Technical University of Leoben

Science 4 Technology – Poster Exhibition 2026

Department: Metallurgy

Chair: Ferrous Metallurgy

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Investigation of the reoxidation behaviour of hot briquetted iron (HBI) samples produced on a laboratory scale

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Introduction and motivation

The expected increased of direct reduction processes implies the necessity of using iron ores with lower quality (with iron content ranging from 60 to 65 wt.%) that are currently used for the blast furnace (BF) process, since high-grade pellets will not be available in sufficient quantities to cover the global demand. Unlike in the BF process, gangue cannot be partially separated as slag during direct reduction. Instead, it is transferred to subsequent processes, influencing the quality of the final steel product. However, clean steel breakthrough technologies could make zero-carbon steelmaking possible by 2030 [1, 2]. The potential and use of DRI resulting from DR processes using low-grade ores must be examined, while also considering H_2 as a future reductant. To investigate the reoxidation behavior of different HBI qualities, the three-step process (see Fig. 1) was designed using existing equipment at AMMR and CRM (reduction step), at TU BAF (hot briquetting step), and the storage system developed at TU Leoben to realize defined conditions (for the re-oxidation studies).

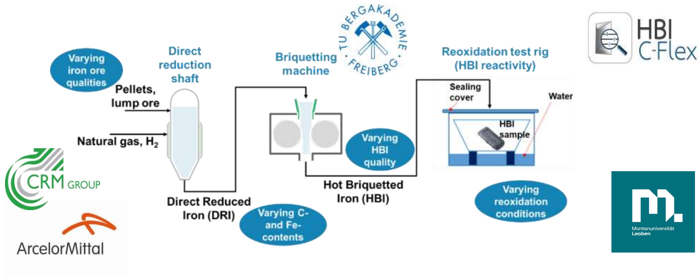


Fig. 1: The lab-scale HBI production and reoxidation comprises the steps: 1.) reduction, 2.) briquetting and, 3.) reoxidation.

Experimental setup

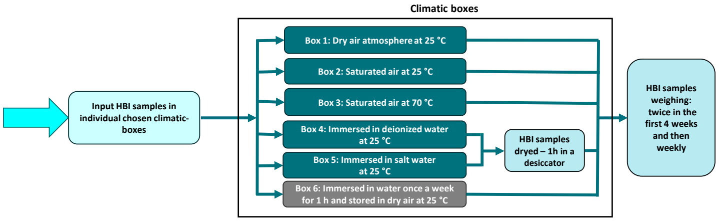


Fig. 2: Schematical illustration of the reoxidation tests with HBI samples.

The reduction tests carried out in CRM's HUGE reactor under defined reduction conditions aim to produce sufficient quantities of DRI-Pellets for the briquetting trials. In the preliminary stages of hot briquetting DRI pellets, TU BAF developed a methodology for briquetting trials in inert atmosphere under consultation of TU Leoben. Different briquetting conditions were set according to the relevant industrial environment to validate HBI. Each test examined the effect of briquetting parameters, such as compression pressure and temperature, on the apparent density of the HBI in relation to the material parameters.

To examine the reoxidation (ReOx) behaviour of the HBI-samples, an experimental plan was developed as follows. The ReOx behaviour of the HBI-samples is investigated under six different storage conditions for a period of 12 weeks, whereby the mass increase during the storage period and further analysis of the reoxidized samples are used to assess the tendency of reoxidation. To realize the defined storage conditions, the samples are placed in opened and sealed boxes, which in turn are stored in climate chambers to ensure a defined conditions are intended to reflect possible extreme cases during the storage and transport of industrial HBI (see Fig.2).

Results & conclusion

The first reduction test with DR grade pellets was aimed at generating sufficient quantities of H_2-DRI for the briquetting trials. In the first trial, HBI samples were produced at a compression temperature of 900 °C and a pressure of 300 Mpa to achieve an apparent density of 5 g/cm³. Tab. 1 shows the results of the mass balance of the dried samples before and after the ReOx tests. The conditions in Box 5 lead to the highest mass gain, followed by Box 2 and Box 6.

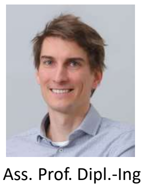
This first results show that the different conditions in the six boxes have an influence on the mass gain and thus on the reoxidation of the HBI samples. With the help of further analyses, the tendency of reoxidation is examined in detail and used to interpret the mass gains.

Table 1: Reoxidation conditions and mass gain of 10 HBI samples with a mass of ca. 1.5 kg in total in each box after a storage period of 12 weeks.

Box	Atmosphere [-]	Temperature [°C]	Mass increase [%]
1	Dry air atmosphere	25	0.014
2	Saturated air	25	0.914
3	Saturated air	70	0.269
4	Immersed in deionized water	25	0.367
5	Immersed in salt water	25	1.269
6	Immersed in water once a week for 1 h and stored in dry air	25	0.897

References

[1]. European Commission (EC): The Green Deal, COM (2019) 640 final, 2019.
[2]. EC: 'Fit for 55' - delivering EU's 2030 climate target on way to climate neutrality, COM (2021) 550, 2021.



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HBI C-Flex

Move mountains

Domestic ore for green steel

Processing and reduction of carbonate iron ore

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Motivation: For its steel production, voestalpine is supplied with domestic, carbonate-based iron ore by VA Erzberg GmbH. The annual delivery volume amounts to approximately 3.0 million tons . This quantity of ore is also intended to be used in future steel production based on new emerging technologies. Despite ongoing development efforts, there is still limited understanding of how the specific properties of domestic iron ore affect the performance and applicability of promising steelmaking processes such as hydrogen-based fluidized-bed reduction technologies. The objective of the research is to contribute to enabling low-carbon steel production using domestic ore in the future.

The research work focusses on the processing, calcination and hydrogen solid state reduction of the carbonate iron ore.

Raw ore concentrate

The ore concentrate originates from Erzberg, Styria. The valuable mineral is a siderite variety (Fe(Mg,Mn)CO_3), accompanied mainly by ankerite and various silicate minerals. The concentrate has a particle size of < 10 mm and an iron content of 33-34 wt%.

Calcination in CO_2

The ore concentrate needs thermal treatment called calcination. The ore is heated to temperatures up to 900 °C. During this process Siderite, one example among several carbonate mineral phases, decomposes, forming iron oxides (Fe_2O_3 and Fe_3O_4) and gaseous carbon dioxide (CO_2). This step is necessary to produce a concentrated stream of CO2 that can be further processed.

Calcined ore

After comminution and calcination the ore consists of fine, porous particles with a size < 0.5 mm. The iron contained is now mostly present in oxidized form as Fe_2O_3 and Fe_3O_4, with the ratio depending on the calcination atmosphere. The iron content rises to about 50 wt%.

Reduction

Hydrogen (H_2) is used to reduce the iron oxides in their solid state to metallic iron. The reduction process takes place at elevated temperatures of 600 to 800 °C in a fluidized bed reactor, in which the iron ore fines can be processed without prior energy-consuming agglomeration.

Direct reduced iron (DRI)

The resulting DRI reaches iron contents of up to 65 wt%. The DRI can either undergo further processing or be directly charged into a electric smelting furnace to produce a pig-iron-like product suitable for downstream steelmaking routes.

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Research partners

Thermodynamic-kinetic characterization of solidification phenomena in lightweight high-Mn and medium-Mn steels

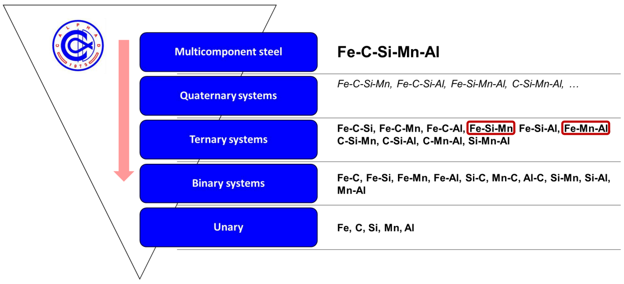
Introduction

This research field is part of an FWF-funded project carried out in collaboration between the Technical University of Leoben and the Silesian University of Technology. The work in Leoben focuses on the effects of higher Mn/Si/Al contents and increased trace elements (Cu, Sn), which results from recycling processes, on equilibrium phase transformations and micro-segregation phenomena. In Gliwice, the hot formability and ductility, mechanical properties and high-temperature brittleness of these advanced steels are being evaluated in order to determine the best possible production parameters.

Introduction to the CALPHAD approach

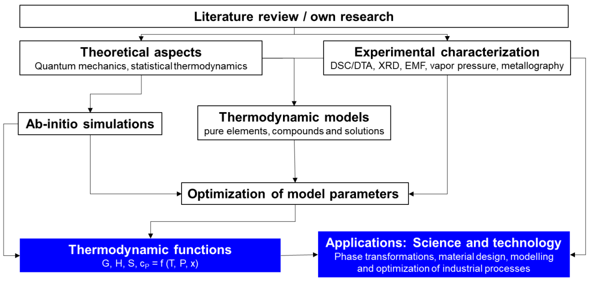
The CALPHAD method is based on hierarchically structured thermodynamic data, starting with pure elements and extending to binary and ternary systems. Critically evaluated literature data are used to model the Gibbs energy of stable phases, and own experimental results (e.g. phase transition temperatures from DTA measurements) are used to optimize and to increase the accuracy of the thermodynamic database.

Structure of a CALPHAD- type database Fe-C-Cu-Sn-P-S system



Multicomponent steel	**Fe-C-Si-Mn-Al**
Quaternary systems	*Fe-C-Si-Mn, Fe-C-Si-Al, Fe-Si-Mn-Al, C-Si-Mn-Al, …*
Ternary systems	Fe-C-Si, Fe-C-Mn, Fe-C-Al, Fe-Si-Mn Fe-Si-Al, Fe-Mn-Al C-Si-Mn, C-Si-Al, C-Mn-Al, Si-Mn-Al
Binary systems	Fe-C, Fe-Si, Fe-Mn, Fe-Al, Si-C, Mn-C, Al-C, Si-Mn, Si-Al, Mn-Al
Unary	Fe, C, Si, Mn, Al

CALPHAD assessment for binary and ternary systems



Literature review / own research

Theoretical aspects
Quantum mechanics, statistical thermodynamics

Experimental characterization
DSC/DTA, XRD, EMF, vapor pressure, metallography

Ab-initio simulations

Thermodynamic models
pure elements, compounds and solutions

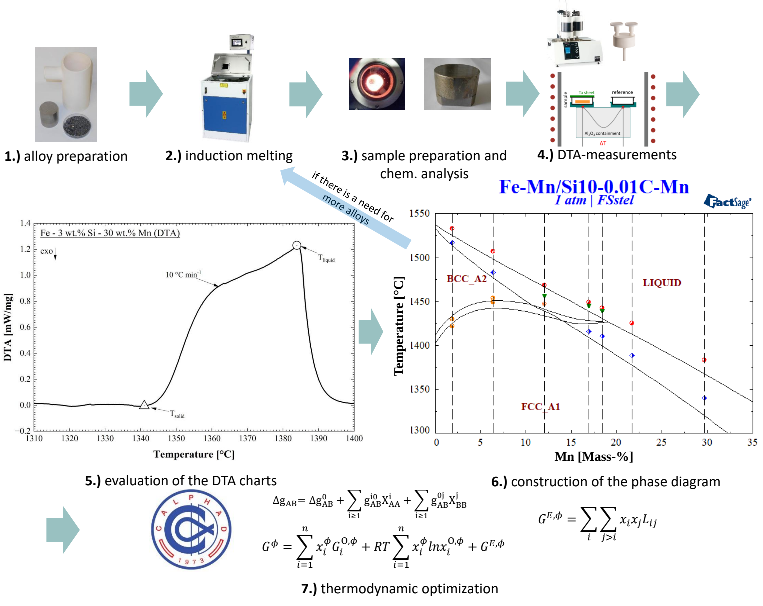
Optimization of model parameters

Thermodynamic functions
G, H, S, c_P = f (T, P, x)

Applications: Science and technology
Phase transformations, material design, modelling and optimization of industrial processes

Workflow - methodology

The in-house workflow from the production of binary, ternary and multi-component alloys (Fe-C-Si-Mn-Al) to measurement, evaluation and assessment of thermodynamic database is illustrated below.



1.) alloy preparation

2.) induction melting

3.) sample preparation and chem. analysis

4.) DTA-measurements

5.) evaluation of the DTA charts

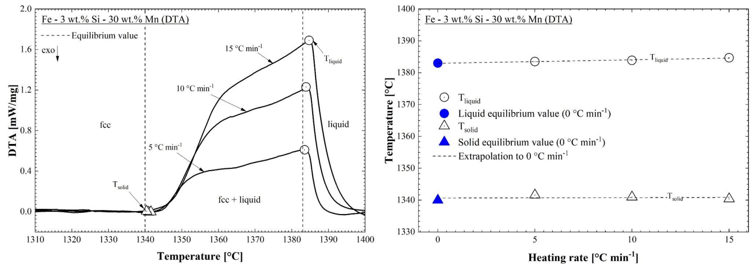
6.) construction of the phase diagram

$$\Delta g_{AB} = \Delta g^{0}_{AB} + \sum_{i\geq1} g^{i0}_{AB} X^{i}_{AA} + \sum_{i\geq1} g^{0j}_{AB} X^{j}_{BB}$$

$$G^{E,\Phi} = \sum_{i}\sum_{j>i} x_i x_j L_{ij}$$

$$G^{\Phi} = \sum_{i=1}^{n} x_i^{\Phi} G_i^{0,\Phi} + RT \sum_{i=1}^{n} x_i^{\Phi} \ln x_i^{0,\Phi} + G^{E,\Phi}$$

7.) thermodynamic optimization



DTA measurements of high-manganese steels are carried out at different heating rates (5, 10 and 15 K/min) in order to determine the equilibrium transformation temperatures by extrapolating back to 0K/min.

Summary and Outlook

Following the successful re-evaluation of the binary systems Fe,Si:*Va* and Fe,Mn:*Va* the ternary systems Fe,Mn,Si:*Va* and Fe,Mn,Al:*Va* still show significant deviations, which are currently investigated in detail. The aim is to create an experimentally verified, self-consistent database for the Fe,Mn,Si,Al:*Va*,*C* system.

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Research focus:

DSC/DTA measurement, CALPHAD method, solidification, casting of advanced steels, high-temperature behavior of Mn-alloyed steels

FWF Österreichischer Wissenschaftsfonds

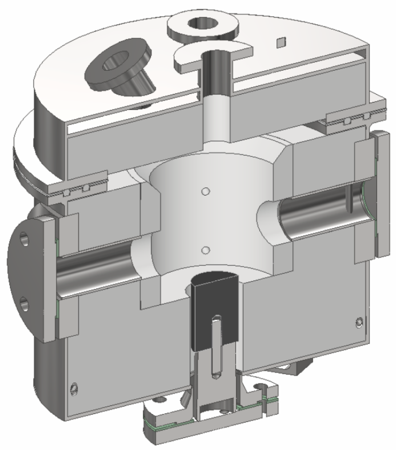
CHAIR OF FERROUS METALLURGY
MONTANUNIVERSITÄT LEOBEN

Politechnika Śląska

Feasibility of Red Mud Recycling via Hydrogen Plasma Smelting Reduction (HPSR)

Motivation

The iron and steel sector contributes about 7–9% of global CO_2 emissions, highlighting the need for low-carbon and circular production routes. At the same time, iron-rich residues such as red mud from aluminum production are mostly landfilled, causing resource loss and environmental concerns. Recovering iron from these wastes using hydrogen plasma smelting reduction offers a carbon-lean pathway that combines metal recovery with pollutant removal and supports more sustainable metallurgical processing.



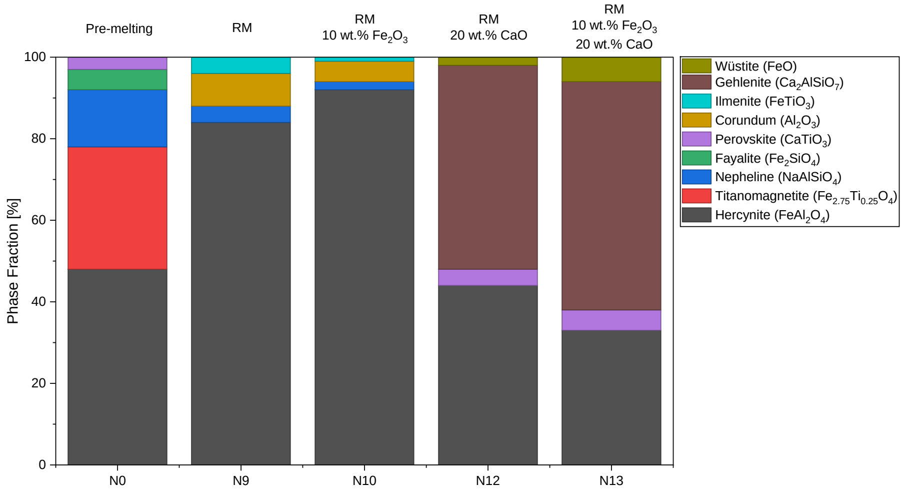
Cross-section of the laboratory reactor

Methods

Hydrogen plasma smelting reduction experiments were conducted in a laboratory-scale plasma reactor at the Chair of Ferrous Metallurgy. The study systematically assesses the effects of **hydrogen partial pressure** and **slag treatment requirements** at larger batch sizes to determine necessary adjustments for further process scale-up. Experiments were conducted under controlled conditions **with** and **without additives** (Fe_2O_3 and CaO). After each experiment, the resulting metallic, slag, and dust fractions were separated and measured gravimetrically. Phase evolution and **quantitative phase fractions** were identified using X-ray diffraction (**XRD**) analysis.

Summary

HPSR allows partial **recovery of metallic iron** from red mud and simultaneous removal of volatile contaminants (Cl, F, S, Na) through evaporation, producing metal droplets with purities up to **99.9 wt.% Fe**. Additive selection greatly influences the reduction pathway: without fluxes, iron stays bound in stable spinel phases, while **CaO-rich slags** destabilize phases and **enhance reduction**. Metallization degrees of 42–67% were achieved, demonstrating the technical feasibility of iron recovery via H_2 plasma treatment.



Quantitative XRD analysis with and without additives

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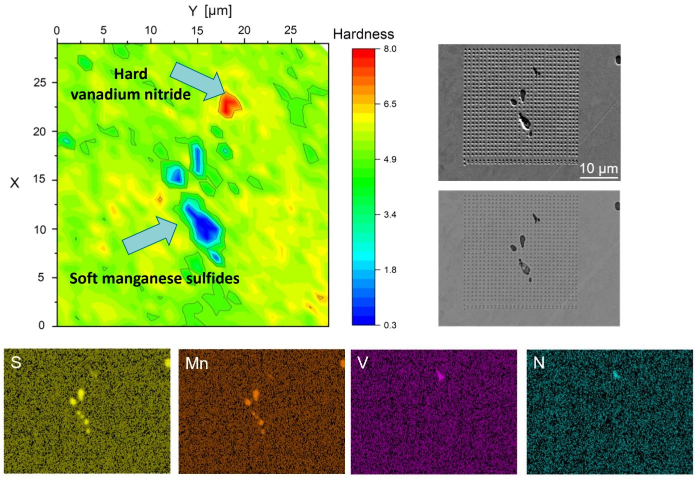
Deformability of Non-Metallic Inclusions

Influence of tramp elements and alkali additions on the plasticity of NMIs

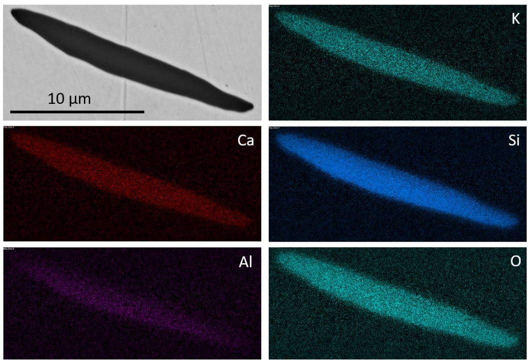
Non-metallic inclusions (NMIs) are phases which are inevitably formed during steelmaking processes. Usually, these phases consist of oxides, sulfides, and nitrides. Their size can vary between some nanometers to hundreds of micrometers. **Properties** of NMIs can differ significantly from those of the steel matrix. During forming processes as well as under dynamic loads in application, differences in **Young's Modulus** and **hardness** between NMIs and steel are critical, as low NMI deformability can lead to **material failure**.



Hardness and elemental mapping of NMIs

Deformability of NMIs heavily depends on their **chemistry**. It is well known that sulfides exhibit rather good deformability while **oxides** deform less with especially **low plasticity** of spinel types. One possibility to impact deformability is modification of NMIs using **alkali elements**. Furthermore, the chemistry of the steel itself can influence deformability, e.g. by increased precipitation of copper around NMIs leading to lower local deformability.

Sources:
J. Cejka et al., Steel Res. Int., (2026)
I. Gruber, Master's thesis (2024)
N. Preisser et al., Metall. Res. Technol., (2026)

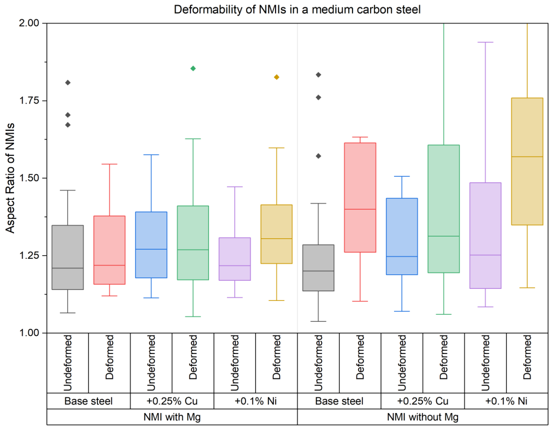


Elongated NMI with potassium

Mechanical properties of NMIs were assessed using two experimental techniques:

- **Nanoindentation:** measuring both hardness and Young's Modulus of NMIs, directly adjacent steel matrix and the bulk material.
- **Controlled deformation** of steel samples combined with SEM: evaluation of NMI deformability by analyzing the shape of a statistically significant number of NMIs before and after deformation.

On the left a **hardness mapping** of sulfides and a nitride and the corresponding SEM **elemental mappings** are depicted.



Comparison of deformability of different NMIs types with and without tramp elements in a medium carbon steel shown via their aspect ratio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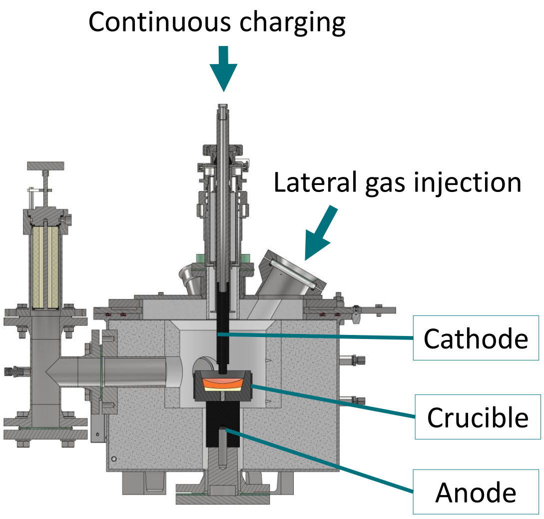
Influence of the Material and Hydrogen Injection Point on the Efficiency of the Hydrogen Plasma Smelting Reduction Process (HPSR)

Lukas Höcher, Daniel Ernst and Susanne K. Michelic

Motivation

The energy-intensive steel industry is responsible for 7 % of total emissions. Amongst other possible pathways, the hydrogen plasma smelting reduction (HPSR) process aims to limit this environmental impact by eliminating mainly Scope 1 emissions. This research aims to find optimal input parameters for hydrogen and iron ore to further enhance the design for a fully commercial plant of the future.



Overview of the laboratory reactor

Source: HPSR process control

Experimental Setup

The laboratory reactor operates an **electric arc** between the cathode and the crucible. Modes of **operation** highly **depend** on the iron ore **charging**.

Modes of operation:

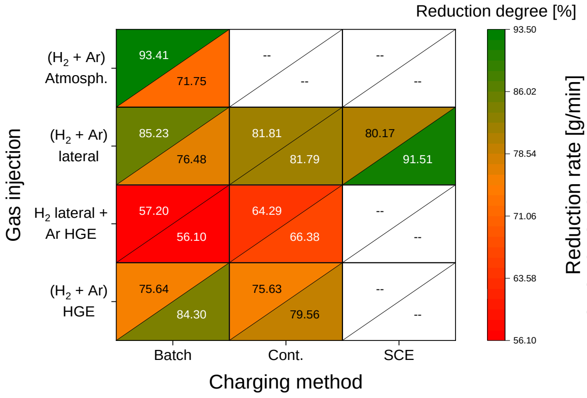
- Batch,
- Continuous charging and
- Self-consuming iron ore-based electrode (SCE).

Gas injection possibilities:

- Through the hollow graphite electrode (HGE),
- By a lateral injection lance and
- Via the reactor roof to set the desired atmosphere.

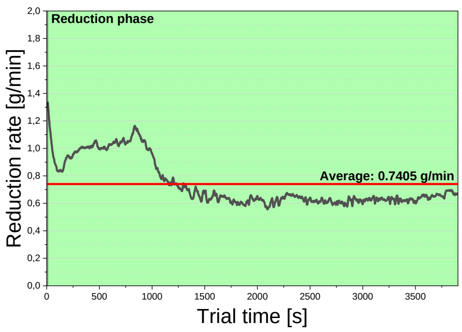
Results and summary

The **highest reduction degrees** were achieved by a **conjoint gas injection**, regardless of its input location.
Iron ore **charging method** has only a **secondary influence** on the reduction characteristics as it mainly **impacts** the **reduction rate** but not the resulting end reduction degree.



Gas injection	Batch	Cont.	SCE
$(H_2 + Ar)$ Atmosph.	93.41 71.75	-- --	-- --
$(H_2 + Ar)$ lateral	85.23 76.48	81.81 81.79	80.17 91.51
H_2 lateral + Ar HGE	57.20 56.10	64.29 66.38	-- --
$(H_2 + Ar)$ HGE	75.64 84.30	75.63 79.56	-- --

Achieved reduction degrees across all experiments



Exemplary trend of reduction rate

Source: Höcher, L. (2025): Influence of the material and hydrogen injection point on the efficiency of the hydrogen plasma smelting reduction process

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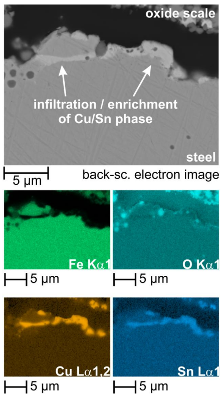
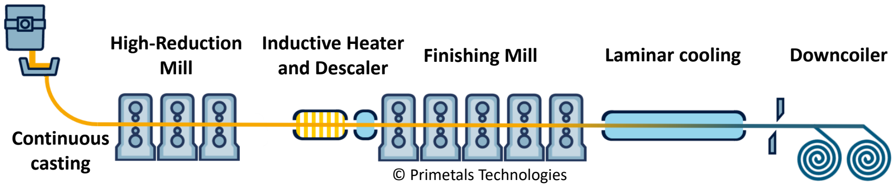
Exploring the potential of Thin Slab Casting and Rolling technologies for future steelmaking under low-grade scrap conditions

Motivation: In future **EAF-based green steelmaking**, the increasing use of **low-grade scrap** poses the risk of contaminating the steel with **harmful tramp elements**, e.g. Cu and Sn. Liquid Cu/Sn phases infiltrate surface-near grain boundaries and lead to surface cracking during straightening in continuous casting (cc). **Thin Slab Casting and Rolling** developments, e.g. the **Arvedi Endless Strip Production** process (Arvedi ESP, Primetals), combine continuous casting with direct hot rolling and are expected to show **higher tolerance for tramp elements** due to the accelerated process and less time in critical high-temperature regions compared to cc.



The Arvedi ESP process:

- **Zero greenhouse gas emissions** during casting and rolling
- > 100 Mio tons of green steel produced *via* Arvedi ESP
- Casting capacity of 3.3 Mio. tons per year
- Casting to coiling in just **5 minutes**
- Inductive reheating instead of gas-fired tunnel furnaces
- **Uniform strip quality** from thinnest strips (0.6 mm) to thick gauges (25.4 mm)
- Direct application of endless Hot Rolled Coils (eHRC): from **commodity** to **high-strength steels** (automotive, technology, line pipes, …)



High-Reduction Mill

Inductive Heater and Descaler

Finishing Mill

Laminar cooling

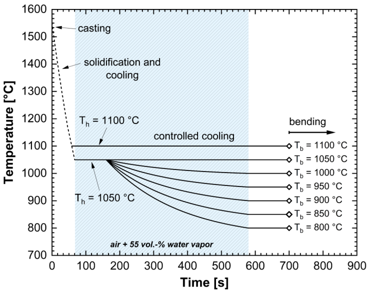
Downcoiler

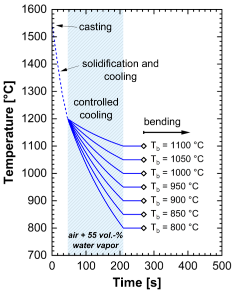
Continuous casting

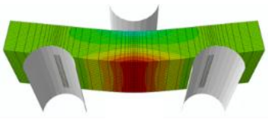
© Primetals Technologies

Target chemical analysis (Medium C construction steel), in wt.-%

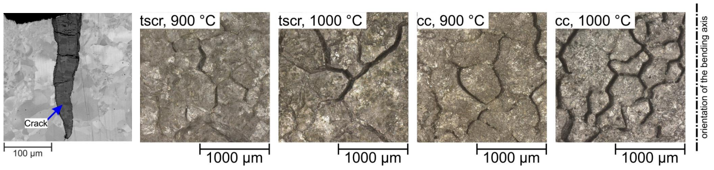
Fe	C	Mn	Si	Al	Cu	Sn	P	S	N
bal.	0.17	1.55	0.4	0.03	0.15	0.01	< 0.011	< 0.004	< 0.008

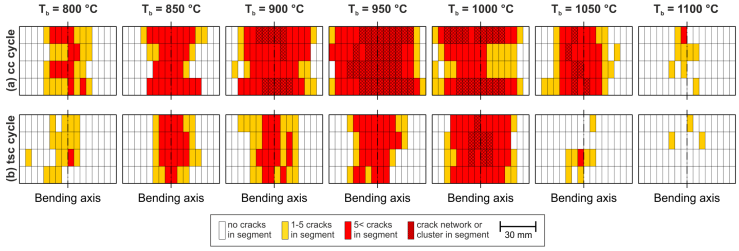






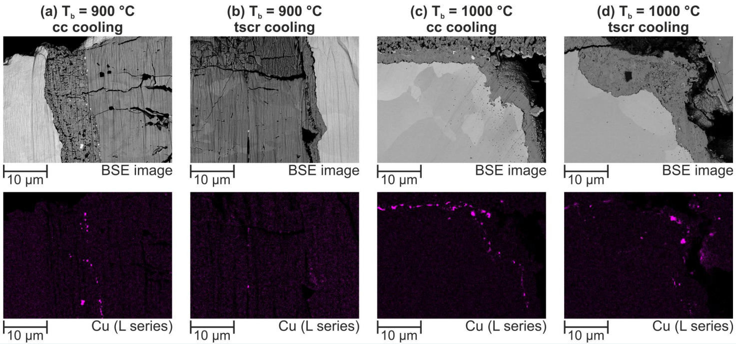
Experimental: The potential of Arvedi ESP for green steelmaking conditions is experimentally assessed using the ***in-situ* materials characterization by bending (IMC-B)** test coupled with high-resolution SEM-EDX. Every sample is prepared by melting technically pure Fe and alloying elements in an induction furnace. The melt is cast into a steel mold, where solidification and primary cooling elapse. Subsequently, process-near cooling is performed under an **air + 55 vol.-% water vapor** atmosphere to simulate secondary cooling. After cooling, the sample is transferred to a bending furnace under air atmosphere. The simulation of straightening is performed at **realistic strain rates** and different bending temperatures (T_b) *via* a three-point bending test. To investigate tscr conditions, **a significantly accelerated cooling cycle is introduced**.





Evaluation and results:

- Critical surface crack formation for conventional cc is observed at 850 °C ≤ T_b ≤ 1050 °C, but **solely at 1000 °C for accelerated tscr conditions** (*see heat maps, upper right fig.).*
- A SEM-EDX study at 900 °C and 1000 °C reveals a **significantly lower amount of Cu-rich particles** (~ 85 wt.-% Cu, 5 wt.-% Sn, 5 wt.-% Fe, 5 wt.-% others) in the crack **after tscr cooling and bending at 900 °C**, but a similar amount for both cooling conditions at 1000 °C.
- **Accelerated process conditions can suppress the precipitation of Cu-rich particles and subsequent surface cracking** below and above 1000 °C; however, T_b = 1000 °C results in surface cracking regardless of the cooling cycle.


(a) T_b = 900 °C cc cooling
(b) T_b = 900 °C tscr cooling
(c) T_b = 1000 °C cc cooling
(d) T_b = 1000 °C tscr cooling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Research topics and interests

- Tramp elements in continuous casting and steel processing
- Surface oxidation phenomena
- Thermal analysis
- Thermodynamics and kinetics of casting processes

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Plasma Pyrolysis of Methane

Pathways to Turquoise Hydrogen and Solid Carbon

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1. Motivation and Background

Conventional hydrogen production via Steam Methane Reforming (SMR) emits ~10 kg CO_2 per kg H_2. Plasma pyrolysis of methane ($CH_4 \rightarrow C(s) + 2\ H_2$) offers a carbon-free alternative — producing “turquoise hydrogen” and solid carbon as a commercially valuable solid carbon by-product. When powered by renewable electricity, the process achieves near-zero net CO_2 emissions.

2. Reaction Fundamentals

$$CH_4(g) \rightarrow C(s) + 2\ H_2(g) \quad \Delta H° = +74.8\ \text{kJ/mol}$$

The endothermic decomposition requires high temperatures. Plasma reactors supply the necessary energy electrically, avoiding combustion. The carbon product morphology (carbon black, graphite, CNTs) depends on process temperature, residence time and feedstock composition.

3. Kvaerner Carbon Black and Hydrogen (CB&H) Process

The Kvaerner CB&H process, schematically shown in Figure 2, uses a DC arc plasma torch. Methane is fed into the plasma jet and thermally cracked. The process yields high-purity carbon black suitable for rubber and pigment industries, along with hydrogen gas.

4. Economics and Carbon Product Utilization

The economic viability of plasma pyrolysis depends primarily on the ratio of electricity to natural gas prices. Figure 1 depicts the cost advantage of the pyrolysis- compared to the electrolysis process for various member states of the EU. The solid carbon co-product further improves the economic case: depending on reactor conditions, it can be valorised as carbon black (rubber, pigments), graphite (electrodes, batteries), or carbon nanotubes (composites, electronics)

5. Outlook

At the recently established 150 kW plasma pilot plant in Leoben, we are optimising process parameters, investigating plasma physics and carbon nucleation kinetics, and assessing the techno-economic viability of turquoise hydrogen at pilot scale.

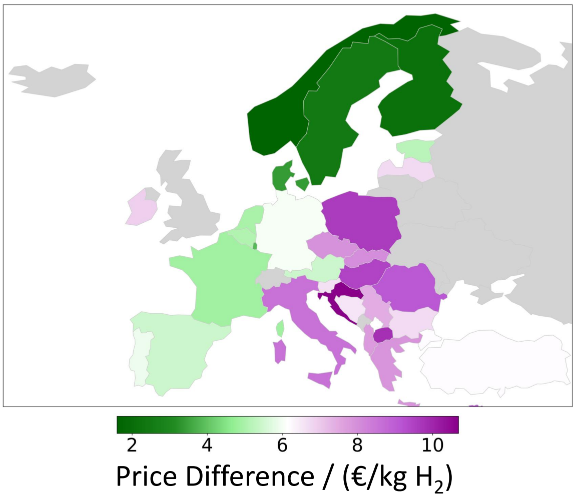

Figure 1: Hydrogen production cost difference across EU Member States, where larger values indicate that methane pyrolysis is more cost-competitive than electrolysis [1,2]

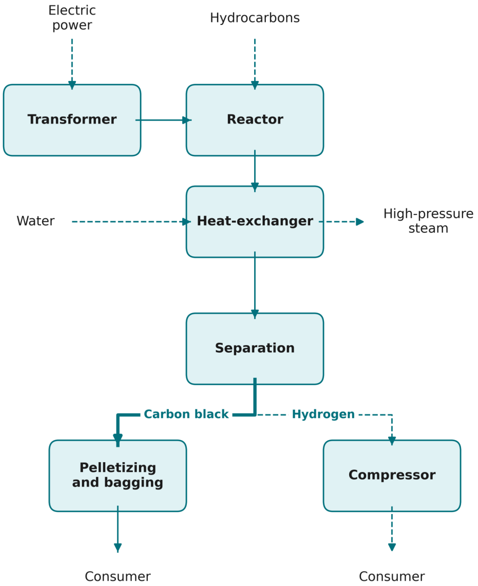

Figure 2: Schematics of the Kvaerner CB&H Process[3]

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Literature:

[1] https://doi.org/10.2908/NRG_PC_203, 1.3.2026
[2] https://doi.org/10.2908/NRG_PC_205, 1.3.2026
[3] Hox, K., Hildrum, R., Lynum, S. (1998). Plasmabased Hydrogen and Energy Production. In: Saetre, T.O. (eds) Hydrogen Power: Theoretical and Engineering Solutions. Springer, Dordrecht. https://doi.org/10.1007/978-94-015-9054-9_16

Projektpartner:

- RAG Austria AG
- Energieinstitut an der Johannes Kepler Universität Linz
- INTECO melting and casting technologies GmbH

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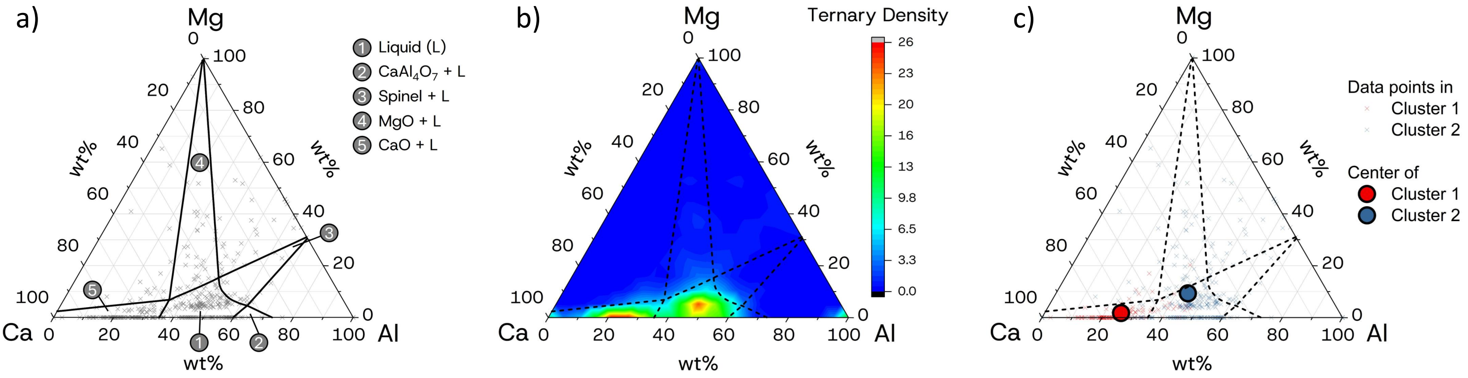
Characterizing Non-Metallic Inclusions with Machine Learning

K-Means Clustering and Kernel Density Estimation in Practice

The elemental composition of **non-metallic inclusions (NMIs)** in the Ca-Al-Mg ternary system is critical for evaluating the success of the **Ca treatment**. During this modification process, NMIs are transformed from solid alumina/spinel particles into **partially** or **fully-liquid calcium aluminates, reducing the risk of nozzle clogging** and **improving castability** [1,2].

Automated SEM-EDS analysis is the state-of-the-art technique for characterizing microscopic NMIs. A common approach is to plot each detected NMI as a point in ternary systems. However, dense scatterplots can hide structure and underlying patterns, leading to difficulties when interpreting the data. Unsupervised machine learning (ML) algorithms, such as **k-means** and **kernel density estimation (KDE)**, help in finding high-density regions and, therefore, enable a clearer assessment of the NMI population. K-means is a clustering algorithm that partitions a dataset into similar groups based on the distance between their centroids. KDE is used to estimate the probability density function and creates a visual representation of the data distribution. [3]

The NMI population of a Ca-treated steel is shown as a scatterplot in (a) for the Ca-Al-Mg ternary system, with marked partially-liquid two-phase and fully-liquid regions at 1600 °C. The KDE map (b) highlights where the NMIs concentrate, predominantly in the **fully-liquid region** with a second high-density area in the **partially-liquid CaO + L** phase field. The k-means algorithm partitions the NMI population into **two interpretable groups** (c), whereas the location of the centroids follows the pattern of the KDE map.



NMI population shown (a) in a scatterplot, (b) in a KDE map, and (c) after k-means clustering.

KDE maps and k-means clustering provide a **clear overview** of the NMI data distributed in the ternary system by showing **high-density areas** in the **calcium aluminate liquid regions**. The results of these unsupervised ML algorithms indicate an **appropriate NMI modification** state after Ca treatment.

Sources:
[1] W. Yang, L. Zhang, Y. Ren, W. Chen and F. Liu, ISIJ Int. 64 (2024)
[2] S.K. Michelic and C. Bernhard, Steel Res. Int. 93 (2022)
[3] C.M. Bishop, Pattern Recognition and Machine Learning, Springer (2006)

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Investigation of the Application of Oxidic Alloying Elements in the Hydrogen Plasma Smelting Reduction Process (HPSR)

Motivation:

While significant efforts focus on carbon-free iron production, ferro-alloy manufacturing remains energy-intensive and partially carbon-based. Future carbon-neutral steelmaking requires not only CO_2-free iron reduction, but also sustainable alloy production. The Hydrogen Plasma Smelting Reduction (HPSR) process provides a unique opportunity to transform oxide mixtures directly into pre-alloyed steel — in a single, carbon-free step.

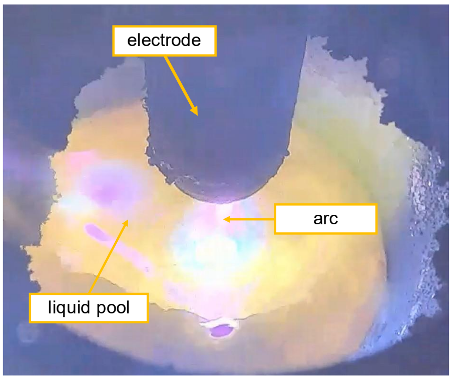
Methods:

Thermodynamic calculations were performed using **FactSage** to evaluate the reducibility of selected metal oxides – see Ellingham-Richardson diagram.

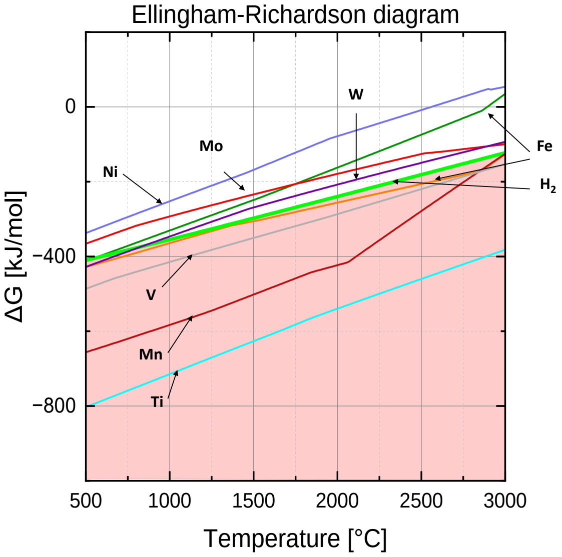
Experimental investigations were conducted in a **laboratory-scale HPSR reactor** using a DC-transferred arc and hydrogen plasma to determine if oxidic material can be used for pre-alloying.

Feed material consisting of iron ore and selected oxides (**NiO, MoO_3, WO_3, TiO_2, MnO, Cr_2O_3** and **V_2O_5**) were melted under argon atmosphere and subsequently reduced with hydrogen.

Process monitoring included gas composition analysis, temperature measurement and electrical parameters, followed by characterization of the metal and slag phases using scanning electron microscopy (SEM).



Electrode, arc and liquid pool during the process



Ellingham-Richardson diagram calculated with FactSage 8.3

Results:

Thermodynamic predictions were confirmed experimentally:

NiO shows the highest reduction tendency and is fully incorporated into the metallic phase.

MoO_3 is also effectively reduced, although partial evaporation may influence yield.

WO_3 is reducible but requires higher hydrogen activity and shows lower mass recovery.

Cr, **V**, **Mn** and **Ti oxides** remain unreduced, indicating thermodynamic stability under the investigated conditions.

Therefore, direct alloying during HPSR was achieved for **Ni**, **Mo** and **W** demonstrating the potential of HPSR to replace conventional ferro-alloy production.

Further work will focus on slag chemistry, process adjustments and detailed phase characterization.

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Advanced Modeling of the Electric Arc Furnace Process for Crude Steel Production

Introduction and Motivation

With 7 % of global greenhouse gas emissions and 8 % of worldwide energy consumption, the steel industry is at the center of global climate protection efforts. Key strategies for the sector's green transformation include electrified process routes, such as the Electric Arc Furnace (EAF). Not only does the EAF allow the use of direct reduced iron, but it also enables the processing of up to 100 % scrap as raw material, hence closing the recycling loop in steel production and providing maximum process flexibility. Process modeling can enhance the economic and ecological performance of crude steel production and deepen process understanding.

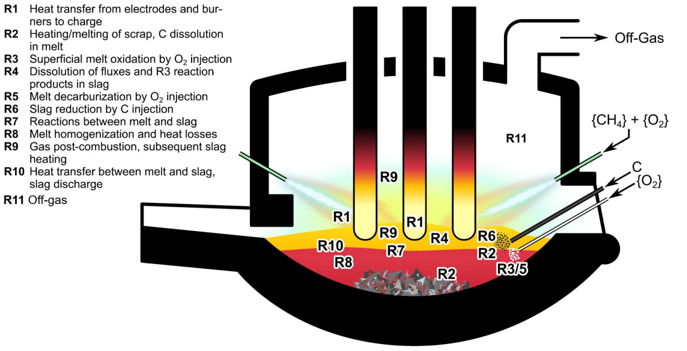
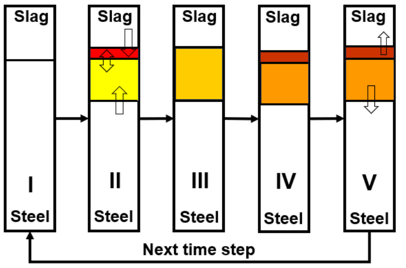


Fig. 1: Schematic representation of reaction zones in the current EAF model.

The CALPHAD/EERZ Approach

Over the last decades, computer-aided thermodynamics based on the CALPHAD approach (CALculation of PHAse Diagrams) have been widely adopted. By coupling advanced thermodynamic models with kinetic analyses of reaction sequences, various metallurgical processes in the production of iron and steel have been successfully simulated. A crucial concept in these models is the highly adaptable "Effective Equilibrium Reaction Zone" (EERZ) method, which allows for the definition of different metallurgical reaction zones within a process. The advantages of the EERZ method lie in its significantly shorter computing time while still providing an accurate description of process analyses.



Calculation Schematic:

I. New time step
II. Add reaction amounts
III. Calculate equilibrium
IV. Separate equilibrium amounts
V. Return equilibrium amounts to bulks

Fig. 2: Schematic calculation procedure of an EERZ zone (Kavić et al. 2024).

The Process Model

Based on a recent master's thesis (Prousch 2025) which demonstrated the adaptability of an EERZ-based EAF modeling approach from literature, the am4EAF project aims to develop a comprehensive process model for the EAF process regarding the production of crude steel. This model is not limited on the calculation of slag and steel temperatures and compositions but also considers the spatially-dependent heat load on various regions in the vessel through radiation, convection and conduction. While the steel production from close to 100 % scrap depicts the classical route in electric steelmaking, some furnaces use DRI–scrap mixes or exclusively DRI as input material. This correlates with a significant change in process conditions, which will also be considered in the present model, since the international relevance of DRI-based steelmaking is expected to significantly gain relevance in the oncoming years.

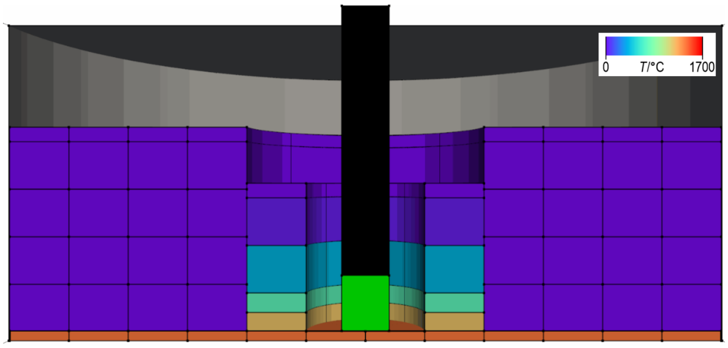


Fig. 3: Cross-sectional view of the vessel during the early melting phase.

Outlook

The central chemical model already yields promising results that are expected to further improve with future process parametrization and validation. A more detailed depiction of the heat transfer in the system is currently being implemented, allowing for the consideration of scrap, melt, and slag, but also of the freeboard volume including gaseous species as well as dust.

Image courtesy: Daniel Kavić, Michael Bernhard, Roman Rössler, Christian Bernhard: "Simulation of Secondary Metallurgical Processes Using Computational Thermodynamics and Comprehensive Statistical Learning Methods", Iron & Steel Technology Magazine 2024, Vol. 12, pp. 34-47

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Research Focus

- Thermal Modeling
- Scrap and DRI in Steelmaking
- Off-Gas
- Melting and Dissolution Behavior
- EAF Dust Formation

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Advancements in REE-Profiling

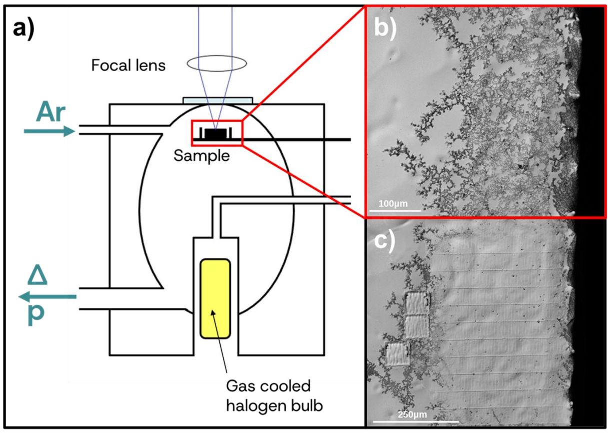
How to Determine the Origin of Microscopic Non-metallic Inclusions

Introduction

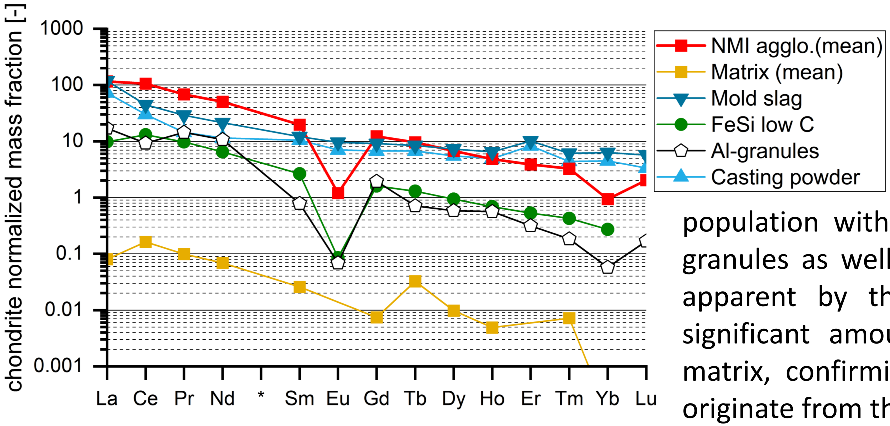
Non-metallic inclusions (NMIs) in steel can affect product quality by deteriorating the final material's physical and chemical properties [1]. Modern steelmaking therefore prioritizes controlling and limiting NMI formation, necessitating techniques to trace and identify their sources. A suitable approach is determining rare earth element (REE) profiles of individual NMIs using LA-ICP-MS and comparing the resulting fingerprints to profiles of potential source materials. While this method has been successfully applied to macroscopic NMIs [2], the trace abundance of REEs imposes a size-dependent detection limit. As NMI size decreases below a certain diameter, there is not enough material available to detect a complete REE profile using LA-ICP-MS.

Experimental Procedure

In order to overcome the size constraints and enable REE profiling of microscopic NMIs, a steel sample was carefully heated using an HT-CSLM (a) until it partially melted on the surface. As the molten layer formed, the lower-density inclusions migrated upward, agglomerated, and formed a network structure on the surface of the sample (b). The area containing the agglomerated NMIs was scanned using LA-ICP-MS (c), yielding a REE profile of the NMI population in the sample. Additionally, the steel matrix was also analyzed by LA-ICP-MS, to determine the baseline REE distribution of the sample. To obtain more conclusive results, several locations were examined and the average value was calculated.



a) Experimental setup of the HT-CSLM; b) agglomerated NMIs; c) NMIs after LA-ICP-MS



REE profiles of agglomerated NMIs, steel matrix and potential sources

Results and Discussion

The REE profiles of the agglomerated NMIs, the steel matrix and some additives as well as auxiliaries are shown on the left. Comparing the REE fingerprint of the NMI population with those of potential sources, reveal that Al granules as well as FeSi might be the origins of the NMIs, apparent by the negative Eu anomaly. In contrast, no significant amounts of REEs were detected in the steel matrix, confirming that the recorded REE profiles actually originate from the inclusions agglomerated on the surface.

Sources:
[1] S.K. Michelic, and C. Bernhard, Steel Research International, 2022, 93(7), 2200086.
[2] K. Thiele, C. Truschner, C. Walkner, T.C. Meisel, S. Ilie, R. Rössler, and S.K. Michelic, Metals, 2024, 14, 103.

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Steel cleanness in high-alloyed PM-steels

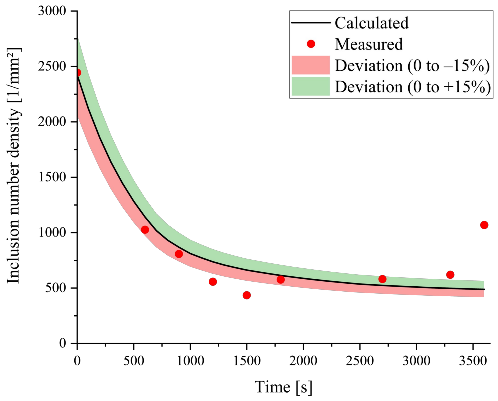
How to describe the modification of non-metallic inclusions

Introduction

Non-metallic inclusions (NMIs) are gaining importance in the production of special steel products such as high-alloyed steels. The impact of these inclusions on process stability and product quality underscores the necessity for both scientific and industrial research to explore the formation and evolution of these inclusions in greater depth [1]. To provide comprehensive depictions of phase developments in laboratory experiments and the associated steel cleanness in powder metallurgic (PM) produced high-speed steels, a combination of modeling approaches is employed and compared with analytical data.

Methodology

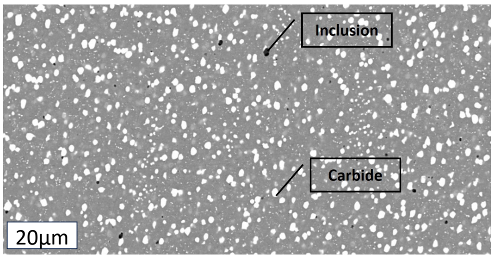
For comparison between the steel cleanness of the steel produced in laboratory tests and the results of the model being developed, a targeted survey of inclusion characteristics must be carried out. A combination of methods were used, allowing for the complete characterization of size distribution, composition, morphology, and maximum inclusion size. The methodology comprised automated SEM/EDS measurements to determine the micro- and meso-cleanness, supplemented by the GPD method for statistical estimation [2] of the maximum inclusion size, as well as sequential extraction with Nital solution for further morphological analysis. To describe the laboratory experiment using a model, the development of the steel cleanness as a microscopic- and the overarching changes as a macroscopic-component were implemented. Macroscopic phase changes are represented using the effective equilibrium reaction zone model. This model, in conjunction with analytical and numerical approaches, also serves to describe steel cleanness modifications.



Actual and modeled inclusion number density as an excerpt from the description of the steel cleanness using the developed model

Results and Discussion

The combination of various analytical methods used, provided in-depth insight into the high-alloyed PM steels, which are very “clean” in terms of steel cleanness [3]. Regarding NMI modification, good agreement between model and reality can be observed through the representation of metallurgical phenomena such as nucleation, agglomeration, separation, and growth. A synthesis of the findings, which are presented here in excerpts, reveals that the developed model provides a robust foundation for both process-assessment and in-depth investigation.



Typical representation of steel cleanness in high-alloyed PM-steels

Sources:
[1] L. Zhang and B.G. Thomas, ISIJ Int. 43 (2003), 3, pp. 271–291.
[2] C.W. Anderson, Extremes 5 (2002), 3, pp. 237–252.
[3] M. Schickbichler, et al., Powder Metallurgy. 2023, 66(4), pp. 316-332.

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Statistical prediction of the heat transfer coefficient

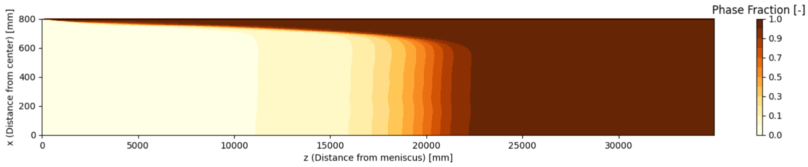
Regression modeling for a continuous casting process simulation

Introduction and motivation

Optimized **slab cooling** is a key requirement for efficient continuous casting and for minimizing quality defects in the final steel product.

The **nozzle measuring stand** (NMS) at the Chair of Ferrous Metallurgy at Montanuniversitaet Leoben was established to characterize spray-cooling nozzles by measuring both **water distribution** (WD) and **heat transfer coefficients** (HTC) across different nozzle types and operating conditions, including single-fluid (water) and twin-fluid (water + air) designs. For WD measurements, a custom MATLAB-based image analysis reconstructs the **water impact density** (WID) and visualizes it. For HTC measurements, the nozzles are rotated to spray upward onto a ceiling-mounted specimen that is heated by conduction and moved *via* an automated linear unit. From the recorded temperature drop and an inverse heat conduction method, the **slab surface temperature** T_S and HTC are determined.

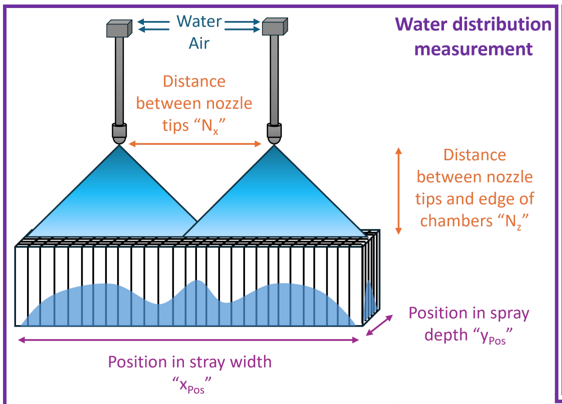
The in-house simulation software **m²CAST** uses a 2D finite-volume approach to predict slab temperature profiles under varying casting conditions, with an adjustable discretization that enables non-uniform meshing for increased near-surface resolution. Thermophysical properties for a given steel composition are provided by the **m²MAT** material module, while industrial cooling-table settings are used to measure WID and HTC across the relevant operating parameter combinations, yielding high-quality input data.

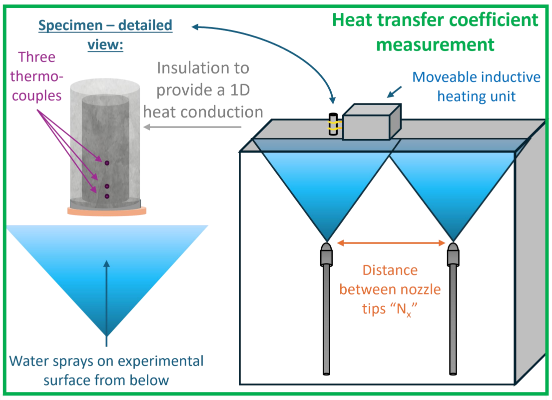


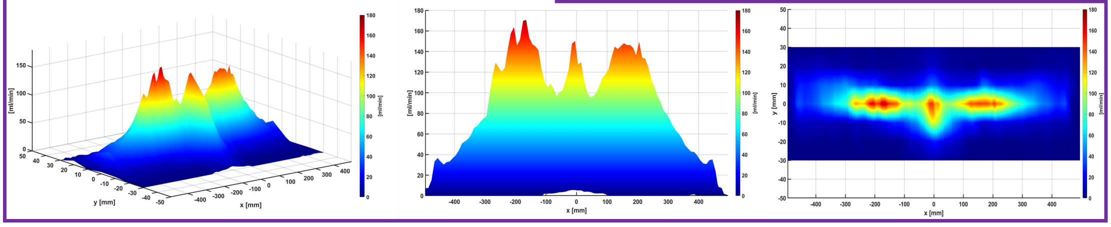
The software supports detailed evaluation of **temperature profiles**, **shell growth**, and **heat transfer coefficients** by extracting user-defined slab cross-sections for visualization. This enables assessment of three-dimensional solidification behavior and provides high-resolution 2D **temperature-field analysis**.

Prediction via machine learning approach

Recent HTC correlations typically express the HTC mainly as a function of T_S and WID, sometimes extended by droplet size and velocity. Building on NMS measurements, a **data-driven** workflow in which data cleaning and **statistical feature analyses** (e.g., Pearson correlation matrix, feature forward selection, and feature-importance/permutation tests) showed that T_S and WID dominate HTC prediction. Multiple modeling approaches were compared, and increasing model complexity beyond the two parameters T_S and WID provided no further improvement in the error metrics **RMSE** and **MAE**. Among the tested methods, **Gradient Boosting Regression** delivered the best accuracy on the test dataset for the spray-cone region.

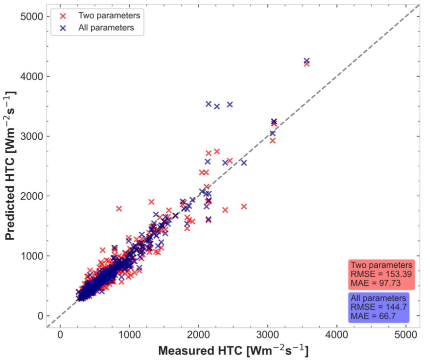




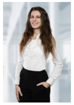


Outlook

In future work, a **physics informed regression** model should be applied in m²CAST by considering a **Leidenfrost-temperature** T_{LF} and WID relation derived from **boiling curve** analysis.



M. Seidl, D. Kavić, S. Ilie, and C. Bernhard, "Application of Statistical Learning Methods to a Data Set of Measured Heat Transfer Coefficients for Continuous Casting", Berg Huettenmaenn Monatsh, Vol. 170, No. 7, pp. 399-408, July 2025, https://doi.org/10.1007/s00501-025-01592-7.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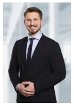
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Research focus

- Boiling behavior in the secondary cooling zone of continuous casting
- Impacts on water distribution and heat transfer coefficient
- Machine learning and statistical prediction with regression models
- Numerical simulation of casting process

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H_2/H_2O Reduction of Electric Arc Furnace Dust

Dependence on the chemical and mineralogical composition

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[1] Technical University of Leoben, Chair of Ferrous Metallurgy, Austria

Motivation

Electric Arc Furnace Dust (EAFD) represents a significant secondary resource for **Zn and Fe recovery**, yet current industrial practices - primarily the Waelz process - rely heavily on coke. This reliance creates a substantial CO_2 footprint. The research addresses this critical gap by exploring H_2 as a carbon-neutral reducing agent. While theoretically promising, the **complex mineralogical composition** of EAFD creates unpredictable reduction kinetics. It is essential to characterize these kinetics to manipulate the process, bridging the gap between current carbon-dependent methods and sustainable, H_2-driven metal recovery.

Material

Sample	Compound, wt.%									
	ZnO	Fe_2O_3	CaO	MgO	MnO	Cl	Na_2O	K_2O	SiO_2	Cr_2O_3
EAFD1	27.68	46.76	3.72	1.91	3.13	0.74	4.85	0.63	3.68	1.08
EAFD2	44.57	31.61	2.60	1.31	1.51	2.09	5.17	1.51	3.59	0.58
EAFD3	19.31	47.53	13.16	8.41	5.04	0.42	1.49	0.46	3.22	2.47

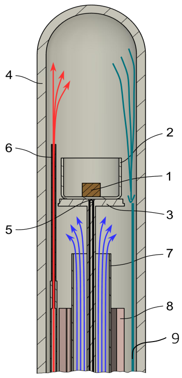
Fig.1. Visual representation of different EAFDs

Experimental Setup

The EAFD samples are reduced in a ***Thermogravimetric analyzer*** (TGA) (Fig.2) with the temperature and gas profile as follows:

Segment	Temp. Range (°C)	Atmosphere (%)
Heating I	RT ▻300	Ar (100)
Heating II	300 ▻ 500	Ar (100)
Reduction I	500 ▻ 800	H_2/H_2O (40:60)
Reduction II	800 ▻ 1150	H_2/H_2O (ramp up to 100:0)
Cooling	1150 ▻ 700	Ar (100)

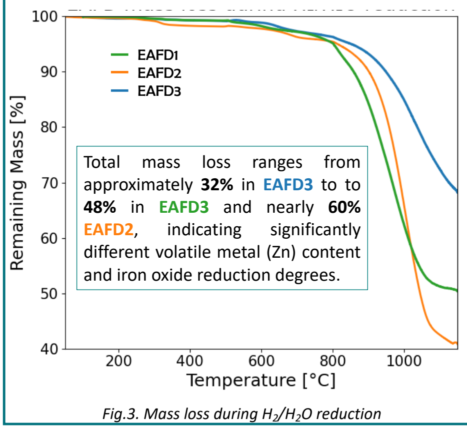
1 Sample
2 Crucible
3 Sample Holder
4 Furnace
5 Thermocouple
6 Gas Inlet
7 Purge Inlet
8 Condensation Unit
9 Gas Outlet



[1] Hoffelner F., (2022). Kinetic Aspects of the Selective Reduction of Zinc Ferrite with H_2 in the Processing of Electric Arc Furnace Dust. [Master’s thesis, Montanuniversität Leoben]. pure.unileoben.ac.at

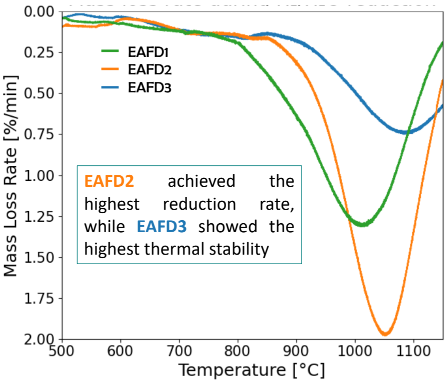
Fig.2. Illustration of the TGA setup[1]

Results



Total mass loss ranges from approximately **32%** in **EAFD3** to to **48%** in **EAFD3** and nearly **60%** **EAFD2**, indicating significantly different volatile metal (Zn) content and iron oxide reduction degrees.

Fig.3. Mass loss during H_2/H_2O reduction



EAFD2 achieved the highest reduction rate, while **EAFD3** showed the highest thermal stability

Fig.4. Mass loss rate during H_2/H_2O reduction

Conclusion

Despite the same temperature and gas profiles, the reduction behavior of EAFD is not universal; it is **strongly dictated by the initial mineralogical and chemical composition** of the dust. Some EAFD samples respond to the reduction at lower temperatures, while others require higher thermal energy to overcome the complex kinetic barriers of their internal phases.

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Move mountains

Investigation of the Reoxidation and Material Behavior of Directly Reduced Pellets and Fines under Simulated Rail Transport Conditions

Bernd Taferner[1], Johannes Schenk[1], Richard Schanner[2], Peter Gluschitz[2], Jan Eisbacher-Lubensky[1]

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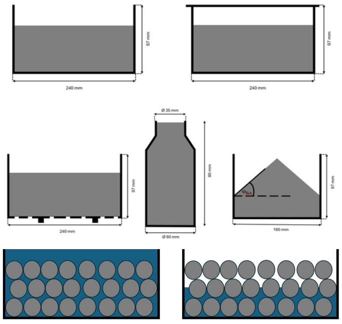
Motivation

Global steel demand will increase significantly by 2050, while steel production continues to cause high CO_2 emissions. The transition from the BF-BOF to the EAF route can reduce emissions, with directly reduced iron (DRI) serving as a substitute for limited scrap. Rising DRI production, especially in pellet form, increases the importance of safe transport, particularly by rail. Due to its porous structure, DRI is highly susceptible to reoxidation, causing material losses and safety risks. The study investigates reoxidation behavior during transport by rail under various environmental and material conditions.

Initial characterization of DRI sample

Reoxidation tests were carried out on directly reduced pellets produced industrially via the **Midrex-Process** and in the laboratory using **H_2-based reduction** with and without carburization. Midrex samples were classified as aged (**aged DRI**) or fresh (**fresh DRI**) according to storage conditions. **Fine particles** (< 6.3 mm) were included to assess size effects. The initial material state was characterized by determining total, bivalent and metallic iron content, carbon content, and specific surface area.



Experimental setup for reoxidation tests

Container geometry, **shape of fill**, and **environmental conditions** were systematically varied to analyse their impact on reoxidation behaviour. Tested conditions included **ambient atmosphere** (20 °C, 21% relative humidity), at **elevated temperature and humidity** (35 °C, 90% relative humidity), and complete or partial submerged in **tap or salt water**. Sample mass was standardised to **1500 g** and test duration was **324 hours**.

Summary

*Reoxidation is governed by **grain size, environmental conditions, container geometry and shape of fill**, and **self-heating** effects. Fine fractions exhibit increased oxidation kinetics due to higher specific surface area. Moisture, elevated temperature, and saline exposure accelerate iron oxidation and reduce metallic Fe content. The **Innofreight-shape** demonstrates performance comparable to a closed container system.*

Source: Bernd Taferner, Johannes Schenk, Richard Schanner, Peter Gluschitz, Jan Eisbacher-Lubensky Investigation of the Reoxidation and Material Behavior of Directly Reduced Pellets and Fines under Simulated Rail Transport Conditions SRIN 2026, https://doi.org/10.1002/srin.202501084

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Application of different carbon sources in electric smelting furnaces for sustainable ironmaking

Biogenic vs. fossile carbon carriers

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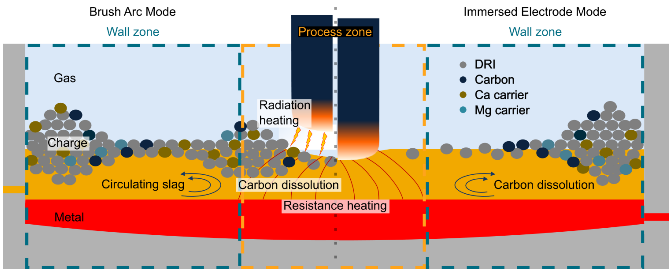
2 K1-MET GmbH

Introduction and Motivation

The steel industry contributes 7–9% of global CO_2 emissions, where the blast furnace (BF) ironmaking step is the most CO_2-intensive (~1.3 $t_{CO_2}/t_{pig\ iron}$), thus transforming ironmaking is a key objective for decarbonisation. Electric smelting furnaces (ESF) combined with direct reduction plants are a promising option to lower CO_2 emissions and can be integrated into existing steel plants while retaining much of the downstream infrastructure, including BOF and continuous casting lines. This retrofit compatibility enables progressive decarbonization without full reconstruction of integrated steel plants.



One key operational aspect of ESF's (see illustration above) is the utilization of carbon carriers, which fulfill two essential roles:

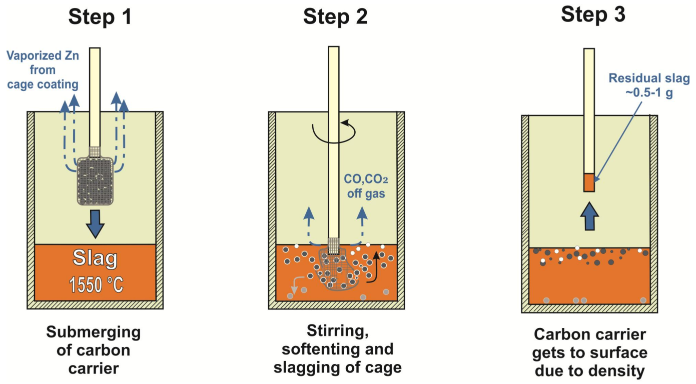
- Reduction of FeO from Direct Reduced Iron (DRI) and subsequently in slag to increase iron yield
- Carburization of molten iron to form pig iron

Biochars offer the potential to partly replace fossil carriers and lower CO_2, but their reduction efficiency and slag interaction may differ significantly. Therefore, fossil and biogenic carbon carriers must be investigated in lab-scale tests under ESF near conditions.

Sources: J.Winkler et al, ESTAD 2025
G. Wimmer, kindly provided by Primetals Austria

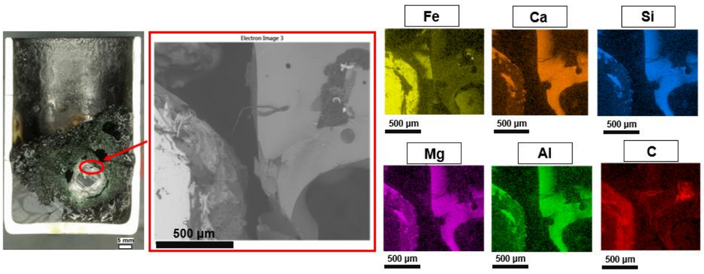
Experimental Approach

Two fossile (coke, anthracite) and two biogenic (wood-chips biochar, wood coal pellets) carbon carriers were compared in lab-scale submerging trials at 1550 °C in a synthetic slag containing 15 wt.-% FeO, to observe the reduction behaviour and differences between fossile and biogenic carbon sources.



Results and outlook

The trials demonstrate that FeO reduction with biochar is possible in ESF-type slags. The developed method enables an evaluation of reduction behaviour of different carbon sources and supports observation of parameters like slag foaming. For example, SEM-EDX of reacted wood chips biochar shows reduced iron and residual carbon in the slag (influence on carburization), providing a basis to further investigate carbon carriers in the ESF process in future trials.



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