savings.
- Shorter blowing time.
- Reduced refractory wear.
- Production of a broad portfolio of different steel grades until the end of campaign.

Conclusion

The successful combination of bottom gas purging with slag maintenance of the converter lining at JSW provided a cost-effective optimisation to process raw material with variable compositions with an additional enhancement of the campaign life and bottom purging availability until the end of the campaign [1].

By implementing standard operation procedures along with modern technology in refractory lining and process control these targets were achieved and a reduction of the specific consumption by 53% was achieved together with a 108% higher campaign life. The bottom purging availability was stable at 100% until the end of the BOF campaign and provided the previously mentioned metallurgical and economic benefits for a cost-effective production of value-added steel grades.

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Andrea Giacobbe, Marcos Tomás Casado, Bill Haynes, Kevin Spurlin, Chris Dudley, Mike Lawrence, Ron Kuehne and Marco Alloni

PROIL™: Value Innovation for Mid American Steel & Wire Inc.

This paper provides an overview on the improvements achieved through the application of PROIL™, when used as lubricant in the open casting process of steel at a billet producer in the USA. Several benefits have been achieved through by implementing this product, as the result of both an improved lubrication and an increased and more uniform heat extraction. These benefits have consisted mainly in the opportunity to cast new steel grades, reduce breakout occurrence, and improved final billet quality, furthermore a reduction in sparkling phenomena has been observed. An overview of plant operations is described, with a focus on the development of a specific dosing and mould feeding of this material. As experienced with traditional casting powders, the product has been tailored to customer conditions, such as steel grades, casting sections and speeds by adapting the solid component of the formulation.

Introduction

The improvement of the continuous casting process through the implementation of new automation as well as refractory technologies is a potential to further optimise process and product quality. To add value, RHI Magnesita (RHIM) and PROSIMET agreed to a cooperation to enhance the portfolio in Ladle-to-mould technology by supplying PROSIMET materials such as tundish covering powders, mould fluxes, and PROIL™ to specific customers [1].

PROIL™ is composed of a solid-liquid dispersion of a specifically formulated casting powder in highly customized synthetic oil and combines the performance advantages of casting powder with the easy handling properties of oil (Figures 1). Figure 2 shows a schematic of the application of PROIL™ when used in a billet mould.

PROIL™ appears like a viscous slurry mixture that is added to the mould directly on top of molten steel by specific electric actuated pumps. This paper describes the value innovation added to Mid American Steel & Wire (MAS), a private USA steel maker, mainly producing wire rod for agriculture (field fencing and barbed wire) and industrial application (bright basic wire and welded wire reinforcements) through the usage and implementation of the PROIL™ system in the continuous casting process.

Figure 1.
Showing the appearance and consistency of PROIL™.

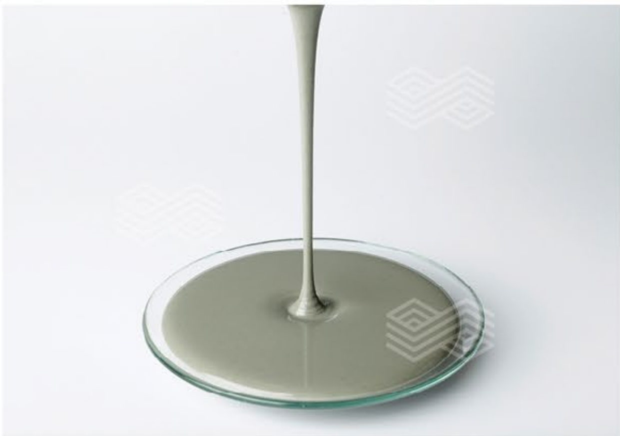
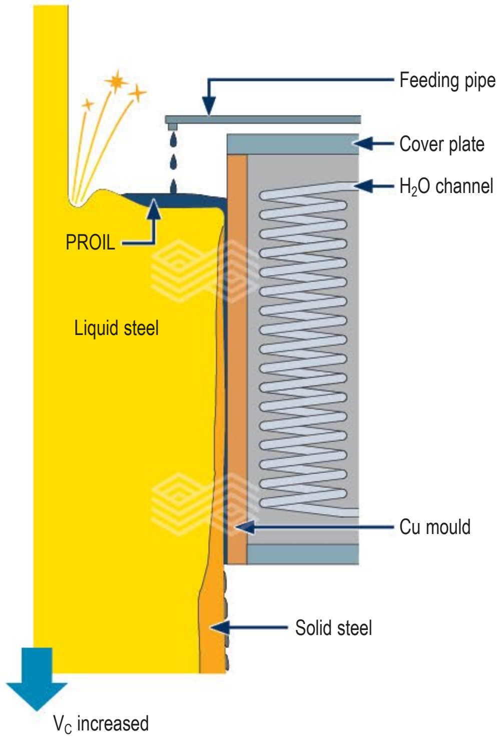


Figure 2.
PROIL™ method of feeding into a billet mould.



Description of the Facilities

Mid American Steel & Wire (MAS) is a steel producer located in Madill, Oklahoma, USA. MAS production capacity is approximately 300 kt of steel. The process route consists of: 1 electric arc furnace (EAF), 1 ladle furnace (LF) and 1 billet continuous casting machine (CCM), Rokop manufactured, 3 strands (2 running).The ladle capacity is 45.3 tonnes, the tundish capacity is 9 tonnes and the CCM is a curved 9 m radius billet caster.

The section cast is 160x160 mm (160 sq) or 6.25 x 6.25 inch and casting speed is between 1.7–2.5 m/min or 70–100 inch/min for an average sequence length of 20 hours (55 min/ladle), the mould is parabolic. Up to 80% of the production consists of 1006-1008 AISI steel grades, reinforcement bar grades A615-60 and A706-60 are also produced. To complete the product portfolio, boron grades such as 10B06 and 10B26 are also produced.

Initial Situation

The driving force for testing PROIL™ was initially driven by customer interest in producing boron grades in order to increase the portfolio and better match market demand. Until July 2017 the plant was not able to cast these grades in a suitable quality, due to the occurrence of large surface cracks in billets, these issues were serious enough to compromise the process itself.

Additional requests from MAS were to improve surface quality, where considerable defects were observed (especially on 1006 grade) and to reduce rhombohedral shape especially on high C grades (1026). Figure 3 shows the problematic aspects of existing production.

As positive results were already available for the use of PROIL™, when used with boron grades [2]. It was anticipated that better lubrication and heat transfer would be achieved in comparison to standard mould lubricant. For the initial trials, a 1200 kg batch of PROIL™, was delivered with testing equipment in July 2017.

Preliminary Consideration: Open Casting, Lubrication oil and PROIL™ Behaviours.

Since the introduction of continuous casting of steel, various types of oils have been used as mould lubricants [3]. The various technological developments and the more recent use of mould flux, has resulted in a consistent increase in surface quality, to obtain the current benchmark of industrial applications. However, mould flux has been implemented only in closed casting processes and there has been minimal advancement on the lubricants for open casting. There have been some field trials on the use of traditional casting powder in an open casting environment, however, these led to an erratic increase in non-metal inclusions (NMI) in the produced billets. Due to the chemical and physical properties, PROIL™ enhances the lubrication and improves heat transmission, with not only an increase in heat transmission but also a more homogeneous transfer between the mould and the steel strand [4]. Figure 4 shows schematically the difference in behaviour between a standard oil and PROIL™ in the mould–steel strand gap.

Considering that many lubrication oils used have a flash point around 300 °C the influence is considered to be limited to the upper meniscus area [5]. This strong “cooling effect” results in billet shrinkage where the air gap formed provides a strong thermal insulation throughout the remaining process. Alternatively using PROIL™ it is assumed that with the formation of a liquid slag on top of molten steel there is a subsequent infiltration of the slag and some solid flux in the mould–strand gap. This lubrication mechanism is more similar to the mould casting powder standard setup used in closed casting. As a result, it is possible to consider an effective lubrication and an enhanced and more homogenous heat extraction. As a consequence, this results in, both an increase in casting speed and a better quality in terms of surface quality and shape.

Figure 3.

Showing (a) “slag pocket” in cast material, (b) the surface cracks, and (c) the rhombohedral shape of a 160 mm billet cast by MAS with standard lubrication oil.

(a) (b) (c)

PROIL™ System

MAS was highly committed to testing the product in both strands of the casing machine from the very beginning. The initial batch lot of four drums (1200 kg) was delivered along with two test skids assembled in USA. The trial setup at MAS is shown in Figure 5.

Initially the product was tested on low carbon grades (1006) and the operators immediately detected an improved quality of the billets cast (6 heats). As a result, the customer elected to start testing PROIL™ on boron grades (10B06). Very good results were achieved during first few days and as a result MAS decided to abandon the previously used lubricant and solely utilise PROIL™. Figure 6 shows the first billets produced at MAS with the new system.

Since that time MAS used PROIL™ on all steel grades and more than 45 tonnes of PROIL™ have been utilised to manufacture more than 450000 tonnes of steel. The standard operating conditions at MAS are shown in Table I.

Specific consumption observed at MAS is in line with the expected figure and close to the previously used mould lubrication rate of 55 g/min. This consumption was considered as optimal as it ensured s good lubrication with no risk of slag entrapment, which has occurred in previous PROSIMET trails, when a consumption of 0.250 kg/t is exceeded.

Table I.
Standard operational conditions at MAS.

Section [mm]	Casting speed av. [m/min]	Flow rate [g/min]	Specific consumption [kg/ton]
160 square	2.16	45	0.090

Figure 5.
PROIL™ system trial setup at MAS, 1 drum and 2 pumping skids.

Figure 6.
First billet produced at MAS with PROIL™.

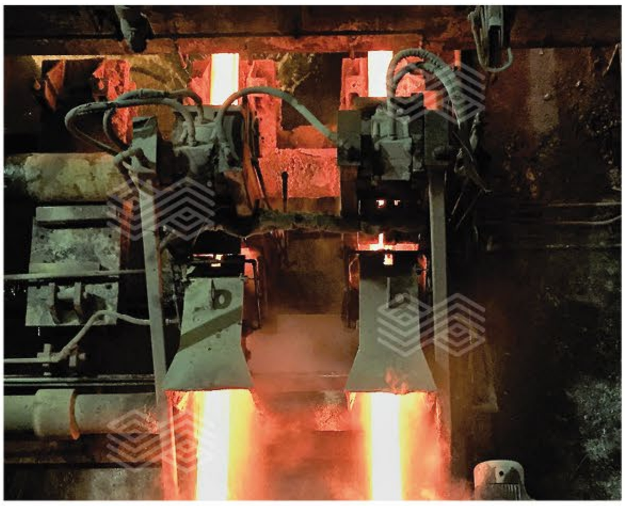
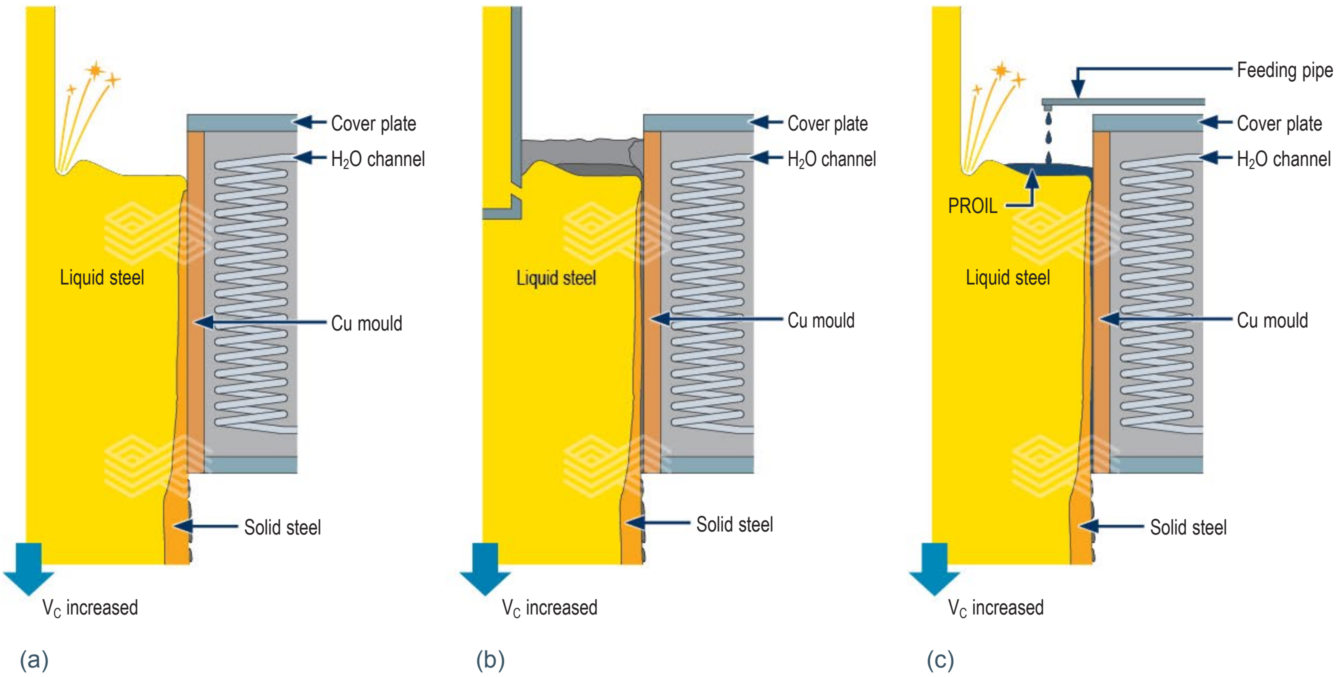


Figure 4.
Showing (a) an oil environment, and (b) PROIL™ environment.



New Steel Grades Produced: Boron Grades

As mentioned previously, the main objective of MAS at the start of the trials was to cast boron steel grades (in particular 10B06 and 10B26). Prior to this, MAS purchased these billets, which represent approximately 20% of the MAS mill output, from a third-party supplier that used the protected casting technology to produce these qualities. Since using PROIL™ MAS has stopped outsourcing for any steel grade and now 100% of material processed in the rolling mill is produced in the melt shop. This achievement, resulted in an unexpected, but additional extremely valuable saving to the company.

Improvement of Quality Surface

The entrainment of "slag pockets", resulting from a lack of lubrication in the mould were often detected by MAS (Figure 3). A significant reduction of these defects was reported when using PROIL™ in a 6 months frame time. The figures consist of 166 "slag pockets" with mould lube oil and 18 when using PROIL™. This represents an approximate reduction of 89% (Figure 7).

Breakout Occurrence

Breakout occurrence was an important issue for several steel grades cast, not only the boron grades. The expense for these occurrences dropped by approximately 75% over 1 year (Figure 8).

Reduced "Splashing" Occurrence

Furthermore, an appreciated side effect of PROIL™ application was the sharp reduction in sparkling or "splashing" phenomena from the mould. This effect created not only advantages in relation to operator safety, but also resulted in material lifetime savings. Feedback from MAS, suggests that nozzle life has been almost doubled.

New "Wavy Moulds" Application

PROIL™ has been also used in combination with new wavy moulds providing outstanding results in terms of final billet quality [6]. These new special mould profiles have proven to be effective in improving billet shape in a standard open casting setup with lube oil as lubricant (Figure 9).

Figure 7.
Showing the indexed reduction in defects.

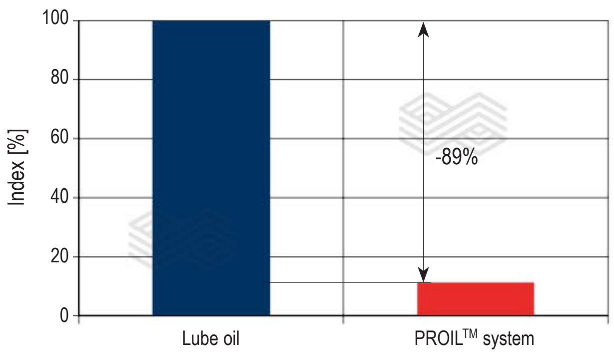


Figure 8.
Breakout cost reduction.

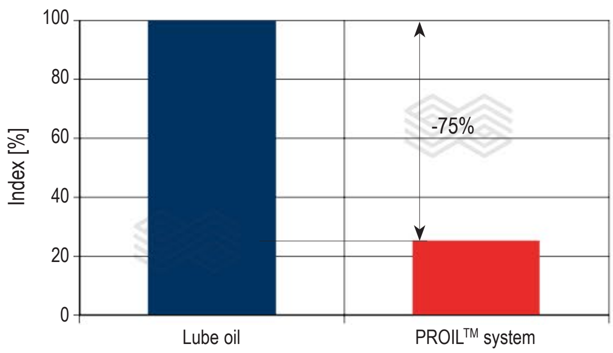


Figure 9.
Showing (a) an example of a wave mould [6] and (b) the billet cast through the supporting rollers in secondary cooling zone.

(a) © KME

(b)

Prior to testing PROIL™ boron grades were only cast by using a closed casting setup. Now MAS is able to produce these grades using a combination of this advanced mould design and lubrication technique.

Final Setup

After the decision from MAS to switch to PROIL™, the demand for a stationary dosing system arose. As MAS was the first end user of the product in the USA, an American pumping system supplier was contacted in order to evaluate feasibility of a solution for this application. The industrial pumping system setup provided by the supplier, met all the expectations of MAS.

The final setup of the pumping system at MAS consists of a steel frame supporting a steel tank (capacity approximately 1500 L) equipped with a stirrer. Beneath the tank, two electrically actuated diaphragm pumps controlled by an inverter were positioned to transfer the PROIL™ to the moulds. The whole system was located close to the moulds on the casting shop floor.

Summary and Conclusion

Through the implementation of PROIL™ at MAS the following results have been achieved:

- It was possible to cast new steel grades (boron grades), the initial target of the trial.
- A significant improvement in terms of quality surface was obtained with a “slag pocket” reduction of almost 90%.
- Square shape was upgraded with a decrease of rhombohedral occurrence.
- The breakout index was diminished, with a reduced downtime cost about 75%.
- Reduced splashing on the casting platform was achieved.

Outlook

In addition to these results, the use of PROIL™ at MAS provides further opportunities for the application of this product, while helping to better understand the potential benefits of using a new mould lubricant in an open casting environment. These results represent both a new approach and a guideline for future requests from end users. Further investigation of unique combinations of lubricant and different mould profiles may provide new opportunities in the future.

Acknowledgement

We thank Mid American Steel and Wire Inc for having provided RHI Magnesita the possibility to test PROIL™ and for the cooperation in achieving these results.

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Securing your future at RHI Magnesita

Beat Heinrich, Roland Bühlmann, Patrik Bloemer and Reinhard Ehrengruber

INTERSTOP® S Gate—Development Steps Towards Smart Slide Gate Operation

The market introduction of the new INTERSTOP® S gate series began 4 years ago and has accelerated recently. More and more customers begin to appreciate the extra features the S gate offers in terms of safety, ease of operation, and low operational costs. Especially the newly introduced feature "open check" increases the confidence level of the operators and can boost the performance.

With growing requirements to increase safety for people and processes at the ladle preparation area and on the continuous casting floor, automation has become increasingly important in steel plants. Based on the experience with the S gate a prototype is currently underway to launch an innovative new gate design striving for full automation. Several critical process steps are already available and successfully used in the steel plants, like cylinder connection, slag detection integration, and ladle shroud handling.

Fully automated operation will be followed by digitalization, allowing for tracking of performance, safety, and quality.

This paper summarizes the success factor of the S gate and outlines individual initiatives towards fully automated operation and data acquisition examples for digitalization.

New Feature for S Gate

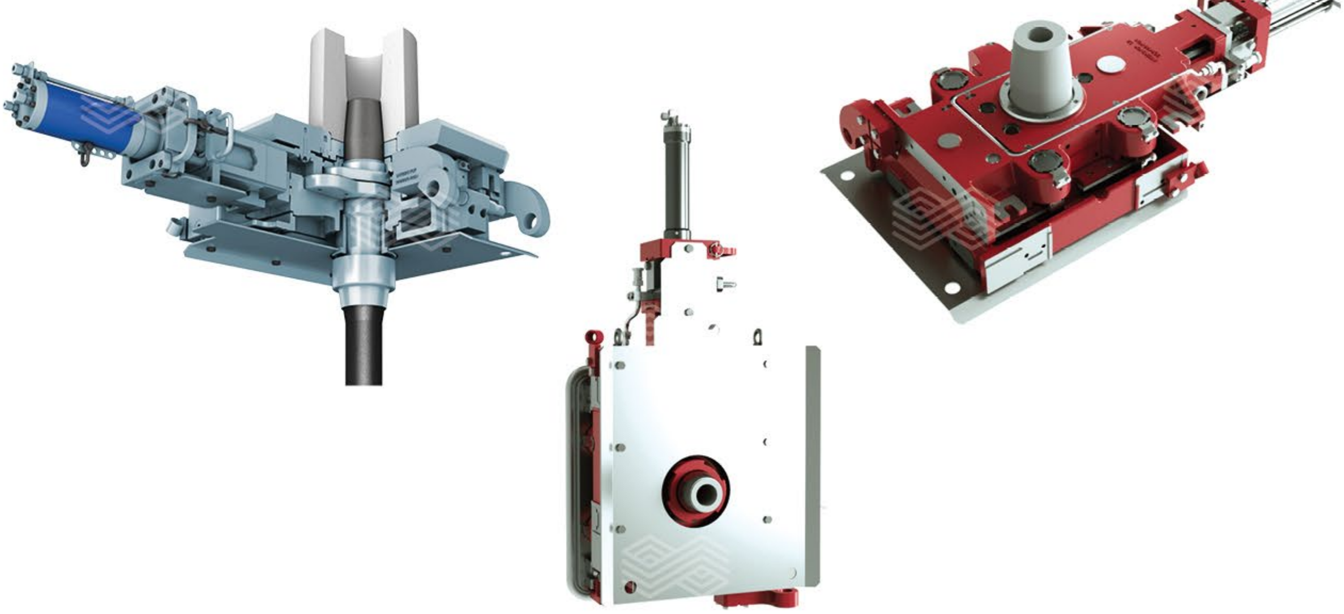
The new INTERSTOP® Lade gate Type S is a high-performance ladle gate system focused on optimising total cost of ownership (TCO) as well as safe and easy operation (Figure 1). The advanced refractory concept covers a range of casting diameters with the same mechanical system, leading to higher efficiency. The smart handling characteristics enable easy and safe operation and are incorporated within a maintenance-friendly design. The new development has a positive impact on the overall operating costs and increases the safety standard during handling and operation.

Moreover, the new S type gate provides the possibility to perform an "open check", a feature allowing the personnel in the ladle preparation area to assess the refractory plates more reliably. This unique extra feature is outlined in the following sections.

Open Check on the INTERSTOP® S Gate

System reliability and availability are the most important objectives in operating a ladle slide gate system. When this is achieved, improved safety is an additional consequence. In addition to this, optimising operating costs and the focus to improve the TCO is a continuing demand. The new "open check" feature of the INTERSTOP® S gate system results in optimising the specific operating costs without increasing the risk of a failure, such as an infiltration between the bottom and the slider plate.

Figure 1.
INTERSTOP® Ladle gate Type S.



How to Carry out an "Open Check"

A main responsibility of the ladle preparation area workers is to determine and decide if a further heat can be done with the ladle slide gate system. Predominantly to check the wear of the plates as a result of the throttling during casting. This process is called "multiple heat check". Potential steel fins between the plates caused by the system movement must be identified in the ladle preparation area, as it can lead to an infiltration or even break out. The wear of the slider plate bore is generally checked with a special tool. However, one of the main drawbacks of this process is that the relevant surfaces cannot be properly viewed. On former systems, a practice was used to open the slide gate, obtaining a direct view of the working surface of the refractory plates, and check the wear of the bottom and the slider plate. If the amount of wear permits another heat, the systems was closed without changing the plates. This practice was used for example in the US and is called "open check". In order to permit a safe application of this practice, clamping the refractory plate is required. It must also be ensured, that the mortar joints between the housing plate and the upper nozzle as well as between the slider plate and the exchangeable nozzle are not affected while opening the system and releasing the tension of the system. The possibility to practice a safe "open check" is now provide by the newly implemented automatic clamping of the S refractory plates.

Benefit of the "Open Check"

The principle of this "open check" procedure is to increase the plate lifetime by minimizing the risk of an infiltration. However, the target remains to achieve as many heats as possible, without opening the system. The "open check" increases the safety standard, as it supports the preparation workers in the decision to proceed with another heat. The plate condition can be properly assessed by having a direct view of the refractory plate surfaces (Figure 2).

Opening the system will also allow measurement of the surface with an optical measurement device in order to evaluate the quality of the plates and to support the ladle preparation workers in the assessment if further heats can be carried out without any risk of failure. The "open check" practice is already in operation, with several customers running the new INTERSTOP® S ladle gate system. The feedback has been positive, as it provides operators in the preparation area an additional feature to make their job easier.

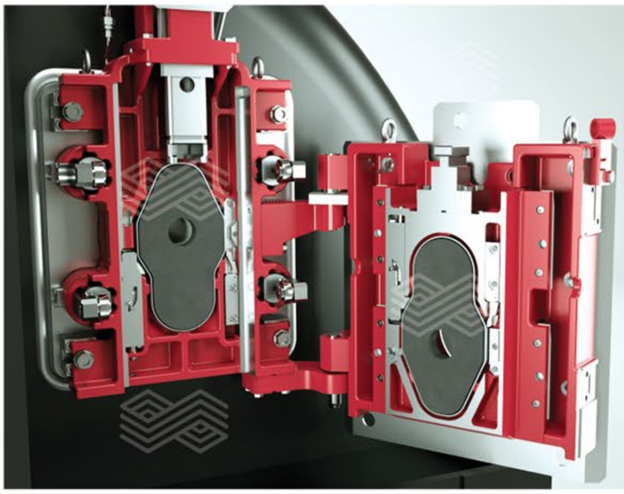
Automation Related to Ladle Slide Gate

In order to automate processes, the systems or subsystems are required to permit an automated operation as well. Currently, an important contributor considered in the developments of new slide gate systems for the steel industry, is the swift and easy manual operation and handling. However, an easy manual operation does not necessarily result in an easy to automate operation. For that reason, in new developments specific emphasis is being placed on defining concepts and interfaces that can be adequately operated in automatic mode whilst still allowing some degree of manual operation in e.g., an emergency situation. Among the new systems recently developed which allow an automated operation, two are presented in the following sections in more detail.

Automated Casting Cylinder Handling on Continuous Casting Floor

The casting floor is one of the areas in a steel plant with a high safety concern for operators. Replacing people from dangerous areas is the goal. For this reason, a special automated casting cylinder has been developed that is designed to be handled by a robot. The operator is only required to monitor the process from the operating room. The automated casting cylinder can be installed on INTERSTOP® slide gates by simply replacing the drive unit. A special built-in safety anti-opening device locks the slide gate during the casting process without external intervention.

Figure 2.
Showing (a) S gate with open slider and (b) preparation area worker carrying out open check procedure.



(a)

(b)

The drive unit has been specifically designed, to allow in the event of an emergency, a manual mounting of the casting cylinder instead of the automated cylinder. An integrated locking/unlocking mechanism prevents the cylinder from disengaging during casting operation (Figure 3). The system also offers the incorporation of an automated slag detection connector and a gate air cooling. With this development, in a single movement, the cylinder and all the utilities are connected and ready to use, reducing the handling time.

Automation at Ladle Preparation Area

The ladle preparation area is a place in steel plants, where critical tasks are carried out by operators under very harsh conditions. Heat, dust, and time pressure can influence the performance quality, in addition to, a constant issue with safety. INTERSTOP® is working towards the development of a fully automated ladle preparation area (Figure 4).

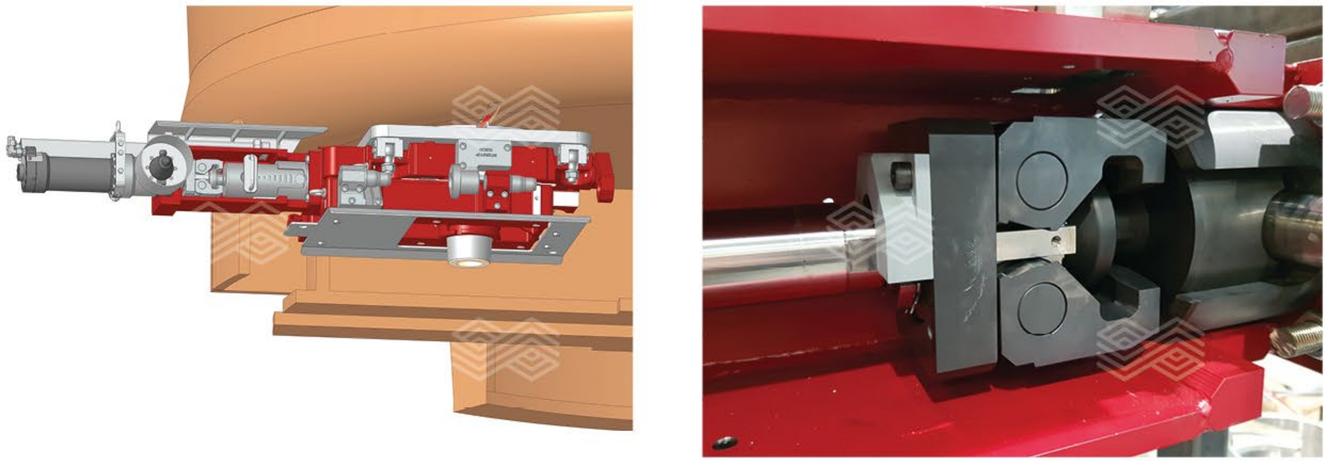
The basic approach is that the human intelligence is used in combination with sensors for diagnostics and robots carry out the dangerous and heavy tasks. To fulfil this, a re-examination of current practices is necessary in several process steps.

Inner Nozzle Repair

As the casting channel is prone to wear, the lifetime of the inner nozzle is limited. It is integrated in the well block of a ladle and needs to be frequently replaced. This exchange is however a very time-consuming and exhaustive job for those in the ladle preparation area. For that reason, an automated nozzle exchange would be very beneficial. However, although an automated mounting of the nozzle is a simple task for a robot, an automated removal of the current nozzles it is not a straight forward process. As it requires high forces due to the very strong adherence (sintered material) which, in general leads to unpredictable cracking of the nozzle, i.e., the nozzle cannot be removed in one piece.

For this reason, a different approach has been taken. Instead of replacing a nozzle, the nozzle will be repaired in order to increase the lifetime, ideally to the life of the ladle itself. Thereby making the nozzle exchange obsolete.

Figure 3.
Showing (a) design of slide gate drive unit including automated handled cylinder and (b) reference example of automated cylinder handling in use.



(a) (b)

Figure 4.
Showing INTERSTOP®'s vision of the ladle preparation area.

The casting channel of the inner nozzle would be repaired by frequently applying a special repair mix designed for this application on the channel surface, i.e., gaps or worn areas would be filled with the special repair mix. Through this, the bore diameter remains more or less unchanged and thus significantly increases the life of a nozzle. The mortar is applied using a method and repair tool as shown in Figure 5. The mortar in the tool pockets is spread taking advantage of the centrifugal forces via the rotation of the tool. Subsequently the mortar adheres to the bore surfaces and hardens immediately. At the same time residue mortar is removed resulting in a very smooth surface of the casting channel (Figure 6).

Using this tool, not only the lifetime of the inner nozzle is increased, it is also expected that oxygen lancing will be eased by this process in addition. Although nozzle repair could be performed manually, one of the main benefits is that a robot as shown in Figure 6, could easily and reliably handle this process.

Condition Monitoring by a Smart Slide Gate

The continuously increasing requirements with respect to safety, process reliability, and quality in the steel industry, is driving also the need for condition monitoring of the operating systems as is already well established in some of the consumer goods. Diagnostics by a Smart Slide Gate is generally also considered an essential contributor or even precondition of automation and digitalization.

However, unlike for example the car industry, there are some challenges that need to be overcome for the steel industry in particular. One of the main challenges is that the available sensor technology is not suitable for the very harsh environment of a steel plant in general.

RHI Magnestia is undertaking significant research into the development of these key technologies. Two examples of the successfully developed condition monitoring systems are presented.

Figure 5.

Showing schematic of the repair tool.

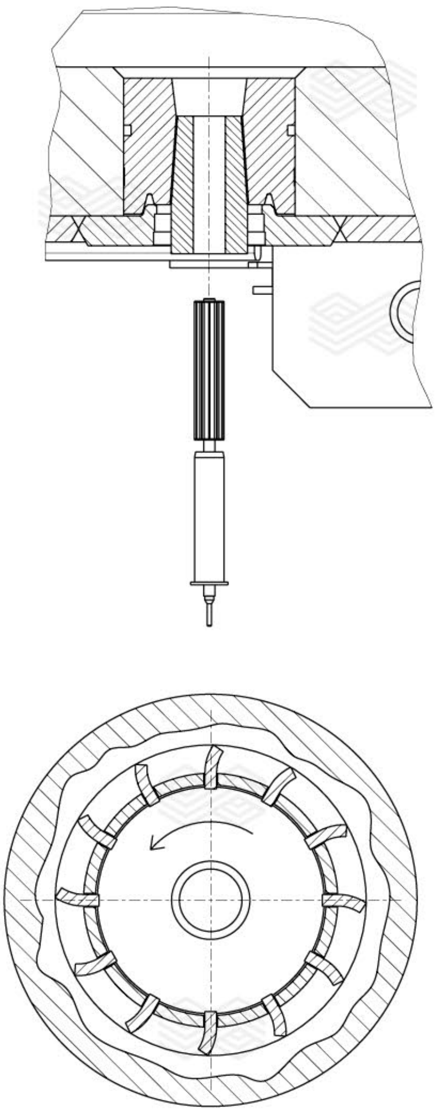
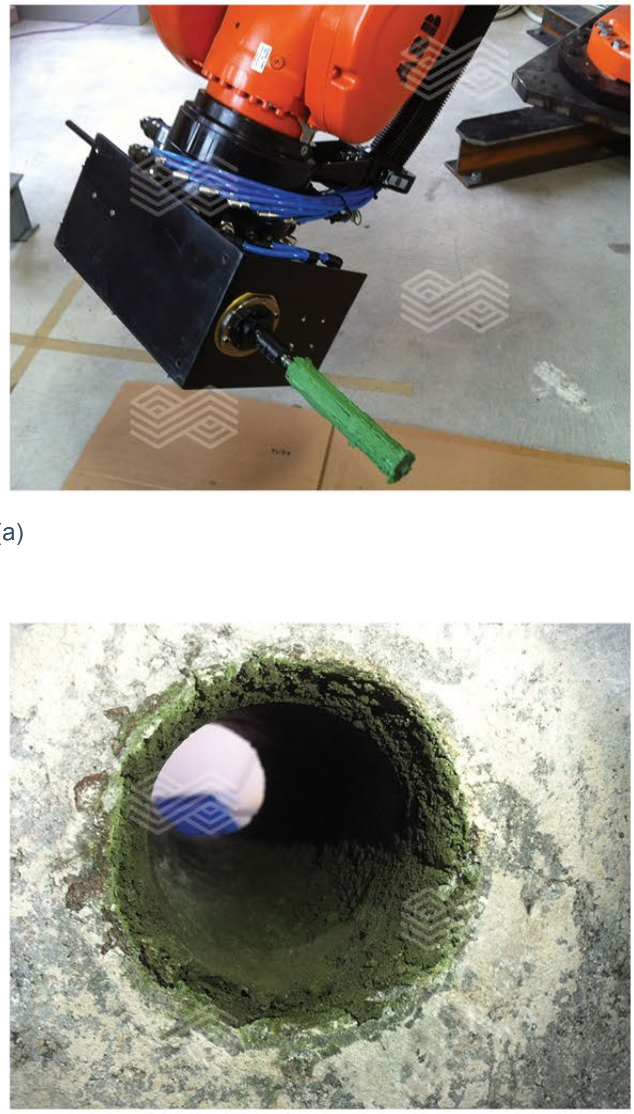


Figure 6.

Showing (a) demonstration of nozzle repair by robot and (b) result of nozzle repair.



(a)

(b)

INTERSTOP® is currently developing the key technologies for a smart ladle gate, providing condition monitoring features, providing following:

- Automatic slag detection system.
- Fault detection.
- Detection of critical conditions, e.g., early detection of a steel infiltration.
- Information with regard to the operation condition and service life.
- Remote diagnostics e.g., via Internet or GSM.
- Communication to other automated systems, e.g., automated ladle prep area.
- Data logging and archiving for quality checks.
- Gathered information will allow big data analysis to allow specific optimizations and predictions.

EMLI Slag Detection

A well-known and established technology in the field of condition monitoring is the slag detection developed by Agellis®. EMLI-LadleSlag is an electromagnetic technology system for monitoring tapping from ladles during casting. The system monitors the final part of the tapping operation automatically and senses the onset of slag so as to provide instantaneous alarms and gate closure signals.

The EMLI-LadleSlag uses electromagnetic fields, which is an operator safe, accurate, and reliable technology. Sensors are installed on the outside of the bottom of ladle, usually in slide-gate levelling plate. The sensors are connected via a flexible cable to the electronics that continuously monitors the metal stream during ladle tapping (Figure 7). The system analyses the received signal during ladle tapping in order to detect when slag enters the metal stream. When this happens, and the amount of slag present reaches a pre-set percentage, the system provides an alarm and sends a closure signal to the slide-gate mechanism.

Operator Support

The system assists the operator by detecting the presence of slag in the metal stream within the ladle-gate nozzle area and provides automatic closure at an adjustable pre-set amount of slag in the stream. Unlike other methods of slag detection, it does not rely on the appearance of slag outside of the ladle, or require a specific amount of slag to create a change in the tapping vibration. This is beneficial to all operators as they no longer need to visually monitor the operation to detect slag or wait until a significant amount of slag causes a vibration change. It is the fastest and most reliable method of slag detection available.

Operations Control

The system monitors each ladle tapping process including sensor signal and slide gate movement. The monitoring of the tapped metal stream is indicated by a displayed signal, which will show the gradual onset of slag in that stream, even centrally entrained slag as a result of vortexing. The operator has a constant feedback as tapping progresses, with the knowledge that the system will provide an instantaneous closure signal and alarm when the slag amount reaches the pre-set limit (Figure 8).

Figure 8.

EMLI-LadleSlag Output signal.

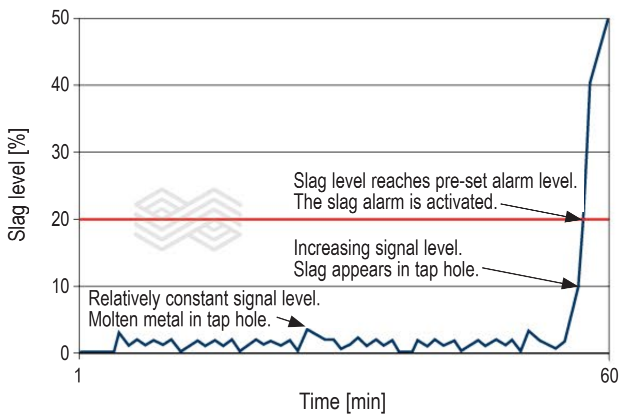
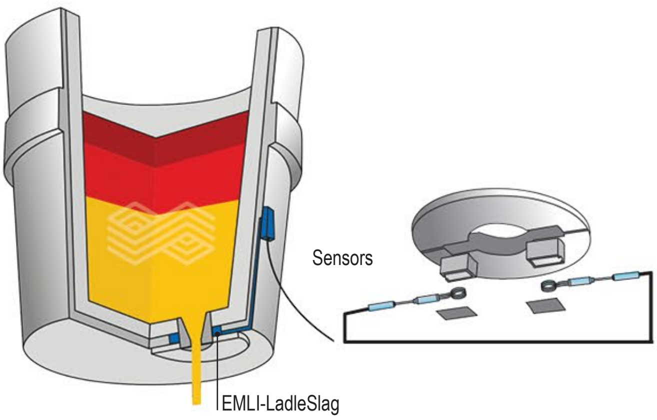


Figure 7.

Showing (a) overview of EMLI installation at ladle and (b) EMLI systems installed in an INTERSTOP® S gate



(a)

(b)


Process Traceability

Each ladle tapping monitoring process is recorded in the system. This enables steel producers to follow-up on the tapping and slag detection performance for any specific heat, which is an important quality assurance function. All good gate closures, as well as early or late closures for any reason, plus any system faults are recorded.

Data Mining

As ladle tapping data is collected over time in the system database, the information is be available for process and production development purposes. Cleaner steel by reduced slag carryover or increased yields, depending on grades of steel being produced, can be linked to changing process parameters and improving product quality.

Description Smart Slide Gate Condition Monitoring System

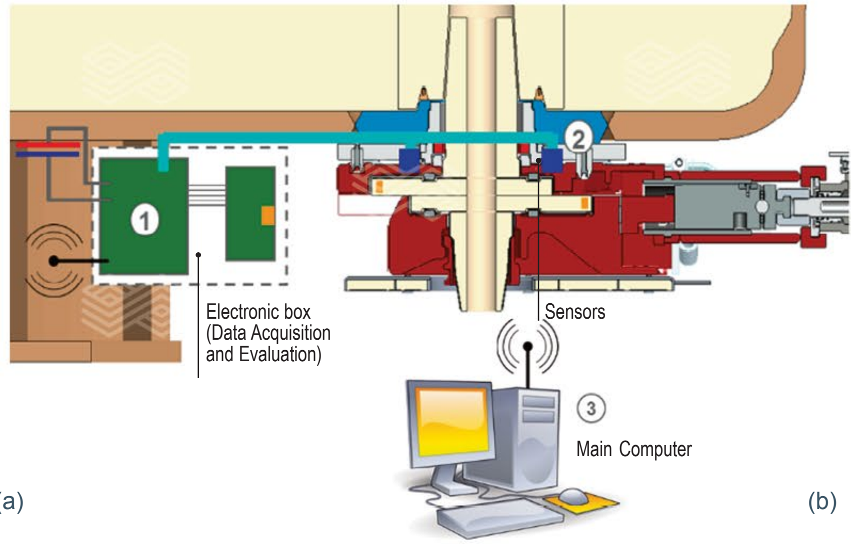
The Smart Slide Gate condition monitoring system currently being developed includes not only sensors as shown in Figure 9, it also includes an electronics box were data is preprocessed and temporarily stored. The collected data can also be transmitted via a wireless link to a main computer. This is of importance when critical situations have to be identified and were rapid alerts and response is essential.

The system has already been hot tested and provided a reliable throttling position, temperature, and force measurements throughout the entire test campaign. In order to provide the throttling position signal, a hermetically sealed potentiometer has been developed, which is, adequate to operate at temperatures up to 300 °C and in a dusty environment.

Conclusion

Initially, the INTERSTOP® S gate was designed for providing low impact on TCO and beneficial features for swift manual operation. More than 60 steel plants are already operating with this gate. In parallel, many system add-ons have been developed that make the manual operation easier, ensure automatic handling by robots, and to incorporate smart features like automatic slag detection. Further innovations, initiatives, and new developments are ongoing, resulting from the exciting opportunities automation and digitalization are offering.

Figure 9.
Showing (a) an overview of condition monitoring system and (b) hermetically sealed potentiometer



(a)

(b)

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João Pedro Chaib de Toledo Alves Pinto, Rubens Alves Freire, Ramon Fraga Resende and Danilo Cunha Martins

Ladle Shroud Design Optimisation through Numerical Modelling

The ladle shroud (LS) is responsible for protecting the steel from re-oxidation at one of the stages of the steelmaking process: transfer from ladle to tundish. This product operates under harsh conditions due to the high temperature gradient between the cold and hot faces. As the failure of the LS can result in operation and yield losses, it is important to develop tools which help to compare stress profiles between different geometries in order to increase product reliability. In this context, a numerical simulation procedure was developed to minimise critical stresses by optimising the LS geometry. The calculations are performed through finite element analysis (FEA) considering thermal stress and varying geometric features. This tool was adopted during product development and some results are shown in this paper.

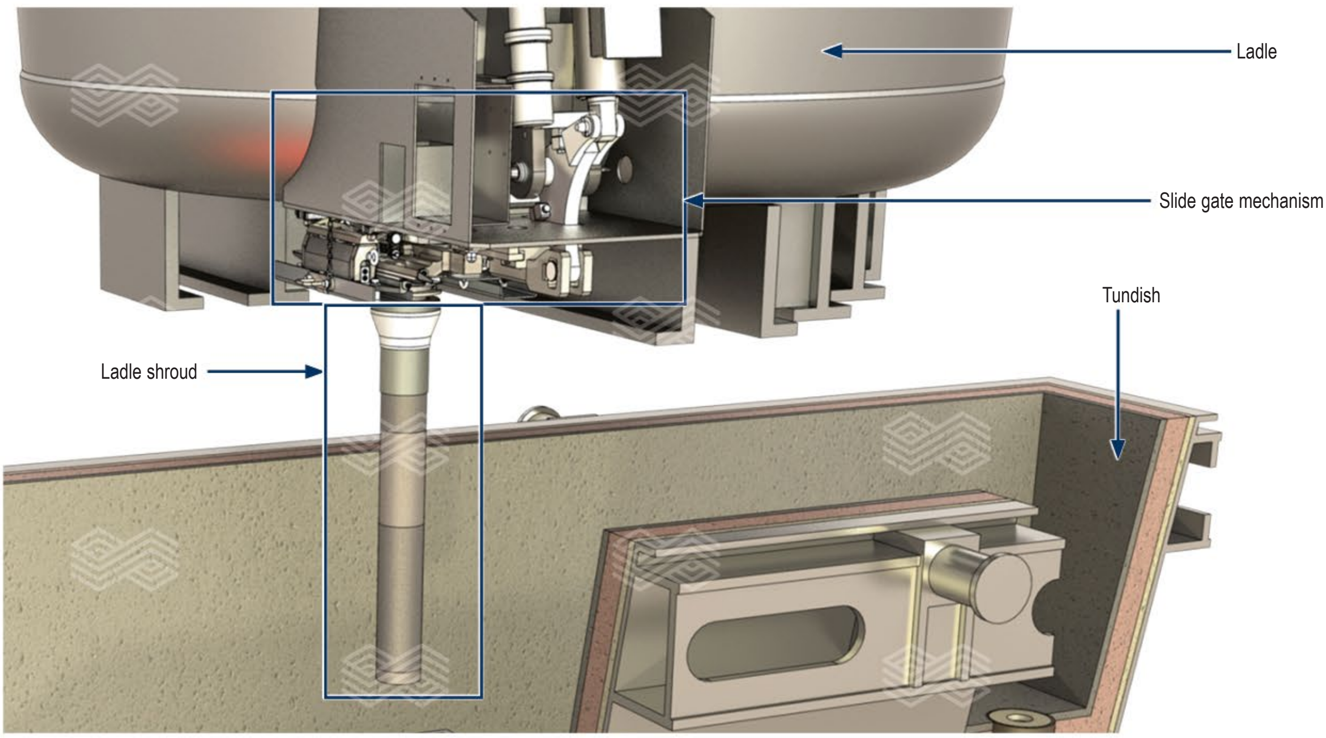
Introduction

The steel industry has spent time and resources refining the continuous casting process in order to produce high quality steel in a safer environment for those responsible for the casting operations. As the refractory has a major contribution to the process performance and safety, it is only natural that new tools are developed to provide the excellence that customers expect. Numerical modelling has already been used to improve various types of equipment in steel mills, in this article the tool was used to optimise ISO-products present at the continuous casting machine. Ladle shrouds (LS) are one of the main consumables in the steel mill, and as the performance is high related to safety, it is of the utmost importance that this product does not fail. The optimisation technique guides the designer in the development process for the ideal ladle shroud for the clients.

Ladle Shroud Application

The continuous casting process consists of a steel flow running from the steel ladle to the tundish and further to a mould in which the steel starts to solidify into slabs, bloom or billets that may receive additional treatments depending on the quality that the steel mill requires for the final product [1]. The steel flow is controlled by different refractory components installed throughout the continuous casting process. One of these components is the object of study in this article, the ladle shroud. This product guides the molten steel from the ladle to the tundish, while protecting it from oxidation, directing it towards an impact region, and preventing steel splashing for increased operator safety. Figure 1 shows the ladle shroud among other components installed in the continuous casting machine.

Figure 1.
Flow control components in the continuous casting process.



The ladle shroud is a cold start refractory and is exposed to liquid steel in high temperature levels, up to 1600 °C. These operational conditions create significant temperature gradients that, together with mechanical restrictions, generate thermal-mechanical stresses through the part. The goal of this work was to reduce these stresses levels by optimising the ladle shroud geometry using numerical simulation.

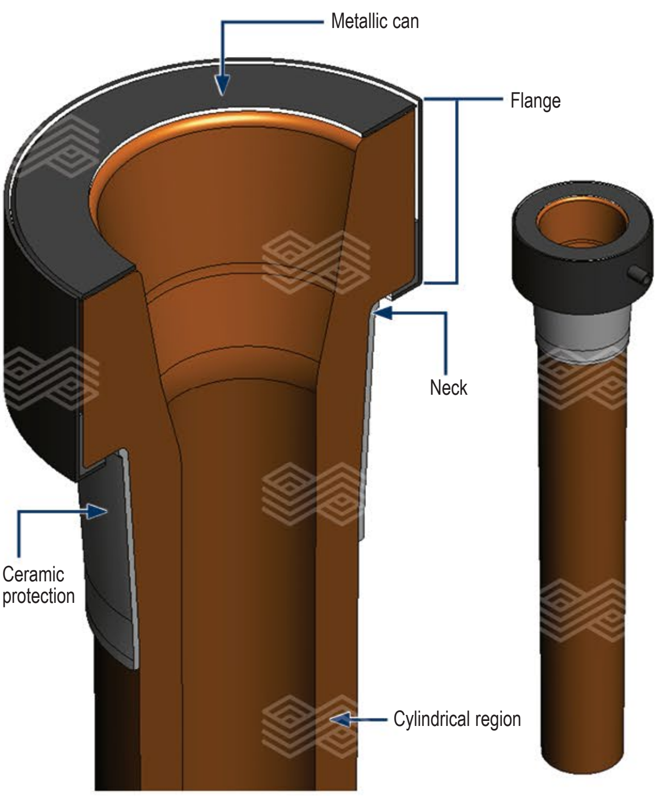
Quick Analysis on the Ladle Shroud Geometry

A ladle shroud can be divided in three important regions: the flange, the neck (or transition), and the cylindrical region, as shown in Figure 2. The most critical part is the transition region due to the large variation in the cross-section profile. Normally, the higher stress levels are found in the neck, thus reducing these stress values were the main goals of the optimising process.

Nevertheless, there are other geometric features that can be modified in order to optimise, if even locally, the LS geometry. One example is the wall thickness from the cylindrical region of the shroud, if the wall is too thick, it can present a greater temperature gradient and, consequently, higher stress values, alternatively, if it is too thin, the region becomes more fragile and more susceptible to failure. Other variables to be optimised are, the angle transition from the neck to the flange, flange height, ceramic fibre, neck radius, and many others. However, a clear communication between the operations and technical marketing is essential for the study, so all the project restrictions are considered during the optimisation.

Figure 2.

Flow control components in the continuous casting process.



Ladle Shroud Failure Consequences

The performance reliability of this product, as mentioned previously, effects not only the steel quality and potential product downgrade, but also the safety of the working environment. A failure of the ladle shroud can result in fire at the caster or injuries to an operator, additionally the installation of a new LS may require a forced opening with oxygen lancing, which can cause additional safety problems. Figure 3 illustrates a ladle shroud that failed below the flange, inside the metallic can.

Furthermore, the methodology used to study the stress profile in the refractories can be divided in three steps, the material model, which defines the constitutive behaviour of the material, the numerical model, which contemplates the discretization of the calculation domain and the boundary conditions, and finally, the optimisation process.

Figure 3.

Showing (a) a failed ladle shroud and (b) a failed ladle shroud from below.

(a)

(b)

The Numerical Model

With the intention to take the thermal loads into account, a coupled model using thermal profiles as input for a structural analysis was developed. Therefore, material properties such as thermal conductivity, thermal expansion, Young's modulus, and Poisson were required for the calculations.

The numerical model was a quasi-static approach, which means the results from the simulations were valid for an equilibrium state, time-dependent phenomena were not considered.

As the ladle shroud has an axisymmetric geometry and boundary conditions, it was possible to reduce the size of the model in order to reduce computational efforts and time, therefore only a 10° section of the whole domain was simulated. For the thermal simulation, a thermal load was applied in the region that is in contact with the molten steel and heat losses were modelled with convection and radiation conditions. It is important to consider that the metallic capsule and holder present different radiation coefficients and must be set separately. Another simulation resource to reduce computational time was to apply boundary conditions instead of modelling elements away from the area of interest, such as the lower region of the shroud.

The Optimisation Process

In order to optimise a geometry, it is necessary to define which parameters to vary with the intention of decreasing or increasing the target variable. In this case, the objective was to decrease the stress levels caused by the thermal gradient of the equipment during operation. Experience is crucial to define these parameters so the user can anticipate where the higher stress levels can be found and which type of variation and ranges to apply in order to observe any improvement in the results. The main goal was to minimise the maximum principal stress using the optimisation algorithm.

To find the optimum design for a ladle shroud is not an easy task. First, a design of experiment (DOE) must be conducted in order to define a response surface in which the optimum values of each varied parameters would be selected. The DOE can be performed using many different methods, each one suitable to a type of variable, continuous or discrete, and a quantity of those input variables. The chosen DOE method was the Box-Wilson Central Composite Design, commonly known as Central Composite Design, the response surface was built through genetic aggregation of the DOE points and, finally, the method of screening was used to find the optimum points at the surface.

However, while much of this approach is fully automated, the proposed candidate points must be subsequently analysed by the design developer to assure improvement. Critical discernment is necessary during the whole process, as there are potential gains that maybe undetected by machines but are instinctive to the human mind.

Results

Case 1

To provide an overview of which parameters were analysed with the optimisation tool, Table I, together with Figure 4, shows the input variables and the minimum and maximum values for a specific study.

After the parameters and the objectives were set, a design of experiment (DOE) matrix was generated combining different values of the geometric features range to create a response surface with regards to the maximum principal stress. A response surface is shown in Figure 5, in which the surface colour gradient is related to the output variable. In this result it is possible to observe the influence of some input parameters variation on the variable of interest. For example, the neck radius has an inverse relation with the maximum principal stress while the external diameter of the shroud displays a direct proportionality.

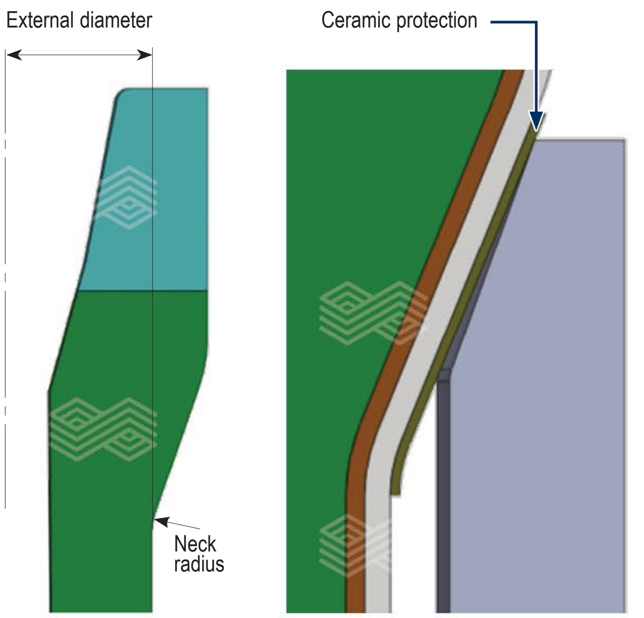
With the proposed parameter values, the new ladle shroud design could achieve lower stress levels in different areas of the geometry. The observed stress value reduction in the neck radius and along the flange of the shroud is shown in Figure 6. The parameter modifications also reduced the maximum principal stress by 20% in some regions of the component.

Table I.
Varied geometric features and the values for the ladle shroud analysis.

Geometry feature	Lower limit [mm]	Upper limit [mm]
Neck radius	20	50
External diameter	155	163
Ceramic protection thickness	1	3

Figure 4.

Showing a schematic of the varied geometry parameters for the ladle shroud.



Case 2

Figure 7 shows a plot of maximum principal stress in the outer surface of the ladle shroud. This LS original design utilised two radii in the “neck” region. When the two radii concept was maintained, the optimisation did not substantially reduce the stress levels present on the LS. The maximum stress value showed only a 5% reduction on the stress level.

Nevertheless, after the optimisation results, a new proposal that merged both radii was simulated. Figure 8 shows the new stress profile of the one radius design. The maximum stress levels in the ladle shroud’s “neck” was reduced by more than 30%. This example demonstrates the importance of critical human analysis on the optimisation method.

Coupling Verification Aided by Rapid Prototyping

Once the LS design was modified through numerical optimisation, is important to verify that the new geometry fits the equipment requirements. At this stage rapid prototyping is beneficial, printing a full-scale model of the ladle shroud flange ensures that it is possible to check the construction of the assembly. Figure 9 illustrates an assembly check of a proposed modification.

With this verification, it was possible to check the exactly height of the mono nozzle penetration with the LS. The cross section view permits observation of the inside the assembly to ensure no interference between components. Figure 10 shows the holder and ladle shroud fitting verification using the 3D printed prototypes.

Figure 5.

Response surface of the DOE: Increasing neck radius and decreasing external diameter, resulting in decreasing stresses.

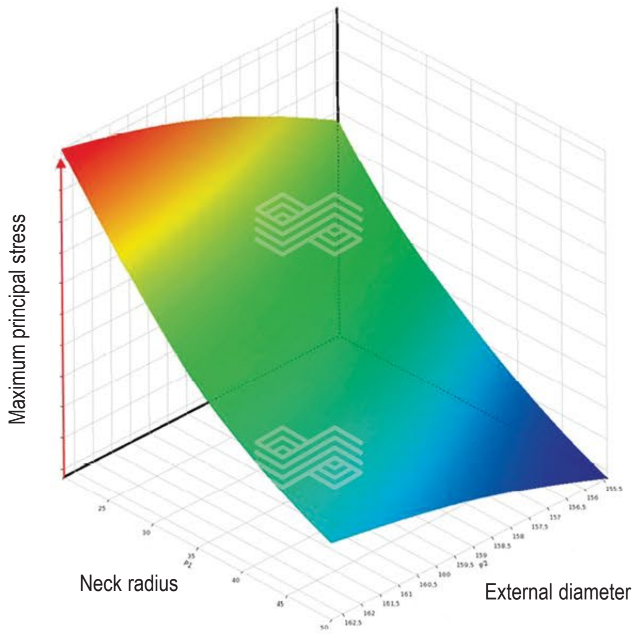


Figure 7.

Stress profile on the two-radii concept (original design).

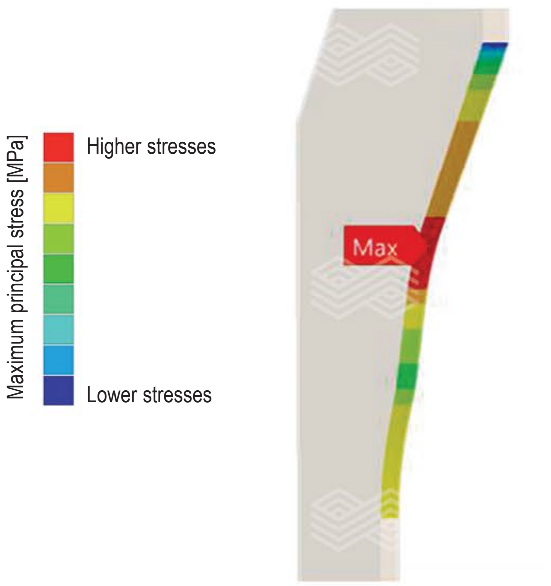


Figure 6.

Ladle Shroud designs comparison.

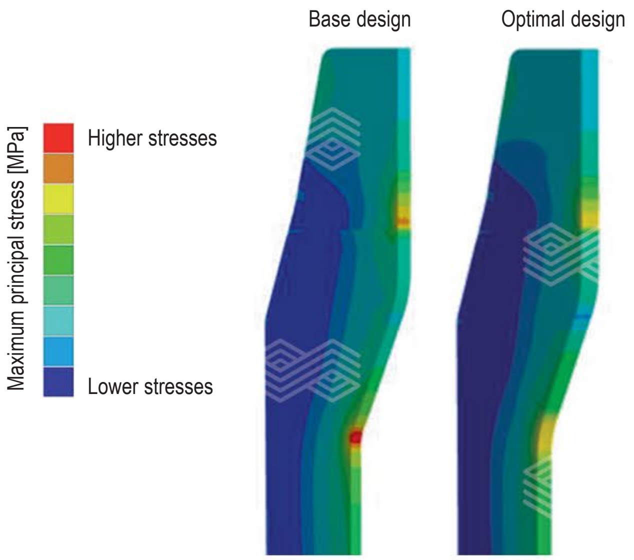
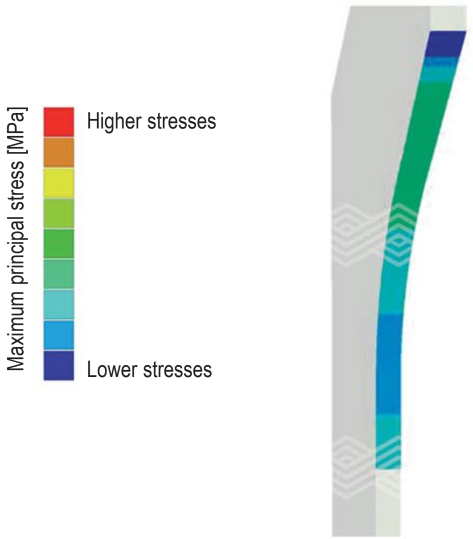


Figure 8.

Stress profile on the one radius concept.



Conclusion

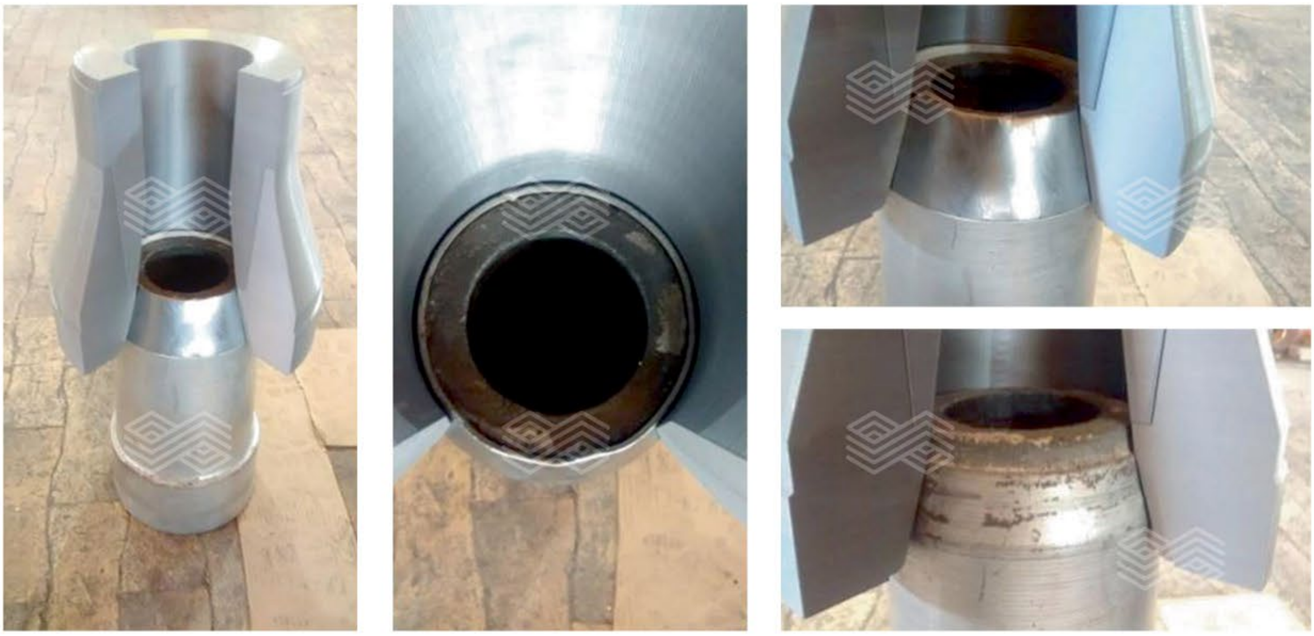
Refractory components are susceptible to thermal-mechanical stresses caused by temperature gradients and structural restrictions that can lead to failure of the material. These stresses can be reduced by modifying relevant topology features in the designs of products. This simple solution can be improved into a sophisticated optimisation process that allows the supply of personalized geometries for customers. RHI Magnesita provides not only a product, but a group of services to assure the best performance on the client's production line.

Figure 10.

Assembly verification between ladle shroud and holder.

Figure 9.

Assembly verification between ladle shroud and the mono nozzle.



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The driving force of the refractory industry

Gernot Hackl, Yong Tang, Gerald Nitzl, Dennis Schurmann, Bernd Willers and Sven Eckert

GYRONOZZLE — An Innovative Submerged Entry Nozzle Design for Billet and Bloom Casting

Introduction

Fluid flow in the mould is known to have a significant impact on the product quality and process stability of the continuous casting process of steel. In addition to the operating conditions, the design of the submerged entry nozzle (SEN) plays an important role. Depending on the caster type, different strategies for the SEN design are being followed to meet the specific requirements. For long product casting, namely billet and bloom casting, usually straight through design nozzles also known as single port SENs are used, due to their simplicity. However, as demand for steel cleanliness increases, research has indicated that this type of SEN may not be suitable to meet all the requirements. Due to the considerable penetration depth of the jet into the liquid pool, flotation of nonmetallic inclusions towards the mould surface where they are absorbed by the slag is prevented. In recent years, there has been a trend to use multi-port SENs in bloom casting for high-grade steel, such as bearing and rail steels. It is considered that the multi-port SEN has a better ability to remove nonmetallic inclusions in the mould than a single-port SEN and provide a better energy transport towards the meniscus. Lately, the process is increasingly supported by the use of electromagnetic fields, such as mould electro-magnetic stirrers (M-EMS). This device is positioned in the mould region and produces an almost homogeneous, planar and rotating magnetic field in the strand. It is reported, that electromagnetic stirring provides a number of benefits such as the homogenization of the liquid steel flow, the reduction of surface and sub-surface defects and an enhanced transition from columnar to equiaxed solidification.

GYRONOZZLE Concept

One of the most recent developments for improving the flow conditions in billet and bloom moulds is the so called GYRONOZZLE. This concept combines the advantages of multiport designs and the application of M-EMS. Triggered by the helical port design this nozzle type imposes rotating flow pattern in the strand, even without the use of an EMS device. In Figure 1, a typical head section of the GYRONOZZLE is shown.

Several benefits are associated with this new concept:

- Deep jet penetration is avoided, resulting in efficient nonmetallic inclusion removal.
- Rotational flow in the mould is achieved to support or reduce the need for electromagnetic flow actuators.
- Efficient mixing in the upper mould region occurs, which results in a better mould powder melting rate to improve strand lubrication as well as a more effective superheat dissipation.
- Reduced steel jet impingement on the solidifying shell is achieved when compared to conventional multi-port designs.

Depending on the mould dimensions the nozzle can be adjusted in terms of size, number of ports and the angle of the helical port to provide the best performance. Computational fluid dynamics (CFD) simulations and water model experiments were conducted on both round and square formats to investigate the flow behaviour. It could be proven that very stable flow patterns were achieved, which was presented in [1]. All these investigations are based on an operation without electromagnetic stirring.

Figure 1.
Head section of a GYRONOZZLE. [2]

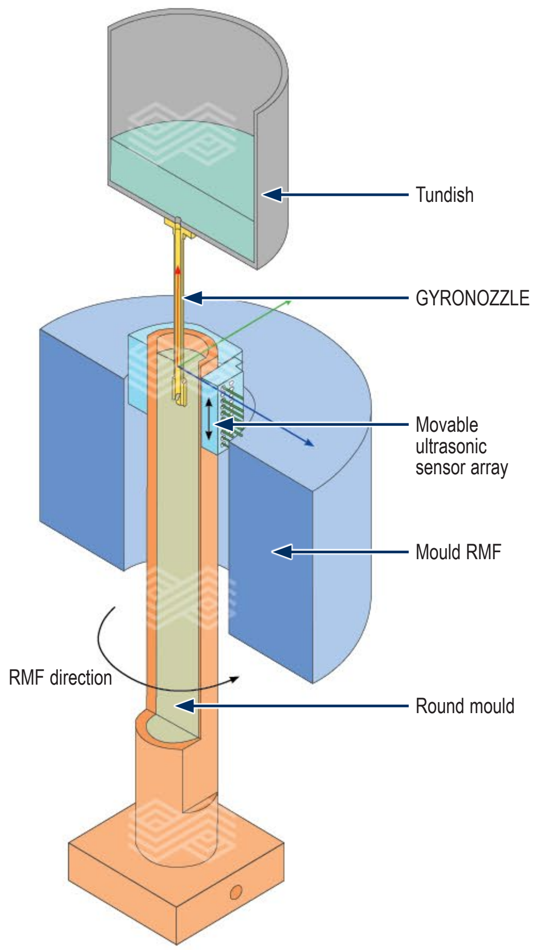
Interaction of GYRONOZZLE with Electromagnetic Stirring

In a further step the interaction of the GYRONOZZLE with a M-EMS was investigated. To this purpose both methods, namely numerical modelling by means of CFD and physical modelling were employed. Since it is not possible to capture the impact of electromagnetic stirring devices with water a liquid melt model operated at room temperature was chosen. Similarity criteria, such as the Stuart number (interaction number) N, the shielding parameter S and to account for the turbulent flow regime the Taylor number Ta, which is equivalent to the Reynolds number for rotating flows, were considered to approximate the real casting conditions as close as possible. A detailed analysis can be found in [3]. For the set of experiments described in this paper a GYRONOZZLE inducing counter-clockwise rotational flow in the mould was selected, such as the rotation induced by the electromagnetic stirrer.

Experimental Set-up

The experiments described in this present study were conducted at the mini-LIMMCAST facility at the Helmholtz-Zentrum Dresden-Rossendorf (HZDR). A detailed description of the equipment itself can be found elsewhere [4,5]. The model is operated with $Ga_{68}In_{20}Sn_{12}$, a model fluid which is liquid at room temperature.

Figure 2.
Sketch of the experimental set up.



The electromagnetic system consists of 12 coils generating a rotating magnetic field (RMF) with a maximum flux density of B_0=20 mT. A schematic view of the experimental set up, as well as the major dimensions is shown in Figure 2.

The model is operated on a scale factor of 1:3. The mould, which is made of acrylic glass, has an inner diameter of 80 mm and a total length of 800 mm. The inner and outer diameter of the GYRONOZZLE SEN are 10 mm and 20 mm, respectively. The immersion depth, which is considered from the bottom of the product to the meniscus, equals 35 mm. The centre of the stirrer is located 225 mm below the meniscus.

The fluid velocity in the mould was measured by means of ultrasound doppler velocimetry (UDV). This method is based on the pulse echo technique and delivers instantaneous profiles of the velocity component projected onto the propagation direction of the ultrasonic beam. An array of ten sensors, which were vertically aligned, was applied to the mould. Measurements were taken at two positions, namely 15 mm and 30 mm away from the centre, Figure 3. This arrangement was used to determine the tangential velocity component along the mould height. The port positions are also indicated in this figure.

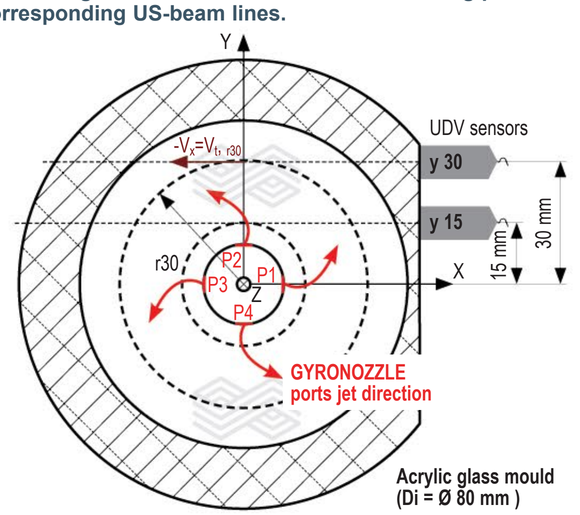
The UDV measurement principle was also used to determine the velocity inside the SEN as a function over the stopper lift. The obtained results were used as input parameter for the numerical simulation.

The material data of the $Ga_{68}In_{20}Sn_{12}$ alloy are provided in Table I, valid for a temperature of 20 °C.

Table I.
Material properties of $Ga_{68}In_{20}Sn_{12}$ at 20 °C [6].

Properties	Unit	Value
Density ρ	kg/m^3	6353
Dynamic viscosity η	kg/(ms)	2.18×10^{-3}
Kinematic viscosity ν	m^2/s	3.43×10^{-7}
Electrical conductivity σ	1/Ω m	3.29×10^{-8}

Figure 3.
Port arrangement with off centre UDV measuring position and corresponding US-beam lines.



Mathematical Modelling

A representation of the system SEN - mould was created for the numerical model. The inlet was defined as pressure inlet. The outlet at the bottom of the domain was defined as velocity inlet, with a negative z-component value to match the desired flow rate. The surface was considered to be a frictionless wall. The mesh consists of almost 5 million volume elements. The incompressible, isothermal fluid flow in the strand is described by the Reynolds averaged Navier-Stokes equations (RANS) using the realizable $\boldsymbol{k\text{-}\varepsilon}$ model for closure. To account for the stirring force employed by the stirring device, the semi-empirical formulation developed by Spitzer was used [7,8], which was implemented as an user defined function (UDF) in the commercial CFD code ANSYS Fluent.

$$\overline{F_r} = -\frac{1}{8}B_0^2\left(\omega - \frac{v_t}{r}\right)^2 \sigma^2\mu_m r^3 \qquad (1)$$

$$\overline{F_t} = \frac{1}{2}B_0^2\left(\omega - \frac{v_t}{r}\right)\sigma r \qquad (2)$$

Equation 1 and 2 describe the radial and tangential force densities dependent on the magnetic flux density B_0, the angular frequency of the magnetic field $\boldsymbol{\omega}$, the radial position r and the fluid's tangential velocity v_t. In addition, the electrical conductivity $\boldsymbol{\sigma}$ and the magnetic permeability $\boldsymbol{\mu m}$ of the fluid are required. This method was successfully used by Barna [9].

The magnetic flux densities used in the experiments were obtained by measurements.

Result

Multiple simulations and experiments were carried out to investigate the interaction of the magnetic field with a varying field strength on the flow induced by the GYRONOZZLE and with a single port nozzle for comparative reasons.

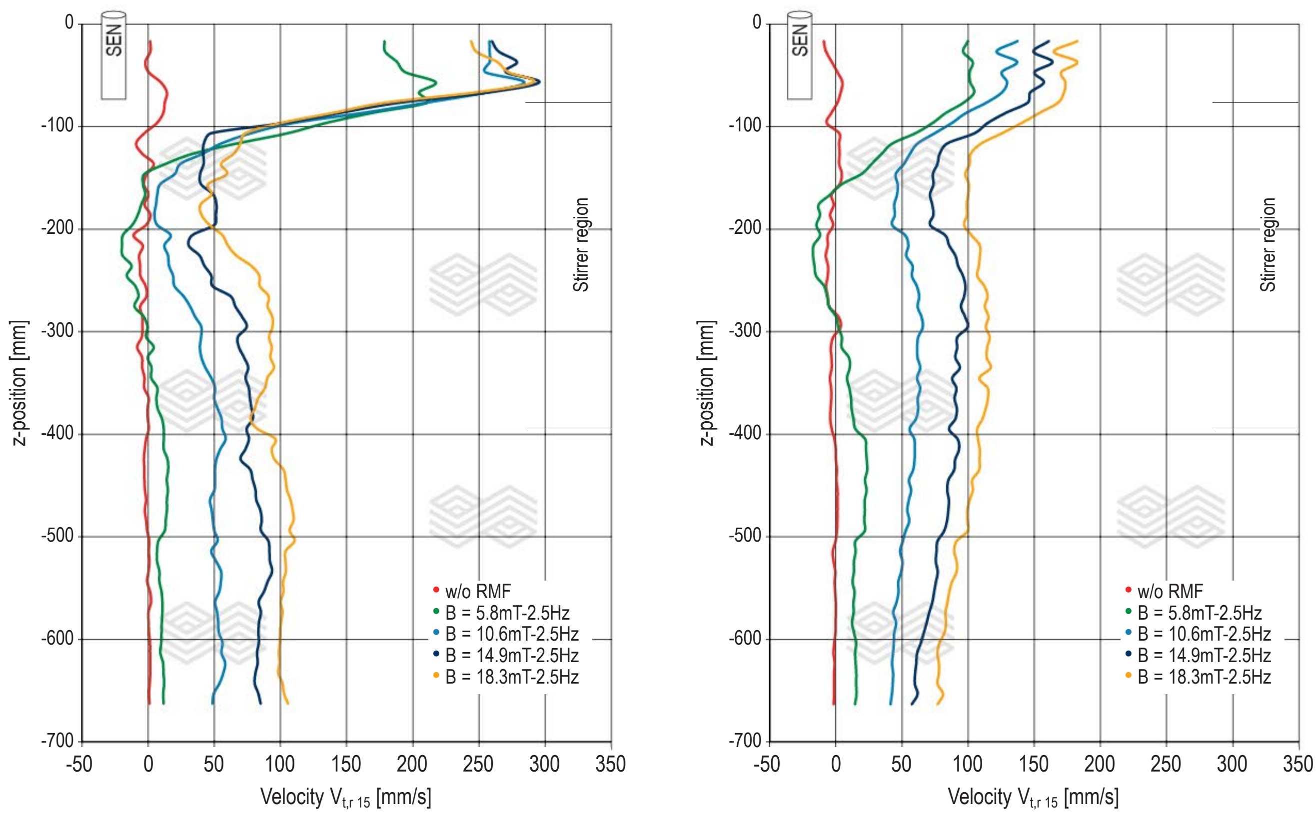
Standard Nozzle

In previous work, Barna and Willers have investigated the behaviour of a standard straight through SEN type. The same measurement principle as described above was used to determine the rotational flow component at different diameters along the height of the model mould. The results for the radial positions of 15 mm and 30 mm are shown in Figure 4 [10,11].

It can be concluded, that the weakest applied magnetic field (5.8 mT) already caused a significant rotational flow in the upper part of the mould close to the meniscus, whereas hardly any difference to the unstirred case was observed at a distance greater than 140 mm away from the meniscus. At a radius of 15 mm velocity reached values above 0.25 m/s at magnetic flux density above 10.6 mT. What was observed in the experiments, in addition to a high surface wave, was a very unstable meniscus with significant formation of vortices, as shown in Figure 5. Such situations might lead to detrimental effects, such as entrainment of mould flux.

Figure 4.

Vertical profiles of the time-averaged tangential velocity measured at r=15 mm (a) and r=30 mm (b) for a conventional straight through SEN.



(a) (b)

GYRONOZZLE

The behaviour of the GYRONOZZLE is significantly different to the straight through standard nozzle. The rotational flow at the meniscus area, which is already induced by the special port configuration, is not affected in such way as the standard SEN. An increasing magnetic field only has a minor impact on the flow velocities in that area. Although there is a slight increase, there is no evidence of strong flow disturbances and excessive wave formation as observed for the standard SEN. The flow in general, remains much more stable and controlled. In Figure 6 the tangential flow velocity along the vertical position at the radial position of 15 mm and 30 mm are shown. The average flow velocity inside the SEN was 1.2 m/s for all experiments.

Figure 7 provides a view on the surface, taken during an experiment with the highest field strength of 18.3 mT and a stirring frequency of 2.5 Hz. Very smooth and undisturbed flow conditions are observed.

Figure 5.

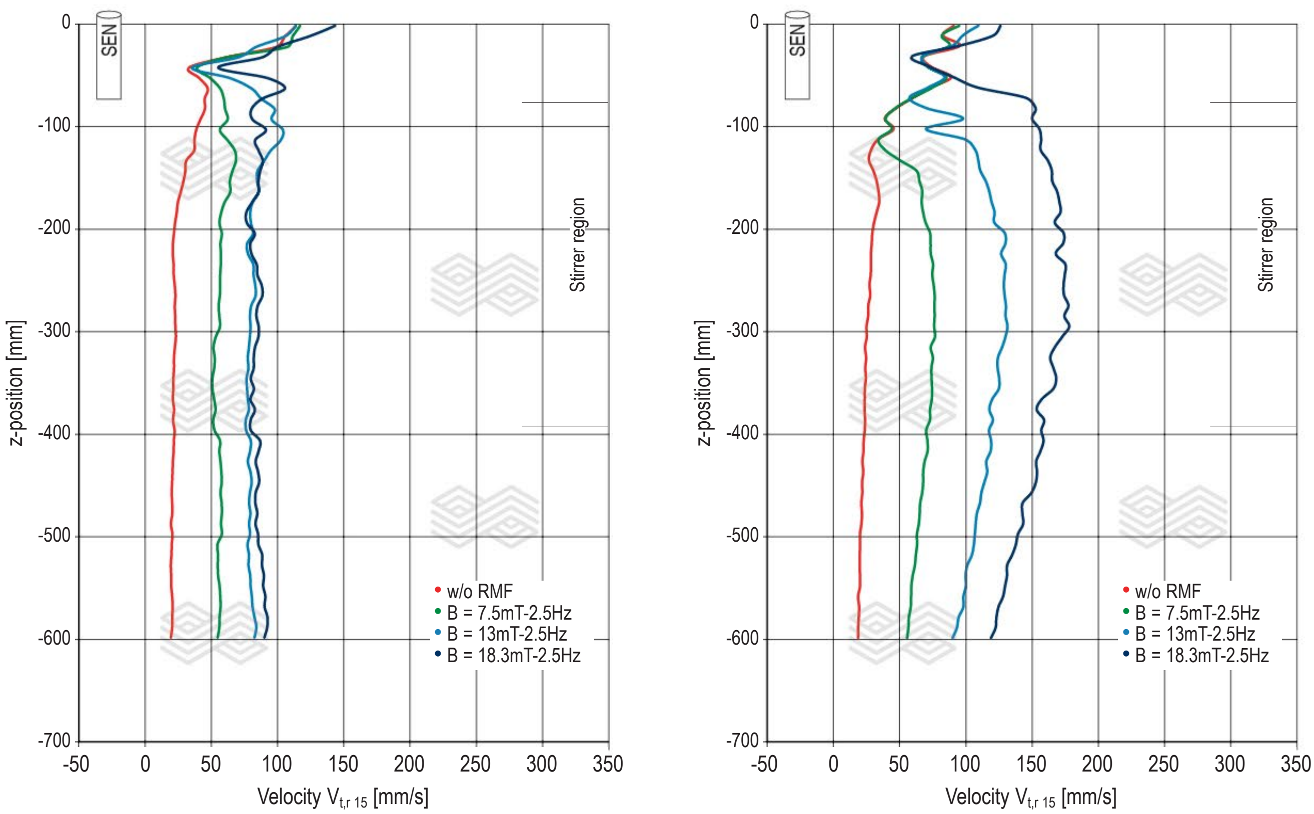
Vortex formation in the vicinity of the SEN.

Figure 7.

Snapshot of the surface taken during the experiment with the GYRONOZZLE with an applied RMF of 18.3 mT at 2.5 Hz and a flow velocity inside the SEN of 2.1 m/s.

Figure 6.

Vertical profiles of the time-averaged tangential velocity measured at r=15 mm (a) and r=30 mm (b) for the GYRONOZZLE.



(a) (b)

The simulation predicts a similar behaviour. The magnitude of the surface velocity is not strongly influenced by the electromagnetic field strength. The flow in the upper part of the mould is therefore mainly dominated by the momentum induced by the jets. The influence of the rotating magnetic field is more pronounced in the lower section of the mould, below the jets. This becomes obvious by analyzing the stream line plot, which is shown in Figure 8. From left to right the results for varying magnetic fields are shown, starting from the unstirred case on the left side up to a strength of 18.3 mT on the right. The tangential velocities obtained by the CFD at the radial position of 15 mm and 30 mm are shown in Figure 9. The results for the radial position of 30 mm show a good match and are qualitatively in line with the measurements. However, the predicted velocity close to the meniscus, especially at the radial position of 15 mm, shows a significant deviation. A strong velocity gradient in the radial direction is predicted by CFD for the nonstirred case and magnetic field strength up to 15 mT close to that measurement point, which did not correspond with the measurements. That could be a matter of the boundary condition used in CFD, e.g., frictionless wall instead of a free surface.

Summary

Mathematical simulations by means of CFD and physical models operated with liquid metal were utilized to investigate the flow characteristics obtained by the use of the GYRONOZZLE in the mould region with a round cross section. The focus of this work was to characterize the interaction with a mould electro-magnetic stirrer (M-EMS) and compare the results with a conventional straight through SEN design. Even without the use of an electromagnetic stirrer the GYRONOZZLE establishes a rotational flow in the mould. When a rotational magnetic field is applied the velocity profile at the meniscus is not severely affected. Strong fluctuations and the formation of vortices, as detected with a standard SEN, were not observed. In contrast, with increasing distance from the meniscus, the rotational flow is established more strongly, when compared to the standard SEN, which should be beneficial in terms of the crystallization pattern of the solidified steel. The flow in general is more stable, independent of the operating conditions. Both modelling approaches show the same trend. Based on the obtained results it can be stated, that the GYRONOZZLE shows a superior behaviour over conventional straight through SEN designs for both the stirred and nonstirred case.

Several observations of this innovative product in use confirm the positive effect. It was reported:

- that due to a better energy dissipation in the mould, the casting speed could be increased without taking the risk of breakouts,
- that grinding losses could be significantly decreased,
- that mould level fluctuations were decreased,
- the surface quality was improved.

Figure 8.

Streamlines (top) and surface velocity plot (bottom) obtained by CFD with varying magnetic field strength (a) no EMS, (b) 7.5 mT, (c) 13 mT and (d) 18.3 mT.

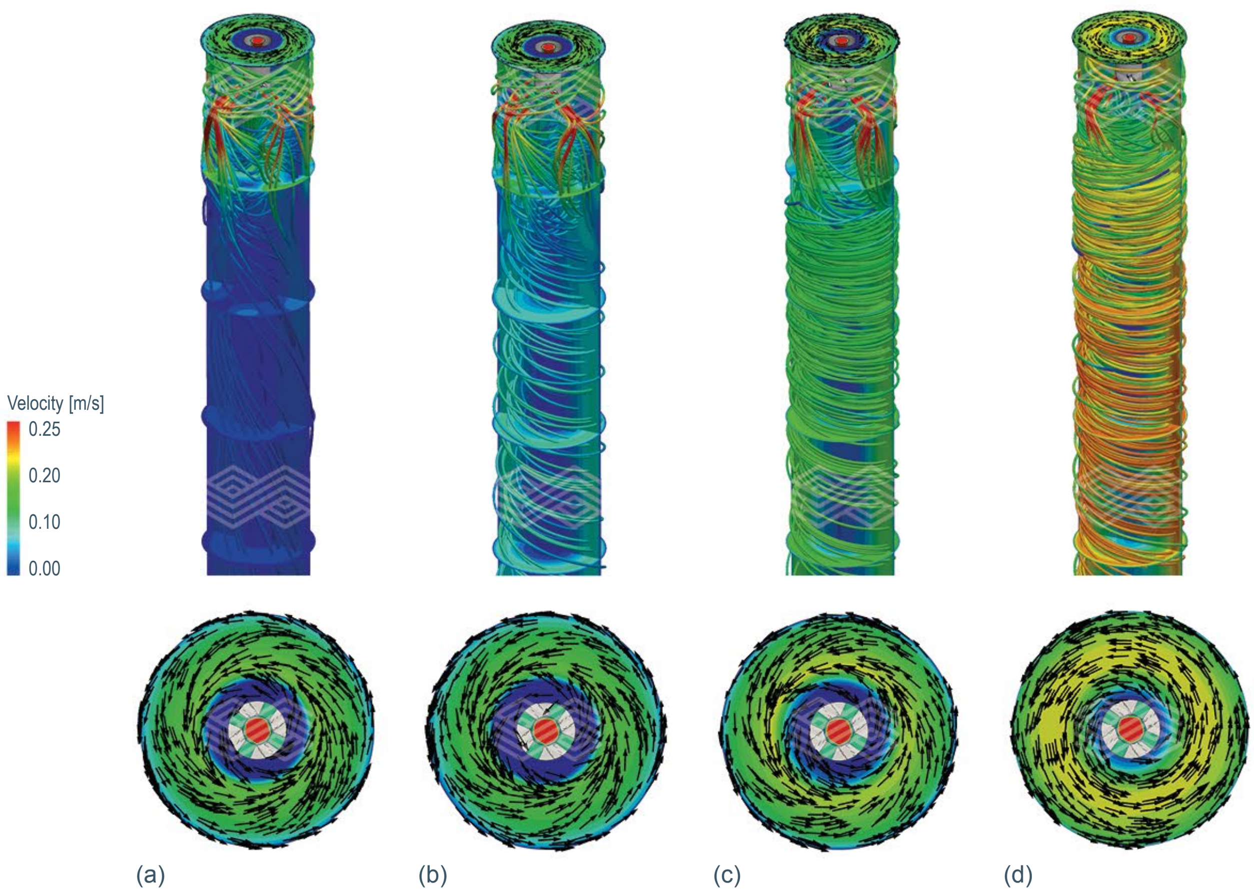
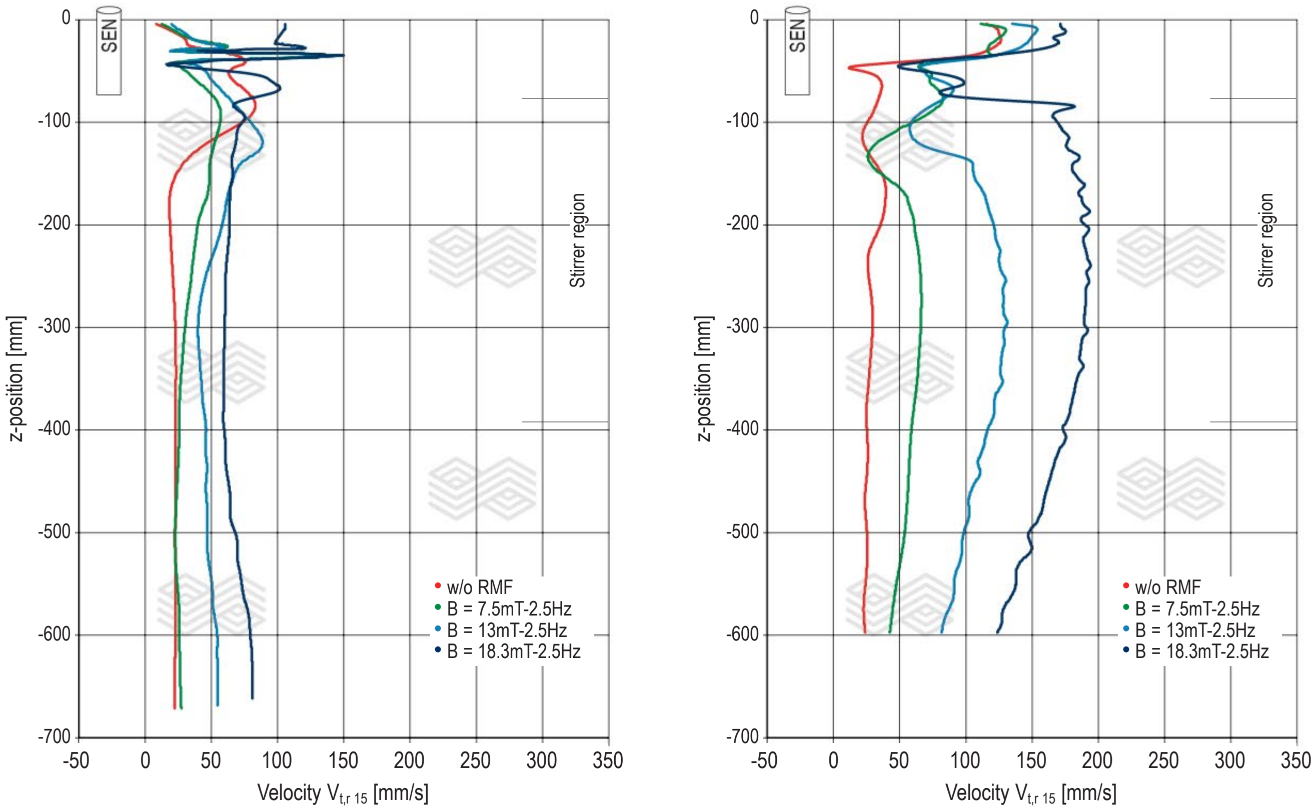


Figure 9.

Vertical profiles of the tangential velocity calculated by CFD at r=15 mm (a) and r=30 mm (b) for the GYRONOZZLE.



(a) (b)

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David Wappel, Lena Glavanovits, Marcos Tomás Casado, Andreas Goedde, Bernd Petritz and David Neuschitzer

New Water Soluble Binder for Foundries

The aim of this publication is to present the newly developed binder system for the foundry industry and the development steps that have been taken. The developments were made with the collaboration and support of the Österreichisches Giesserei Institut (ÖGI) over the last 3 years.

Among some major benefits, such as the water solubility for cleaning after casting (easy mould and core removal) and the eco-friendly feature, this paper also describes some limitations and/or potentials for improvement that need to be explored together with industrial partners in the future.

RHI Magnesita is looking for partners in the foundry industry in order to further develop and customize, this environmentally friendly water-soluble binder system.

Introduction

Furan resin, sodium silicate, phenol resin, among others, are binders commonly used in the foundry industry together with the mould materials quartz, chromite/zircon sands. On one hand these binders are mainly used due to their physical characteristics suiting the industrial process, but on the other hand they have some disadvantages that cannot be overlooked when analysing the industry trend [1].

The currently used organic resin systems have the main advantage of a good workability, good strengths and minimal required amount of binder but show significant disadvantages in terms of high odour and emission concentrations in the workplace, which could lead to health issues for the employees. Alternatively, binders based on sodium silicate, which have low emissions, show significant disadvantages in terms of mould and core removal after casting.

In order to overcome the main disadvantages related to such binders and at the same time having comparable physical properties, working, and setting times, RHI Magnesita started in 2014 the development of an alternative water-soluble binder system based on an existing binder system which has been used in tundish wear lining applications for many years. The main advantages of this binder system were the expected easy mould and core removal in combination with the usage of a phenolic free, environmentally friendly binder.

The present work was conducted together with the ÖGI and has achieved following milestones:

- development and characterisation of the binder system to give a detailed understanding of the possible raw materials and influences on the achievable strengths of the binder.
- core production showing the parameters and influences to produce stable cores with the self-hardening (SH) binder.
- mould production and practical casting tests to evaluate the casting performance and influences on the cast product.
- de-moulding of cores after casting to determine the expected advantage of easy core removal in comparison with standard binder systems.

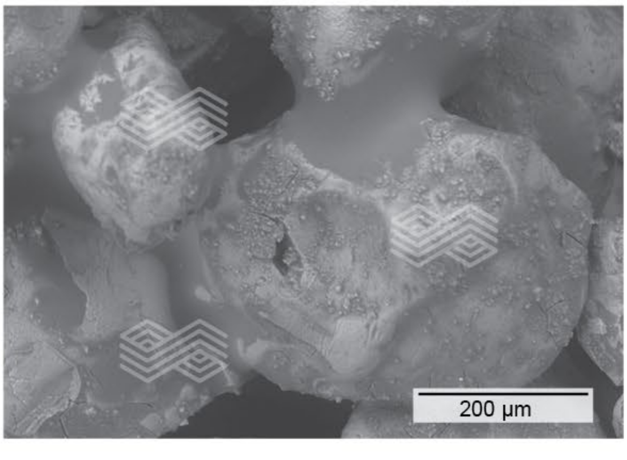
Characterisation of the Binder System

Originally this self-hardening binder system (SH binder) was developed for the tundish wear lining in steel plants and has been successfully used since 2009 [2]. In steel plants the tundish mix including the SH binder is mixed with 1.5 wt.% of water and filled into the gap between the tundish permanent lining and a template. After the setting of the mix, the template is removed and the tundish is ready for casting. As the tundish lining process in the steel plant can be compared with the mould production in the foundry industry, the use of the SH binder with standard foundry sand should also be possible.

The SH binder consists of a solid organic acid component, in combination with a solid inorganic basic material. This SH binder is mixed in a dry state with the mould material. Due to the addition of minor amounts of water (1.2–1.7 wt.%) the SH binder forms a metal-organic complex leading to the formation of binder bridges with the moulding material (Figure 1). The main mould/core material used in all trials was, quartz sand type GLG 30.

Figure 1.

Scanning electron microscope image of SH binder bridges with quartz sand.



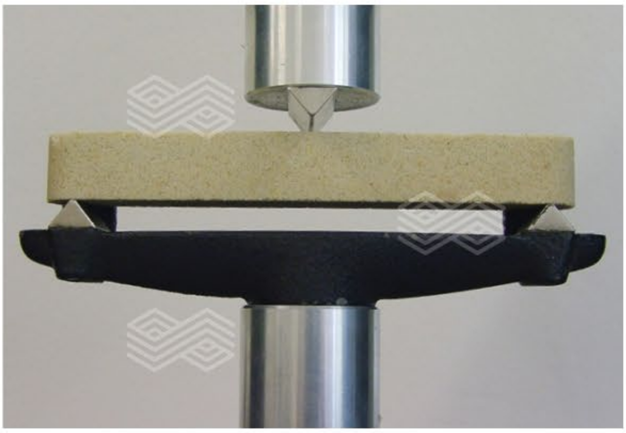
For the physical characterisation of the SH binder system and the comparison with existing and well proven binder systems, the measurement of the modulus of rupture (MOR) is considered as standard measurement technique in the foundry industry [3]. Therefore, the dry mixture (SH binder and GLG30 quartz sand) was mixed for 30 sec and then another 30 sec with 1.5 wt.% of water addition using an Eirich DL5 laboratory mixer or a standard KitchenAid stand mixer. Directly after the mixing process, the moist mix was hand rammed into a mould, to form the required bars with a dimension of 22.5 x 22.5 x 150 mm. The modulus of rupture was then measured after the desired setting time with a Zwick Z005 table-top testing machine as illustrated in Figure 2, which was the most appropriate method for the testing of binders [3].

The use of different types of basic inorganic raw materials, in combination with the reaction rate and the setting time, can influence the setting strength of the SH binder system. For a better characterisation, different types of RHIM internal and externally purchased sources of basic inorganic components were tested in combination with the standard organic acid. Figure 3 shows the setting behaviour and the achieved modulus of rupture for the SH binder (5 wt.%) using different inorganic binder types in comparison with a standard furan resin (1.5 wt.%) and sodium silicate binder (3 wt.%).

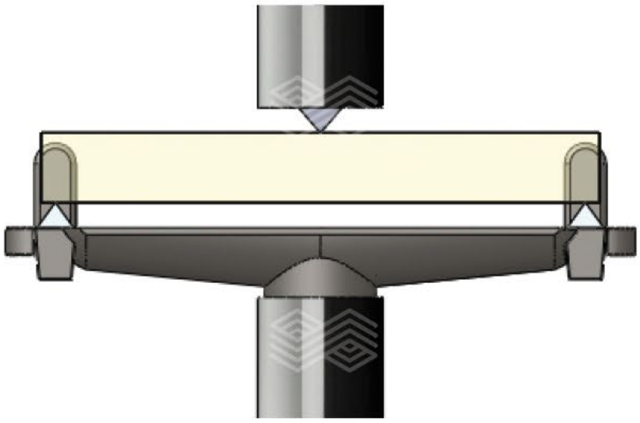
The optimum binder amount for a sufficient strength with consideration of the binder costs, was also determined by varying the concentration and measuring the modulus of rupture after 24 h. Figure 4 shows the strength development with increasing binder content, showing that a binder addition of 5 wt.% provides a sufficient strength for general usage in core and mould production. Therefore, 5 wt.% was set as the standard for all further trials. With a higher binder content, the strength can be increased a little further, but would lead to a negative impact in terms of gas venting during the casting process and higher binder costs.

Figure 2.

Measurement of modulus of rupture at the ÖGI laboratory. Showing (a) actual device and (b) schematic of the process.



(a)



(b)

Figure 3.

MOR of various basic binder components in comparison with standard binder systems.

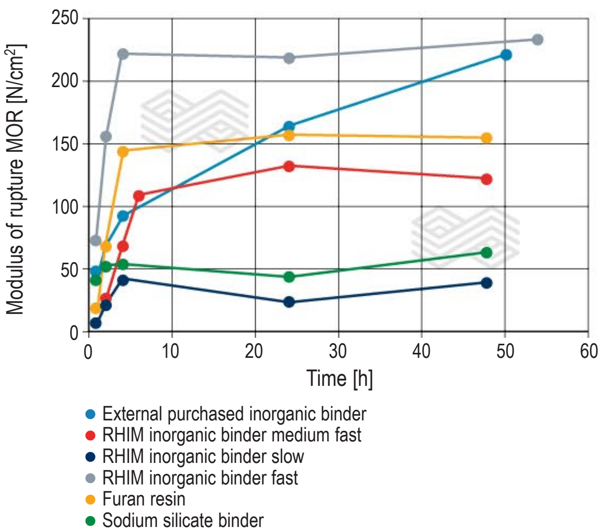
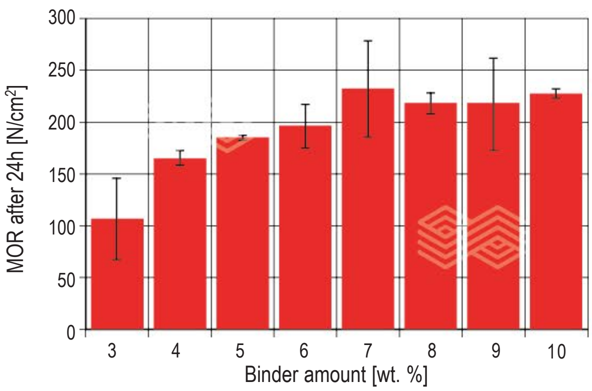


Figure 4.

Influence of binder content of rupture at room temperature.

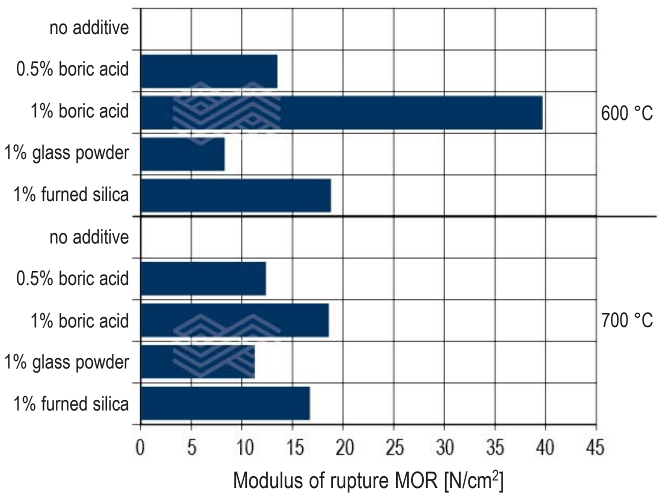


As the organic binder decompose at > 600 °C there is minimal strength remaining when the binder is exposed to high casting temperatures. This generally leads to an easy core removal after casting which is considered a positive effect. Nevertheless, for some special applications greater strength is required for the core, which can be achieved by the inclusion of additives to increase the strength at temperatures above 600 °C. The influence and the achievable strength increase of such additives is illustrated in Figure 5.

In addition to the influence of the basic inorganic binder component, the influence of the different grain size distributions and types of quartz sand were also investigated to verify the influence of the moulding material. It was observed that sand types with a lower specific surface and a smooth grain surface show a greater strength compared to the standard GLG30 sand.

Figure 5.

Influence of binder content and additives to modulus of rupture at temperatures of 600 °C and 700 °C.



Core Production

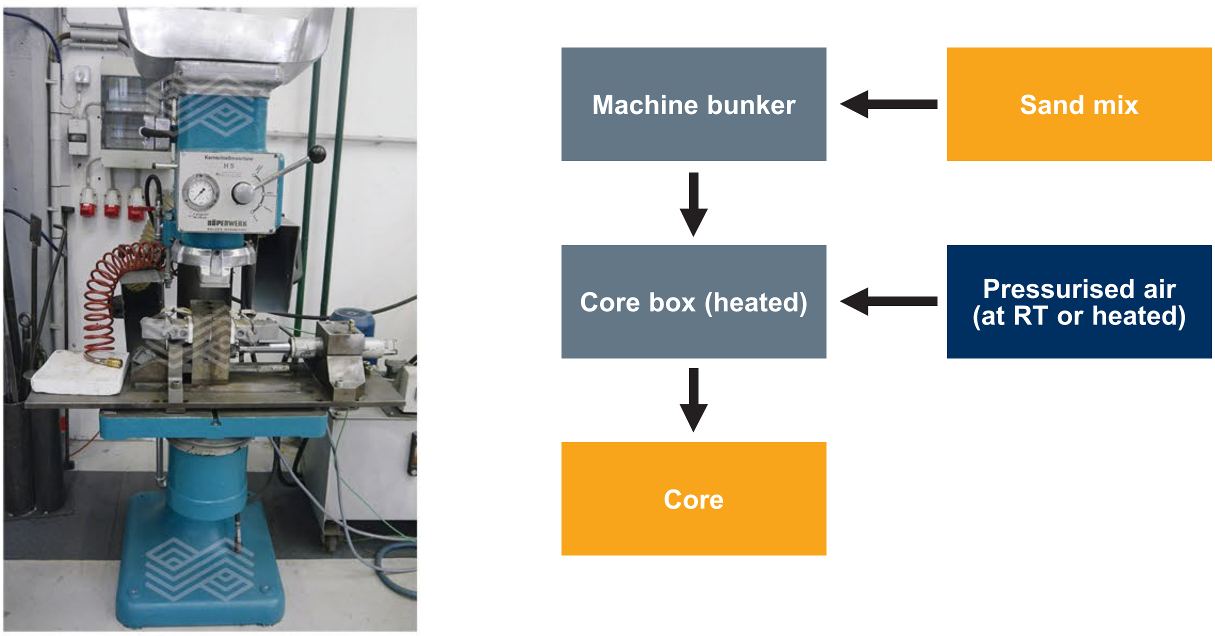
The production of cores is one major application in the foundry industry, where special binder properties are required. Therefore, various trials and detailed investigations for a realistic core production were performed using the core shooting machine Röperwerk H5 and setting process at the ÖGI as illustrated in Figure 6.

As the SH binder reaction is initiated when the dry materials (sand + binder) are mixed with water, and the mix is then filled into the receiver tank, it must be ensured that the mix remains processable for a certain period of time. The required workability cannot be obtained with a water addition of 1.5 wt.% as the mix reacts within 10 min and the viscosity of the mix is drastically reduced. To overcome this issue and to ensure a shooting time of >45 min, the sand was mixed with an excess of water (3 wt.% addition). This extra water addition, lowers the reaction rate of the binder and the mix stays processable for a longer period of time. However, after core shooting, the mix must react as quickly as possible in order to form a stable outer surface, so that the core can be removed within a short period of time. Therefore, the core box was preheated and purged with hot air after the shooting process. Figure 7 shows the influence of the core box temperature (a) and the cycle time (b) on the modulus of rupture when using RHIM medium fast inorganic binder component. As illustrated with an optimum core box temperature of 135 °C in combination with hot air purging (150 °C), the cycle time of core production can be lowered to <30 sec, while still achieving correct strengths. These trials illustrate that with the SH binder system short cycle times are also possible with only minor impact on the strength.

To improve the quality of the surface of the cast product, the use of a refractory coating is essential for some cores. In general, these coatings are applied to the core by spraying or painting and they can be either water or alcohol based.

Figure 6.

Core shooting machine and setting process at the ÖGI.



The water-based coatings have the main advantage in that there are no issues in terms of organic emissions. To evaluate interaction of the SH binder with such a coating material, the SH binder was tested with different types of refractory coatings. As the SH binder in general is water soluble, there is a clear negative impact by adding a water-based refractory coating to a core made from the SH binder as the binder can be dissolved due to the water in the refractory coating.

This negative impact can be seen in Figure 8 where the decrease of the MOR was much higher for the water based refractory coatings (Disopast and Hydra A) than for the alcohol based refractory coatings (Kaolid).

Although the water solubility is a disadvantage in this case, generally the water solubility of the SH binder is considered an advantage for the removal of residual binder.

Mould Production and Practical Casting Test

In addition to the previously describe core production, the manufacturing of moulds using the SH binder was also studied. These moulds were produced in an industrial scale trial, using a modified version of a tundish lining machine from company AAGM GmbH - Wöhr Gießereianlagen. During the mould production, initially the silica sand was mixed with the dry SH binder in the transport screw and shortly after 1.5 wt.% of water was injected. The moist mix was transported through the mixing screw providing the required energy to start the setting reaction of the SH binder with the silica sand. With this continuous mixing process various moulds with different patterns were filled and hand rammed. Two examples of such forms are shown in Figure 9.

After the production of the moulds the actual samples were cast with cast iron at a casting temperature of 1470 °C. Figure 10 shows the cast samples of the moulds.

All samples reflect the details of the mould accurately, demonstrating that the binder does not negatively influence the casting process. Similar tests were also performed as a direct comparison to the SH binder with furan resin and "green sand" (bentonite binder), which also showed no negative impact from the SH binder. Additional casting trials were also performed for various coatings and in addition to cast iron, aluminium was also used as alternative liquid metal for casting. All the performed casting trials reflect that the mould production and the casting with different liquid metals were possible using the SH binder for the mould production.

Demoulding of Cores Produced with Different Binder Systems

After the cooling process of the cast samples, the cleaning of the product and the removal of the residual sand of the cores is a critical issue to achieve clean and smooth surfaces or inner structures in the product. This cleaning behaviour is a disadvantage when using standard sodium silicate and cold box binders compared to the new SH binder system.

Figure 8.

Influence of refractory coating on modulus of rupture.

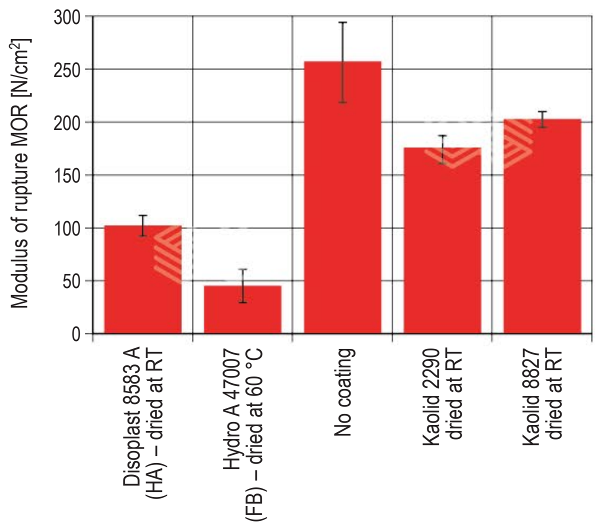
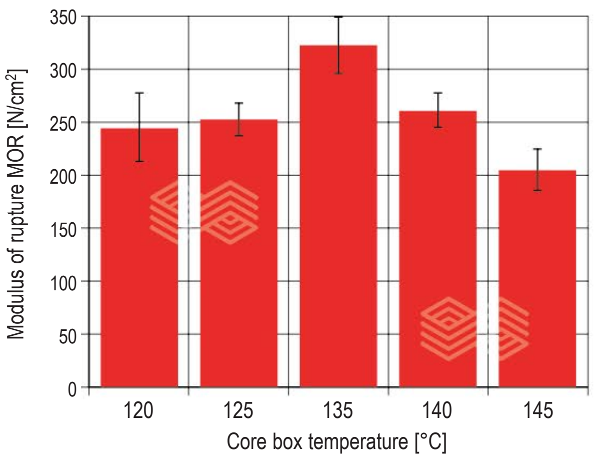
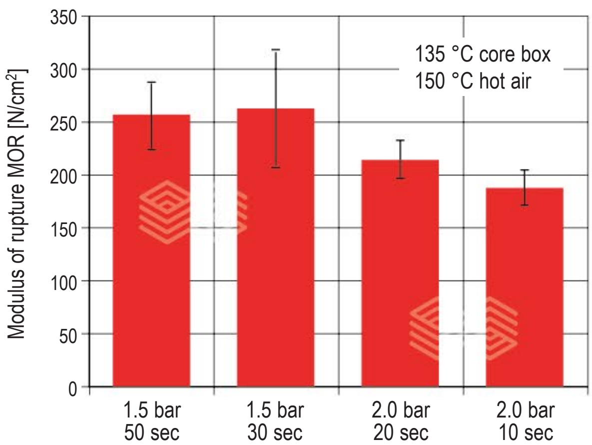


Figure 7.

Influence of core temperature (a) and cycle time (b) on modulus of rupture.



(a)



(b)

As one of the major components of the SH binder is an organic acid in combination with water, the mix releases the water above 100 °C and starts to decompose during casting due to the elevated temperature. This breakdown of the organic binder structure is complete at a temperature of 600 °C, so all volatiles are released below this temperature. As the casting temperature of the liquid metal is generally higher than 700 °C, the binder bridges near the cast metal will be broken and the core can be removed more easily compared to a sodium silicate system which is much more temperature stable. To verify and illustrate the easy core removal a cleaning test was created to show the different behaviour of the SH binder, sodium silicate, and a cold box system. As shown in Figure 11 samples with an inner core were cast with the different binder systems. To remove the residual inner core, the sample was exposed to high pressure water for 60 sec and the removal of the core was measured. As seen in the diagram of Figure 11 the core using the SH binder showed approximately 80% removal, while the samples using sodium silicate and cold box binder showed only 10% removal. This clearly demonstrates that the binder has advantages in de-moulding and this new demoulding process may be an interesting option for casting products where this issue is from significance.

Emissions

Additionally, to the behaviour of the binder during core or mould production, the emissions released during the casting process are from importance in terms of environmental and health issues. As the binder consists of an organic component, various substances depending on the temperature and oxygen partial pressure can be released in addition to CO_2 and H_2O. The measurement of these substances and the qualitatively and quantitatively analysis was more complicated than expected, as there is currently no standardized measurement procedure available to determine the evolving emissions. Therefore, additional cooperation, including a bachelor thesis with the University of Leoben – Department of Process Technology and Industrial Environmental Protection was initiated.

The main target of these measurements was to find a suitable method to define the released substances qualitatively and then to estimate the amount of those substances quantitatively during the casting process. Further, a comparison of the SH binder with standard binder systems such as furan resin and cold box systems will be carried out. These measurements are currently under investigation and the initial results show that the emissions from the SH binder are lower, when compared to furan resin or cold box systems. A detailed description of the measurement method and the final results will be included in a later publication.

Figure 9.
Mould production with SH binder.

Figure 10.
Cast mould samples with SH binder.

Conclusion and Outlook

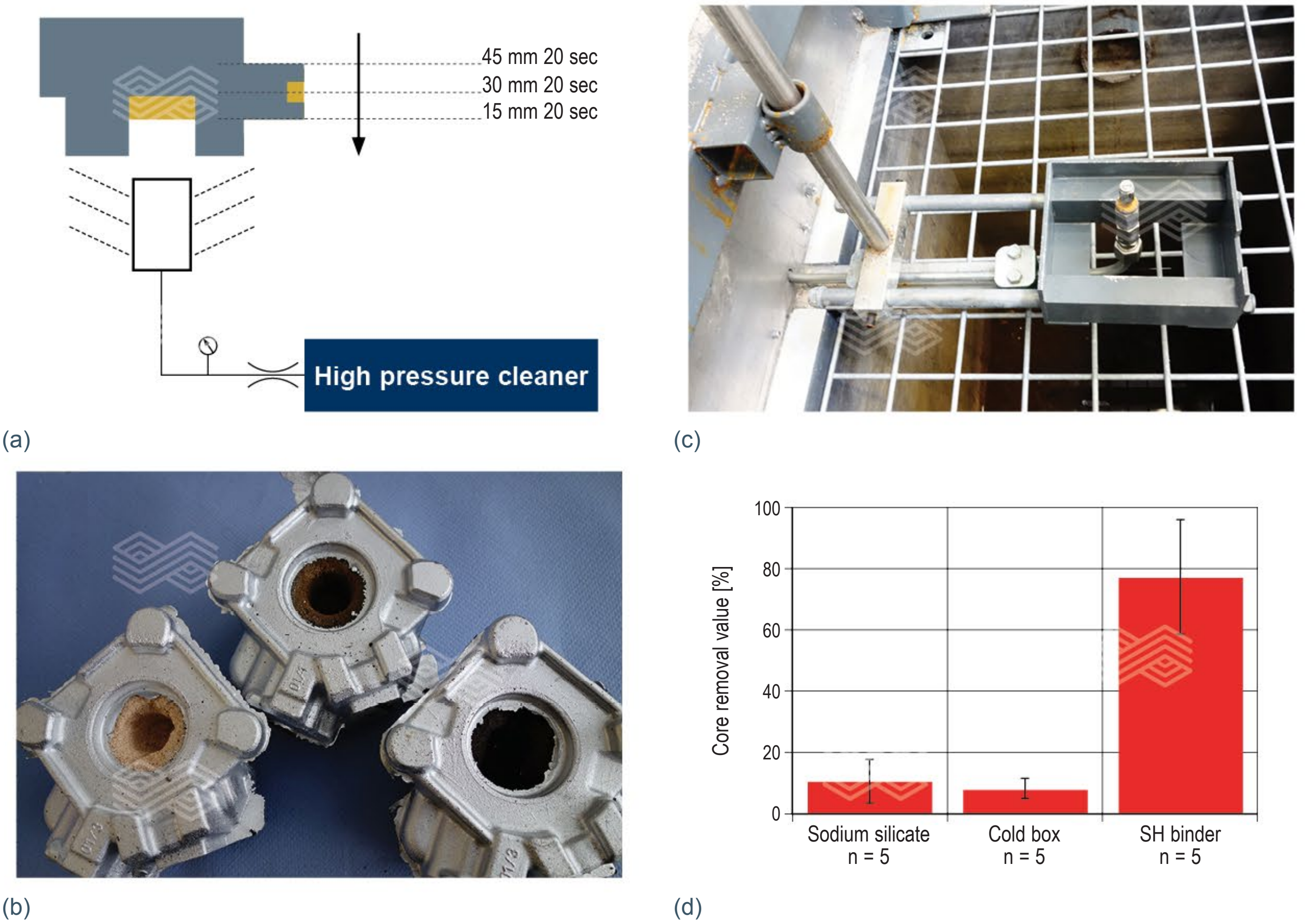
A new water-soluble binder system for foundries has been developed to the prototype and laboratory testing stage by RHIM in collaboration with ÖGI. Results have shown a significant potential for the new binder, specifically, the water solubility for cleaning after casting (easy mould and core removal) and the eco-friendly features. However, it is clear that there is a need for further analysis and field tests of the system on an industrial scale in order to investigate a wider range of applications. Specifically focusing on the development of processes and equipment for industrial applications.

Some major achievements regarding binder system characterisation core and mould production and casting performance have been presented; and some limitations of the current water-soluble binder system, were described. As most of the foundry sand is reused, binder recycling must also be evaluated in more detail in order to understand the full potential.

Further studies are ongoing regarding emissions analysis, the initial results are promising and will be published in the future.

Figure 11.

Showing (a) schematic of the demoulding test, (b) the testing station, (c) the cast samples after water injection and (d) the comparison results of the demoulding test with SH binder, sodium silicate and cold box binder.



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Return to Content

Günter Unterreiter, Daniel Rene Kreuzer, Bojan Zivanovic, Hans U. Marschall and Gernot Hackl

Applying Numerical Simulation for the Design Process of a Novel Roof Panel Brick Suspension System

A novel and innovative prototype of a water-cooled roof panel brick suspension system was developed in a cost-effective way by means of virtual prototyping. Conventional prototypes first need to be manufactured and tested within the appropriate environment and then under real process conditions. As real furnace conditions are difficult to recreate, a virtual prototype based on finite element analysis was used in this study. This methodology leads to a substantial reduction of time to market. Numerical models were used to analyse the behaviour under static load, the thermomechanical in-service performance of the refractories and the steel construction. Furthermore, a comparison was done to demonstrate the difference between thermal expansion compensated and uncompensated layout. This process resulted in a physical roof panel without the need for several iterations and costly physical prototypes.

Introduction

In the ferroalloys and nonferrous industry, water cooled roof systems are widely applied to reduce refractory wear. The most commonly used cooled roofs are steel panels or segments with cooling channels in a double wall design and a refractory mix on the hot face as shown in Figure 1.

Due to the harsh conditions and high heat loads in the furnaces the refractory mixes very often act like a sacrificial layer which is lost during early operation. On one hand this increases heat losses and on the other hand poses a risk to the integrity of the furnace.

The application of bricks could remedy these problems. In general bricks show a better resistance to erosion, infiltration, and chemical attack than mixes. The biggest challenge of installing bricks on a water-cooled panel is to guarantee a holohedral connection between the steel structure and the bricks for a sound heat transfer. Therefore, a new brick suspension system named self-clamping hanging brick system SCHBS was developed [1,2].

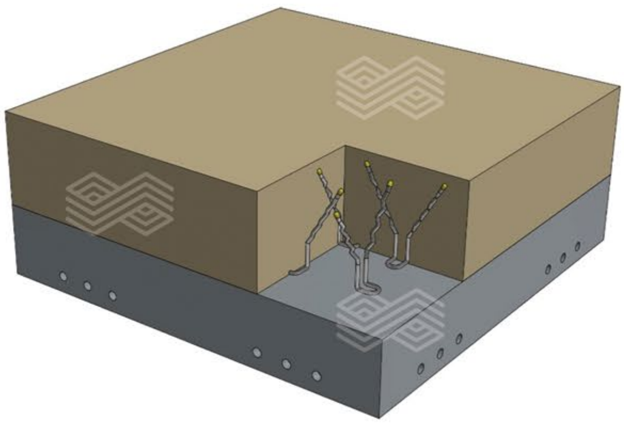
Design of the new Brick Suspension System

The installation of bricks to a cooler is most commonly realized by a tongue and groove system. This can lead to rather complex cooler designs and brick shapes, which result in increased production costs, susceptibility of the bricks to cracking if exposed to thermo-mechanical loads and expenses to generate a tight fit, due to manufacturing tolerances.

The newly developed system utilises prismatic bricks, incorporating a pin-hole and reduced recess, minimising the challenges in the production of the bricks (Figure 2). The bricks are fixed with long steel rods. The rods are mounted to steel plates and can move along a bearing surface. The provision of movement along the bearing surface enables compression between the brick back face and the cooling panel as a consequence of the thermal expansion of the brick. The plates are welded to the flat surface of a water-cooled panel. As the suspension steel parts are located inside the refractory bricks they are exposed to elevated temperatures. A verification of the structural strength of these steel parts is essential. Therefore, a finite element simulation was conducted to calculate occurring stresses for different clearance conditions in between the bricks [1].

Figure 1.
Showing (a) water cooled segment of a FeMn furnace and (b) roof panel with steel anchor suspended refractory mix.

(a)

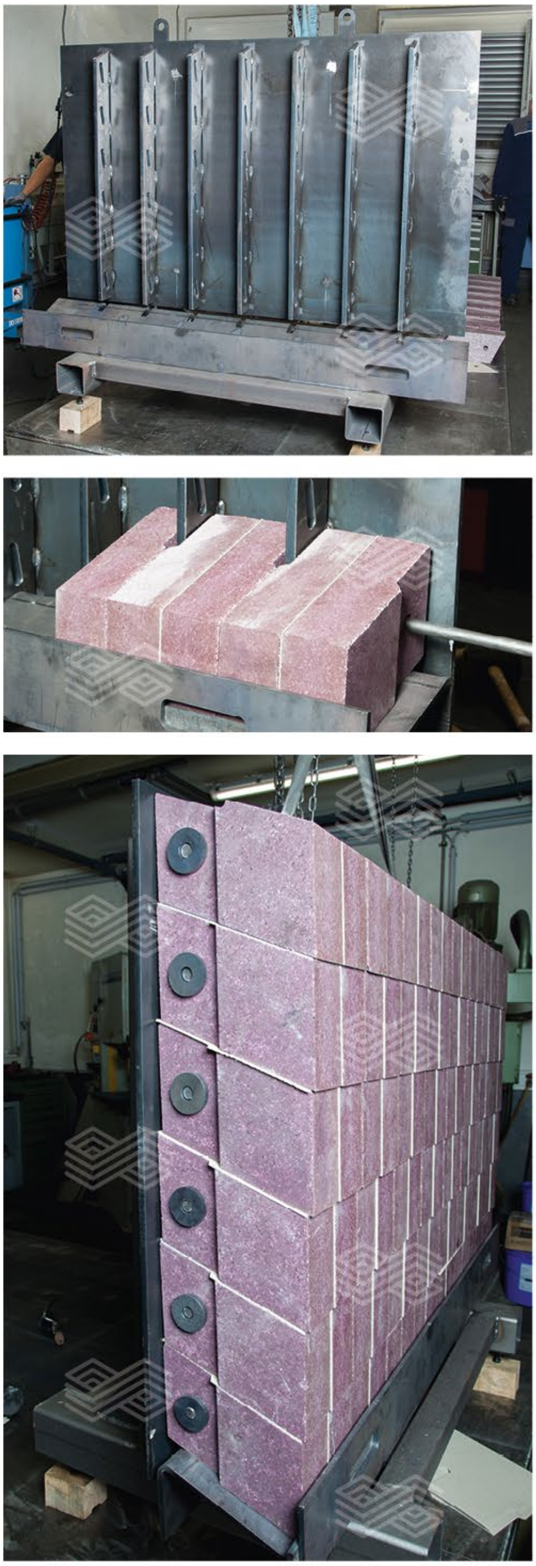

(b)


Numerical Simulation Methodology

Typical product development demands prototypes to be manufactured and tested within the appropriate environment and under real process conditions before an initial customer installation. As real furnace conditions are difficult to simulate via a physical model, a virtual prototype based on finite element analysis was used in this study. This methodology leads to a substantial reduction in time to market [3].

Figure 2.

Installation of novel brick suspension system.



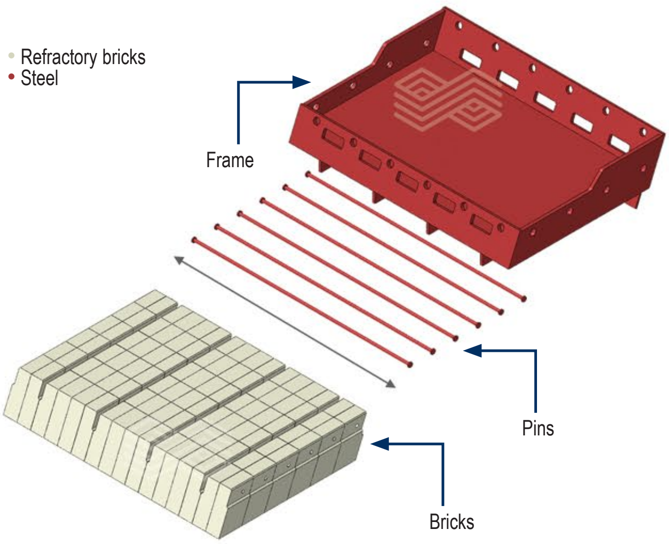
A sequentially coupled model approach was used, starting with a pure heat transfer analysis. In the subsequent structure analysis, the temperatures were mapped to the mechanical calculation domain. Hence thermomechanical stresses, strains, and the final shape of the deformed panel were calculated. Solid elements were used, thermal and mechanical contacts were considered via steel–steel, steel–brick and brick–brick interfaces.

The goals of the simulation were to calculate the temperature field of the suspension parts, the stresses and strains and to determine the final dimensions and design of the SCHBS. Furthermore, a comparison between an expansion compensated and non-compensated version of the panel was conducted. Based on an initial layout and the aforementioned calculations the suspension system was designed virtually [1].

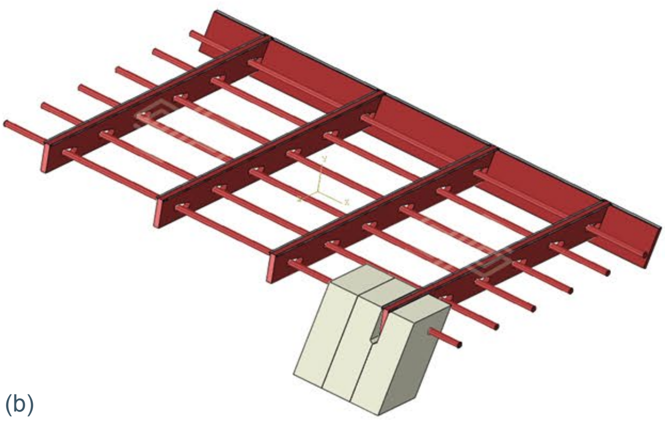
In Figure 3 the overall 3D CAD geometry used in the simulation is shown. It consists of 96 bricks, 6 pins and the steel body. A total weight of 1536 kg was calculated from which the frame weighs 728 kg, the pins 13 kg, and the bricks 795 kg.

Figure 3.

Showing (a) an overview of the SCHBS construction and (b) lower part of the suspension system.



(a)



(b)

Thermal Model

A steady-state heat transfer analysis involving conduction and radiation was set up. As an initial temperature for the whole model was defined at 25 °C. The model considered a uniform atmosphere which transfers thermal energy to the panel. The radiative heat transfer between the sections was modelled with surface to surface radiation considering an emissivity of 0.7. Due to the symmetrical construction of the panel, only one half, including the corresponding bricks, was taken into account (Figure 4).

The boundary condition for the water cooling was a fixed temperature of 50 °C on the surface which is in contact with the cooling liquid. For the hot face boundary an estimated furnace atmosphere temperature of 1650 °C and a heat transfer coefficient with a value representing a typical gas radiation and convection was specified [4].

Mechanical Model

The second step of the analysis involved the use of the thermal results predicted by the previous thermal model as an input for the mechanical model. The structural assessment was conducted for a maximum mechanical load and maximum thermal load. The frictional sliding was modelled by the Coulomb friction law with the interfaces brick–brick, brick–steel, and steel–steel.

Thermal Results

Figure 5a shows the temperature field of the refractory. The elevated temperatures in the steel sections, shown in Figure 5b, lead to time dependent irreversible deformation under constant load. This aforementioned mechanism is called creep [5]. Therefore, a highly alloyed stainless steel was used to fulfil the thermomechanical demands concerning creep resistance at high temperatures.

The temperature profile of the steel suspension was from 50 °C up to 550 °C. A cross section of the pin with the highest thermal load shows a minimum temperature of 308 °C and a maximum temperature of 424 °C and is shown in Figure 6.

Mechanical Results

It is shown in Figure 7 that inside the steel frame and the pins, a maximum of Von Mises stresses in the order of 25 MPa (at room temperature) occur, this is due to static load. Due to the high temperature load (Figure 6) the strength of the steel decreases, the weight of the lining or the dimensions of the steel construction were adjusted accordingly.

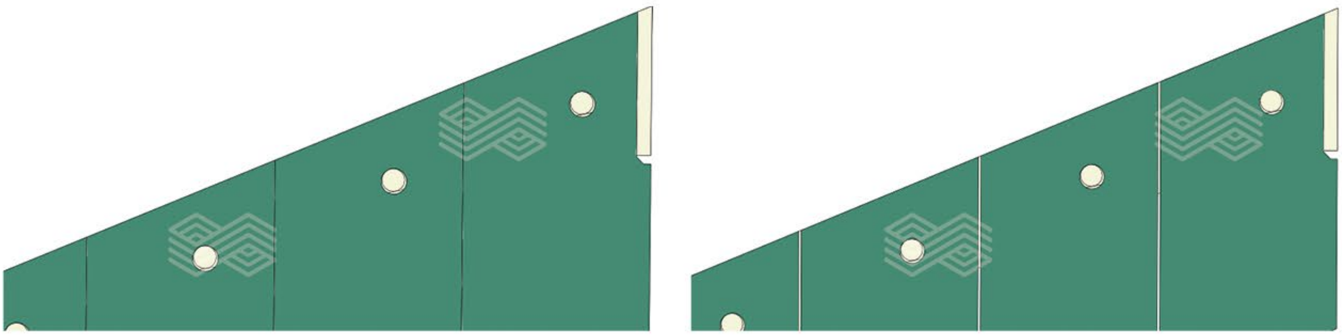
Another crucial design criterion was the behaviour of the system when heated and thermal expansion occurs (Figure 8). The general principle should be to avoid any additional loads induced into the suspension sections, resulting from thermal expansion [1].

In Figure 8, the influence of the thermal compensation clearance on the stress field is obvious. In the red coloured areas high tensile stresses arises. The tensile stress areas above the bricks evolve due to the high contact pressure between the steel plate of the cooling system and the bricks. More critical are the tensile stresses which arise between the bricks. These stresses can be reduced by specific measures for the expansion compensations which generate clearances for the brick movement. Initial clearance between the bricks was achieved by the installation of expansion allowances which burnout in operation.

In Figure 9a, a clear separation of the bricks from the steel panel is shown, this develops due to uncompensated thermal expansion, which causes strong deformation in the whole system. In addition to the high tensile stresses the cooling function is partially disordered which leads to higher temperatures resulting in increased thermal expansion.

Figure 4.

Showing (a) version 1 without thermal expansion compensation and (b) version 2 with expansion compensation.



(a) (b)

Figure 5.

Simulated temperature field of (a) the bricks and (b) inside the steel construction.

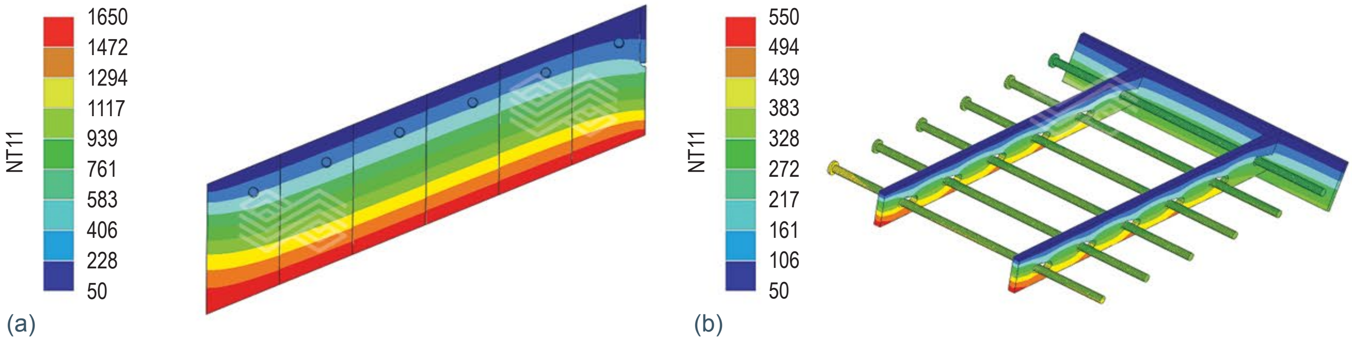


Figure 6.

Temperature distribution in °C of (a) the steel suspension and (b) the pins.

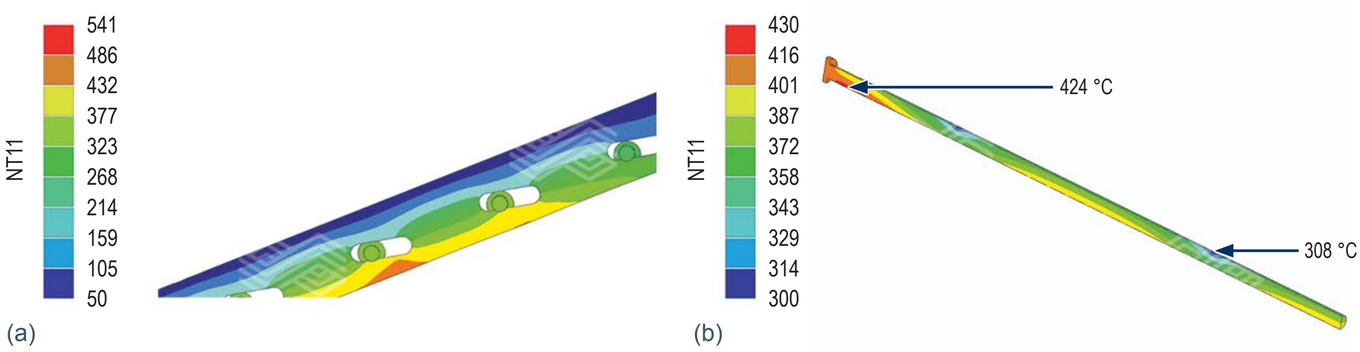


Figure 7.

Showing the Von Mises Stresses in the (a) frame and (b) pins due to static load in the uncompensated arrangement.

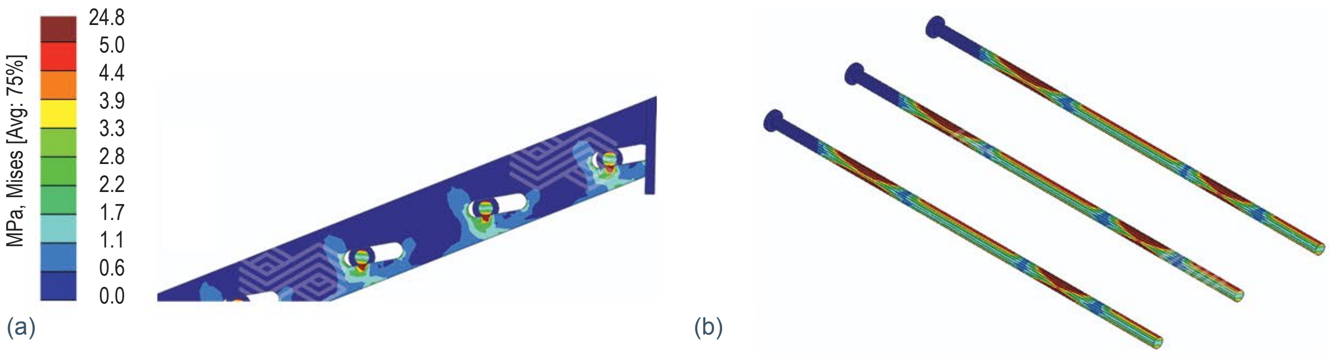
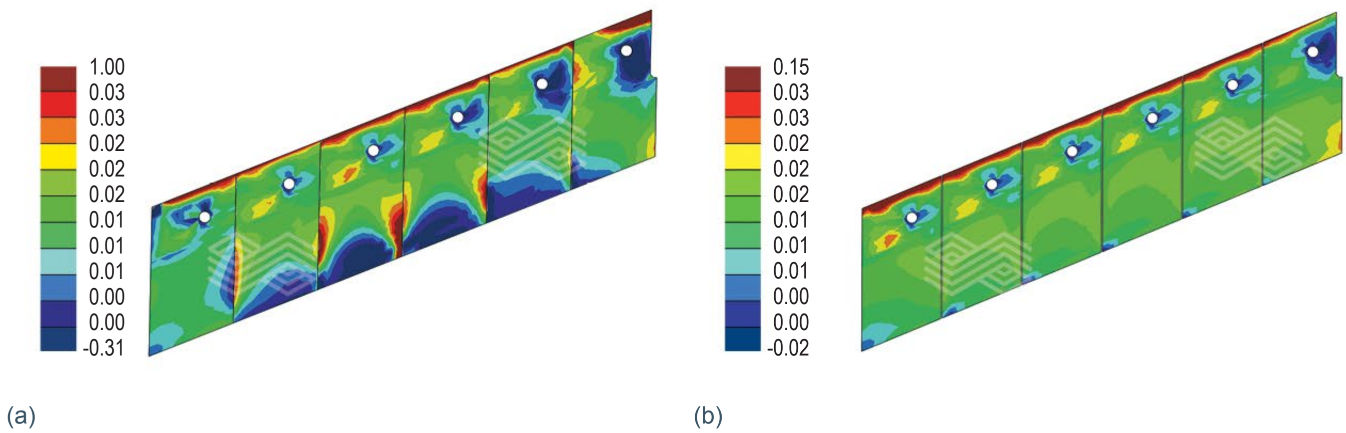


Figure 8.

Maximum principal stresses in the (a) nonexpansion compensated and (b) compensated arrangement.

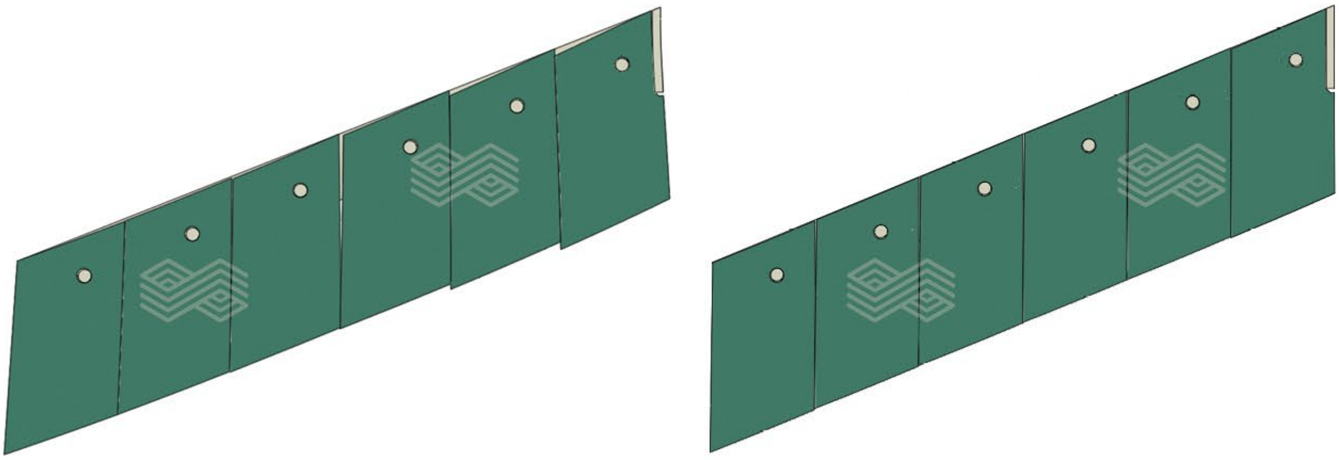


Conclusion

A virtual prototyping methodology based on FEM analysis was used for the design of a novel roof panel brick suspension system. The dimensions and final layout of the steel construction were established based on the simulation results for static and thermomechanical loads. The mechanical behaviour of the system under maximal thermal load was analysed. The difference in terms of stress and strain between the thermal expansion compensated and uncompensated layout was shown. By iterative numerical simulations an optimal definition of the thermal expansion clearance could be found avoiding cost extensive physical trial and error experiments. The working principle of the suspension system, which establishes an ideal heat transfer was proven via the simulation. Three panels have been installed for a trial phase in an electric arc furnace (Six-In-Line-Furnace) for the nonferrous metals industry and have confirmed the design approach.

Figure 9.

Deformation with a twofold scale factor in the (a) nonexpansion compensated and (b) compensated arrangement.



(a) (b)

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Katja Reinharter, Dean Gregurek, Christian Majcenovic, Jürgen Schmidl and Alfred Spanring

Influence of Arsenic on the Chemical Wear of Magnesia-Chromite Refractories in Copper Smelting Furnaces

Arsenic can be found in different sulfidic copper concentrates and residues, which for several years have commonly been used in copper metallurgy, as the "arsenic-free" resources are becoming rare. Due to the high toxicity the removal of arsenic in the copper smelting process is a very important topic. The typical chemical slag and sulphur attack on the refractory material is enhanced by the presence of arsenic. This work addresses with post-mortem investigations of a magnesia-chromite brick and castable used in copper smelting furnaces showing an additional and increased chemical attack by arsenic. The evidence on the wear behaviour is not only based on a detailed chemical and mineralogical characterisation, but also on thermochemical calculations, which are carried out on provided post-mortem samples.

Introduction

Due to the high demand of copper products, copper metallurgy increasingly has to deal with more complex copper containing ores with a lower amount of copper and a higher amount of minor elements. Arsenic can be found in mainly sulphidic copper/iron concentrates such as arsenopyrite (FeAsS) and enargite (Cu_3AsS_4). Typically, copper concentrates must not exceed a certain arsenic limit to be able to treat them without blending.

These increasing amounts of minor elements (As, Sb, Sn, Ni) will not only have metallurgical consequences but impact the interaction with refractory materials. In order to sustain the products quality (metal, slag, acid) the fractional distribution of these elements during the smelting process is a necessary prerequisite for a smelter to be able to deal with the increasing complexity of feed materials.

Influence and Removal of Arsenic in Copper Smelting Furnace

Arsenic compounds are often associated with copper and their removal during copper smelting is not straight forward. Depending on operating conditions and the type of reactor the partitioning of arsenic can be controlled in order to meet the requirements for product quality. Unintentional arsenic additions to the metal creates problems as it lowers the product purity and quality and additionally influences the viscosity, the surface tension, and the liquidus temperature of matte and copper metal in a negative way. Also the electrical conductivity decreases and the electrical resistivity increases due to arsenic impurity [1].

The most common solution today is blending, which means mixing "clean" and "dirty" concentrates to ensure a certain arsenic level in the smelter feed. For high As-bearing copper concentrates both, hydro and pyrometallurgical processes have been developed and are described in literature [2–5]. The most common used option for arsenic removal is the roasting process. Arsenic is transferred into gas phases, e.g., As-trioxide (As_2O_3) or As-trisulfide (As_2S_3) [2,3] and collected in the off-gas. The phases that form depends on the oxygen and sulphur partial pressure [6].

For example, roasting of high arsenic bearing concentrates: At 600 °C and defined oxidizing atmosphere decomposition of enargite (Cu_3AsS_4) under formation of Cu-sulphide, gaseous As2S3 and further on As_2O_3 takes place [4]:

$$2Cu_3AsS_{4(s)} \rightarrow As_2S_{3(g)} + 3Cu_2S_{(s)} + S2_{(g)} \quad (1)$$

$$As_2S_{3(g)} + 4.5O_{2(g)} \rightarrow As_2O_{3(g)} + 3SO_{2(g)} \quad (2)$$

As-trioxide is extremely volatile and sublimes at temperatures above 135 °C. This means that the off-gas has to be cooled to sufficiently low temperatures to ensure that most of the arsenic is condensed and can be collected. In an oxygen atmosphere it is likely that As-trioxide can oxidize to higher oxides like As_2O_5, which is less volatile and form stable nonvolatile arsenates with other metallic oxides [5]. Nevertheless, minor amounts of arsenic will always remain in the slag or matte. This is highly dependent on the furnace type and process conditions.

Post-Mortem Investigation

Magnesia-chromite brick

The analysed brick from the bath area of a copper smelting furnace had a residual thickness between 160 mm and 170 mm after eight months of operation. The original brick thickness was 450 mm. The immediate brick hot face was rough and covered with a thin slag coating. In the cross section a thick reaction zone and several cracks running parallel to the bricks hot face can be recognized (Figure 1a). The lower part of the refractory (approximately 40 mm from the cold face) broke off when removed from the furnace. On the fracture surface a yellowish-reddish coating was visible, which is indicative of arsenic bearing phases (Figure 1b).

Chemical Analysis

At the brick hot face within the area 0-15 mm an extremely high SiO_2 and Fe oxide content was determined. Additionally, slightly higher amounts of CaO and CuO were detected. The middle part of the refractory (85–100 mm) is enriched with SO_3, whereas at the cold face of the brick (140–155 mm) a high content of sulphur and arsenic (up to 1.4 wt.% As_2O_3) was determined. The arsenic content at the hot face and the middle part of the refractory is about 0.3 wt.%.

Mineralogical Investigation

For the mineralogical investigation polished sections from the hot face and the fracture surface of the brick were prepared (Figure 1). At the immediate brick hot face corrosion of the magnesia component with the formation of forsterite took place. Additionally, a phosphor and sulphur containing Mg-V-Ca-As-oxide was observed (Figure 2a). At the top of the fracture surface near the cold side a 3 mm thick layer consisting of As-oxide and As-sulphide was determined. Below this layer, a thin metallic arsenic layer (thickness of 0.03 mm) was formed. The brick microstructure below the As-containing layer was infiltrated with As-sulphide (up to 1 mm). Due to corrosion of the magnesia components by SiO_2 and As-oxide supply As-Mg-sulphate, Ca-Mg-silicate of type monticellite ($CaMgSiO_4$) and minor merwinite ($Ca_3Mg(SiO_4)_2$) were formed as main reaction products (Figures 2b and 2c).

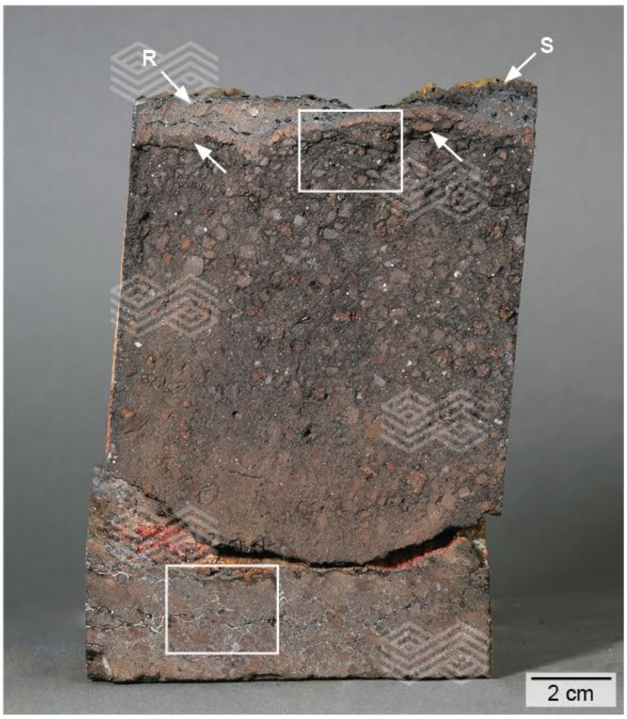
Table I.
Chemical analyses (semi-quantitative, without calibrating standard) of the magnesia-chromite brick from a copper smelting furnace (wt.%).

Sample	MgO [%]	Al_2O_3 [%]	SiO_2 [%]	SO_3 1) [%]	CaO [%]	TiO_2 [%]	Cr_2O_3 [%]	Fe_2O_3 2) [%]	CuO [%]	As_2O_3 3) [%]
Hot face (0-15 mm)	41	6	9	0.5	2	0.3	12	28	1	0.3
Middle part (85-100 mm)	59	5	1	2	1	0.2	19	12		0.3
Cold face (140-155 mm)	64	6	1	1	1	0.1	16	11		1.4

1) Sulphur calculated as SO_3
2) Total iron calculated as Fe_2O_3
3) Total arsenic calculated as As_2O_3

Figure 1.

Cross sectional view. Magnesia-chromite brick from a copper smelting furnace. (a) The immediate brick hot face is covered with a thin slag coating (S). In addition a thick reaction zone up to 10 mm is visible (R). Cracks running parallel to the hot face are observed (arrows). The lower part of the brick was completely broken. (b) On the fracture surface a yellowish-reddish coating is visible. Rectangle indicates location of polished sections.

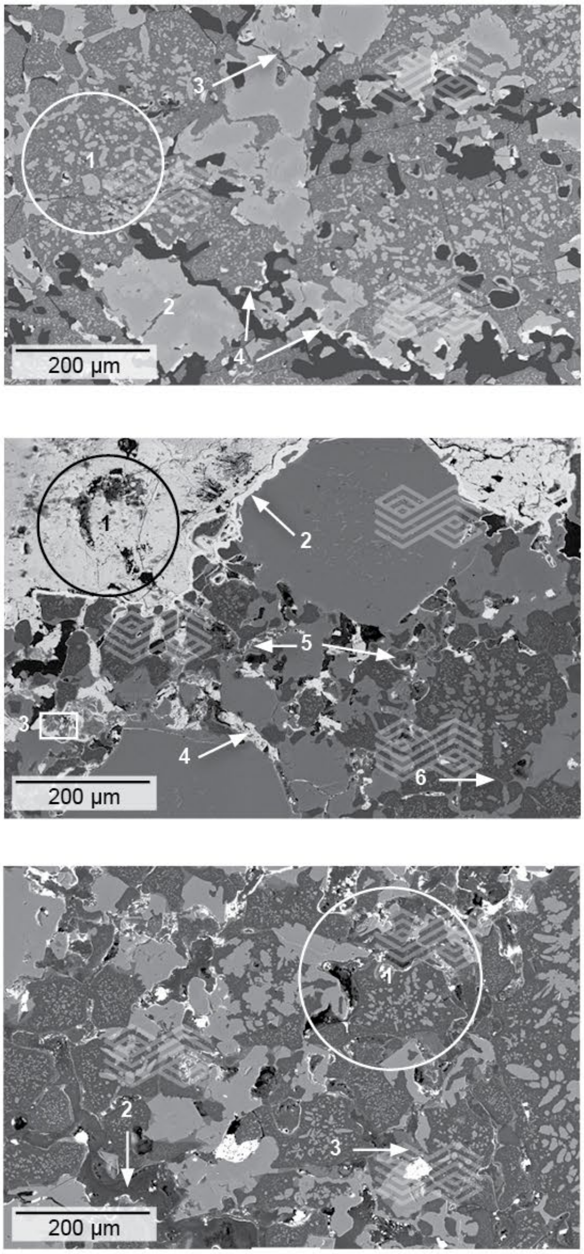


(a)

(b)

Figure 2.

Photomicrographs of the hot face and the fracture surface near the cold face. (a) Hot face: magnesia component (1), chromite (2), monticellite (3), phosphor and sulphur containing Mg-V-Ca-As-oxide (4). (b) Fracture surface near cold face: As-sulphide and As-oxide layer (1). As_{met} (2), mix analysis containing sulphur-rich Mg-Al-Cr-Fe- and As-oxide (3), infiltration of As-sulfide (4), new formed As-Mg-sulphate (5), monticellite (6). (c) 3 mm below fracture surface: magnesia component (1), As-Mg-sulphate (2), monticellite (3).



Magnesia-Chromite Castable

The magnesia-chromite castable from the upper area of a copper smelting furnace (6 weeks of operation) was completely degenerated (from hot face to the cold face). The residual thickness was approximately 170 mm. A crumbly surface was visible on the hot face. The sample is completely infiltrated (Figure 3).

Chemical Analysis

Chemical analysis was carried out on the hot and cold face of the sample. The hot face was highly enriched with PbO, arsenic, CuO, SiO_2, Sb_2O_3 and ZnO. The cold face was also enriched with lead, arsenic, and copper. The arsenic content is approximately 5 wt.%.

Mineralogical Investigation

Microscopically the castable was completely degenerated. A thick reaction layer was visible at the hot face. Predominately corrosion of magnesia and chromite could be detected (Figure 4a). There were two mechanisms of wear observed, corrosion and infiltration. The corrosion was observed mainly in the magnesia component due to SiO_2 supply with formation of forsterite (Mg_2SiO_4) and additionally the chromite component was strongly corroded and enriched with Cu-Zn-Ni-Fe-Sb- and Sn-oxide at the rims.

Figure 3.

Cross sectional view. Complete infiltration of the sample. Samples for chemical analysis (A) (B). Sample location for polished section (1).

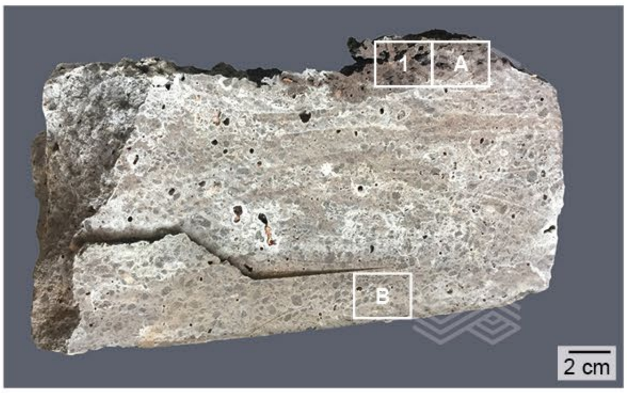


Table II.
Chemical analyses (semi-quantitative, without calibrating standard) of the magnesia-chromite castable from a copper smelting furnace (wt.%).

Sample	MgO [%]	Al_2O_3 [%]	SiO_2 [%]	SO_3 1) [%]	CaO [%]	Cr_2O_3 [%]	Fe_2O_3 2) [%]	ZnO [%]	CuO [%]	PbO [%]	As_2O_3 3) [%]	Sb_2O_3 [%]
Hot face (0-15 mm)	24.0	3.0	5.0	0.7	0.3	12.0	9.5	1.0	7.5	28.5	5.0	1.3
Cold face (160-170 mm)	22.0	3.0	3.0	0.2	1.0	14.0	10.0		2.0	39.0	4.6	0.4

1) Sulphur calculated as SO_3 2) Total iron calculated as Fe_2O_3 3) Total arsenic calculated as As_2O_3

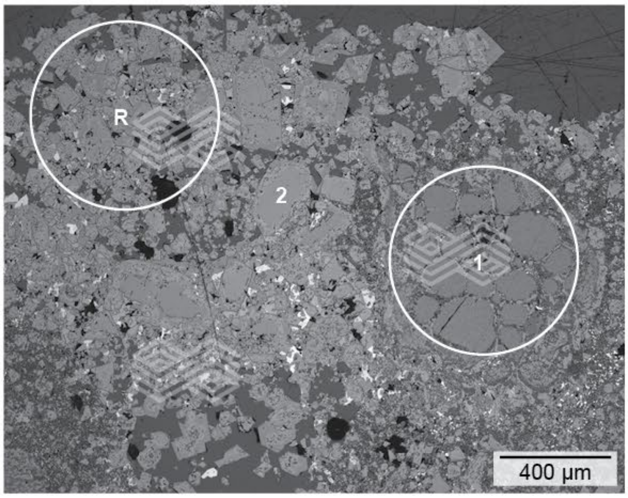
The infiltration aspect of the wear was observed up to the cold face, with Pb-arsenate of type $Pb_4As_2O_9$ and $Pb_8As_2O_{13}$ (Figure 4b). Cu oxide and Cu_{met} could also be detected up to the cold face.

Thermochemical Calculations

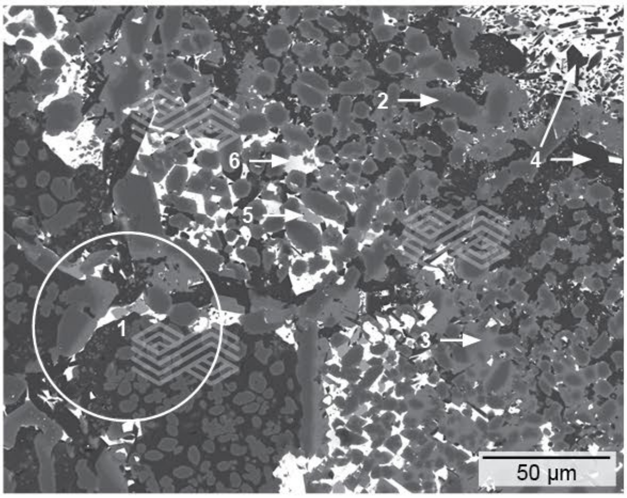
Arsenic corrosion mechanism can be presumed as comparable to the well-known sulphur corrosion [14]. In an oxidizing atmosphere (for example while matte blowing in a converter) As-sulphide will oxidize forming As-oxide and sulphur-oxide.

Figure 4.

(a) Immediate hot face. Reaction layer: corroded magnesia component (1), recrystallized chromite enriched with Cu-Zn-Ni-Fe-Sb- and Sn-oxide at the rims (2). (b) Corroded magnesia (1) and chromite (2) component. Chromite highly enriched with Cu-Zn-Ni-Fe-Sb- and Sn-oxide (3). Formation of a forsterite rich layer (4). Additionally forsterite crystals were found in the infiltrate. Cu oxide (5). $Pb_4As_2O_9$ and $Pb_8As_2O_{13}$ (6).



(a)



(b)

For example, when in contact with the refractory material, As-trioxide (As_2O_3) will react with the most basic components in the brick, in this case MgO and CaO, and form Mg/Ca-arsenate.

According to thermochemical calculations by FactSage™ the following phase reactions and reaction temperatures were calculated:

$$2As_2S_3 + 9O_2 \rightarrow 2\,As_2O_3 + 6SO_2\ (800\ °C) \qquad (3)$$
$$SO_2 + ½O_2 \leftrightarrow SO_3\ (> 760\ °C)$$

$$3MgO + As_2O_3 + O_2 \rightarrow Mg_3(AsO_4)_2\ (800\ °C) \qquad (4)$$
$$SO_3 + MgO \rightarrow MgSO_4\ (< 1050\ °C)$$

$$3CaO + As_2O_3 + O_2 \rightarrow Ca_3(AsO_4)_2\ (800\ °C) \qquad (5)$$
$$SO_3 + CaO \rightarrow CaSO_4$$

As described in the second post-mortem study As-oxide can react as As-pentoxide As_2O_5 with volatilized lead (PbO) in the off-gas. These phases become liquid > 640 °C depending on the As_2O_5 / PbO ratio (Figure 5).

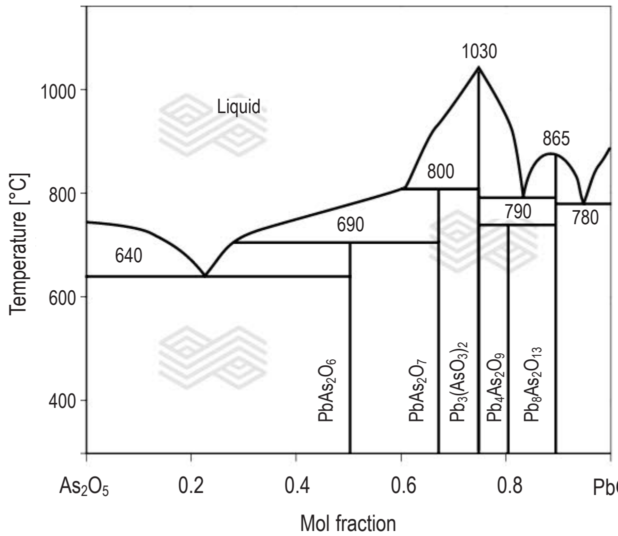
With help of the scanning electron microscope the PbO-As_2O_5 phases $Pb_8As_2O_{13}$ and $Pb_4As_2O_9$ have been detected. Following reactions can be assumed:

$$8PbO + As_2O_5 \rightarrow Pb_8As_2O_{13} \qquad (6)$$
$$4PbO + As_2O_5 \rightarrow Pb_4As_2O_9 \qquad (7)$$

The first liquid is formed at 790 °C considering $Pb_8As_2O_{13}$ and $Pb_4As_2O_9$.

Figure 5.

PbO-As_2O_5 phase diagram [7].



Conclusion

As the arsenic content in copper ores has become an increasingly important factor over the last years it is essential to know the influences of arsenic in the copper smelting process and its contribution to refractory wear. Post-mortem studies are especially important for recommendation of tailor-made materials for the specific customer requirements.

In addition to the typical chemical attack by SiO_2 and SO_3, the supply of arsenic is an additional factor negatively influencing lining wear and lifetime of the refractory material. Due to arsenic supply to refractory material, formation of arsenates (e.g., Mg/Ca-arsenates, Pb-arsenates) and, in presence of sulphur, As-sulphates (e.g., Mg-As-sulphate) can be observed at the post-mortem samples. These arsenic compounds in the zone of liquid metal and slag (for the brick) and off-gas area (for the castable) may have been caused by insufficient arsenic volatilization, as a result of process conditions that were not optimised.

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