FURNACE TAPPING 2022

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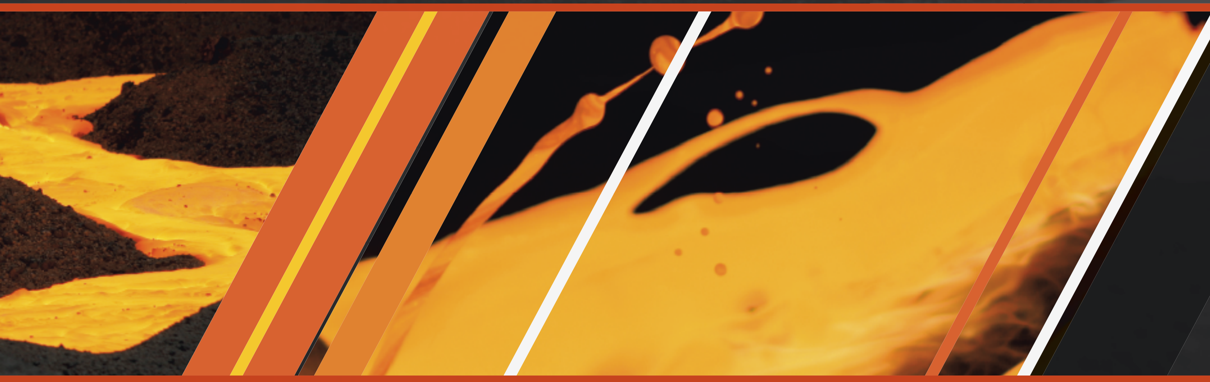

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Preface

It is my honor and privilege to present to you the proceedings of Furnace Tapping 2022, the third event in the series and the first time it has been co-hosted with the TMS Annual Meeting & Exhibition.

The proceedings is the culmination of the efforts of the authors, peer reviewers, organizing committee, and TMS staff. Firstly, I would like to thank the authors for sharing their perspectives on a problem common to most pyrometallurgical smelter operations, namely the tapping of furnaces. The strength of the Furnace Tapping conference series lies in the diversity of the perspectives shared: across commodities, across disciplines, and across business type.

Secondly, I want to thank the organizing committee for the enthusiastic participation in the committee meetings and their hard work behind the scenes, first to solicit abstracts and then to manage the peer-reviewing process. All the papers published in the conference proceedings were independently peer reviewed. The organizers either reviewed the papers themselves or drew on the expertise and insights of a number of specialists, from around the world, who generously offered constructive criticism and suggestions. We are grateful for the inputs from these expert reviewers

Lastly, the support of the TMS staff, in particular Trudi Dunlap and Patricia Warren, was outstanding.

At the time of writing, the organizing committee is still hoping for an in-person event. Only time will tell whether or not travel restrictions, imposed by countries due to the ongoing COVID-19 pandemic, will allow us to meet in person or require us to go online. Either way, I trust that you will enjoy the event and that the proceedings will serve the pyrometallurgical industry at large, taking the tapping of furnaces from an art to science and engineering.

Joalet D. Steenkamp
Lead Organizer

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About the Editors

Joalet D. Steenkamp is employed as a Technical Specialist in the Pyrometallurgy Division at Mintek, South Africa. Her research focus areas are Furnace Containment and Manganese Ferroalloys Production. She holds a Ph.D. in Metallurgical Engineering from the University of Pretoria and an appointment from the University of the Witwatersrand as Visiting Adjunct Professor. Joalet has 13 years of experience in the South African Industry/Private Sector (secondary steelmaking, ilmenite roasting and smelting, and manganese ferroalloy production) and 13 years in the Research/Public Sector. Dr Steenkamp has been a TMS member since 2009. At TMS, she has served on the Pyrometallurgy Committee since 2017, served on the Industrial Advisory Committee (2018–2021) for which she was the inaugural Chair (2018–2020), serves on the Extraction and Processing Division Council as a representative for the Professional Development Committee (2021–2023), and chairs the Organizing Committee for Furnace Tapping 2022. She is the founder of the Furnace Tapping Conference series for which she also chaired the Organizing Committees in 2014 and 2018 when the events were hosted by the Southern African Institute of Mining and Metallurgy in South Africa.

Dean Gregurek is a senior mineralogist in the RHI Magnesita Technology Center Leoben, Austria since 2001. Dr. Gregurek received his M.Sc. degree at the University of Graz in 1995 and his doctorate degree in Applied Mineralogy from the University of Leoben in 1999. Prior to RHI Magnesita, he worked for two years for Luzenac Europe in talc business. His current research interests and technical expertise are focused on chemical and mineralogical studies related to interactions between refractories, molten metals, and slags from pyrometallurgical furnaces. Dr. Gregurek has been a TMS member since 2012, *JOM* advisor (2014–2017), chair of the Pyrometallurgy Committee (2018–2020), and a co-organizer for the 7th–12th International Symposium on High-Temperature Metallurgical Processing (TMS Annual Meetings 2016–2021) and Furnace Tapping (TMS Annual Meetings 2022).

Quinn G. Reynolds holds an undergraduate degree in Chemical Engineering from the University of Kwazulu-Natal, a Masters in Engineering from the University of the Witwatersrand, and a Ph.D. in Applied Mathematics from the University of Cape Town. He has worked in the Pyrometallurgy Division at Mintek for the past 23 years. Mintek is a research institute conducting applied research and development to serve the extensive mineral processing and metallurgical industry in South Africa and worldwide.

Dr. Reynolds' expertise includes mathematical and computational modelling of complex coupled phenomena in high temperature processes and in particular the application of high-performance computing and open-source modelling software to pyrometallurgy. His current areas of research include magnetohydrodynamic modelling of electric arcs, multiphysics fluid flow problems in furnace tapping and phase separation, combustion modelling for metallurgical processing, and discrete element modelling for particle flow problems. He has also performed extensive work in the characterization of the dynamic behavior of direct-current plasma arcs using high-speed photography and electrical measurement techniques.

Gerardo Alvear Flores is a Chemical Engineer with a Doctor of Engineering degree in Materials Science and Processing. He has over 25 years of experience in non-ferrous metallurgy, with a focus in extractive metallurgy of copper, lead, zinc, and nickel and multi metal recovery.

Dr. Alvear initiated his carrier in the academic field in Chile. In 1990 he was awarded by the Japanese government with the Monbusho Ministry of Education scholarship to continue his education as a graduate student at Nagoya University, receiving his D.Eng. in Materials Science and Engineering in 1995.

In 1995 he joined NGK Metals in Japan for one year as a Post-Doctoral Fellow. After returning to Chile to work for Enami's Las Ventanas smelter in 1996, he joined the Research Centre for Advanced Waste and Emission Management in Japan, to work as assistant professor, with a special focus in pyrometallurgical processing of copper containing materials.

In 1999, he joined Codelco's Institute for Innovation in Mining and Metallurgy, where he worked as senior researcher, project manager, and finally as technology program leader to develop technical solutions to Codelco's copper smelters.

In 2005, he joined Xstrata technology (now, Glencore Technology) working in several roles until 2016, supporting the development and implementation of ISASMELT technology.

In 2016, he joined Aurubis as Executive Director Research, Development and Innovation supporting the development of Aurubis's multi-metal strategy.

In January 2021 he was appointed Adjunct Professor of the University of Queensland and joined Rio Tinto Singapore Holdings as Technical Marketing Manager for Copper.

Dr. Alvear Flores is an active member of professional societies in Canada and the US and is a member of the Copper Conference International Organizing Board. Dr. Alvear Flores has been selected by TMS as Co-Chairman of Copper 2025.

Hugo Joubert is a Mechanical Engineer with 28 years of furnace and smelter design experience. Working in numerous roles in production, technical development, business development, and management, Joubert specializes in furnace equipment design and solution development. He started his career as a plant engineer on iron blast furnaces in South Africa and completed his master's degree in 1998 on furnace lining/cooling system design including the use of Computational Fluid Dynamics. He first joined Tenova Pyromet in 1998 as a Design Engineer and, following a stint with Glencore Technology as Engineering Manager, rejoined Tenova Pyromet in 2015. His experience includes electric furnace as well as top submerged lance furnace technology.

Phillip J. Mackey obtained his B.Sc. (Honors) and Ph.D. degrees from the School of Metallurgy at the University of New South Wales, Australia. He then moved to Montreal, Canada to join Noranda to work on a new copper smelting process. As Pilot Plant Supervisor, Dr. Mackey helped develop the Noranda Process, which was first implemented at the Horne smelter in the early 1970s. Here he first learned the art and technique of tapping a high temperature melt—blister copper, copper matte, and slag. The Noranda Process, one of the most important copper smelting technologies of the twentieth century, also achieved early success in the United States, Australia, and China. Dr. Mackey was later instrumental in developing the Noranda Converting Process, of which he is a co-inventor, and which was installed at the Horne smelter in the late 1990s providing enhanced environmental performance.

At Noranda and Falconbridge, he was involved with other initiatives, including new developments for processing nickel laterites and concluding technology agreements with other nations, notably Chile. He conducted due diligence studies on a range of projects around the world.

He later formed his own consulting company, and this has led to a range of projects worldwide, including work on the development of a new nickel laterite project in Brazil.

He is a co-founder of the Copper-Cobre conferences, which expanded from a joint Canadian-Chilean enterprise to embrace the entire global industry. Dr. Mackey is on the Board of Hazen Research of Denver, USA. A Past-President of Metsoc of CIM and a Fellow of CIM and TMS, Dr. Mackey has authored or co-authored more than 100 technical papers covering diverse aspects of non-ferrous metallurgy. His CIM Awards include the Silver Medal, a Special Medal of Honour, the Selwyn G. Blaylock Medal, and the prestigious Airey Award for "outstanding contributions" to the field of extractive metallurgy. The Phillip Mackey Symposium was held in his honor at the 2019 Copper Conference in Vancouver. He presented the TMS EPD Distinguished Lecture in 2020 and received the John Elliott Lectureship Award of the Association for Iron and Steel Technology for 2021–2022. He will be inducted into the Canadian Mining Hall of Fame in 2022.

Part I
Session I

Controlled Tapping—The Research Project

Merete Tangstad, Michal Ksiazek, Jan Erik Olsen, Quinn Reynolds, and Eli Ringdalen

Abstract Controlled Tapping is a research project funded by the Norwegian Research Council and the Norwegian silicon and ferroalloy industry. The overall goal of the industry is to minimize the amount of uneven tappings and thus to reduce the energy consumption and the risk of hazardous events. In addition, the gassing, in the silicon industry, and the slag/metal separation in the ferroalloy industry, is a concern. The project Controlled Tapping will give fundamental and industrial knowledge to the industry, so these concerns can be addressed. The project focus is how the furnace interior, that is the furnace operation, is affecting the tapping. Tapping is an experience based sub-process that is developed over time at the various plants. To expand the knowledge into the scientific world, numerical modelling is a valuable tool and is the basis in the project. This has been done in SINTEF, NTNU in cooperation with Mintek. A variety of models have been developed calculating the tapping rate. Models describing the whole furnace with accumulated materials, e.g. TiC banks in the SiMn furnace, models that describes the slag metal separation in cascade tapping with various ladle positions, and models describing the tapping where the slag and metal properties are changed, has been developed. For a models to give the true picture, realistic input data is needed, and one of the Ph.D. projects has been to measure the interfacial tension between slag and metal in Mn-ferroalloy production. We also need to know the mechanisms affecting the tapping of industrial furnaces and on the consequences if furnaces accumulate metal and slag. Both industrial campaigns and investigations on mechanisms and material at the lab has been conducted. The industrial campaigns have been to excavate both Mn-ferroalloy and Si furnaces, to find that the tapped silicon is above 1800 °C when all literature says 1600 °C, to see the variances of the metal and slag during a tapping-cycle and over a year and investigating the energy in the gassing. In lab scale, the formation of

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TiC banks in the SiMn furnaces, the formation of slag, and the formation of SiO gas in Si furnaces and the pressure build up in charges by fines, have been investigated.

Keywords Tapping · Furnace excavations · Modelling · Mn-ferroalloy production · Si/FeSi production

Introduction

The Norwegian production of ferroalloys and silicon takes place in submerged arc furnaces. From these furnaces, up to 450 tons/day of metal is being tapped in liquid state at high temperatures, from 1400 to 1700 °C. In addition to the liquid metal, also liquid slag and furnace gas will follow the metal. Some producers tap their furnace continuously, like some of the silicon producers, and others tap the furnaces discontinuously, by closing and opening the tap-hole on a regular basis, e.g. every other hour. In the ideal case, the metal and slag will be tapped in the same rate as it is produced, it will be tapped in a controlled and steady mode and no furnace gas will exit the tap-hole. In the real world, there are a number of challenges when it comes to tapping.

Uneven drainage from furnace is often one of the major challenges. With unstable tapping, metal and slag may accumulate in the furnace and lead to variation of flow as well as variations in metal chemistry and back reactions inside the furnace. Large tappings will lead to disturbance of furnace operation and logistics, safety issues and diffuse emissions. In worst case the furnace load must be decreased, and this will hence have a major effect on production rate and cost. Back reactions lead to losses in yield and reduced production of metal.

Gassing from tap-hole is another challenge, maybe more detrimental in the high-temperature Si/FeSi process. In the silicon production, SiO/CO gas may exit the tap-hole at 2000 °C. First, this constitutes a serious safety risk for operators, as the operators may be exposed to the heat and dust. Next, it will lead to a lower silicon yield and loss of energy. Finally, it will lead to an increased maintenance cost on tapping equipment due to heat load and dust.

Slag and metal separation is a typical KPI in the slag producing processes. Slag droplets may be trapped in the metal, deteriorating the quality of the metal, and metal may be trapped in the slag, leading to a low metal yield and hence a higher energy consumption. The extent of these phenomenon is affected by the tapping process and the properties of the metal and, especially, the slag during the tapping process.

Physical geometry of the tap-hole will also affect the stability of the tappings. As the tap-hole is changing over time with increased wear followed by maintenance work, the geometry of the tap-hole will thus change both continuously and discontinuously, and thus effecting the above mentioned points.

The challenges described above are a result of the furnace operation, the geometry of the tap-hole and the tap-hole area, and the tapping process itself. The furnace operation and the tapping process are based on long-time experience in the industry.

The furnace operation has been summarized in textbooks [1–4] and the geometry close to the tap-hole have been investigated and reviewed in [5, 6] scientific studies. This project is however focusing on the interaction between the furnace state and its effect on tapping. Important input is of course the materials and zones in the furnace. This has previously been published for some industrial furnace excavations [7–11]. It is seen that zones in the furnaces will be different from furnace to furnace even with the same product, and hence more industrial excavations are necessary.

The basis for the tapping of the furnaces is a fluid flow phenomenon, and hence *numerical modelling* of fluid flow is one of the three platforms in the project. Some modelling on the whole furnace has previously been done, however, in the previous work the interior of the furnace are assumed ideal, with simplified zones [12–14]. The Controlled Tapping project are hence developing models both for sub-processes and for the entire furnace. There are however quite a lot of knowledge needed to input the model work, from phenomenon describing the model framework to boundary conditions to physical properties and reaction rates of the fluids involved. The other two parts of the project is hence *physical model* and *industrial data*. This paper will hence describe some of the work done in the *numerical modelling part*, the *physical model* as well as the *industrial data*.

For the industry the access of good students is essential, and recruitment is hence an important part of the project. Both B.Sc., M.Sc. and Ph.D. students are hence working in the project. Of the students finished so far, five of totally six of the B.Sc. and M.Sc. students have been employed by the project partners.

To seek the highest possible quality on the scientific work internationalization is essential, and the Norwegian partners NTNU and SINTEF have been not only working closely with especially MINTEK (South Africa) but also the University of Reykjavik (Iceland) and the University of Science and Technology Beijing (China) in this project. The dissemination through scientific journals and conferences are also important and so far 18 papers have been published [15–42] in addition to internal reports. It has also been focused on a "conceptual model" which described the main features affecting the tapping. This model is a simple model, where the main features may be transferred to both management and operators. An attempt to discuss the tapping in the Si/FeSi process on an overview level is shown in the publication "Conceptual model of tapping mechanisms in a FeSi/Si furnaces" at Infacon 2021 [35] (Fig. 1).

Modelling Concept and Implications to Tapping

In the Controlled Tapping project, two modelling techniques have been pursued: multiphase computational fluid dynamics (CFD) with interface tracking and reduced order modelling (ROM). The latter offers much shorter computational times, but the models are based on more assumptions and empirical correlations. When studying

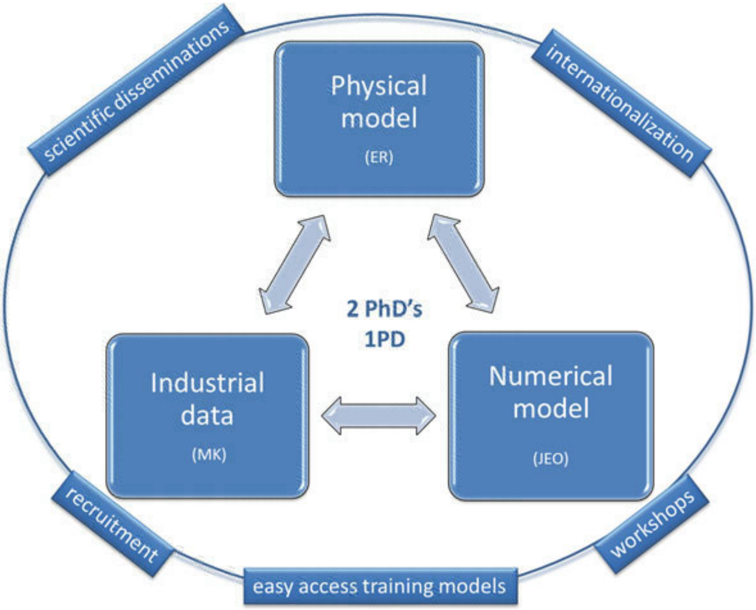

Fig. 1 Work packages of the controlled tapping process, also showing the focus on internationalization, recruitment and various dissemination levels

drainage of furnaces, both modelling concepts need to account for the flow resistance provided by the particle bed in the furnace. The modelling concept have been validated against drainage experiments with particle beds.

From basic physics (e.g., Bernoulli's equation) and earlier work, we know that the furnaces are drained by the hydrostatic pressure. The driving mechanism is gravity which increase with increasing density and level of the liquid being drained. In some furnaces, the gas pressure is also driving the drainage. The drag from the particle bed on the metal and slag reduces the driving force and the tapping rate. In the project a more accurate term for the pressure loss due to the particle bed has been introduced compared to earlier work. It has also been shown that the tapping rate is very sensitive to the particle configuration close to the tap-hole. This indicates that small variations due to closing and opening of tap-holes can cause variations in tapping rates.

Accumulated TiC-Banks in the SiMn Furnaces

Two SiMn furnaces were excavated where in the project FerroGlobe 2017 [29] and Kvinesdal 2020 [38]. They can be compared with the previous excavation in Elkem Sauda [11]. In addition to the observations in the active zones, that is the prereduction and the coke bed-zone, inactive banks containing carbides were observed in the

Ferroglobe furnace (Fig. 2) and one of the Kvinesdal furnaces. Of special interest was the observation of TiC in the banks, and though the Ti content was very low in the charge (<1%), the Ti was measured up to 12% in the bank material. As Fig. 3 shows, the sample was mainly containing slag, metal, and graphite precipitations in addition to the carbide.

The presence of inactive banks in the furnace will affect the tapping conditions as well as well as leaving less room for reduction work, and in general affect the energy and mass flows in the furnace. The formation of TiC and also the removal of carbides in the furnace is hence an interesting question. The stability of TiC in

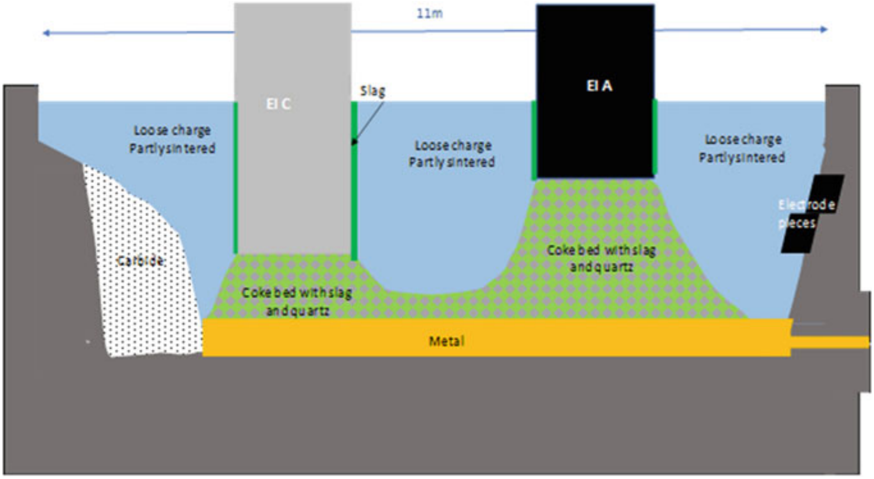

Fig. 2 Zones in the excavation of a furnace at Glencore Norway in 2017 (27.5 MW, 16% Si)

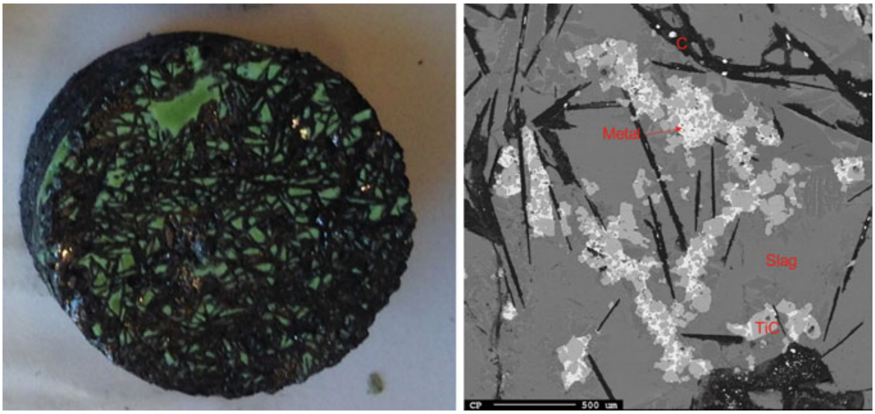

Fig. 3 Carbide banks containing 12%Ti is mixture of slag, metal, graphite, and TiC

the slag/metal/C SiMn system has hence been investigated both through lab-scale investigations and thermodynamic calculations [42].

The presence of banks in slag producing processes has also been modelled by CFD [41]. The results show that in principle all metal and slag produced around all electrodes are drained from the furnace if sufficient time for tapping is allowed. At the beginning of a tap, most of the products leaving the tap-hole emanate from the zone around the electrode close to the tap-hole, whereas towards the end of the tap most products emanate from the back electrodes. The products leaving from the back electrodes will thus have some longer residence time in the furnace. Normally, tapping is stopped somewhat before all slag and metal is drained. It is therefore expected that more products from the back electrodes are accumulated in the furnace than from the electrode close to the tap-hole.

Slag/Metal Separation in the Mn-Ferroalloy Processes

In all processes, the slag/metal separation is an important Key Performance Indicator affecting the productivity and hence the cost and environmental aspects. The slag/metal separation has in this project been investigated with various numerical models. One of the parameters affecting the slag/metal separation, that has not been well known, is the interfacial tension between the slag and the metal. The interfacial tension will affect the terminal velocity of metal droplets in the slag. One of the two Ph.D. candidates in the project is hence focusing on determining the interfacial tension experimentally between slag and metal, and some examples can be seen in Fig. 4. This is experimentally not trivial and new methods has been developed combining experimental and modelling work.

For studies on how to reduce metal loss in cascade tapping a multiphase CFD model was developed, and case studies performed [19]. This is illustrated in Fig. 5.

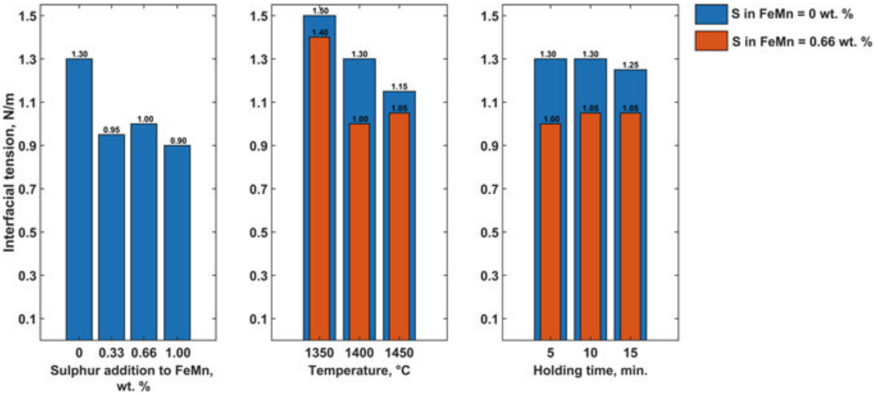

Fig. 4 Examples of interfacial tension as a function of temperature and S-content [16, 17]

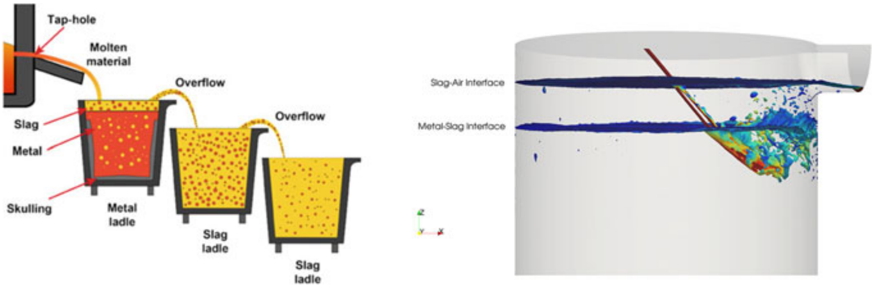

Fig. 5 Illustration of cascade tapping (left) and example of CFD results (right) for fluid interfaces colored by velocity

The amount of metal carried over from the metal ladle to the other ladles in the cascade during tapping of FeMn was extracted from the simulation data. Maintaining a significant thickness of slag layer on top of the metal layer reduced the quantity of metal entrained in the overflow stream from the metal ladle. Adjusting the position and layout of the ladles in the cascade was also seen to reduce metal losses. The density and viscosity of the tapped materials had a stronger impact on the results than surface tension, due to the momentum-dominated nature of the bulk flow in tapping streams and ladles. Although surface tension had no significant impact on cascade tapping, it is expected to have an impact on post-tapping slag/metal separation where settling and coalescence dynamics govern the separation.

Slag in Si/FeSi Furnaces

The Si and FeSi process is often referred to as a slag-free process, as the main impurities in the raw materials, Al and Ca, is dissolved in the metal tapped in about equal amounts. During previous excavations [7–9] and excavations done in this project [21], it is however seen large amounts of slag as accumulated in the furnaces, especially in the bottom of the furnace and in the periphery along the lining, sometimes from the bottom to the charge top. This will in the same manner as other high viscosity materials affect the mass flow in the furnace, and hence the tapping. In Fig. 6 one can see how the tapping channel is enveloped in a wide slag layer. This layer also contains SiC particles that adds to the viscosity.

The slag in the FeSi/Si furnaces contains about equal parts of CaO, Al_2O_3 and SiO_2. The CaO/Al_2O_3 ratio will however be dependent on the raw materials used, and the SiO_2 may vary from 40% and up. This means that the liquidus is typically around 1400–1500 °C and solidus 1100–1200 °C. As the high temperature area in the Si/FeSi furnaces are from 1800 to 2000 °C, it is also believed that the main part of the slag may be liquid/semi-liquid, except from very close to the lining. It is seen that the slag tapped from the furnace are close to the accumulated slag, and also that

Fig. 6 Tapping channel of silicon through a more than 1 m wide slag layer

the slag behind the various tap-holes are quite similar. As the slag from the furnace is not typically sampled, special equipment was made to sample this slag.

In FeSi production, the iron source may be metallic or oxidic. During experimental work, the iron is always reduced to metallic iron, long before the quartz melts above 1700 °C, and hence in experimental work FeO is typically not present in the slag phase. Industrially, it is however seen that $FeO–SiO_2$ slag is found on the charge top [36], and this is believed to be the case if there are very high temperatures high up in the charge, and so the iron oxide has not had time to be reduced before it dissolves the quartz, producing a liquid slag.

Temperatures and Heat Loss of Tapped Metal (Si/FeSi)

One of the large variables in understanding the process, as well as in fluid flow calculations, is the temperature. As the temperature in the ladle is typically measured to 1500–1600 °C, this is also the temperature that has been reported to be the tapping temperature. In this project the temperature close to the tap-hole has been measured for a semi-continues tapping at a FeSi furnace and continues tapping at a Si furnace [24]. The temperature from the tap-hole is seen to be above 1800–1900 °C, where the highest temperature is seen for the non-continues tappings (FeSi) and may be due to the higher flow rate. It is also seen that the composition may vary a bit during the tapping, especially in the beginning, and hence samples for analyses should not be taken to early after opening the tap-hole. The difference between the temperature out of the tap-hole and the ladle, which is the order of 100–300 K, has also been modelled and can be explained with radiation and conductive losses into the runner and ladle [29].

Quartz: Impurities, Melting, Fines- and SiO-Formation

As quartz/quartzite is the main raw material in Si/FeSi processes, several aspects of the raw material have been investigated. As previously seen [43], it is also here seen that the softening and melting of quartz may vary with 100 K and at a constant temperature at 1750 °C the melting may take between 20 and 80 min depending on the quartz type. With heating, the impurity phases will also change. The initial main impurities are CaO, Al_2O_3 phases and it is seen that with heating the impurity phases will start to dissolve SiO_2. When the temperature is 1800 °C it will be more than 75% SiO_2 in the impurity phases, and hence compared to the slag in the lower part of the furnace, the impurity phases will hence be reduced again wither to SiO gas or directly to silicon.

The fines formation of quartz has been investigated previously by among others Jusnes [44]. In this project, the crack formation during heating was investigated together with USTB (China) in a high-temperature confocal microscope. Crack formation in the quartz during heating to 1600 °C mainly happens at two temperature intervals, ~300–600 °C and ~1300–1600 °C and is mostly due to volume changes in the sample. The cracks occur from impurity areas, expanding grain boundaries, damaged or uneven surface and in some cases from the cavities from the escaped fluid inclusions. It can however be mentioned that not all crack formation leads to higher fines production [20].

In furnaces where tapping is hindered and an accumulation of Si/FeSi happens, a higher SiO-loss is experienced industrially. The rate of the SiO production from Si and quartz ($SiO_2 + Si = 2SiO(g)$) was experimentally determined and modelled for a number of various commercial quartz types. No difference was however found between the quartz types, even at both high and low impurity concentrations [30].

Present Activities

Though several of the above-mentioned activities will finish by the end of 2021, the activities of gassing during tapping in the Si-furnace and excavation of a HC FeMn furnace will also be investigated before the project end.

Summary

Controlled tapping is a 5-year project funded by the Norwegian ferroalloy and silicon industry and the Norwegian Research Council. The main focus is to get more knowledge regarding the fundamental aspects of the tapping process, as a basis for the industry to reduce the amount of uneven tappings. Industrial campaigns and physical laboratory work set the input to numerical sub-models, describing the various features of the tapping process. The project is a cooperation between the Norwegian industry, the Norwegian University of Science and Technology, SINTEF (Norway), and Mintek (South Africa).

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MIRS Robotic Tapping and Plugging of Non-ferrous Smelting Furnaces

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Abstract The tapping operation of a metal, matte, or slag at a non-ferrous smelting furnace has a number of common aspects from one facility to another. In simple terms, the tap-hole initially requires the safe opening, the molten phase is allowed to flow through the tap-hole, and then the tap-hole needs to be safely closed. Until now, tapping in non-ferrous smelting operations is largely performed by an operator. Safe operations around the tap-hole require proper process control of the smelting furnaces, the proper tap-hole design for the required duty, and high-quality, robust tapping equipment. The present paper describes the successful development of a robotic system for automating the slag tapping operation at a full commercial scale on a large copper flash furnace. The development of this robotic tapping machine is described, and the operating features and performance are discussed.

Keywords Robot · Automation · Mining · Furnace · Smelter · Tapping · Lancing · Plugging · Mud gun · Tap-hole · MIRS

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Introduction

Throughout the world, the metallurgical industry is in the process of transforming the way plants are designed and operated. A number of changes have prompted this trend, including responses to climate change and global warming, cost reduction, and improved safety at plants; higher computing power and connectivity and automation technologies; and the shift in metal demand—and also production—from west to east. It has been stated that the trend to the so-called "smart automation" is part of the fourth-generation industrial revolution which is also referred to as "Industry 4.0" [1]. Briefly, it is generally considered that the first generation was motive power production (initially steam, later electricity) along with early mechanical machines (mid-end 1800s), the second was wide-scale industrialization (most of the twentieth century), the third was the beginnings of automation and digitalization, and now, the fourth—as stated above—smart automation through connectivity. Most mining and metallurgical companies are embracing this transformative trend.

Furnace tapping is a critical step in the operation of all pyrometallurgical processes involving molten phases—both the tap-hole design and operation are vitally important. As companies embark on new stages of transformation, automation of operating processes at the non-ferrous smelter is anticipated, including the steps of concentrate feeding and furnace tapping, which typically involves manual operation in fairly high-risk plant areas.

Virtually all non-ferrous pyrometallurgical furnaces today rely on manually operated tapping machines—some remotely operated—for tap-hole opening and closing. Combining the unrivalled quality and performance of foundry model industrial robots and the technological skills at MIRS, the company has pioneered the successful development of a new robotic tapping and plugging machine. This paper briefly describes the development of the world's first robotic furnace tapping machine for non-ferrous furnaces. The paper then describes the successful commercial operation of this tapping equipment for slag tapping at the flash furnace at the large Chuquicamata copper smelter in Chile. The installation is described together with operational results.

The History of MIRS

In 2001, MIRS's parent company, HighService Corporation, entered into a commercial and technological agreement with KUKA Roboter to begin the development of robotic applications for the mining industry. After the successful implementation of several industrial robotic solutions, MIRS was founded in 2007 to provide robotic solutions to the global mining industry. MIRS provides conceptual development, design engineering, manufacturing, integration, and support services for state-of-the-art robotic solutions and has developed applications for mines, concentrators, tank houses, smelters, and refineries. The applications are specially designed to withstand the harsh environments associated with heavy industrial operations, including acid environments, extreme high temperature and high-altitude conditions, severe vibration, and highly dusty conditions. They also cover a broad range of industrial processes and are aimed at providing the following benefits:

- Lowering operating costs.
- Increasing plant availability and lowering maintenance costs.
- Increasing process reliability.
- Improving occupational health and safety aspects and reducing risks to personnel.

Development of the MIRS Robotic Tapping Machine and Testing at Chuquicamata

The Chuquicamata Smelter

Chile produced 5.73 million tonnes of copper in 2020 and is the world's largest copper-producing country, representing some 32% of the world's mined copper. About one-third of Chilean mined copper is smelted at one of the country's seven smelters. The Chuquicamata smelter, part of the largest mine-smelter complexes in Chile operated by Codelco, began operations in 1953 based on reverberatory furnace smelting with a capacity of about 145,000 tonnes of copper per year. The plant has undergone numerous expansions and improvements since that time. The following is a brief outline and is included in part here to illustrate the progressive changes and improvements at the smelter.

Oxy-fuel burners were introduced in 1979 on the reverberatory furnaces, and a moderate-sized El Teniente converter for smelting was built in 1984 (and replaced by a much larger El Teniente unit in 1993). In 1988, an Outokumpu flash furnace was commissioned. In 2004, HighService entered discussions with Chuquicamata for consideration of robotic tapping at the smelter. It is noted that by 2018 following the initial tapping trials as discussed below, Codelco undertook further changes at the Chuquicamata smelter which necessitated several plant shutdowns. These ongoing changes would, also as discussed below, impact the sequencing of the robotic tapping trials. The plant changes Codelco introduced starting about 2018 included closing the El Teniente converter and expanding the capacity of the flash furnace (by enlarging the physical size of the reaction shaft) to maintain smelting capacity and yet meet the D28 environmental regulations [2].

In 2004, Codelco entered into an agreement with HighService to begin the development of a robotic tapping machine. In 2007, the world's first robotic tapping and plugging system was installed and used on a slag tap-hole at Chuquicamata flash furnace. In 2008, a jackhammer tool was developed and in 2009 this tool was added to the robotic system.

Initial Test Work—Development of Tap-Hole Lancing and Plugging Systems

Starting in 2004, laboratory test work began on the development of the system and the associated tools. The work included testing all the individual steps involved in the tap-hole opening and closing operations. Some of the tests were carried out on a specially constructed "pilot" rig before initiating the work at the smelter. In 2007, when the on-site program at Chuquicamata commenced, the typical slag composition and conditions of the tapping operation were as follows (Table 1).

Table 1 2007 Slag condition and composition

2007 flash furnace Slag conditions	
Condition	Details
Tapping method	Manual lancing with hollow 14 mm outer diameter lance and occasional 25 mm solid bar, no machine
Plugging method	Manual with clay cone, no machine
Cu Conc	Up to 3,000 tpd (nominal)
Slag	1,220–1,575 tpd
Shift schedule	Three, 8-h shifts
Slag tap temp	1250–1330 °C
Length of tap-hole[a]	700 mm
Number of slag tap-holes used	4, each one ~150 mm
Approximate slag tonnage/tap	30–40 tonnes
Approximate number of taps/day	35–45
Opening time for slag tap-hole	10 min for the first tap, 1 min for successive taps during shift

2007 Typical flash furnace Slag composition	
Component	Assay range, wt%
Cu	1.5–2.5%
Fe	37.5–45.5%
Fe_3O_4	10.0–25.0%
Zn	1.0–5.0%
S	0.5–1.5%
SiO_2	28.0–35.0%
CaO	0.8–2.0%

[a] The horizontal length from the faceplate to the inside of the wall of the furnace, refer to Fig. 1