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OPTIMIZATION OF SECONDARY METALLURGY WITH RESPECT TO NON-METALLIC INCLUSIONS

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Summary

The project JK 23045, "*Optimization of secondary metallurgy with respect to non-metallic inclusions for improved steel properties and production efficiency – focus on special and high alloyed steel production*", belongs to the Strategic Steel Research Programme for Sweden 2007-2012 jointly funded by VINNOVA and Jernkontoret. The project has been carried out as a close collaboration between Swerea MEFOS, Division of Applied Process Metallurgy and Division of Micro Modelling at KTH, Royal Institute of Technology. This report is an overview of performed work. The technical reports that each section is based on are given in the included footnotes.

Steel cleanliness is a focal point for Swedish steel industry in order to maintain as well as strengthen their global competitiveness. In the production of clean steel it is most important to combine a low amount of impurities with a minimization of the formation of non-metallic inclusions as well as an enhanced transport of inclusions to the slag phase.
The primary objective of the project has been to define operating practices of secondary metallurgy towards improving the steel cleanness during steel production. As an outcome of this research, substantial measures to improve product quality have been implemented. The industrial benefits are

- **Improved steel quality**: Improved inclusion removal by optimization of operating practice enhancing product quality.
- **Higher productivity**: Optimal stirring improving steel cleanliness and shortening process times in secondary steelmaking.

This has been achieved through a deep investigation on how different process parameters affect the impurity element levels as well as the amount and size distribution of non-metallic inclusions (NMI) during secondary metallurgy. The mechanisms for formation and removal of NMI have been investigated with experimental as well as modelling methods such as:

- **Extensive sampling:** To collect data of high quality for a mapping of non-metallic inclusions at the involved steel plants.
- **Physical, mathematical and thermo-dynamical modelling together with plant trials:** Investigation of formation, growth and separation of non-metallic inclusions, determination of thermodynamic equilibrium of non-metallic inclusions and optimised stirring strategies for a minimisation of non-metallic inclusions.

The project has lead to the realisation of nearly all of the specified industrial goals.

Uddeholms AB stated an industrial objective for the project to quantitatively reduce the number of specified classes of NMI and it is clear that all the industrial goals were achieve except for the B class NMI, (size range 11.3-22.4 μm). It may be concluded that minimizing the reoxidation before casting is necessary to meet this final goal.

Ovako Hofors AB has worked with improving the approval rate for micro-inclusions tested by a new method from 50 % to higher than 95 % during the scope of the project. They have reported that the current approval rate is higher than 98 % for micro-inclusions partly as a result of activities and the knowledge gained within the framework of the present research project.

SAMMANFATTNING

Projektet JK 23045, "*Optimering av sekundärmetallurgi med avseende på icke-metalliska inneslutningar ledande till förbättrade stålegenskaper, med fokus på special- och höglegerade stål*", ingår i Strategiskt Stålforskningsprogram för Sverige 2007-2012 finansierat av VINNOVA och Jernkontoret. Projektet har bedrivits som ett samverkansprojekt mellan Swerea MEFOS, Avdelningen för Tillämpad processmetallurgi och Avdelningen för Mikromodellering vid KTH. Denna rapport ger en översikt av utfört arbete. De tekniska rapporter som ligger till grund för de olika avsnitten i rapporten finns angivna i fotnoter fogade till texten.

Rent stål är en av de viktigaste faktorerna för svensk stålindustri för att kunna upprätthålla och stärka den globala konkurrenskraften. Vid tillverkning av rent stål är det mycket viktigt att kombinera en minimering av genereringen av icke metalliska inneslutningar med en optimerad transport av inneslutningar till slaggen tillsammans med låga koncentrationer av övriga orenheter.
Det primära målet med detta projekt har varit att definiera en praxis för skänkmetallurgi-processen som leder till en optimering av stålets renhet. Resultat från projektet har lett till implementering av konkreta åtgärder som ökar produktkvaliteten. De industriella fördelarna är:

- **Ökad stålkvalitet:** Förbättrad avskiljning av inneslutningar genom optimering av skänk-metallurgiprocessen ledande till förbättrad stålkvalitet.
- **Högre produktivitet:** Optimerad omrörning i skänken har ökat stålets renhet och kortat av behandlingstiden för sekundärmetallurgin.

Dessa mål har uppnåtts genom noggranna studier av hur olika processparametrar påverkar mängden av orenheter såväl som antal och storleksfördelning av förekommande inneslutningar i sekundärmetallurgin. Mekanismerna bakom generering såväl som avskiljning av inneslutningar har undersökts genom:

- **Omfattande provtagning:** För att erhålla högkvalitativa data för en mappning av generering, tillväxt och avskiljning av inneslutningar hos de deltagande stålverken.
- **Fysikalisk, matematisk och termodynamisk modellering och verksförsök:** Undersökning av generering, tillväxt och avskiljning av inneslutningar, fastställande av termodynamiska jämvikter för inneslutningar samt optimering av omrörning för en minimering av mängden inneslutningar.

Projektet har lett till realiseringen av nästan alla uppställda industrispecifika mål.

Uddeholms AB mål i projektet har varit att kvantifierbart reducera antalet inneslutningar av specificerade klasser och det står klart att alla dessa mål har uppnåtts utom för inneslutningar av klass B (storleksgruppen 11.3-22.4 μm). Det kan konstateras att för att nå detta sista mål så krävs det en minimering av reoxidation innan gjutning.

Ovako Hofors AB har arbetat med att öka godkännandegraden avseende inneslutningar, med en ny metod, från 50 % till högre än 95 % under projektets löptid. De rapporterar att nuvarande godkännandegrad är högre än 98 % delvis som ett resultat av de aktiviteter och den kunskap som detta projekt genererat.

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1 INTRODUCTION

The Swedish steel industry has chosen a very high degree of specialization in material properties of steel to meet increased international competition. The result is that Swedish companies are very niche orientated and operates profitable in narrow market segments. It is imperative that research activities are undertaken to improve the efficiency and performance of the steel process technology in Sweden.

The demand for clean steel, i.e. steel grades with low amounts of impurities and non-metallic inclusions is steadily increasing. Production of clean steel grades has become one of the largest concerns of the steel producers. During secondary metallurgy, a conditioning of the liquid steel is performed to achieve a homogeneous chemical composition, an exact casting temperature and a very high steel cleanliness level. Although widely used, many aspects of secondary metallurgy still need to be further improved. One important example is the case of non-metallic inclusions (NMI) in steel melts, which may originate from, i) deoxidation products, ii) reoxidation reactions, iii) slag entrapments during various unit processes and iv) through erosion and corrosion of refractory during secondary metallurgy. The production of clean steel is highly focused on the minimization of impurities by controlling the formation of non-metallic inclusions during steel processing as well as improving the transport to the slag phase of inclusions formed. Therefore, an extensive research is necessary to improve the knowledge on and performance of secondary metallurgy in order to meet the demand for clean steel with low amounts of impurities and non-metallic inclusions.

Steel cleanliness is a focal point for Swedish steel industry in order to maintain as well as strengthen their global competitiveness. In the production of clean steel it is most important to combine a low amount of impurities with a minimization of the formation of non-metallic inclusions as well as an enhanced transport of inclusions to the slag phase. The predominantly removal of impurities such as sulphur, hydrogen and nitrogen as well as non-metallic inclusions are completed during ladle treatment.

During ladle treatment gas stirring, electromagnetic stirring (EMS) or a combination of both stirring methods is used for chemical and thermal homogenisation. Furthermore, vacuum treatment is often applied to promote chemical reactions such as steel desulphurization and gas removal (H, N). These stirring methods are also used for promotion of inclusion separation in a ladle during steel processing. In most cases however, the optimum stirring practices that are applied for chemical reactions and gas removal (H, N), do not coincide with the optimum conditions for inclusion removal. For example, emulsification of the top slag through vigorous stirring, which is beneficial for sulphur removal, can lead to the generation of inclusions as well as reoxidation of the deoxidized steel melts. Near the ladle walls, the interaction between the flow of steel and slag with the refractory lining may also cause inclusion formation through chemical and/or mechanical erosion. Therefore, it is clear that in order to improve the conditions for production of clean steel it is necessary to carry out intense research studies on the optimum stirring conditions during ladle refining.

It's important to have a deep understanding on how different process parameters affect the impurity element levels as well as the amount and size distribution of NMI during secondary metallurgy. Finally, the mechanisms for formation and removal of NMI need to be invest-igated with experimental as well as modelling methods.

The primary objective of the present project is to define operating practices of secondary metallurgy towards improving the steel cleanness during steel production. As an outcome of this research, substantial measures to improve product quality will be implemented. The expected industrial benefits are as follows:

- **Improved steel quality**: Improved inclusion removal by optimization of operating practice will enhance product quality.
- **Higher productivity**: Optimal stirring to improve steel cleanliness is expected to shorten process times in secondary steelmaking.

The project results are of significant value to the Swedish steel industry in tuning their processes towards better understanding of operating practices, for example optimum stirring for effective inclusion removal. This will enable a reduction in product defects and hence leads to a higher competitiveness.

2 OBJECTIVE

The **overall objective** of the research project is to provide new and more detailed knowledge concerning influences of different process parameters affecting the quality of steel produced by the industry. A specific goal is to lower the content of non-metallic calcium-aluminate inclusions > 10 µm in liquid steel with 30%.

The specific goals for the two steel plants, Uddeholms AB and Ovako Hofors AB (hereafter called Uddeholm and Ovako) participating in the plant trials, are listed below.

Uddeholm have stated an industrial objective to reduce the number of specified classes of NMI, summarized in Table 1, for the project.

Table 1: Industrial objectives for Uddeholm

Project	**NMI Classification**	**Size range (N/mm^2)**	**Max size (N/mm^2)**
Start	B class	(11.3-22.4µm)=0.00055	(>22.4µm)=0.00
Start	D class	(11.3-22.4µm) = 0.0098	(>22,4µm) = 0.00165
End	B class	(11.3-22.4µm) = 0.00	(>22.4µm) = 0.00
End	D class	(11.3-22.4µm) = 0.005	(>22,4µm) = 0.0002

Ovako has been working on improving a quality index used to classify the final product for the company's largest steel ball bearings client. The client made a change in routines for testing of micro-inclusions from ASTM E45-97 to ISO 4967:1998 (E), Method A, with no special additional requirements.

The two standards are fairly similar but the new method is D class inclusions. These new requirements were difficult to achieve and at the start of the project only around 50% of the produced heats were approved using the new testing classification. It needs to be mentioned that even if the produced heats were outside the specifications of micro-inclusions they were still approved for delivery to the customer. The main industrial objective was to significantly improve the approval rate to higher than 95% of micro-inclusions according to the new testing routine.

3 METHODS

To be able to create the correct starting point in a ladle metallurgy strategy, aiming at a minimised generation together with an enhanced separation of non-metallic inclusions, it is necessary to optimise heating and homogenisation of the steel. To be able to reach this goal, ladle age, stirring strategy, and temperature have to be considered. Furthermore it is vital to understand how the number and composition of non-metallic inclusions are affected by parameters as, temperature, pressure, stirring and ladle geometry together with the composition of steel, slag and refractory. Specifically, the stirring strategy also needs to consider what is best for other refining operations as H- and S removal that can be in conflict with the inclusion removal strategy since they are performed simultaneously during the same process step. With this in mind and to be able to reach the specified goals the project has focused on:

- Extensive sampling to collect data of high quality for a mapping of non-metallic inclusions at the involved steel plants.
- Physical, mathematical and thermo-dynamical modelling together with plant trials for:
  - Investigation of formation, growth and separation of non-metallic inclusions
  - Determination of thermodynamic equilibrium of non-metallic inclusions
  - Optimised stirring strategies for a minimisation of non-metallic inclusions, at the same time maintaining other necessary refining operations.

The above-described activities have been performed by three research partners, Swerea MEFOS, Division of Applied Process Metallurgy and Division of Micro Modelling at KTH Royal Institute of Technology. The plant trials have been performed at Uddeholm and Ovako.

3.1 Kinetic and mechanism studies[1]

The studies were performed to gain an in-depth understanding of the formation of calcium aluminate inclusions bigger than 10µm, thereafter to reduce their formation and facilitate their removal by optimizing the ladle operation.

To reach this goal, theoretical and experimental studies were carried out in the laboratory at KTH and industrial trial studies were conducted jointly with the researchers at Uddeholm as well as Ovako.

3.1.1 Laboratory studies

The laboratory studies have been performed to evaluate different mechanisms involved in formation of non-metallic inclusions in steel. The setups used in these laboratory studies are described below.

[1] M. Thunman, J. Gran, M. Song, M. Nzotta and Du Sichen, "*Study of slag-line reaction and optimization of the same with respect to minimize calcium aluminate inclusions for ladle treatment*", JK Technical Report TO23-137 (2011).

Cold model using liquid metal (Ga-In-Sn)

For an evaluation of the size of the "open eye" in the top liquid (slag) for different thicknesses and gas flow rates, and to examine semi quantitatively the entrainment of top liquid into the liquid metal, a cold model has been used. The experimental setup is rather simple and schematically shown in Figure 1. The vessel, having dimensions of 150mm x 350mm x 250mm (L, H, W), was made from 16mm Perspex plate. About 6.8 litres (~ 44 kg) of Ga-In-Sn alloy was filled into the container up to a predetermined height of 18cm of the liquid. Compared to a cylindrical configuration the use of rectangular vessel facilitates the visual observation and reduces the necessary amount of the Ga-In-Sn alloy.

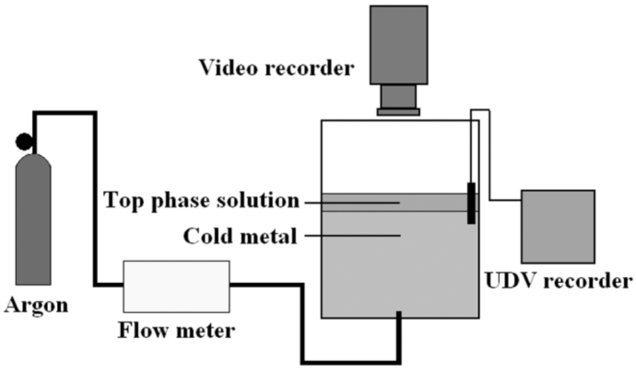

Figure 1: Cold model using Ga-In-Sn

Chemical reaction between glazed refractory and molten steel

It is commonly observed in all collected samples, irrespective of the position in the ladle and which plant that the linings were taken from, that the investigated ladles have four layers in general, viz. the original carbon bearing magnesium oxide, a decarburized layer, a slag infiltrated layer and the outer slag layer. The two outer layers are referred as ladle glaze. Ladle glaze is formed when slag ends up at the ladle wall during emptying of the ladle. The ladle glaze can then react with the steel in the next heat and result in formation of non-metallic inclusions in the steel. The experimental apparatus for the study of chemical reactions between glazed refractory and molten steel is described in Figure 2.

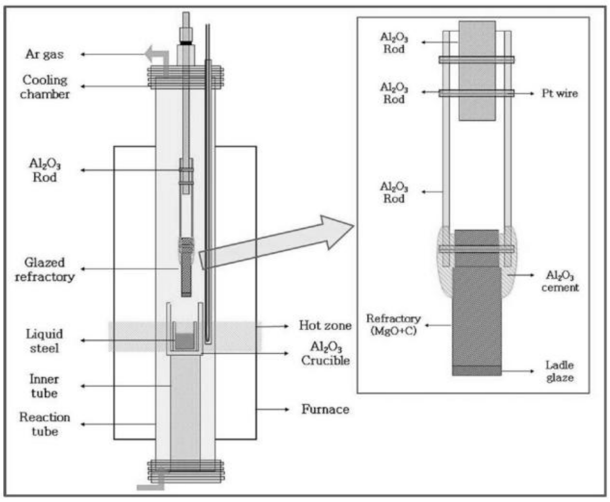

Figure 2: Experimental setup for steel-glaze reaction study

A steel grade ORVAR 2M supplied by Uddeholm was used in the experiments. About 250 g of steel pieces were first melted in an Al_2O_3 crucible (40 mm in diameter and 60 mm in depth) at 1873K. The glazed refractory specimen was dipped into the molten steel for 5, 30, 45, 60 and 120 minutes. After the reaction, the refractory samples were pulled out from furnace and quenched in air. During the whole procedure, the furnace was kept under an argon gas atmosphere.

Ladle glaze formation - MgO-rod immersion

For a study of the formation of a slag glaze layer on the lining, dense and porous MgO rods was studied by dipping MgO rods into liquid slag at 1873 K. Thereafter the rods were cooled at a predetermined cooling rate. Three different slag compositions and three different cooling rates were employed. It was found that the phases formed upon cooling were mostly dependent on slag composition and to a minor extent the cooling rate. All the initially liquid slag was transformed into crystalline phases for all the samples except the ones terminated at 1573 K and one of the samples with high cooling rate. In addition, the three slags were equilibrated at 1773 K, 1673 K and 1573 K in order to get an understanding of the equilibrium phases and their relationship during cooling.

3.1.2 Industrial trials

Sampling of steel and slag

To gain an insight into the mechanisms of formation and removal of inclusions steel samples and slag samples were taken at different stages of the process. Most of the steel samples were taken using an automatic sampling equipment. Samplings in EAF and just after tapping were made manually. All the samples were of the lollipop type. To ensure the success of the sampling, two samples were always taken at each stage. Slag samples were collected using a scoop through a hatch in the lid of the ladle furnace. Steel temperatures and dissolved oxygen activities were also measured at different stages of ladle treatment using a Celox® equipment. The Celox® probe was inserted into the melt through the hatch in the lid of the ladle. The total sampling time at each step (steel, slag and Celox®) was always less than one minute

Refractory samples

Refractory samples were taken from both participating steel plants. Both employ magnesite as their lining material. The samples were collected from different positions of the walls in old ladles taken out of the production. For both steel-melting shops, two samples were taken from the slag line and at different heights of the ladle between the bottom and the slag line. The precipitated phases in the slag layers, and the cracks and pores of the refractory were examined.

Tracer trials

Tracer trials have been performed for a determination of how slag from one heat is affecting the inclusion situation in the next couple of heats.

The effect of the ladle slag of previous heat on the number of non-metallic inclusions

Plant trials were carried out at Uddeholm. Size-categorizations (scales) were used to de-termine the extent to which respective operational heats were deslagged.

3.2 Slag carry over and inclusion characteristics[2]

An in-depth study of ladle treatment and non-metallic inclusions during various stages of steel production at Uddeholm was performed. More specifically, the characteristics of the inclusions as well as some process parameters affecting the formation and the development of inclusions were studied.

In addition, computational thermodynamic calculations were applied to predict the:

- Influence of slag carryover on the slag composition
- Aluminium content in steel and
- Sulphur distribution ratio during the ladle treatment

3.2.1 Theoretical methods

Two theoretical methods have been used during this work, mass balance calculations and thermodynamic calculations including computational thermodynamic calculations. For a continuous steady-state process it can be expressed that subtraction of material input and material output is equal to zero. This principal has been utilized to calculate the weight of slag carryover. In addition computational thermodynamic calculations were used for the calculation of the equilibriums of metal-slag and inclusion-metal.

Mass balance calculations

The weight of slag carryover can be estimated by carrying out a mass balance calculation for the most stable components of the slag samples taken before de-slagging (BD) and before vacuum degassing (BV).

Computational thermodynamic calculations

In general, the equilibrium of a system is described by thermodynamics. Predictions of the content of various phases, which are functions of temperature, pressure and composition can be done within the frames of computational thermodynamics.

Thermodynamic calculations of slag-metal equilibrium

Two types of calculation approaches were used to calculate the equilibrium state between slag and metal. In the first approach the equilibrium state between steel and added synthetic slag after vacuum degassing process is calculated without consideration of slag carryover and deoxidation products. The effects of slag carryover and deoxidation products are assumed to be negligibly small. In the second approach the additional effects of slag carryover and deoxidation products have been taken into account.

Thermodynamic calculations of slag and inclusion components

The thermodynamics of the situation at the end of vacuum treatment was studied. The oxide component activities for large-size inclusions, as well as the top slag, were computed.

[2] H. Doostmohammadi, M. Andersson, A. Karasev, P.G. Jönsson and M. Nzotta, "*Initial trials to study slag carry over and inclusion characteristics at Uddeholms AB*", JK Technical Report TO23-138 (2011).

3.3 Optimization of secondary metallurgical process parameters[3]

The work has been focused on the control of inclusions characteristics and steel cleanliness during secondary metallurgy. Investigations on de-slagging practice, slag composition, stirring practice, treatment time and casting operation on steel cleanliness with respect to non-metallic inclusions were performed at Uddeholm. The focus of the research has been to investigate the influence of process parameters such as overall steel making logistics, de-slagging practice, slag composition, stirring policy, treatment time and casting operations on the formation of inclusions.

3.3.1 Study of the impact of carry-over slag on inclusion formation

Slag removal from the ladle is performed when changing the oxidation state of the next processing stage. Unfortunately, the amount of the carry-over slag varies from heat to heat. This variation poses a threat to the product quality, since it leads to reoxidation of the deoxidized steel melts as well as reduces the sulphur removal efficiency. In this study, attempts were made to monitor the de-slagging process.

3.3.2 Effect of steel production logistics on NMI

Previous works **strongly** suggested that a reduction of the SiO_2 content in the top slag could reduce the number of NMI > 10 µm in the next heat which is produced in the ladle. Based on earlier results it was decided to carry out studies to investigate the impact of the previous steel grade processing on the ladle glaze.

3.3.3 Optimization of stirring practice

Most commonly, Uddeholm uses the combined stirring method, gas stirring and electromagnetic stirring (EMS), for promotion of inclusion separation during vacuum degassing. The combined stirring method is also used for sulphur as well as gas (nitrogen, hydrogen) removal. Normal stirring policy is that a 900 A current is used for the first 30 minutes of induction stirring (during the vacuum treatment), then the current is changed to 650 A during the last 20 minutes (at normal atmosphere). In addition, a strong gas stirring is used in combination with the induction stirring during the first 30 minutes during the vacuum treatment. The inert argon gas is purged through the melt from two bottom porous plugs.

New stirring practice during vacuum treatment

Previous studies indicated that after 15 minutes of vacuum treatment, the content of N, H and S in the steel is low enough to meet final product criteria. This means that the liquid steel, the melt no longer have to be in direct contact with the evacuated atmosphere, and therefore, no Open Eye (OE) is needed. The hypothesis for the present study is that when having an OE for a shorter period of time, the risk for regeneration of new inclusions by entrapment of top slag droplets in the melt decreases. Figure 3 gives a schematic illustration of the possible mechanism for to slag entrapment and regeneration of inclusions at the OE.

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[3] K. Malmberg, M. Nzotta, M. Andersson and P.G. Jönsson, "*Optimization of secondary metallurgical process parameters to decrease the number of large non-metallic inclusions in tool steel*", JK Technical Report TO23-139 (2011).

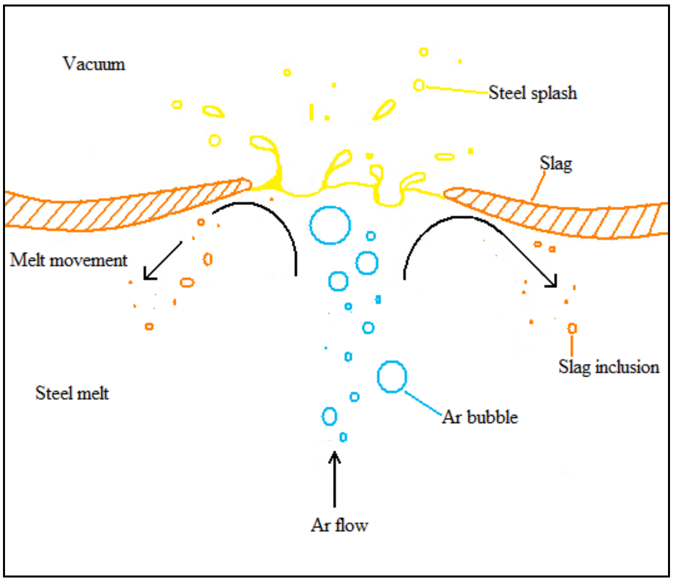

Figure 3: Schematic illustration of slag/metal movement close to the open eye during vacuum treatment with argon stirring

Changed stirring practice after vacuum treatment

After vacuum treatment, the steel melt is stirred slowly by induction during a final stirring period for about 20 minutes before ingot casting. The fundamental idea is to remove some inclusions that take a longer time to separate to the slag, and also to reach the target casting temperature. Sometimes during the final stirring period, pieces of lining have been found in the steel. This might be due to a hard lining wear during vacuum treatment, where refractory pieces were loosened from the lining during the slow stirring. Therefore, different final stirring times and different types of final stirring methods after vacuum treatment were studied.

3.4 Modelling of stirring and inclusion generation/removal[4]

During ladle treatment argon stirring, electromagnetic stirring (EMS) or a combination of both stirring methods is used for chemical homogenisation and thermal homogenisation, for promotion of chemical reactions such as steel desulphurization and gas removal (H, N). On the other hand, argon-stirring, electromagnetic stirring (EMS) or combination of both stirring methods is also used for promotion of inclusion separation in a ladle during steel processing. In most cases however, the optimum stirring practices that are applied for chemical reactions and gas removal (H, N), do not coincide with the optimum conditions for inclusion removal. Therefore the modelling in this project has focused on stirring strategies for lower generation and enhanced removal of inclusions during ladle refining operations, maintaining other objectives as H and N removal. Modelling has been performed for the two participating steel plants ladles. Both these plants use combined gas and induction stirring. Both have two porous plugs. The difference is that Uddeholm has both plugs close to the induction stirrer while Ovako has one plug close to the stirrer and one on the opposite side of the ladle. The size and geometry of the ladles are also different see Figure 4.

[4] J. Alexis and J. Björkvall, "*Stirring strategies for an optimized ladle metallurgy process*" (in Swedish), JK Technical Report TO23-140 (2011).

Uddeholm **Ovako**

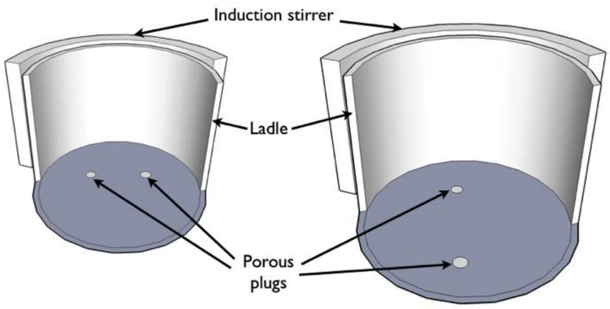

Figure 4: Placement of induction stirrer and porous plugs at Uddeholm and Ovako.

To model the ladle stirring operation it is necessary to consider forces from the induction stirrer and gas stirring flow rates, separately or together for combined stirring. It is also necessary to include both steel and slag phase to be able to predict slag movement and open eye sizes for different stirring intensities. Last, the ladle age i.e. the number of heats the ladle been exposed to is also an important parameter, since the refractory wear affect the stirring forces from the induction stirrer.

3.4.1 Stirring strategies

Since the goal of optimizing on low generation and high removal of inclusions might be in conflict with other refining operations during ladle treatment, simulations investigation of key parameters as mixing times, velocities open eye sizes etc. has been performed. The objective has been to define acceptable changes in stirring intensities with maintained refining rates. Results from simulations were also used in plant trials planning.

Gas stirring

Simulations have been performed for different gas flow rates for both Uddeholm and Ovako.

Induction stirring

Simulations have been performed for different stirring currents for Uddeholm.

Combined stirring

Simulations have been performed for both Uddeholm and Ovako.

3.4.2 Validation of models

All mathematical models needs to be validated to show that predictions are valid when compared to measurements in the real system. The induction-stirring model has been validated using a model stirrer at Swerea MEFOS, and it has also been validated in previous projects, by velocity measurements at Ovako. The gas-stirring model has been validated in previous projects.

3.4.3 Ladle age[5]

The ladle age, i.e. the number of previous heats in the ladle, affects the stirring intensities from the induction stirrer. An investigation on of this has been performed.

3.4.4 Inclusion generation/removal

Since inclusions have a lower density than the surrounding steel they will eventually float up to the surface where they are separated to the slag layer. But small inclusions are hard to remove and need help by stirring to be transported up to the slag/steel interface to facilitate separation.

Simulations of simultaneously generating inclusions from the ladle wall and separation of inclusions to the top slag have been performed.

3.4.5 Water modelling of porous plugs

One of the parameters that need to be controlled during gas stirring are the porous plugs. Steel plants use different suppliers and different design for their plugs. Therefore a water model study of porous plugs was performed. The study focused on three different designs from one supplier.

4 RESULTS

4.1 Stirring strategies[6]

Simulations were performed for combined stirring (gas and induction) for the plants participating in trials. The simulations were used for planning of plant trials and also for a prediction of how changes in stirring intensities affect critical key parameters for other refining goals than inclusion removal.

4.1.1 Uddeholm

Simulations of combined stirring intensities, asymmetric stirring for inclusion removal predictions and ladle age were performed.

Combined stirring

In Table 2 simulated stirring currents and gas flow rates during combined stirring (Induction stirring together with gas stirring).

Table 2: Stirring currents and gas flow rates investigated

Stirring Current(A)	Gas Flow (l/min)	60	120	180	240	300	360
300-1000	120	X	X	X	X	X	X
300-1000	180	X	X	X	X	X	X
300-1000	240	X	X	X	X	X	X

The aim of the investigation was to investigate which effect a change in stirring intensity has on the overall behaviour of stirring in the ladle.

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5 J. Alexis, "*Ladle age effects on generation of inclusions*" (in Swedish), JK Technical Report TO23-141 (2011).

6 J. Alexis and J. Björkvall, "*Stirring strategies for an optimized ladle metallurgy process*" (in Swedish), JK Technical Report TO23-140 (2011).

Steel velocities

One parameter that is affected by a change in stirring intensity is the steel velocity. A lower intensity leads to lower maximum velocities in the ladle. For inclusion generation this may be a good effect since the highest velocities are close to the wall and high velocities can lead to higher erosion of the lining resulting in the generation of more inclusions. But on the other hand may lower velocities lead to a lower agglomeration of inclusions resulting in a slower separation. In Figure 5 a plot of velocities for different stirring intensities is presented.

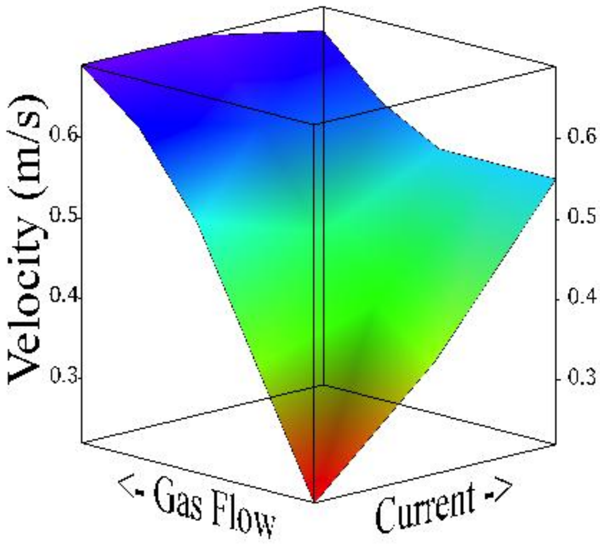

Figure 5: Maximum steel velocities in the ladle as a function of induction stirring current and gas flow rate.

The plot shows that for higher gas flow rates the induction stirring is not affecting the velocities in the ladle. A higher induction stirring intensity is however likely to create higher velocities close to the wall of the ladle since the highest stirring forces are created there. This may lead to the above-mentioned generation of inclusions from ladle glaze, see section 3.1.1 above.

Open eye size

The open eye size is also affecting refining operations. For inclusion generation /removal the open eye is not needed, see section 3.1.1 and 3.3.3 above.

Figure 6 shows the change in open eye area as a function of induction stirring and gas stirring intensities. The plot shows that the induction stirrer is reducing the size of the open eye. A higher gas flow rate leads to a larger open eye size, but combined with induction stirring the open eye can be closed favouring less reoxidation reducing the generation of inclusions.

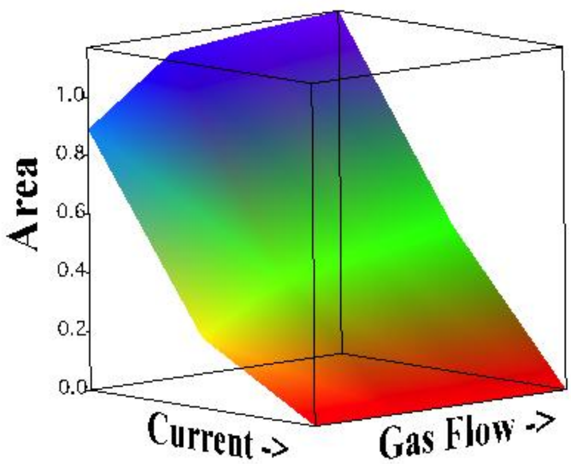

Figure 6: Area of open eye as a function of induction stirring current and gas flow rate.

Gas volume in the steel

A high gas volume in the steel is favourable for desired gas-metal reactions during refining. The gas volume is higher for higher flow. However, if combined stirring is used simulations indicate that the gas volume in the steel can be increased without the need of the creation of large open eyes from high gas flow rates, see Figure 7. This effect is due to the changed stirring pattern created from the induction stirrer resulting in longer residence time for gas bubbles in the steel.

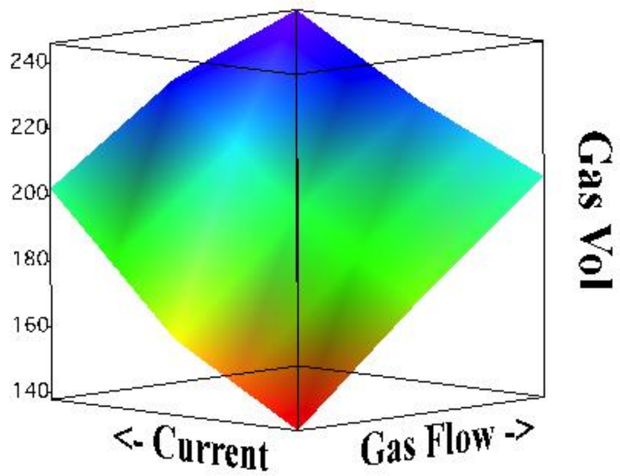

Figure 7: Gas volume in steel as a function of induction stirring current and gas flow rate.

Gas plume area

Simulations also indicate that the changed stirring pattern imposed by the induction stirrer leads to wider gas plumes in the steel, due to the effect described above. This effect is also favourable for enhancing gas-metal reactions as mentioned above. **Figure 8** shows that the gas volume in steel is the same for low gas flow and high induction stirring current as for high gas flow low induction stirring current.

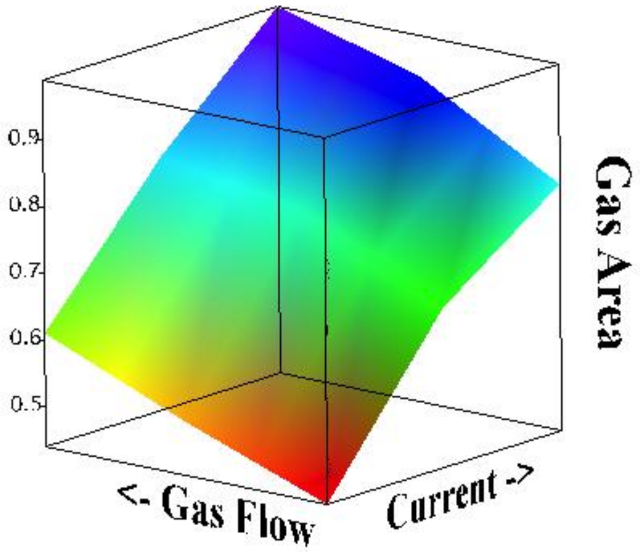

Figure 8: Gas plume area as a function of induction stirring current and gas flow rate

4.1.2 Ladle age

The ladle age is measured as the number of heats in the ladle. For each heat produced the lining is getting thinner. This will affect stirring in two ways. First, the geometry changes since the radius is increasing leading to a lower height for the same amount of steel. Second, and probably more important is that the thinner lining makes the induction stirring forces increase since steel is getting closer to the stirrer. This effect leads to higher velocities close to the wall and also to overall higher velocities in the ladle. This could be unfavourable for keeping the amount of generated inclusions from the refractory and ladle glaze down (see section 3.1.1 above). Simulations were performed for the cases listed in Table 3 below.

Table 3: Investigated ladle ages and stirring currents

Ladle age	**Stirring current (A)**							
	300	450	600	750	900	1050	1200	1350
New	X	X	X	X	X	X	X	X
Half worn	X	X	X	X	X	X	X	X
Worn	X	X	X	X	X	X	X	X
Extra worn	X	X	X	X	X	X	X	X

Ladle age effect on steel velocities

As mentioned will the highest velocities in the ladle during induction stirring be along the ladle wall close to the stirrer since the stirring forces are highest there. When the lining thickness is reduced from wear the forces will be even higher thus affecting the velocities. In Figure 9 these velocities are plotted as a function of ladle age and stirring intensity.

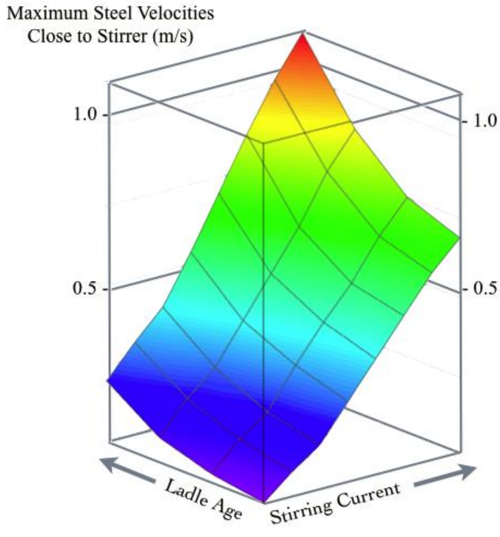

Figure 9: Maximum steel velocities in the ladle as a function of ladle age and stirring intensity.

The plot shows that in the oldest ladle are the velocities almost twice as high than the velocities in a new ladle. This probably leads to a higher erosion of the ladle wall resulting in more inclusions in the steel. Another problem is the open eye size. If the open eye area is to be kept constant, a reduction of stirring intensity is needed for older ladles as illustrated in Figure 10.

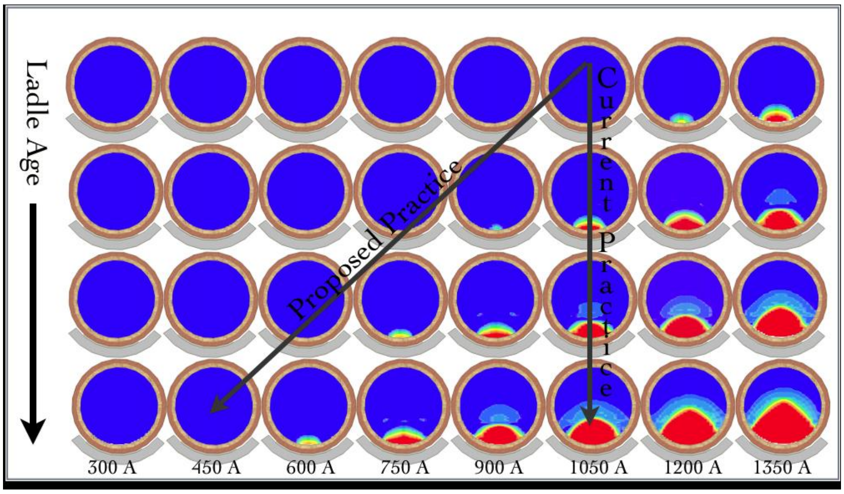

Figure 10: Open eye size as a function of ladle wear and stirring current

In Figure 10 the ladle is shown from a top view for a number of ladle ages and induction currents. Blue colour is slag and red colour is steel. It can be seen that keeping the open eye closed when stirring during the ladle lifetime requires that the stirring current is halved. Otherwise the stirring will lead to higher generation of inclusions from ladle wall and reoxidation, see section 4.2.1. Simulations also show that a reduced stirring current can be used with increased ladle age without affecting mixing times in a significant way, thus maintaining other vital refining operations at the same time. Figure 11 shows that for most ladle ages and stirring currents give almost the same mixing times apart from when using very low stirring current.

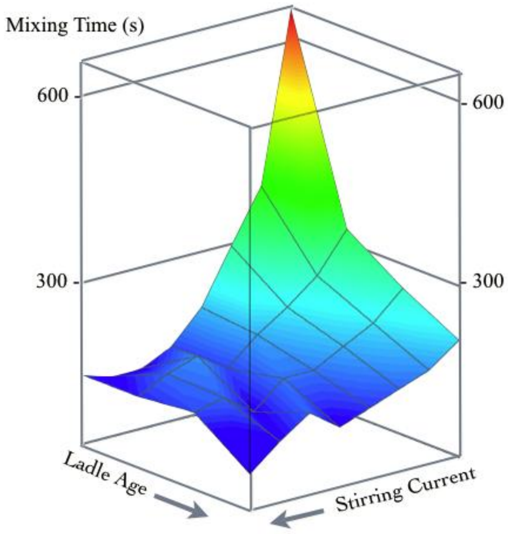

Figure 11: Mixing times for induction stirring as a function of ladle age and stirring current.

Inclusion generation from erosion of the ladle wall

Particles created from the erosion of the ladle wall are generally assumed to float up and be separated to the slag layer. However, normal practice shows that part of these particles are maintained in the melt and are involved in the generation of inclusions. From earlier work[28] testing the erosion of ladle refractory as a function of steel velocity the derived relation has been used in a simulation of the behaviour of eroded particles.

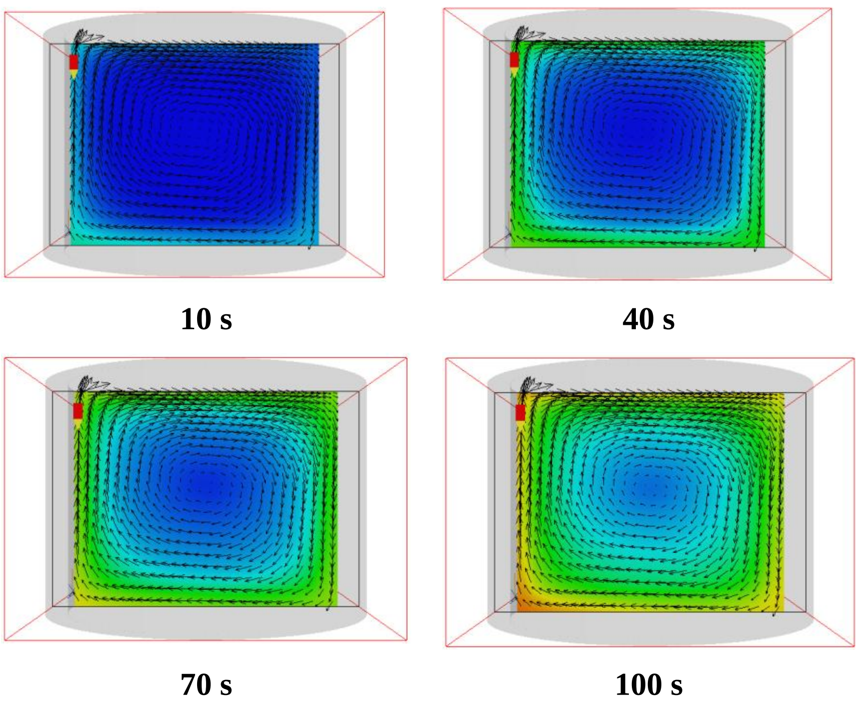

Figure 12: Generation and separation of inclusions from the ladle wall as a function of stirring time.

Figure 12 shows the generation of inclusions from the ladle wall during induction stirring. The shown plots are from a vertical section through the centre of the ladle and stirrer. The induction stirrer is placed at the left hand side of the plotted sections (note that the red squares are just position markers and can be ignored). The figure show that for 10 μm sized particles the amount generated is higher than the amount separated. For larger particles this is not generally the case since larger particles have higher flotation velocities and are more likely to be separated.

4.1.3 Changed vacuum practice

To reduce the regeneration of inclusions during vacuum treatment the operation practice was revised, see section 3.3.3 above. The revised practice was tested with the help of CFD-simulations predicting open eye size and flow intensities for suggested changes. Figure 13 shows the open eye size, seen from above (red colour is steel and blue colour is slag), and the velocities in a vertical plane through the centre of the ladle for flow intensities used during the first 15 minutes. The induction stirrer is situated on the left hand side of the ladle, in the figure.

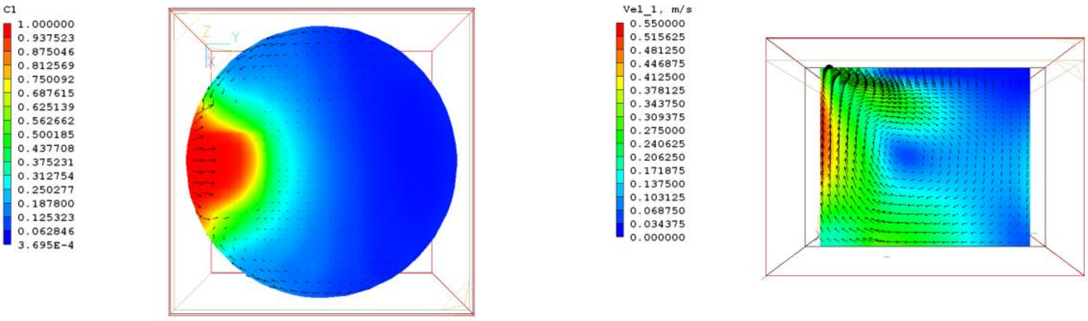

Figure 13: Flow characteristics during the first 15 minutes of vacuum treatment.

Figure 14 shows the flow situation after 15 minutes when the flow intensities has changed. The figures show that during the first 15 minutes of vacuum treatment an open eye is maintained and the velocities inside the steel phase are high.

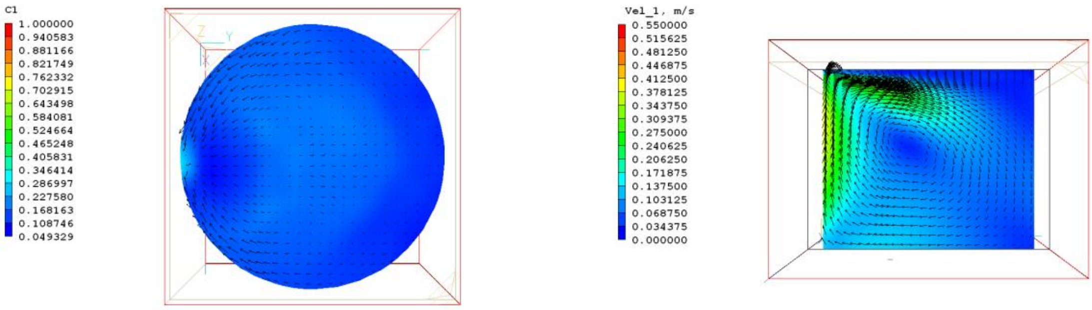

Figure 14: Flow characteristics after 15 minutes of vacuum treatment.

After 15 minutes the induction stirring intensity and the gas flow rate is lowered leading to a closed open eye and lower velocities inside the steel phase. Both these effects will likely lead to a reduced regeneration of inclusions.

4.1.4 Water modelling of porous plugs

The results from the water modelling are inconclusive and a further investigation needs to be performed. This work was ruled to be out of scope of the project and therefore the activity was ended.

4.2 Origin of non-metallic inclusions

A number of different hypothesises of the origin of non-metallic inclusions are available in the literature[7] [8] [9, 10]. Among the most important mechanisms for the generation of non-metallic inclusions are reactions with the slag, deoxidation products, reactions with the lining and reactions with slag attached on the lining from earlier heats, ladle glaze.

4.2.1 Ladle glaze[11]

Plant trials and laboratory trials show that a major part of the non-metallic inclusions found in liquid steel are formed by the so called ladle glaze[1-4] that is formed when the slag is stuck to the lining when emptying the ladle.

Industrial trials

Refractory sampling

For both steel shops, Uddeholm and Ovako, two samples were taken from the slag line (S-sample) and two samples (M-sample) at different heights of the ladle between the bottom and the slag line. There is no substantial difference between the S-samples for the same ladle, which is also true in the case of the M-samples. The glaze layer found in the Ovako ladle has a thickness varying between 2 and 8 mm. The glaze is white-grey in colour. It is noticed that the erosion of the refractory at the slag line is more profound than at the position a certain distance below this line. Figure 15 shows the cross section of a sample taken in the slag line of Ovako.

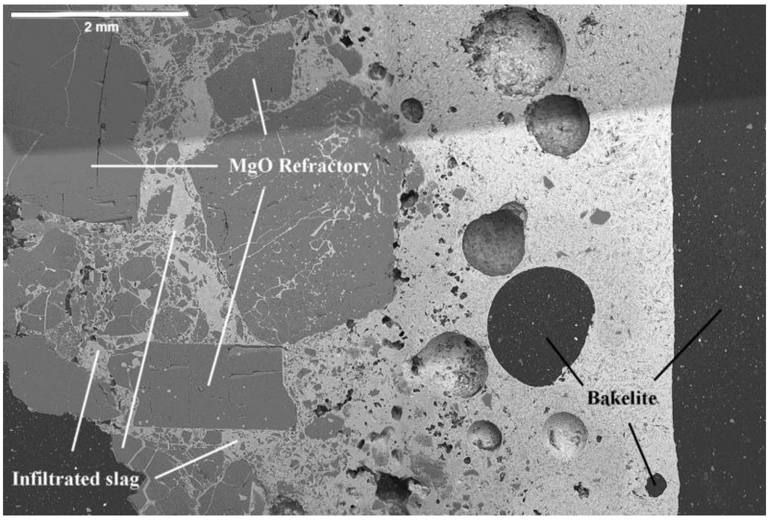

Figure 15: Ovako S-Sample.

[7] M. Thunman, "*Formation of inclusions and their development during secondary steelmaking*", Doctoral Thesis, KTH, Stockholm, 2009.

[8] M. Thunman and Du Sichen, "Origins *of non-metallic inclusions and their chemical development during ladle treatment*", Steel Research International, 2008, vol. 79, pp.124-132.

[9] J. Gran, M. Thunman and Du Sichen, "*Effects of slag composition and cooling rate on the formation of glaze on MgO refractory*", Ironmaking and Steelmaking, for publication, 2010, vol.37, pp.27-34.

[10] M. Thunman, J. Gran and Du Sichen, "*Slag-refractory reaction during ladle refining and teeming*", Steel Grips, 2009, vol. 7, No. 2, pp. 129-135

[11] M. Thunman, J. Gran, M. Song, M. Nzotta and Du Sichen, "*Study of slag-line reaction and optimization of the same with respect to minimize calcium aluminate inclusions for ladle treatment*", JK Technical Report TO23-137 (2011).

It can clearly be seen that the outer layer (to the right in the picture) consists of mostly ladle slag, while the slag infiltrated layer consists of both MgO matrix and slag. In fact, the slag region is composed of more than one phase. Figure 16 presents the SEM microphotograph with higher magnification.

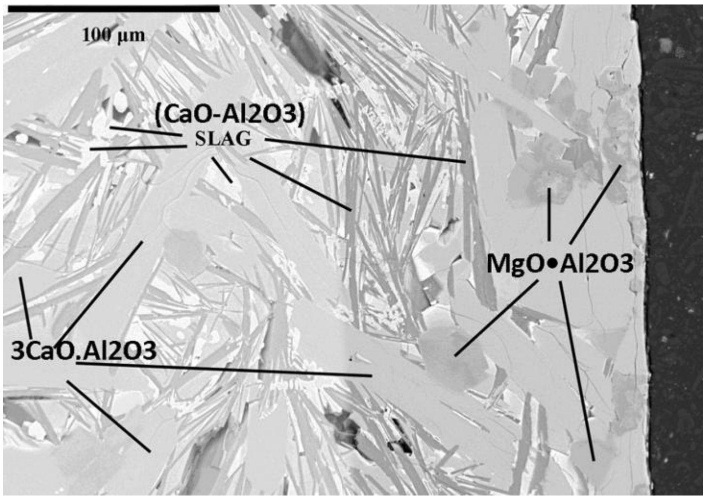

Figure 16: Ovako S-sample with higher magnification.

Two oxide phases, namely $MgO.Al_2O_3$ (spinel) and the $3CaO.Al_2O_3$ calcium aluminate compound are found. It should be pointed out that in some cases it is difficult to clearly distinguish between the two phases of calcium aluminate, $3CaO.Al_2O_3$ and $12CaO.7Al_2O_3$, by EDS analysis since the compounds are quite close to each other in chemical composition. Figure 17 presents the microphotograph of an M-sample from Ovako.

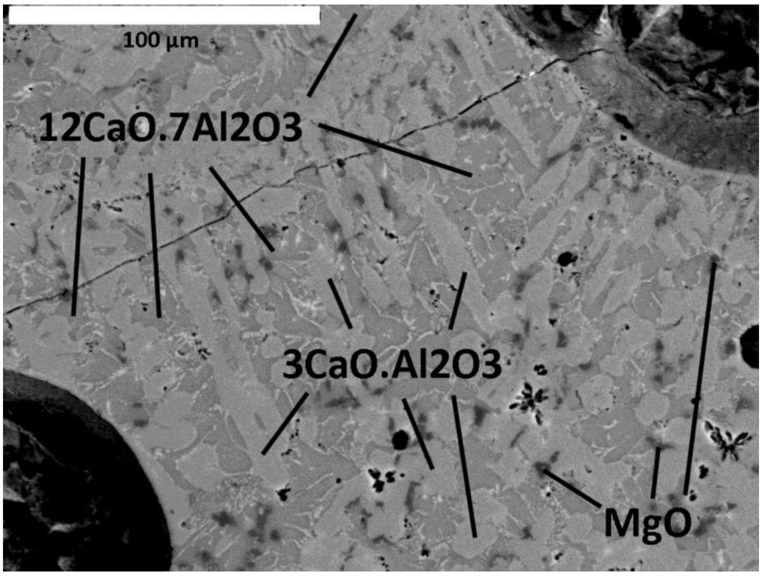

Figure 17: M-sample of Ovako.

While calcium aluminate phases are also found in the M-samples, no $MgO.Al_2O_3$ spinel phase is detected as in the S-samples. It is noted in the figure that the precipitated calcium aluminate phases are most likely to be the $3CaO.Al_2O_3$ and $12CaO.7Al_2O_3$ compound. Although, it is hard to distinguish these two phases with the EDS, the composition of the grey phase is likely to be the $3CaO.Al_2O_3$ compound, while the dark grey phase is likely to be the $12CaO.7Al_2O_3$ compound. Note that traces of super cooled slag are also detected by EDS analysis. On the other hand, it is difficult to identify it on the SEM microphotograph. The structure of the M-sample is somewhat different from the S-samples.

The refractory samples from the ladle of Uddeholm are a bit different compared to the samples from Ovako. The slag layer is greenish in colour and glassier in appearance. The thickness of the slag layer, on the other hand is similar to that of Ovako, although the layer appears to be denser. Similar to Ovako, the erosion at the slag line is more severe in comparison with the other parts of the wall. The phases found in the S-samples and M-samples are identical in the ladle of Uddeholm. As an example, Figure 18 shows the micrograph of the M-sample.

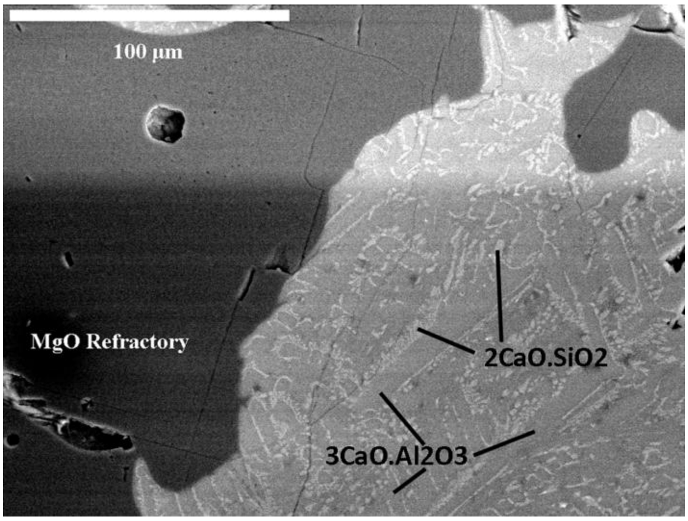

Figure 18: Uddeholm M-Sample with higher magnification

In addition to the precipitated MgO, two oxide phases and super cooled slag are identified. The two oxides are $2CaO.SiO_2$ and $3CaO.Al_2O_3$ as marked in the figure. There are also region consisting of two phases, namely a precipitated calcium aluminate compound (mostly likely $3CaO.Al_2O_3$) along with super cooled slag.

The phases detected in different lining samples are listed in Table 4. It is seen that the phases present in the glaze layers from the two steel plants are somewhat different. The calcium silicate phase is only detected in the samples from Uddeholm, while the $MgO.Al_2O_3$ phase is only found in the S-sample of Ovako. In the table the $3CaO.Al_2O_3$ and $12CaO.7Al_2O_3$ has been put in the same category for reasons mentioned earlier.

Table 4: Phases (besides MgO) in the samples detected by EDS X-ray.

Phases	Ovako		Uddeholm	
	S-Sample	**M-Sample**	**S-Sample**	**M-Sample**
$12CaO.7Al_2O_3$ and/or $3CaO.Al_2O_3$	X	X	X	X
$2CaO.SiO_2$			X	X
CaO	X	X		
$MgO.Al_2O_3$	X			
Super cooled slag	X	X	X	X

Another very interesting observation is that the overall SiO_2 content in the samples of Ovako is very low (< 1 mass-%) with regard to the silica content in their typical ladle slag. It should be mentioned that point analysis indicates that pure CaO exits as a separated phase in the S-sample and M-samples from Ovako. However, the particles are too small to show in the microphotographs.

Tracer trials[12]

Tracer experiments were carried out at Uddeholm. $BaCO_3$ was employed as the raw material of the tracer. At steelmaking temperature, the barium carbonate would decompose immediately into BaO and CO_2[5]. The types of inclusions found at different stages of the ladle treatment are essentially the same as those reported in the previous studies[1-4] from Uddeholm. To make the discussion easier, the part of the table reported earlier[3] relevant to the present work is reproduced in Table 5.

Table 5: The different types of inclusions at different stages of the ladle treatment at Uddeholm[3]

Type	Specification	Stages			
		Ladle Arrival	After Al Addition	Before Vacuum	After Vacuum
2	Liquid oxide solution having high SiO_2 content	X			
3	$MgO{\cdot}Al_2O_3$ Spinel	X	X	X	
4	Combination of 2 and 3	X			
6	Spinel + Oxide solution having low SiO_2 content		X	X	X
7	Oxide solution having low SiO_2 content			(X)	X
8	MgO + Oxide solution having low SiO_2 content			(X)	X

Inclusions of type 2 have a spherical shape consisting of Al_2O_3, CaO, MgO and SiO_2. The concentration of SiO_2 in this type of inclusions can be very high, around 30 wt%. While the composition of the inclusions varies from one to another, it is quite uniform in each inclusion. The shape and homogeneity of the inclusions suggest that they were in liquid form in the melt. Inclusions of type 3 are more irregular in shape and are found to consist of Al_2O_3 and MgO. The composition of these inclusions is found to vary within the non-stoichiometric range of the $MgO{\cdot}Al_2O_3$ spinel phase. The inclusion of type 4 is a combination of type 2 and type 3, with the $MgO{\cdot}Al_2O_3$ spinel in the centre surrounded by a phase containing Al_2O_3, CaO, MgO and SiO_2. Inclusion of Type 6 consists of also $MgO{\cdot}Al_2O_3$ spinel and a liquid phase of oxide solution. The inclusions of Type 6 distinguish themselves from Type 4 by their low SiO_2 content, in general at a level of less than 5 mass%. Type 7 inclusions consist of only the liquid oxide, which is the outer layer in inclusion of Type 6. Again, the difference between Type 7 and Type 2 is the considerable difference in SiO_2 content. The inclusions of type 8 consist of two phases also, MgO island(s) in the centre surrounded by the same liquid oxide solution of Type 7. Note that inclusions of Type 1 and Type 5 are not included in Table 4.

[12] M. Song, M. Nzotta and Du Sichen, "*Study of the formation of non-metallic inclusions by ladle glaze and the effect of slag on inclusion composition using tracer experiments*", Steel Research International, 2009, vol.80, pp.753-760.

Type 1 inclusions are tiny MgO particles found only in the ladle of the first usage (new ladle). Inclusions of Type 5 are agglomerated Al_2O_3 clusters, which can only be detected during aluminium addition. These two types of inclusions are not relevant to the present discussion, as no steel sample was taken under the same experimental conditions.

The EDX results indicate clearly that no BaO is detected in Type 3 inclusions. Except for spinel inclusions (Type 3), all the other types of inclusions contain a liquid oxide solution phase with high concentrations of CaO and Al_2O_3. While not all these inclusions contain BaO, barium oxide is detected in a certain fraction of the inclusions of each type. Hence, the main focus of this paper is given to these types of inclusions. The composition ranges of the oxide solution in the inclusions at different stages are listed in Table 6.

Table 6: The composition ranges of inclusions found at various stages, mass-%

Type	Characteristics	MgO	Al_2O_3	SiO_2	CaO	BaO
2	Oxide solution having high SiO_2 content	1~17	23~47	10~36	15~55	0~17
3	Spinel (MgO·Al2O3)	21~28	56~70	0~2	0~3	0~1
4	Spinel +	20~28	55~70	0~7	0~9	0
	Oxide solution having high SiO_2 content	1~15	21~50	9~30	20~31	0~2
6	Spinel +	19~28	60~69	0~1	0~9	0
	Oxide solution having low SiO_2 content	2~12	51~58	0~3	16~33	0~16
7	Oxide solution having low SiO_2 content	3~9	45~56	1~2	24~43	0~15
8	MgO +	60~75	8~18	1~5	9~21	0
	Oxide solution having low SiO_2 content	2~7	38~46	2~10	38~42	0~13

In the two series of tracer trials, only in the first heat of each series, BaO was added to the ladle slag as tracer. The fractions of BaO containing inclusions and the variation of the average BaO content in these two first heats indicated that the barium transfer from slag to the inclusions was very slow process. The large fractions of inclusions containing BaO in the steel of the second and third heats after BaO addition showed that ladle glaze was responsible for a great number of non metallic inclusions generated during ladle treatment. The inclusions supplied by ladle glaze are relatively big. The sizes could be even larger than 100 µm. On the other hand, no evidence was found for the formation of inclusions from the entrainment of slag.

Figure 19 present the fractions of the inclusions containing BaO over the total numbers of inclusions at different stages, AD after deslagging, BV before vacuum, AV after vacuum and in different heats in the two trial series, respectively.

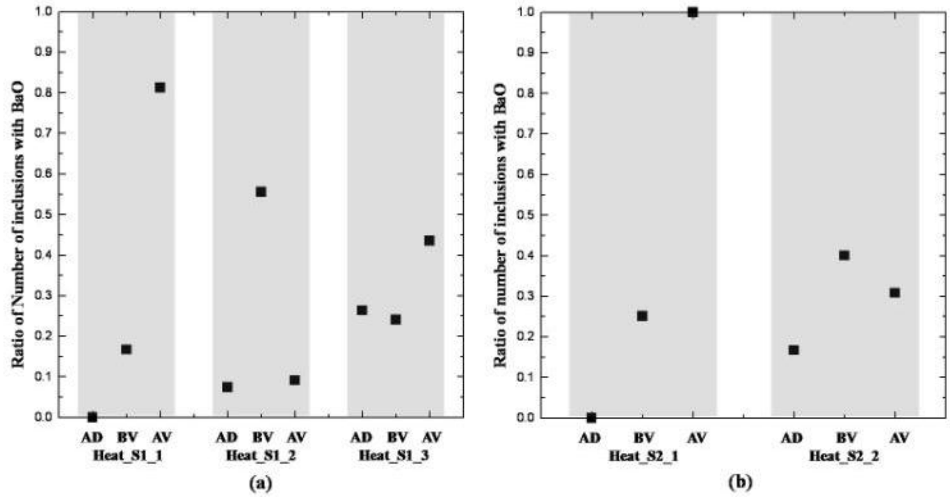

Figure 19: Fractions of the number of inclusions with BaO at various process steps (a. Heat series 1, b. Heat series 2)

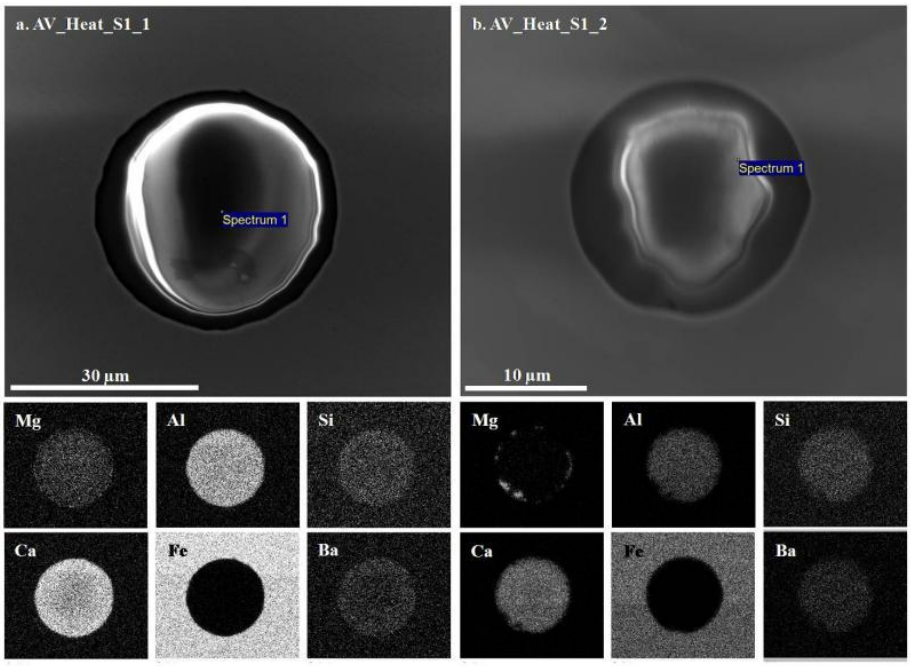

Figure 20: The SEM micrograph and element mappings of type 7 inclusions

Figure 20a presents a typical Type 7 inclusion found after vacuum treatment in the first heat of the first series. The element mapping of this inclusion is also presented in the same figure. BaO occurs uniformly in the whole inclusion. Similarly, the micrographs of a BaO containing Type 7 inclusion found in the second heat of the first series is presented in Figure 20b. While the BaO content is lower than the inclusion in Figure 20a, its presence in the inclusion is evident.

Laboratory trials

Ladle glaze formation - MgO-rod immersion

Thirteen experiments were carried out for the MgO-rod immersion. The slag compositions along with the experimental conditions are found in Table 7 and Table 8 respectively.

Table 7: The slag compositions used in this study

Composition (wt%)				
Slag No.	CaO	Al_2O_3	SiO_2	MgO
S1	55	30	8	7
S2	45	30	15	10
S3	49	30	12	9

Table 8: Experimental conditions for the MgO-rod immersion.

Sample No.	Slag No.	Cooling rate	Rod type	Termination temp
1	S1	10 K/min	dense	1573
2	S1	6.7 K/min	dense	1573
3	S1	10 K/min	dense	1373
4	S1	5K/min	dense	1373
5	S2	10 K/min	dense	1373
6	S2	6.7 K/min	dense	1373
7	S2	5 K/min	dense	1373
8	S3	10K/min	dense	1373
9	S3	6.7 K/min	dense	1373
10	S3	5K/min	dense	1373
11	S1	6.7 K/min	porous	1373
12	S2	6.7 K/min	porous	1373
13	S3	6.7 K/min	porous	1373

Three slag compositions were studied. The phases found in the sample after the experiment along with the visual observations for the MgO-rod are summarized in Table 9

Table 9: Phases found in the samples after the experiment and visual observations.

Sample No.	Slag No.	MgO	$2CaO.SiO_2$	$3CaO.Al_2O_3$	Continuous glass phase	"Multi phase mixture"	Cracks	Dusted
R1	S1	yes	yes	major	yes	no	no	no
R2	S1	yes	yes	major	yes	no	no	no
R3	S1	yes	yes	major	no	minor	minor	no
R4	S1	yes	yes	major	no	minor	minor	no
R5	S2	yes	yes	minor	no	major	yes	yes
R6	S2	yes	yes	minor	no	major	yes	yes
R7	S2	yes	yes	minor	no	major	yes	yes
R8	S3	yes	yes	no	yes	no	no	no
R9	S3	yes	yes	minor	no	major	yes	yes
R10	S3	yes	yes	minor	no	major	yes	yes
R11	S1	yes	yes	major	no	minor	no	no
R12	S2	yes	yes	minor	no	major	At surface	yes
R13	S3	yes	yes	minor	no	major	At surface	yes

Sample R1 and R2 were immersed in slag S1. The slow cooling of the samples was terminated at 1573 K. Despite the different cooling rates above this temperature, the phases present and the behaviour of the two samples are identical. As an example, an SEM microphotograph of sample R2 is presented in Figure 21. Besides the un-reacted MgO rod, four phases are detected in both of the samples, as marked. The four phases identified by EDS are $3CaO.Al_2O_3$, $2CaO.SiO_2$, MgO and some super cooled liquid. The homogeneity in composition of the continuous liquid phase and the fact that it did not match with any compound in the quarternary system suggest that it is super cooled liquid. The major phase found is the compound $3CaO.Al_2O_3$. The continuous liquid phase surrounds big pieces (around 100 μm) of $3CaO.Al_2O_3$. Some amount of calcium silicate phase in the form of small dendrite (5-10 μm) distributes randomly in the $3CaO.Al_2O_3$ phase. The calcium silicate phase is also observed within the continuous liquid phase. MgO pieces are found to distribute randomly in the reacted layer.

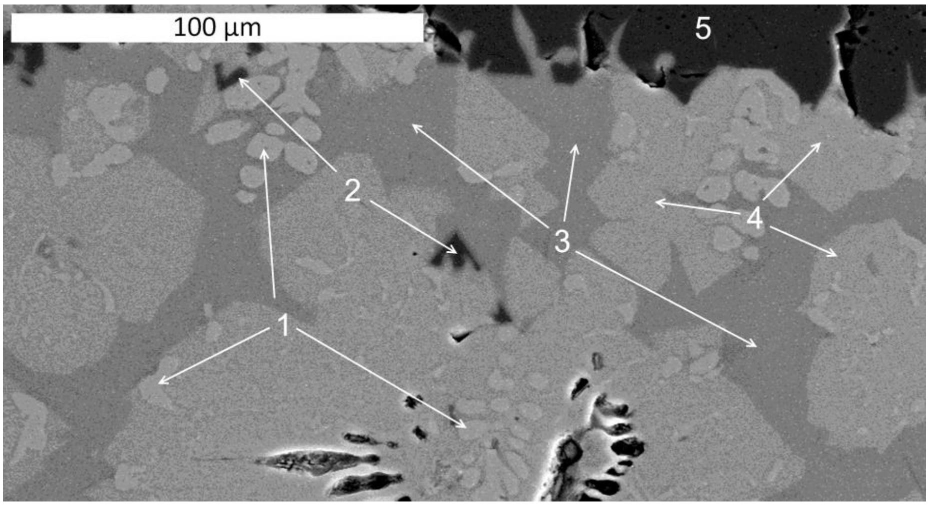

Figure 21: SEM microphotograph of sample R2; $2CaO.SiO_2$ marked as 1, MgO marked as 2, super cooled liquid marked as 3,$3CaO.Al_2O_3$ as 4, and the MgO rod is marked as 5.

Chemical reaction between glazed refractory and molten steel

Refractory samples from Uddeholm were used. A steel grade ORVAR2M also supplied by Uddeholm was used in the experiments. About 250 g of steel pieces were first melted in an Al_2O_3 crucible (40 mm in diameter and 60 mm in depth) at 1873K. The glazed refractory specimen was dipped into the molten steel for 5, 30, 45, 60 and 120 minutes. After the reaction, the refractory samples were pulled out from furnace and quenched in air. During the whole procedure, the furnace was kept under the atmosphere of argon gas.

In Figure 22 a glazed refractory sample after reaction with steel for 5 minutes is compared with the sample without reaction. The liquid slag layer on the lining surface is usually 2 ~ 3 mm thick on the ladle walls. While a great portion of the outer slag layer is removed after 5 minutes in contact with liquid metal, most of the infiltrated layer still remains in the refractory. Because of the low interfacial tension between slag and refractory in comparison with that between metal and refractory, the slag has clambered up along the fresh surface of the refractory.

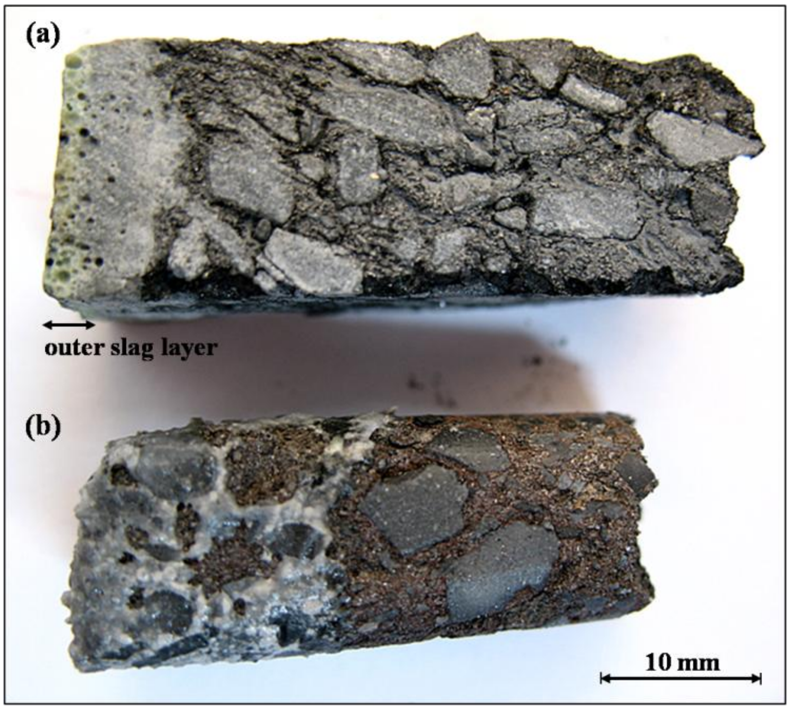

Figure 22: Comparison of the glazed refractory samples before and after experiments (a. Before experiment, b. After experiment (5 minutes))

Figure 23a-c presents the SEM microphotographs of the lining samples before reaction, after 5 minutes of reaction and after 120 minutes of reaction respectively.

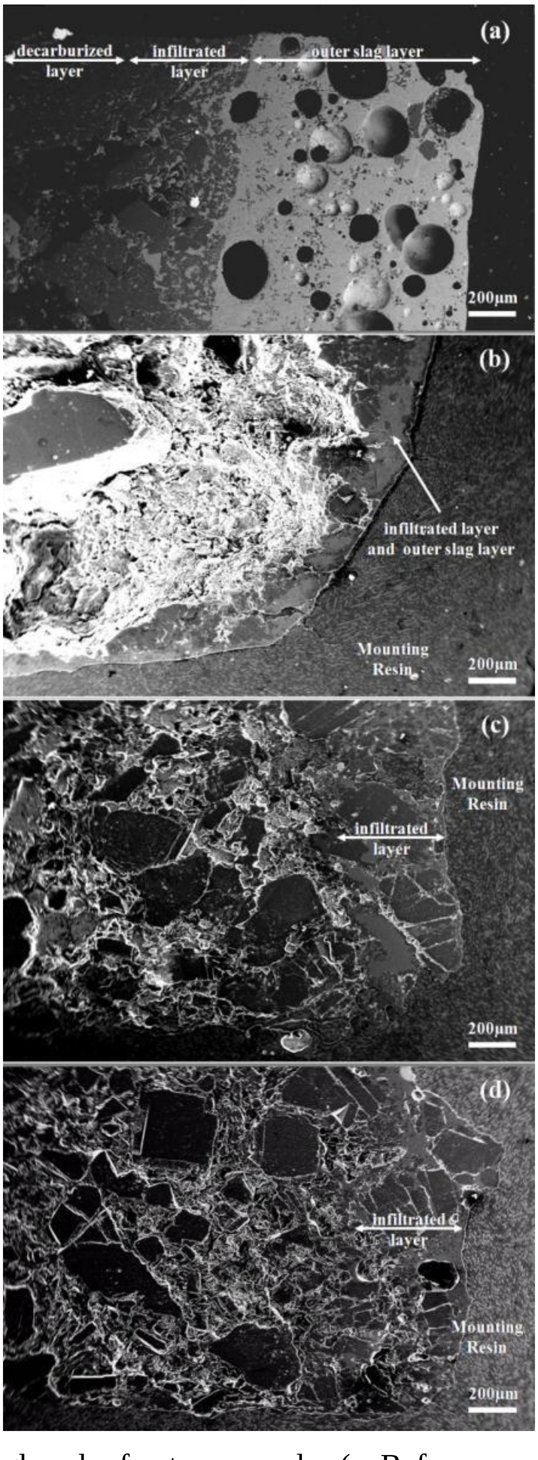

Figure 23: SEM pictures of glazed refractory samples (a. Before experiment, b. After experiment (5 min.), c. After experiment (120 min.), d. After experiment (rotated in steel))

Note that the surface layer, which is covered by clambered slag, is removed to obtain the inner sections of the samples. The thickness of the remaining slag layer on the refractory surface is only about 200 µm after 5 minutes of reaction. The SEM microphotograph of the sample rotated in the steel (Figure 23d) shows that even the relative movement of the liquid steel has not removed the entire glaze layer.

Entrainment of top liquid into the liquid metal[13]

Sampling was made in the metal bulk at 9 different positions in the case of 3 different gas flow rates. The positions of sampling are schematically shown in Figure 24. The samples were left for a period of about 15 minutes outside the vessel. Afterwards no noticeable amount of top liquid was observed at the free surface of any sample. Note that the present method has to be considered as very rough and delivers only qualitative results. Nevertheless, the absence of the top liquid in all samples suggests that the entrainment of top liquid into the liquid metal does not play a significant role irrespective of the gas flow rate.

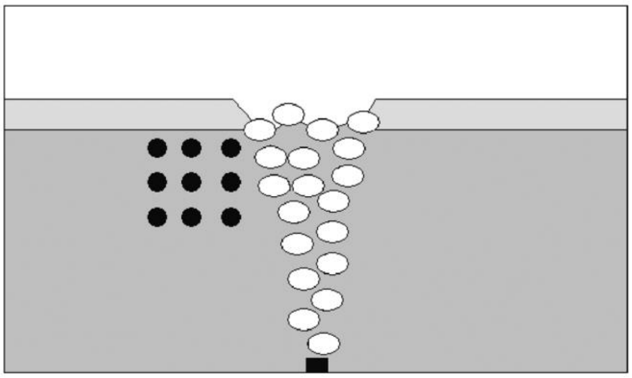

Figure 24: Sampling positions in the Ga-In-Sn metal.

4.2.2 Theoretical study of the impact of carry-over slag[14] [15] [16] [17] [18]

Two theoretical methods have been used during this work, namely mass balance calculations and thermodynamic calculations including computational thermodynamic calculations. More specifically, the weight of slag carryover has been calculated by a mass balance method. In this method, for a continuous steady-state process it can be expressed that subtraction of material input and material output is equal to zero. In addition computational thermodynamic calculations were used for the calculation of the equilibriums of metal-slag and inclusion-metal. Details regarding each method are given below.

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[13] M. Thunman, S. Eckert, O. Hennig, J. Björkvall, and Du Sichen, *"Study on the formation of open-eye and slag entrainment in gas stirred ladle*", Steel Research International, 2007, vol. 78, pp.849-856.

[14] H. Doostmohammadi, "*A study of slag/metal equilibrium and inclusion characteristics during ladle treatment and after ingot casting*", Doctoral Thesis, KTH, Stockholm, 2009

[15] H. Doostmohammadi, M. Andersson, A. Karasev, P.G. Jönsson and M. Nzotta, "*Initial trials to study slag carry over and inclusion characteristics at Uddeholms AB*", JK Technical Report TO23-138 (2011).

[16] H. Doostmohammadi, M. Andersson, A. Karasev and P.G. Jönsson, *"Use of Computational thermodynamic Calculations in Studying the Steel/Slag equilibrium during Vacuum Degassing"*, Steel Research International, Vol. 81, No. 1, 2010, pp. 31-39.

[17] H. Doostmohammadi, A. Karasev and P.G. Jönsson, *"A Comparison of a Two-Dimensional and a Three-Dimensional Method for Inclusion Determinations in Tool Steel"*, Steel Research International, Vol. 81, No. 5, 2010, pp. 398-406.

[18] H. Doostmohammadi, M. Andersson, A. Karasev and P.G. Jönsson, *"Thermodynamic and Experimental Considerations of the Inclusion Characteristics during Vacuum Degassing of Tool Steel"*, ISBN 978-91-7415-520-4

Mass balance calculations

The weight of slag carryover can be estimated by carrying out a mass balance calculation for the most stable components of the slag samples taken before de-slagging and before vacuum degassing[10]. In doing this, the CaO content is considered as a tie compound in the slag.

Computational thermodynamic calculations

In general, the equilibrium of a system is described by thermodynamics. Calculation of the equilibrium state using thermodynamic functions can be done by computational thermodynamics using the Calphad technique[6]. More specifically, predictions of the content of various phases, which are functions of temperature, pressure and composition can be done within the frames of computational thermodynamics. Thermo-Calc was used for thermodynamic calculations in this work[7].

Thermodynamic calculations of slag-metal equilibrium

Two types of calculation approaches were used for calculation of the equilibrium state between a slag and a metal[8][9-26]. The first Case A, calculates the equilibrium between steel and added synthetic slag after vacuum degassing process without consideration of slag carryover and deoxidation products. More specifically, the effects of slag carryover and deoxidation products are assumed to be negligibly small. In the second Case B, the additional effects of slag carryover and deoxidation products have been taken into account.

4.2.3 Study of the impact of carry-over slag on inclusion formation

The measurements were grouped into the following classes: (1) no carry-over slag, (2) few carry-over slag islands along the lining, (3) many carry-over slag islands along the lining and (4) a lining fully covered with floating carry-over slag islands. See Figure 25.

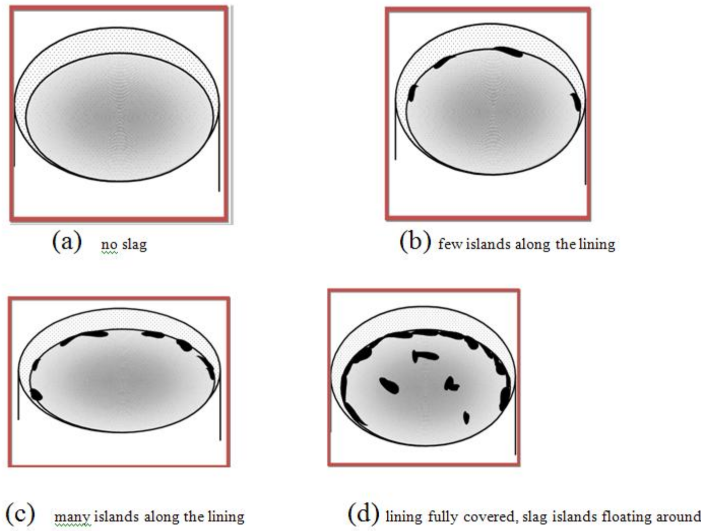

Figure 25: 4 scales of estimating amount of carry-over slag were used to monitor the efficiency of the deslagging process.

Visual monitoring of EAF deslagging and slag carry-over

The results from the monitored heats with respect to EAF deslagging and slag carry-over results are shown in Table 10**.**

Table 10: Results from monitoring of deslagging

Heat number	Scale	Comments to scale
DV 61331	c	Many islands around the lining
DV 61332	d	Lining fully covered, islands floating around
DV 61334	b	Few islands around the lining
DV 61340	c	Many islands around the lining
DV 61348	c	Many islands around the lining

It can be seen that none of the studied heats obtained complete de-slagging. The best heat was DV61334 which had few islands of remaining EAF slag floating around the lining. In Table 11 the results from assessment of the number of larger inclusions are shown. It can be seen that for large D-type of inclusions all studied heats obtained better results compared to the reference heats. The only heat, beside the reference heat, that did not reach the project goal with respect to D-inclusions was heat DV61340. For large B-type inclusions, most of the studied heats had equal results compared to the reference heat. The only heat that showed an increase in BH-type inclusions was heat DV61334. However, none of the heats reached the project goals for large B-types of inclusions.

Table 11: Inclusion number assessment in final product

Inclusion classification	Number of inclusions /mm^2 in final product					
	Project goal	DV61331 (ref) c*)	DV61332 d**)	DV61334 b**)	DV61340 c*)	DV61348 c*)
BH (11.3-2.4µm)	0	0.0200	0.0200	0.008	0.0200	0.0020
BP>22.4 µm	0	0	0	0	0	0
DH (11.3-2.4µm)	Max. 0.005	0.01	0.0033	0.0133	0.007	0.002
DP>22.4 µm	Max. 0.0002	0.007	0	0.00033	0.001	0.00033

*) Many islands around the lining

**) Lining fully covered, islands floating around

**) Few islands around the lining

For large B-type inclusions, most of the studied heats had equal results compared to the reference heat. The only heat that showed an increase in BH-type inclusions was heat DV61334. However, none of the heats reached the project goals for large B-types of inclusions.

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4.2.4 Effect of steel production logistics on NMI[19]

The steel production logistics were studied where:

- A low silicon steel grade was followed by the production of a ORVAR2M steel grade, which is a steel grade with a higher silicon content, and
- The production of a ORVAR2M (a higher silicon steel grade) steel grade followed by another ORVAR2M heat.

The results are given in Figure 26 where the number of inclusions and the total oxygen content are given. They show that for the low Si steel grade → ORVAR2M arrangement the number of inclusions is considerably lower than for the ORVAR2M → ORVAR2M arrange-ment[32-35]. This means that when producing steel grades with a requirement of a low number of inclusions, the steel production logistics should avoid a high Si-alloyed heat in the previous ladle.

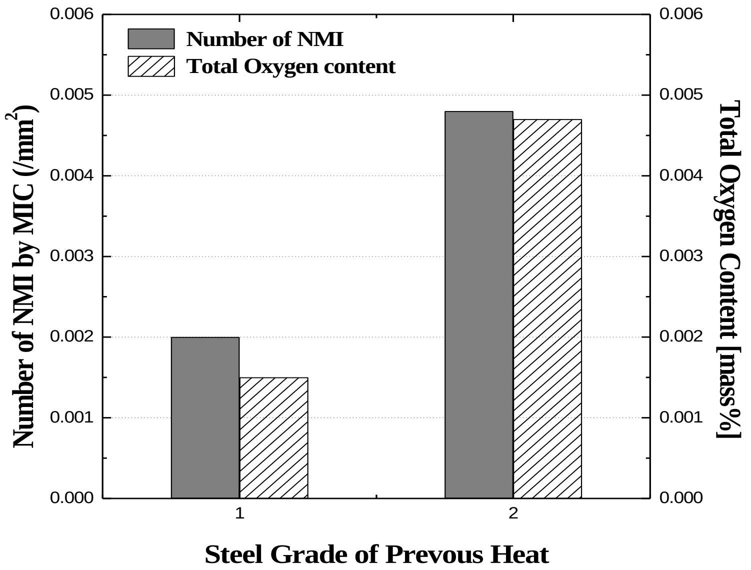

Figure 26: 1) Lower Si-content steel grade – ORVAR2M arrangement and 2) ORVAR2M – ORVAR2M arrangement

4.3 Removal of non-metallic inclusions[20]

The change of inclusion characteristics, the change in sulphur, hydrogen and nitrogen during vacuum degassing have been investigated in an earlier work at Uddeholm[27-28]. These studies indicate that the first 15 minutes are very important for the removal of impurities.

4.3.1 New stirring praxis during vacuum treatment

In Figure 27 the result from modified vacuum treatment can be observed. DM inclusions vary in size between 5.2-11.3µm, DH between 11.3-22.4µm and DP>22.4µm. The plot shows the amount of removed inclusions / mm^2 during the vacuum treatment. Furthermore, an increased number

[19] K. Malmberg, M. Nzotta, M. Andersson and P.G. Jönsson, "*Optimization of secondary metallurgical process parameters to decrease the number of large non-metallic inclusions in tool steel*", JK Technical Report TO23-139 2011.

[20] J. Björklund, *"Thermodynamic aspects on Inclusion Composition and Oxygen Activity during Ladle Refining"*, Doctoral Thesis, KTH, Stockholm, 2008.

reflects a more effective inclusion removal. The amount of DM inclusions is very scattered, while it can clearly be seen that the DH and DP inclusion removal increases with the decreased stirring rate. The DM inclusions are small and are easily influenced by the streams of molten steel in the melt. This makes them hard to control and gives a scattered result. However, the bigger DH and DP inclusions are bigger and therefore less effected by the melt movement. Furthermore, the DH and DP inclusions can more easily float and make contact with the slag.

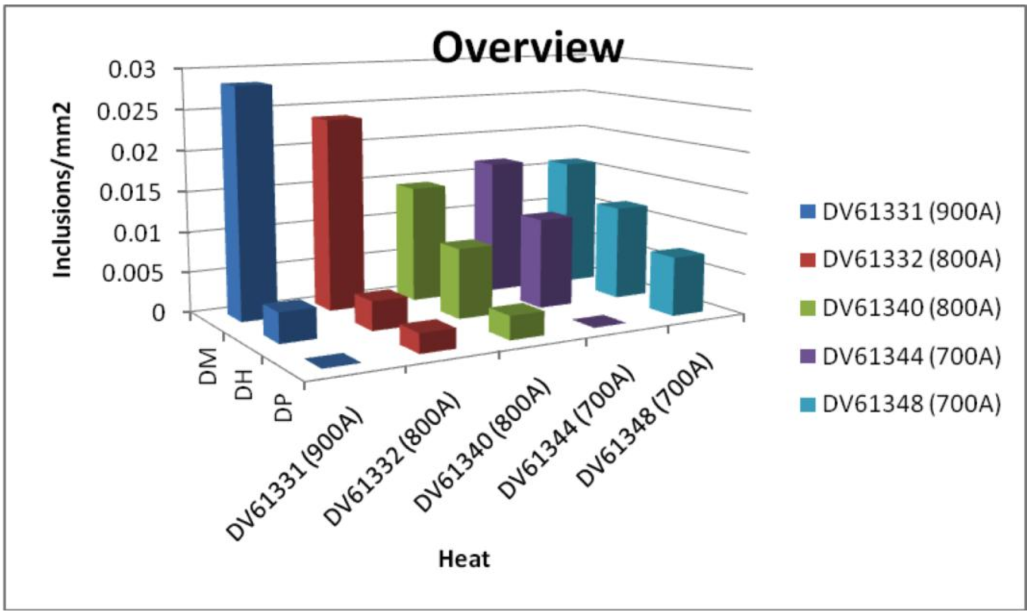

Figure 27: The amount of removed inclusions /mm^2 during the vacuum treatment (trials 1-5)

The amount of DM inclusions is scattered, while it can clearly be seen that the DH and DP inclusion removal increases with the decreased stirring rate. The DM inclusions are small and are easily influenced by the streams of molten steel in the melt. This makes them hard to control and gives a scattered result. However, the bigger DH and DP inclusions are bigger and therefore less effected by the melt movement. Furthermore, the DH and DP inclusions can more easily float and make contact with the slag.

4.3.2 Changing stirring praxis after vacuum treatment

The main objective was to study the effect of a changed stirring praxis after vacuum degassing, on the inclusion characteristics. More specifically during the slow stirring period prior to ingot casting. From earlier trials several experiences were obtained and some conclusions were drawn. Thus, it was decided that the following process parameters (besides the slow stirring parameters) should been controlled and monitored.

Initial silicon content of steel

Tap [Si] from EAF furnace was set to a maximum level to avoid excessive FeSi additions at tapping

De-slagging and carry-over of EAF slag

To support the visual observation of de-slagging an IR- Camera was used to monitor the operation.

Steel production logistics

The studied steel grade was ORVAR2M (high Si-content). The preceding steel grade in the ladle was alternating between low Si-grades and high Si-grades.

Ladle age

Was monitored.

Vacuum treatment practice

Since the changing of vacuum treatment praxis in campaign 1 had shown promising results regarding a decrease of D-type inclusions it was decided to choose the following vacuum degassing procedure for all heats in campaign 2: using 700A current during induction stirring during the first 15 minutes. This was followed by a lowered and controlled argon flow leading to a closed OE during the 15 last minutes of vacuum treatment.

In Figure 28 the amount of removed DM type inclusions / mm^2 during the final stirring can be seen. Furthermore, the use of argon in the final stirring process seams to increase the inclusion removal. However, as seen in Figure 29 and Figure 30 the use of Argon during final stirring does not seem to benefit the inclusion removal for DH and DP type of inclusions, since fewer inclusions are removed during the treatment. For both the DH and DP type inclusions, the removal of inclusions is lower than in the case of not using Argon. However, from these figures the results show an increase in inclusion removal by using only half the time for final stirring.

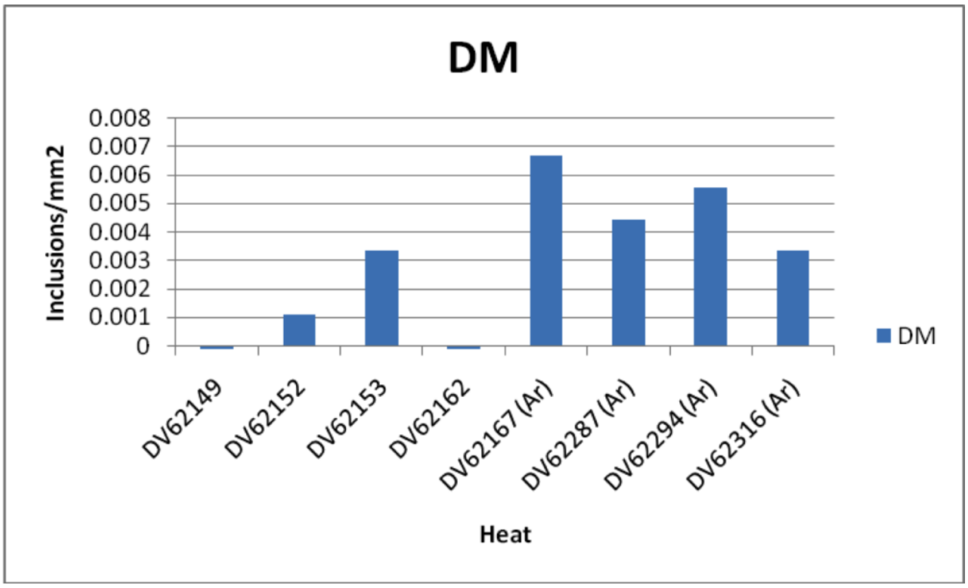

Figure 28: Amount of removed DM type inclusions/mm^2 during the final stirring period.

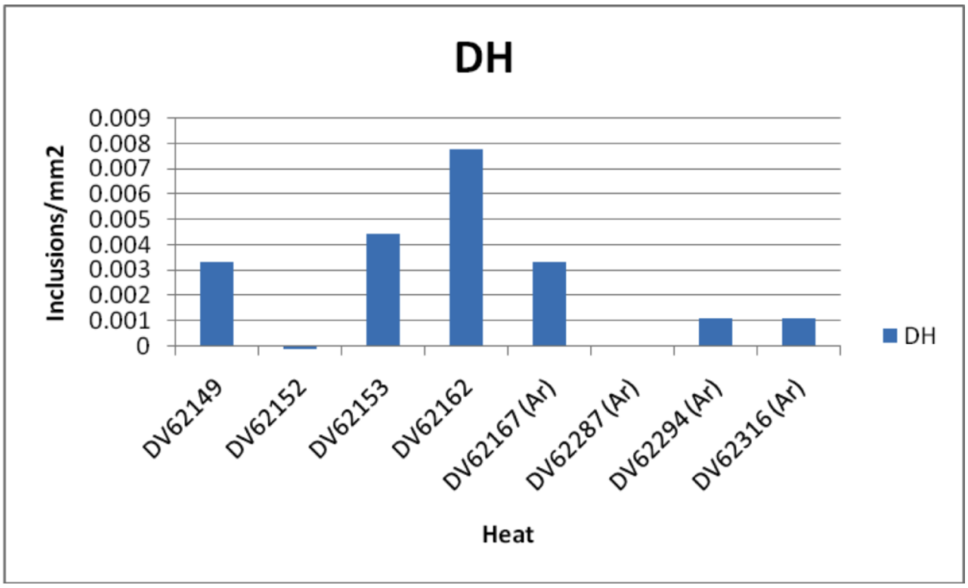

Figure 29: Amount of removed DH type inclusions/mm^2 during the final stirring period.

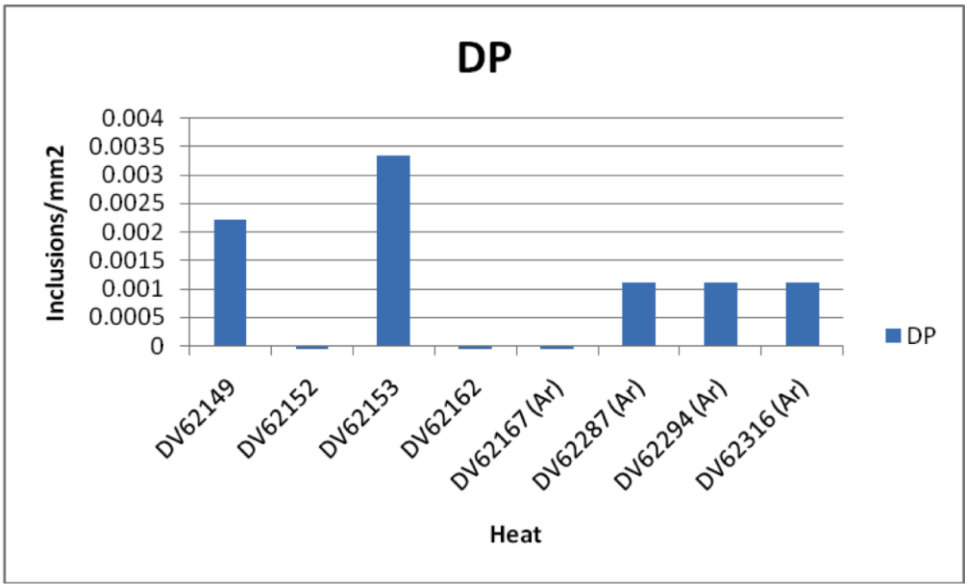

Figure 30: Amount of removed DP type inclusions / mm^2 during the final stirring period.

5 DISCUSSION

The contents of NMI may be presented in respect to the different process steps involved during steel production. The most important process steps are EAF-processing and logistics, deslagging, deoxidation, heating and vacuum degassing. The characteristics of the ladle slag play an important in all process steps during ladle treatment. The total production scheme may be illustrated as in Figure 31 for Uddeholm.

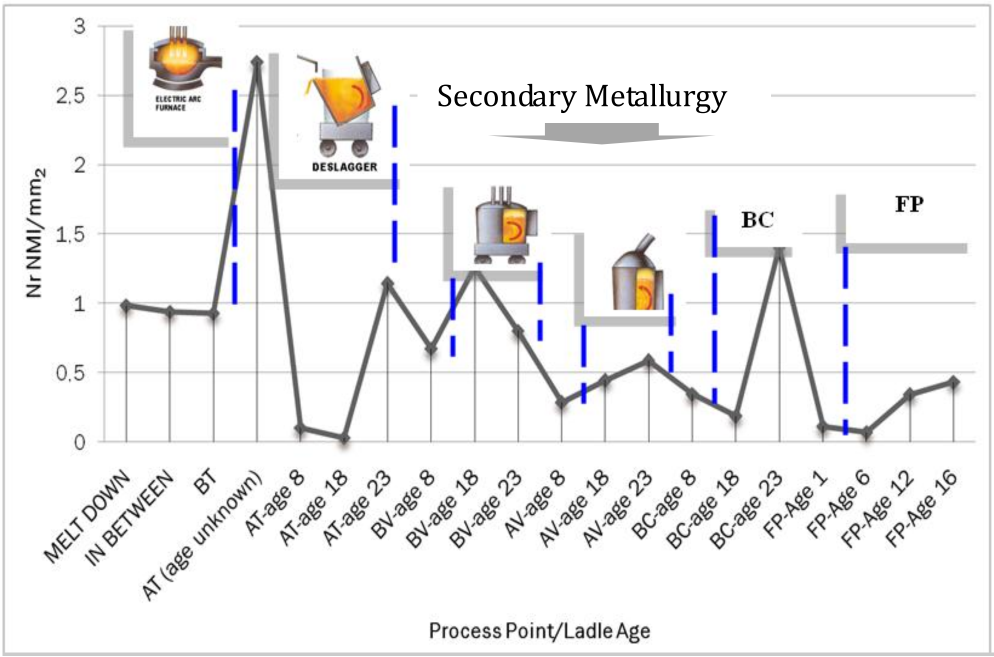

Figure 31: Evolution of NMI during different production steps at Uddeholm, where MD is Melt down, IN BETWEEN during treatment in the EAF, BT and AT stands for Before tap and after tapping of the EAF, BV: Before vacuum, AV: After vacuum, BC: Before casting and FP: End product. The numbers refer to the ladle age.

In the two series of experiments of tracer trials, only in the first heat of each series, BaO was added to the ladle slag as tracer. The fractions of BaO containing inclusions and the variation of the average BaO content in these two first heats indicated that the barium transfer from slag to the inclusions was very slow process. The big fractions of inclusions containing BaO in the steel of the second and third heats after BaO addition showed evidently that ladle glaze was responsible for a great number of non metallic inclusions generated during ladle treatment. The inclusions supplied by ladle glaze are relatively big. The sizes could be even larger than 100 µm. On the other hand, no evidence was found for the entrainment of slag to form inclusions.

Dipping MgO rods into liquid slag at 1873 K and thereafter cooling the rods at a predetermined cooling rate studied the formation of a slag glaze layer on dense and porous MgO rods. Three different slag compositions and three different cooling rates were employed. It was found that the phases formed upon cooling were mostly dependent on slag composition and to a minor extent the cooling rate. All the initially liquid slag was transformed into crystalline phases for all the samples except the ones terminated at 1573 K and one of the samples with high cooling rate. In addition, the three slags were equilibrated at 1773 K, 1673 K and 1573 K in order to get an understanding of the equilibrium phases and their relationship during cooling.

MgO refractory samples with attached ladle slag were taken from old ladles at two steel plants. The precipitated phases in the slag layers, and the cracks and pores of the refractory were examined. The phases found were $3CaO.Al_2O_3$ (and/or $12CaO.7Al_2O_3$), $MgO.Al_2O_3$ and CaO in the case of Ovako Steel and $3CaO.Al_2O_3$ (and/or $12CaO.7Al_2O_3$) and $2CaO.SiO_2$ in the case of Uddeholm. THERMOCALC calculations, on one hand showed similar trends of the phase precipitations, and on the other hand showed discrepancy. The absence of $12CaO.7Al_2O_3$ in the database could be the explanation of this discrepancy.

The detachment of ladle glaze and the chemical transformations of oxide solution in the MgO matrix were investigated. After 120 minutes of reaction with liquid steel, the infiltrated layer of ladle glaze still remained on the surface of refractory samples. This observation showed evidently that the ladle glaze could be the source of inclusions continually during the ladle treatment. The results also explained why the infiltrated liquid oxide could supply inclusion to the steel after two heats.

Trials were carried out using the same ladle to examine the effect of ladle slag on the number of non-metallic inclusions in the next heat. Steel and slag samples have been taken after the vacuum station of ladle treatment for the chemical composition, also the final product steel samples were analysed for the number of non-metallic inclusions. The number of non-metallic inclusions and the difference between total oxygen content and dissolved oxygen content of steel samples were carefully compared. Figure 32a presents the number of non-metallic inclusions per unit area plotted as a function of SiO_2 content of previous heat's slag after vacuum step. The difference between total oxygen content and dissolved oxygen content of steel samples with SiO_2 content of previous heat's slag after vacuum step is shown in Figure 32b. These two figures obviously show that the increase of SiO_2 content of previous heat's ladle slag increases the number of non-metallic inclusions. Other components of ladle slag, Al_2O_3, CaO and MgO, were also employed for this examination. Only SiO_2 had a significant effect.

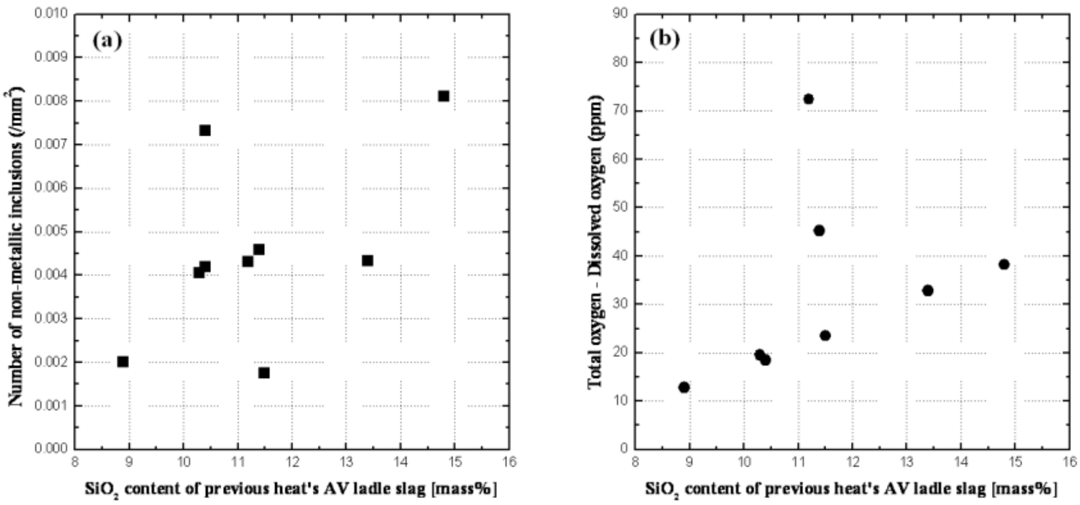

Figure 32: The effect of SiO_2 content of previous heat's ladle slag
(a) Plot of the number of non-metallic inclusions per unit area,
(b) Plot of the difference between total oxygen and dissolved oxygen of steel sample

It is found that the number of inclusions increases with SiO_2 content of previous heat' ladle slag. The formation of $2CaO.SiO_2$ followed by dusting (as found in the laboratory study) is believed to be the reason for the effect of SiO_2 content in the previous heat. To minimize the amount of inclusions it is crucial to reduce the amount of remaining EAF slag. The results obtained at Uddeholm indicate that by careful control of the SiO_2 content in the slag, the number of inclusions bigger than 10µm can be considerably reduced.

The accordance of the laboratory cold model study using Ga-In-Sn metal and industrial results suggests that the entrainment of slag into the steel bulk around the open-eye cannot be considered as the major contribution to inclusion formation.

The present results also indicate that the increase of argon flow rate would not improve the inclusion removal since the plume will bring up more inclusions and at the same time a smaller fraction of inclusions will meet the slag. The larger vertical velocities close to the ladle wall are associated with higher argon flow rate. The momentum of the liquid steel would enhance the flushing off of tiny pieces in the refractory matrix of the ladle wall. This would be an important source of non-metallic inclusions. Too high argon flow rate would possibly result in slag-metal emulsification at the slag-metal-refractory T joint, which would also form inclusions.

6 CONCLUSIONS

In the present project the focus has been on the formation and separation of inclusions during secondary metallurgy. As earlier mentioned both the performance of the deslagging as well as the amount of SiO_2 in the ladle slag have been investigated with respect on their impact on the number of inclusions.

The performance of the deslagging has as shown a direct impact on the formation of inclusion entitled to reoxidation from the presence of furnace slag with a high oxygen potential.

From the results is shown that the silicon content of the previously produced steel grade has a strong impact on the number of NMI. This implies that the logistics e.g. production planning may effect the formation of inclusions. If several steel grades with high silicon content are produced in sequence this will have a negative effect on the number of inclusions due to a high content of SiO_2 in the ladle slag. This high silicon content in the slag may increase the negative effect of ladle glaze on the formation of inclusions.

Finally optimization of the stirring during vacuum and after vacuum has shown promising results decreasing the number of inclusions.

6.1 Potential source for exogenous inclusions

Ladle slag attached to the refractory material from the earlier heat has previously been reported as an important source of inclusion formation in steel. The present results show that the slag lining reactions can indeed be a potential source for the exogenous inclusions during ladle treatment. The following mechanisms could be expected.

(i) The glassy phase with solid particles embedded within it is peeled off due to heavy stirring practice and is entrained in the steel.

(ii) Physical detachment of solid particles without any continuous glass phase.

(iii) Dusting and cracks in the solidified layer create particles of small sizes that might be entrained in the liquid steel in the next heat.

It should be pointed out that the continuous glassy layer would be melted directly when the molten steel is tapped into the ladle and separated to the top slag. On the other hand, the liquid phase inside the pores of the MgO matrix might have good opportunity to remain under the surface layer. Some of the solid particles encountered in this study have a quite high melting point, and some of them have a melting point much lower than the liquid steel. For example, $12CaO.7Al_2O_3$ that is found in most samples in the "multi phase region" has a melting point of 1673 K, which implies that this phase will melt as the molten steel is tapped into the ladle. This complicates further the situation. Nevertheless, too strong stirring during ladle treatment would possibly entrain some tiny particles, droplets and even their combination from the MgO matrix. Again, bigger particles and droplets would float up, while the droplets and particles in micro sizes would stay in the steel as exogenous inclusions. Since the pores of the MgO matrix could be very small, the continuous entrainment of tiny particles or droplets is favourable.

The phases found were $3CaO.Al_2O_3$ (and/or $12CaO.7Al_2O_3$), $MgO.Al_2O_3$ and CaO in the case of Ovako and $3CaO.Al_2O_3$ (and/or $12CaO.7Al_2O_3$) and $2CaO.SiO_2$ in the case of Uddeholm. THERMOCALC calculations, on one hand showed similar trends of the phase precipitations, and on the other hand showed discrepancy. The absence of $12CaO.7Al_2O_3$ in the database could be the explanation of this discrepancy.

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6.2 Realisation of industrial objectives

Uddeholm stated an industrial objective for the project to reduce the number of specified classes of NMI summarized in Table 1. In Figure 33 the overall results from Uddeholm is presented and it is clear that all the industrial goals were achieve except for the B class NMI size range (11.3-22.4 µm). It may be concluded that minimizing the reoxidation before casting is necessary to meet this final goal.

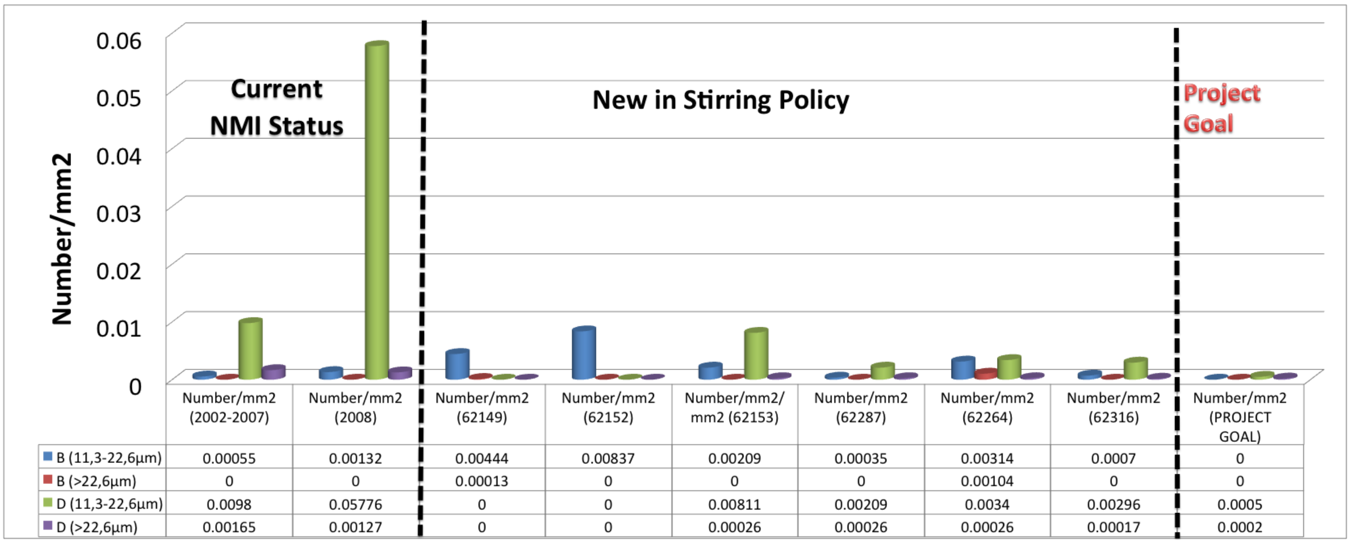

Figure 33: Overall results from Uddeholm.

In Table 12 the outcome of the project is reviewed with respect of the original industrial goal of the project.

Table 12: Outcome of the project for Uddeholm.

NMI Classification	NMI 11.3-22.4 µm (N/mm^2)	NMI > 22.4 µm (N/mm^2)
B class	Goal not reached	Goal reached=0
D class	Goal reached=0.005	Goal reached=0.0002

Ovako has as early mentioned work with improving the approval rate for micro-inclusions tested by a new method from 50 % to higher than 95 % during the scope of the project. They have now reported that the current approval rate is higher than 98 % for micro-inclusions partly as a result of activities and the knowledge gained within the framework of the present research project.

7 FUTURE RESEARCH

- Longer campaigns of changed vacuum praxis to confirm the results from the present project.
- Further experiments during final stirring using lower EMS stirring combined with Ar, only a lower EMS stirring or only the use of Ar purging.
- Implementation of the IR-camera for control of deslagging and soft Ar purging during final stirring period in production.

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9 APPENDICES

1. Project organisation and participants
2. Publications
3. Other results and knowledge transfer
4. Programme description

PROJECT ORGANISATION AND PARTICIPANTS

Research Committee
JK 23045

Project period
2007-07-01 – 2010-12-31

Chairman

Alf Sandberg	Uddeholms AB

Project Coordinator

Jonas Alexis	Swerea MEFOS AB

Research Manager

Lars-Henrik Österholm	Jernkontoret

Industrial committee members

Hongliang Yang	ABB AB
Arto Gaidarzjiskij*	Calderys Nordic AB
Tuomas Antola	FNSteel OyAB
Fredrik Persson	Höganäs AB
Therése Sterneland*	Outokumpu Stainless Avesta Works
Johan Björklund*	Sandvik Materials Technology
Lars Karlsson*	Sandvik Materials Technology
Mats Söder	Scana Steel Björneborg AB
Lennart Gustavsson*	SSAB EMEA Luleå
Sten Ångström*	SSAB EMEA Luleå
Fredrik Dahl*	SSAB EMEA Oxelösund
Jenny Hurtig	SSAB EMEA Oxelösund
Niklas Kojola*	SSAB EMEA Oxelösund
Anders Gustafsson	Ovako Bar AB
Robert Eriksson	Ovako Hofors AB
Mselly Nzotta	Uddeholms AB

Associated researchers

Margareta Andersson	KTH Tillämpad processmetallurgi
Johan Björklund*	KTH Tillämpad processmetallurgi
Lage Jonsson*	KTH Tillämpad processmetallurgi
Pär Jönsson	KTH Tillämpad processmetallurgi
Andrey Karasev*	KTH Tillämpad processmetallurgi
Kristofer Malmberg*	KTH Tillämpad processmetallurgi
Hamid Doostmohammadi*	KTH Tillämpad processmetallurgi
Du Sichen	KTH Mikromodellering
Jimmy Gran*	KTH Mikromodellering
Mikael Thunman*	KTH Mikromodellering
Johan Björkvall	Swerea MEFOS

* Did not participate during the whole project period

PUBLICATIONS

1 Technical reports

M. Thunman, J. Gran, M. Song, M. Nzotta and Du Sichen, "*Study of slag-line reaction and optimization of the same with respect to minimize calcium aluminate inclusions for ladle treatment*", JK Technical Report TO23-137 (2011).

H. Doostmohammadi, M. Andersson, A. Karasev, P.G. Jönsson and M. Nzotta, "*Initial trials to study slag carry over and inclusion characteristics at Uddeholms AB*", JK Technical Report TO23-138 (2011)

K. Malmberg, M. Nzotta, M. Andersson and P.G. Jönsson, "*Optimization of secondary metallurgical process parameters to decrease the number of large non-metallic inclusions in tool steel*", JK Technical Report TO23-139 (2011).

J. Alexis and J. Björkvall, *"Omrörningsstrategier för en optimerad skänkmetallurgiprocess"* ("*Stirring strategies for an optimized ladle metallurgy process*"), JK Technical Report TO23-140 (2011). In Swedish.

J. Alexis, *"Reducerad generering av inneslutningar – Skänkålder"* ("*Ladle age effects on generation of inclusions*"), JK Technical Report TO23-141 (2011). In Swedish.

2 Reviewed publications

M. Thunman and Du Sichen, *"Origins of non-metallic inclusions and their chemical development during ladle treatment"*, Steel Research International, 2008, vol. 79, pp.124-132.

J. Gran, M. Thunman and Du Sichen, *"Effects of slag composition and cooling rate on the formation of glaze on MgO refractory"*, Ironmaking and Steelmaing for publication, 2010, vol.37, pp.27-34.

M. Thunman, J. Gran and Du Sichen, *"Slag-refractory reaction during ladle refining and teeming"*, Steel Grips, 2009, vol. 7, No. 2, pp. 129-135

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M. Song, M. Nzotta and Du Sichen, *"Study of the formation of non-metallic inclusions by ladle glaze and the effect of slag on inclusion composition using tracer experiments"*, Steel Research International, 2009, vol.80, pp.753-760.

M. Song, L. Ragnarsson, M. Nzotta and Du Sichen, *"Mechanism Study on the Formation and Chemical Development of Calcium Aluminate Inclusions Containing SiO2 in Ladle Treatment of Tool Steel"*, Ironmaking and Steelmaking, in press, 2010.

H. Doostmohammadi, M. Andersson, A. Karasev and P.G. Jönsson, *“Use of Computational thermodynamic Calculations in Studying the Steel/Slag equilibrium during Vacuum Degassing”*, Steel Research International, Vol. 81, No. 1, 2010, pp. 31-39.

H. Doostmohammadi, A. Karasev and P.G. Jönsson, *“A Comparison of a Two-Dimensional and a Three-Dimensional Method for Inclusion Determinations in Tool Steel”*, Steel Research International, Vol. 81, No. 5, 2010, pp. 398-406.

H. Doostmohammadi, M. Andersson, A. Karasev and P.G. Jönsson, *“Thermodynamic and Experimental Considerations of the Inclusion Characteristics during Vacuum Degassing of Tool Steel”*, ISBN 978-91-7415-520-4

3 Dissertations

J. Björklund, *"Thermodynamic aspects on Inclusion Composition and Oxygen Activity during Ladle Refining"*, Doctoral Thesis, KTH, Stockholm, 2008.

M. Thunman, *"Formation of inclusions and their development during secondary steelmaking"*, Doctoral Thesis, KTH, Stockholm, 2009.

H. Doostmohammadi, *"A study of slag/metal equilibrium and inclusion characteristics during ladle treatment and after ingot casting"*, Doctoral Thesis, KTH, Stockholm, 2009.

J. Gran, *"Some Fundamental Aspects Concerning Secondary Steelmaking"*, Doctoral Thesis, KTH, Stockholm 2011.

OTHER RESULT AND KNOWLEDGE TRANSFER

Work-shops

Mid-term work-shop 11 March 2009 at KTH, Stockholm.

End work-shop 8 December 2010 at Jernkontoret, Stockholm.

Conferences

Jonas Alexis: Presentation at Programme Conference Steel Research Programme, 10 June 2009, Borlänge.

Robert Eriksson: Presentation at Meeting of Metallurgists (Metallurgmötet), 19 January 2011, KTH, Stockholm.

Pär Jönsson: Presentation at Ladle Metallurgy Days (Skänkmetallurgidagar), March 15-16, Oxelösund.

Jonas Alexis: *"Mathematical Modeling on Stirring for an Optimized Ladle Furnace Process"*, AISTech 2011, Indianapolis, USA.

Presentations and discussions of achieved results during meetings with the Research Committee (11 meetings) and with Research Area JK23040 Ladle Metallurgy.

Annex 4

Strategiskt Stålforskningsprogram för Sverige 2007-2012

Svensk stålindustris marknadsledande position inom ett antal högt specialiserade nischer har sin grund i en konsekvent och långsiktig satsning på forskning. VINNOVA och Jernkontoret utarbetade 2006 på regeringens uppdrag ett gemensamt forskningsprogram, Strategiskt stålforskningsprogram för Sverige 2007-2012 (Stålforskningsprogrammet), som syftar till att behålla och stärka denna position och samtidigt förbättra miljöprestationen. Programmet är ett branschforskningsprogram vars mål är att förbättra den svenska stålindustrins konkurrenskraft, vilket också är skälet till att programmet administreras av Jernkontoret.

Stålforskningsprogrammet omfattar 245 miljoner kronor varav VINNOVA finansierar hälften. Resterande medel kommer från industrin, som kontanta medel eller i form av naturainsatser, t.ex. personal, forskningsresurser och experiment i produktionsanläggningar.

Branschens inflytande över programmet utövas genom en programstyrelse bestående av representanter för stålföretagen, Jernkontoret och VINNOVA. Programstyrelsen tar beslut om vilka projekt som ska beviljas medel. Prioritering av projektförslagen och den vetenskapliga granskningen av dessa handläggs av en grupp bestående av ordförandena i Jernkontorets teknikområden och adjungerade representanter från forskningsutförarna. Dessutom görs en extern utvärdering av ansökningarna som är vägledande för beslutet. Utlysningsprocessen administreras av Jernkontoret.

Sammanlagt 30 projekt har beviljats anslag inom programmet. Forskningen genomförs i nära samarbete mellan järn- och stålindustrin, stålbranschens forskningsinstitut Swerea MEFOS och Swerea KIMAB, samt universitet och högskolor med utbildning och forskning inriktad på ståltillverkning och handlar såväl om att utveckla nya produkter som att effektivisera och miljöanpassa produktionsprocesserna. I vissa projekt deltar även kunder och leverantörer till stålindustrin. Det praktiska arbetet utförs inom forskningskommittéer inom Jernkontorets gemensamma forskning. I forskningskommittéerna deltar representanter för industriföretagen och forskningsutförarna. I arbetet tillämpas Jernkontorets regler för den gemensamma forskningen.

Programmets projekt täcker fyra ämnesområden:

- **Utveckling för hållbar tillväxt**
  från minskade utsläpp till högpresterande stål med minskad materialåtgång.
- **Morgondagens material och tillverkningsmetoder**
  från utveckling av lättare och starkare stål till hur materialet formas och sammansätts.
- **Avancerad modellering**
  från modellering på atomär nivå till studier av hur stålet beter sig i olika applikationer.
- **Förbättrad processteknik**
  från förbättrade mätmetoder till effektivare processteg.

Kraven på projekten inom Stålforskningsprogrammet är en tydlig förankring i industrin, och att programmet som helhet täcker hela värdekedjan, från råvaror till produkter. Huvuddelen av forskningsmedlen är avsedd för projekt med en tydlig anknytning till konkreta industriella behov, vars resultat relativt snabbt kan implementeras i produktionen. Resterande del av forskningsmedlen kan användas för så kallade innovativa forskningsprojekt med betydligt högre risk både vetenskapligt och i fråga om de kommersiella möjligheterna för stålindustrin på kort och medellång sikt.

THE SWEDISH STEEL PRODUCERS' ASSOCIATION

Since its foundation back in 1747, Jernkontoret has been owned jointly by the Swedish steel companies. Jernkontoret represents Sweden's steel industry on issues that relate to trade policy, research and education, standardisation, energy and the environment as well as taxes and levies. Jernkontoret also manages the joint Nordic research in the steel industry. In addition, Jernkontoret draws up statistical information relating to the industry and carries on research into the history of mining and metallurgy.

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