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Contribution of the Chair of Ferrous Metallurgy at the Montanuniversitaet Leoben to Enhance the Sustainability of Steel Production and Application

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Abstract: The research work at the Chair of Ferrous Metallurgy at the Montanuniversitaet Leoben contributes in different aspects to a sustainable steel production and application. New advanced methods for characterization of ferrous raw material and carbon carriers are developed with the aim to enhance the efficiency for the use of raw materials and energy input in the blast furnace as well as in direct and smelting reduction processes. The chair is involved in the development of new breakthrough technologies such as endless strip production and hydrogen smelting reduction, sponsored by the Austrian industries. This venture is a contribution to reduce the fossil fuel energy consumption and an enhancement of steel production with lesser carbon consumption. A valuable contribution to the sustainable use of steel in products is done by the research on the prevention of defect formation in casting processes or the control of the nature, shape, and size of non-metallic inclusions.

Keywords: Sustainability, Steel, Raw materials, Energy

Beitrag des Lehrstuhls für Eisen- und Stahlmetallurgie der Montanuniversität Leoben zur Steigerung der Nachhaltigkeit von Stahl in der Produktion und Anwendung

Zusammenfassung: Der Lehrstuhl für Eisen- und Stahlmetallurgie beschäftigt sich in seiner Forschung mit verschieden Problemstellungen für nachhaltige Stahlerzeugung und –anwendung. Neue Methoden zu Charakterisierung von Möllereinsatzstoffen sowie Kohlenstoffträgern werden mit dem Ziel entwickelt, die Rohstoff- und Energieeffizienz im Hochofen sowie in den Direkt- und Schmelzreduktionsverfahren zu steigern. Der Lehrstuhl ist an der Entwicklung der neuen disruptiven Technologien für die endlose Stahlbandproduktion und der Wasserstoffschmelzreduktion beteiligt. Ziel dieser Verfahrensentwicklung der österreichischen Industrie ist die Reduktion des Einsatzes fossiler Energie für die Stahlerzeugung. Die Forschungsarbeiten zur Fehlervermeidung beim Stranggießprozess und zur Kontrolle der Bildung, der Form sowie der Größe von nichtmetallischen Einschlüssen ist ein Beitrag zur nachhaltigen Anwendung von Stahl in Produkten.

Schlüsselwörter: Nachhaltigkeit, Stahl, Rohstoffe, Energie

1. Sustainability

The term sustainability refers to all actions to improve the quality of the life for everyone in present and future generations. This includes all aspects related to environment, economics, and society. Steel as a product helps to meet the targets of a sustainable development of our world. Steel is a unique material characterized by the broad variety of its properties like strength, ductility, durability, or hardness. In many applications the cost competitiveness is paramount, and steel cannot be substituted by other materials. Moreover, steel is 100 % recyclable and can be recycled nearly infinitely. This saves energy and raw materials, which consequently reduces CO_2 emissions and generation of waste from raw materials mining.

The World Steel Association defined the steel life cycle phases and recycling in a circular economy as shown in Fig. 1 [1]. The research work of the Chair of Ferrous Metallurgy at the Monatuniversitaet Leoben contributes in different aspects to fulfilling the requirements for this cycle. The main focus is on the steel production step considering the interfaces of the upstream raw material extraction and recycling as well as the downstream steps as manu-

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Fig. 1: Steel life cycle phases and recycling [1]

facturing and use. This paper gives an overview of current research at the Chair which contributes to the enhancement of the sustainability of steel production and application. The research subjects specifically related to this topic are introduced in the following three chapters:

- Raw material characterization
- Energy efficiency and alternative energy resources
- Steel quality

2. Raw Material Characterization

The methods applied for raw material characterization comprise experimental simulation, physical and chemical analytics as well as thermodynamic simulation. The objective of the research work is to develop a deeper understanding of the behaviour of ferrous and carbonaceous raw materials in the blast furnace and in alternative ironmaking processes as the smelting and direct reduction processes. The knowledge should help not only to specify the required quality of raw material of the process but also to optimise the operation of the processes with regard to plant productivity and resource efficiency for given raw materials.

2.1 Ferrous Burden Material for Ironmaking Technologies

Different types of lumpy ferrous burden materials, namely lump ores, pellet brands, and sinter samples of industrial scale, were studied and analysed concerning their reducibility performance, mechanical stability before and after the reduction procedure and their morphological evolution during the conversion from oxide to metallic iron. Different testing procedures led to a deeper understanding of their behaviour in the blast furnace as well as in the COREX® and MIDREX® shaft furnace. A correlation between raw material properties and their performance during the reduction process could be determined. It has been observed that for the prediction of the behaviour of different types of ferrous burden within any industrial process, testing procedures that are most closely related to the actual process parameters are needed [2, 3].

In order to optimise fluidized bed based technologies for ironmaking like the smelting reduction process FINEX®, the investigation of reduction behaviour and structural evolution of iron ore fines have also been performed. For that purpose, a 160 mm fluidized bed reduction facility was constructed and operated. This installation allows the continuous measurement of the main relevant process parameters, especially the weight loss of the fluidized sample caused by reduction and the sampling of bed material during operation. The benefit is that the test conditions are close to real industrial processes [4, 5].

Alkaline metals like sodium and potassium are generally known as unwanted elements in ironmaking processes. Apart from the negative effects on refractory and coke consumption, alkalis have a negative influence on the mechanical stability of the burden feed material. To investigate the effects of sodium and potassium on all kinds of lumpy iron carriers, reduction and tumbling tests were executed under various experimental conditions. Limonitic and hematitic raw ores and pellets were treated with alkali bearing aqueous solutions to soak the particles. Investigations by SEM and microprobe showed different alkali adsorption properties of mineralogical phases of the feed materials. Elevated contents of sodium and potassium were detected in limonite, gangue, and glass phases after soaking. Reduction tests and mechanical stability tests were performed with the soaked materials. A significant effect of alkalis on disintegration, degradation, and sticking behaviour of lumpy iron carriers during reduction could be demonstrated. The effect on the mechanical stability of sodium and potassium of different types of lump ore and pellets inside the blast furnace could be quantified [6].

In addition to the experimental investigations, a model was developed to predict the alkali distribution in the blast furnace [7]. Based on thermochemical calculations, regions with enriched contents of alkali-compounds can be determined. A multi-stage model approach connects the gas, temperature and pressure profiles of the blast furnace with the thermochemical calculation of stable alkali compounds. Statistical calculations complete the model due to their mass balance. The model enables the prediction of the K/Na-distribution and circulation inside the blast furnace as well as an overall alkali balance. By this means the attack of alkali compounds of the burden material and coke in the different zones of the blast furnace can be predicted. The results serve as the basis for further experimental investigations to characterise the sensitivity of raw materials for alkali attack.

2.2 Coke and Char for Ironmaking Technologies

Coke is not only the major fuel as well as the costliest raw material of the blast furnace but also the main source for the CO_2 emission of the steel production in the integrated route. Therefore, it requires careful investigation of its physical, chemical, and mechanical properties for determining its suitability under operational requirements. In order to enhance the sustainability of the hot metal production, the minimizing of the coke consumption and maximizing the furnace efficiency are two paramount challenges for the blast furnace operator. This research work emphasizes the behaviour of cokes under blast furnace conditions. Various industrial coke samples were examined in the laboratory under standard conditions (ISO 18894) as well as varying conditions from that. Different process parameters such as temperature, particle size, and gas compositions were varied to observe their effect on the strength and reactivity on cokes in terms of CRI (Coke Reactivity index) and CSR (Coke Strength after Reaction) values. The changes in the coke structures were observed by using Raman spectroscopy and petrographic methods. The interdependence of CRI and CSR values to the obtained parameters has been investigated. The results from this work pertaining to structure-property correlation of blast furnace cokes under variable process conditions will not only provide a deeper knowledge about the behaviour of this extremely valuable raw material but will also offer a ground for quality forecast for the blast furnace engineer [8]. Similar characterisation work was performed for char, which is an intermediate product produced in-situ by pyrolysis of non-coking coal in the melter-gasifier of the smelting reduction processes COREX® and FINEX®.

Further research work is aiming at the development of a holistic model for structure-property correlation of cokes under process conditions. The objective is to predict the coke quality beforehand and to look into the micro and nano domain of coke structure in the course of its evolution during process steps.

3. Energy Efficiency and Alternative Energy Resources

Energy is one of the main driving forces for innovation in the steel industry because it is the main cost factor. In 2012, the steel industry consumed about 5 % of the primary energy produced worldwide and contributed to 7 % of the total CO_2 emission [9].

The following sections introduce the research on new technologies which has the objective to reduce the energy consumption and CO_2 emission in comparison to the state of the art technologies. The Chair of Ferrous Metallurgy supports the development of new technologies of Austrian companies in the steel industry with its expertise in fundamental and applied research expertise.

3.1 Arvedi ESP Technology

Apart from energy efficiency and environmental aspects, other driving forces for the development of metallurgical technologies include the improvement of product properties and economic efficiency. Thin Slab Casting and Rolling (TSCR) represents a technology for hot strip production that combines all these trends. The Arvedi Endless Strip Production (Arvedi ESP) line is the first and till today the only representative of the endless TSCR process and was put into operation in 2009 [10]. Since the start-up, the ESP process has demonstrated stability and high production capacity comparable to that of the TSCR double casting-line process and has proved to be suitable for producing a wide range of steel grades comprising HSLA steel grades, silicon steels, dual phase or even sour gas-resistant pipe steels on the basis of electric steelmaking with remarkable reduction of energy consumption and CO_2 emissions [11, 12].

Since 2009 Primetals Technologies and the Chair of Ferrous Metallurgy have collaborated in the development of the process technology for the production of high performance steel grades via the Arvedi ESP process. Within the framework of an Energy2020 project, a coupled macroscopic solidification and hot rolling model with implemented microscopic models for precipitation and recrystallization kinetics and computational databases in the background was applied to develop new alloying strategies and production concepts [13]. Recently, the coupled product quality prediction models were successfully verified in plant trials in Cremona. Ongoing activities focus on the adaption of alloying concepts for high-strength cold rolled steels for the Arvedi ESP process route.

3.2 Hydrogen Plasma Smelting Reduction

The application of hydrogen for direct production of steel from iron ore by plasma smelting reduction is a disruptive technological approach. The production of steel with hydrogen plasma is an alternative route to the conventional steel production routes such as blast furnace with basic-oxygen-furnace, direct reduction with electric arc furnace, or smelting reduction with basic-oxygen-furnace. Due to the essential input of carbon carriers like coke, coal, and natural gas, a high amount of CO_2 is emitted by the current routes during production. By the reduction with H_2, only H_2O is produced as waste gas.

Fundamental research on plasma smelting reduction was initiated and promoted at the Chair of Ferrous Metallurgy already in the 1990s. In lab-scale tests basic data for such a process were evaluated and the reliability of the process-concept was confirmed [14]. However, the industrial implementation of the process concept requires further research and development for the upscaling of the technology to a production plant. For the further development up to industrial application, a step-by-step upscaling is needed. The next phase will be the construction and operation of a lab-scale facility with 10–20 kg tapping weight together with the industrial partners voestalpine and Primetals Technologies. With the results of these tests, mass flows and energy consumption of future industrial plants can be determined and first calculations according to investment and production costs can be done.

4. Steel Quality

The development of steel products with steadily increasing demands on their properties, such as strength, toughness, fatigue resistance or corrosion resistance helps to significantly reduce the weight of structural components and/or to extend the life cycle. This provides a valuable contribution to the sustainable use of steel. Higher demands for the steel quality at the same time mean higher demands for process control and process safety. The prevention of defect formation in casting processes and the control of the nature, shape and size of non-metallic inclusions are only two examples for research activities at the Chair of Ferrous Metallurgy, both in line with this trend.

4.1 Inclusion Metallurgy

In terms of a possibly high product quality and the avoidance of material failure, a high steel cleanness is essential not only for specific applications but is also a must for a broad field of steel grades. Steel cleanness can be primarily influenced in secondary metallurgical processes. Next to purging or vacuum treatment, reactions with a slag phase are essential. Since the formation of non-metallic inclusions cannot be avoided completely, an efficient removal of inclusions or a specific inclusion modification needs to be ensured.

Several research projects at the Chair of Ferrous Metallurgy deal with the improvement of the final steel cleanness based on a better understanding of reactions and interactions of inclusions in the system steel-slag-refractory. The latter is achieved through the combination of various lab scale facilities for the experimental simulation of the inclusion behaviour, thermodynamic and kinetic considerations as well as analytical instruments for inclusion characterization. The main research topics are:

- Reactions of inclusions (agglomeration, adhesion) at the steel/refractory interface—related to the clogging phenomenon during continuous casting, [15, 16]
- In-situ observation of inclusion dissolution in a slag phase using High-Temperature Laser Scanning Confocal Microscopy, [17, 18]
- Relationship between microscopic and mesoscopic steel cleanness especially considering the effect of heterogeneous nucleation, [19]
- Comparison and correlation of different characterization methods (SEM/EDS, OES/PDA). [20]

Although in general non-metallic inclusions are regarded to have a negative effect on steel properties, interesting efforts summarized under the definition "Oxide Metallurgy" emerged in the 1990s [21] aiming at the control of microstructure through the appropriate tailoring of inclusions. A current FWF-funded project [22, 23] deals exactly with this aspect investigating the relationship between inclusion properties and the nucleation of acicular ferrite. The latter nucleates intergranularly at inclusions, and consequently the propagation path for a cleavage crack in the metal is retarded due to the chaotic crystallographic orientation finally resulting in an increased toughness for selected steels [24].

4.2 Defect Formation in Casting Processes

Depending on its composition, steel may be very sensitive to deformation at elevated temperatures. Hypo-peritectic steels show for example a strong tendency to form an uneven strand shell during initial solidification. The consequences for process and product are manifold: Uneven heat transfer in the mold and mold level fluctuations may result in breakouts. Mold level fluctuations, deep oscillation marks, and surface depressions may result in surface and subsurface defects [25]. Scarfing of the cast semi is then necessary and causes additional production costs and yield losses. Countermeasures are still rare, and thus the prevention of the hypo-peritectic range is becoming more and more a guideline for the development of new steel grades.

The research on the behaviour of hypo-peritectic steels in casting processes at the Chair of Ferrous Metallurgy goes back to the 1990s [26]. Today the following topics represent the main research activities:

- Characterization of the phase transformation sequence by DSC measurement and the assessment of thermodynamic databases, [27, 28]
- The investigation of the kinetics of the peritectic phase transformation by high-temperature laser scanning confocal microscopy, [29–31]
- The measurement of shrinkage during solidification, [32]
- The experimental simulation of surface and subsurface defect formation during and after solidification.

5. Conclusions and Outlook

The research at the Chair of Ferrous Metallurgy contributes to a sustainable steel production and application in different aspects. Advanced methods for raw material characterization are under development and should help the operators for ironmaking facilities to a more efficient use of raw materials and to optimise the energy efficiency of the processes. With its expertise in fundamental and applied research, the Chair contributes to the development of the new breakthrough technologies such as endless strip production and hydrogen smelting reduction sponsored by the Austrian industries. These technologies should enable the steel industry in the future to produce steel with higher energy efficiency and lower CO_2 emission. A valuable contribution to the sustainable use of steel is the research work on the control of the nature, shape and size of non-metallic inclusions and on the prevention of defect formation in casting processes. The introduced research activities are ongoing and are executed in close cooperation with industrial partners in Austria. They are also financially supported by the federal ministries bmvit and bmvitj as well as the provinces Upper Austria, Styria, and Tyrol.

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References

1. World Steel Association, Sustainable steel policy and indicators 2014, Download https://www.worldsteel.org/dms/internetDocumentList/bookshop/2014/Sustainable-indicators-2014/document/Sustainable%20indicators%202014.pdf on Sept. 1, 2015
2. Hanel, M. B.; Kain-Bückner, B.; Schenk, J.; Mali, H.; Hauzenberger, F.; Thaler, C; Stocker, H.: Chemistry vs. Morphology vs. Reducibility — Some (Non-) Existing Correlations, AISTech 2015 Proceedings, Cleveland, Ohio, May 4–7 2015, pp. 593–602
3. Hanel , M. B.; Schenk, J F.; Mali, H.; Hauzenberger, F.; Thaler, C.; Stocker, H.: Characterization of Ferrous Burden Material for Use in Ironmaking Technologies, BHM Berg- und Hüttenmännische Monatshefte, 160 (2015), no. 7, pp. 316–319
4. Skorianz, M.; Mali, H.; Pichler, A.;Plaul., F.; Schenk., J.; Weiss, B.: Reduction Behaviour and Structural Evolution of Iron Ores in Fluidized Bed Technologies-Part 1: Method for the Determination, Steel Research International, 86, 2015, in press
5. Pichler, A.; Mali, H.; Plaul, F.; Schenk, J.; Skorianz, M.;Weiss, B.: Impacts of energy market developments on the steel industry, Presentation at 74th Session of the OECD Steel Committee, Paris, 2015, in press
6. Pichler, A.; Schenk, J. L.; Hanel, M. B.; Mali, H.; Hauzenberger, F.; Stocker, H.;Thaler, C.: Influence of alkalis on mechanical properties of lumpy iron carriers during reduction, Proceedings of Metal 2014, Brno, Czech Republic, May 21–23, 2014
7. Pichler, A.; Hauzenberger, F.; Schenk, J. L.; Stocker, H.; Thaler, C.: Thermochemical modelling of the alkali balance in blast furnaces, Proceedings of Asia Steel Conference 2015, Osaka, Japan, Oct. 5–8, 2015, in press
8. Bhattacharyya, A.; Rantitsch, G.; Schenk, J.; Thaler, C.; Stocker, H.: Effect of variable process conditions on the reactivity, strength and structural features of blast furnace cokes, Proceedings of Asia Steel Conference 2015, Osaka, Japan, Oct. 5–8, 2015, in press
9. Laplace Conseil, Impacts of energy market developments on the steel industry, Presentation at 74th Session of the OECD Steel Committee, Paris, 1–2 July 2013
10. Bragin, S.; Rimnac, A.; Linzer, B.; Bianchi, A.; Mantova, A.; Rizzi, A.;Bernhard, C.: ARVEDI ESP process—an ultimate technology connecting casting and rolling in endless mode, Proceedings of the 9th International/6th European Rolling Conference 2013, Venice, Italy, Jun. 10–12 2013, pp1–13
11. Bragin, S.; Bernhard, C.; Linzer, B.; Rimnac, A.; Guindani, A.;Venturini, R.: Thermomechanical processing of low-carbon steels on Arvedi endless strip production lines: Modelling and plant results, Proceedings of the TMP2012 (4th International Conference on Thermomechanical Processing of Steel), Sheffield, United Kingdom, Sept. 10–12 2012, Session 9—Paper—1
12. Linzer, B.; Watzinger, J.; Bragin, S.; Bernhard, C.;Bianchi, A.: Influence of thin slab thickness on final strip property in Arvedi ESP plant, Proceedings of the 8th European Continuous Casting Conference, Graz, Austria, Jun. 23–26 2014
13. Schmidtchen, M.; Kawalla, R.;Rimnac, A.: Simulation of Inhomogeneous Materials Evolution in Hot Rolling using a Layer Model, THERMEC 2013 (8th Internation Conference on advanced materials), Las Vegas, USA, Dec. 2–6 2013
14. Bäck, E.; Schenk, J.; Badr, K.; Sormann, A. I.; Plaul, J. F.: Wasserstoff als Reduktionsmittel für die Eisen- und Rohstahlerzeugung—Ist-Situation, Potentiale und Herausforderungen, BHM Berg- und Hüttenmännische Monatshefte, 160 (2015) , no. 3, pp 96–102
15. Bernhard, C.; Xia, G.; Egger, M.; Pissenberger, A.; Michelic, S.: Experimental investigation into the influence of Ti on the clogging of ULC steels in continuous casting, AISTech 2012 Proceedings, Atlanta, USA, May 3–5, 2015, pp 2191–2200
16. Michelic, S.; Dieguez-Salgado, U.; Bernhard, C.: In-situ observation of the behaviour of non-metallic inclusions at different interfaces in the system steel-slag-refractory, Liquid Metal Processing and Casting Proceedings, Leoben, Austria, Sept. 20–24, 2015, in press
17. Feichtinger, S.; Michelic, S.; Kang, Y.-B.; Bernhard, C.: In-situ observation of the dissolution of SiO2 particles in CaO-Al2O3-SiO2 slags and mathematical analysis of its dissolution pattern, Journal of the American Ceramic Society, 97 (2014), no. 1, pp 316–325
18. Michelic, S.; Goriupp, J.; Feichtinger, S.; Kang, Y.-B.; Bernhard, C.; Schenk, J.: Study on Oxide Inclusion Dissolution in Secondary Steelmaking Slags using High Temperature Confocal Scanning Laser Microscopy, steel research int., 86 (2015), in press
19. Michelic, S.; Loder, D.; Reip, T.; Ardehali Barani, A.; Bernhard, C.: Characterization of TiN, TiC and Ti(C, N) in titanium-alloyed ferritic chromium steels focusing on the significance of different particle morphologies, Materials characterization, 100 (2015), pp. 61–67.

20. Michelic, S.; Wieser, G.; Bernhard, C.: On the Representativeness of Automated SEM/EDS Analyses for Inclusion Characterisation with Special Regard to the Measured Sample Area, ISIJ international, 51 (2011), no. 5, pp 769-775
21. Sawai, T.; Wakoh, M.; Ueshima, Y.; Mizoguchi, S.: Analysis of Oxide Dispersion during Solidification in Ti, Zr-deoxidized Steels, ISIJ International, 32 (1992), no. 1, pp 169–173
22. Loder, D.; Michelic, S.; Mayerhofer, A.; Bernhard, C.; Dippenaar, R.: In situ observation of acicular ferrite formation using HT-LSCM: possibilities, challenges and influencing factors, Proceedings of MS T14, Pittsburgh, USA, Oct. 2014, pp 1–8
23. Loder, D.; Michelic, S.: Specific use of non-metallic inclusions for the formation of acicular ferrite structures: Thermodynamic modeling and laboratory experiments, Clean Steel 2015, Budapest, Hungary, Sept.8–11, 2015, in press
24. Sarma, D. S.; Karasev, A. V.; Jönsson, P. G.: On the Role of Non-metallic Inclusions in the Nucleation of Acicular Ferrite in Steels, ISIJ International, 49 (2009), no. 7, pp 1063–1074
25. Xia, G.: Mold metallurgy in the conventional slab casting of steel, Habilitation thesis, Leoben, Montanuniv., Lehrstuhl für Eisen- und Stahlmetallurgie, 2012
26. Wolf, W.: Initial solidification and strand surface quality of peritectic steels, Continuous Casting, 9 (1997), Warrendale, USA, 1997
27. Presoly, P.; Bernhard, C.; Pierer, R.: Identification of Defect Prone Peritectic Steel Grades by Analyzing High-Temperature Phase Transformations, Metallurgical and materials transactions, 44 (2013), no. 12, pp 5377–538
28. Presoly, P.; Bernhard, C.; Xia, G.: Identification of peritectic steel grades by thermal mould monitoring and DSC measurements, Proceedings of the 8th European Continuous Casting Conference, Graz, Austria, Jun. 23–26, 2014
29. Griesser, S.; Reid, M.; Bernhard, C.; Dippenaar, R.: Diffusional constrained crystal nucleation during peritectic phase transition, Acta materiala, 67 (2014), pp 335–341
30. Griesser, S.; Bernhard, C.; Dippenaar, R.: Mechanism of the Peritectic Phase Transition in Fe-C and Fe-Ni Alloys under Conditions Close to Chemical and Thermal Equilibrium, ISIJ International, 54 (2014), no.2, pp 466–473
31. Griesser, S.; Bernhard, C.; Dippenaar, R.: Effect of Nucleation Undercooling on the Kinetics and Mechanism of the Peritectic Phase Transition in Steel, Acta Materialia, 81 (2014), pp 111–120
32. Rowan, M.; Thomas, B. G.; Pierer, R.; Bernhard, C.: Measuring mechanical behavior of steel during solidification: Modelling the SSCC test, Metallurgical and materials transactions B, 42 (2011), pp 837–851