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the dew point of atmosphere from 223 K to 285.5 K (-50°C and 12.5°C), the primary crystalline phase of fluorine-containing mold flux was changed from cuspidine (Ca4Si2O7F2) to Ca2SiO4 with accelerated nucleation rates. Enhancement of fluorine evaporation due to hydroxyl is attributed to the main reason for the abnormal crystallization behavior of the fluorine-containing mold flux under humid atmosphere, which may bring a sticking-type breakout during the commercial continuous casting process. In contrast, the effect of water vapor on crystallization of fluorine-free mold flux was negligible. This implies that the application of fluorine-free mold fluxes can become a countermeasure to prevent the hydrogen-induced breakout during the continuous casting process under wet atmosphere.

**A review of mold flux development for the casting of high-Al steels.** W. Wang, B. Lu, D. Xiao

Mold flux plays key roles during the continuous casting process of molten steel, which accounts for the quality of final slabs. With the development of advanced high strength steels (AHSS), certain amounts of Al have been added into steels that would introduce severe slag/metal interaction problems during process of continuous casting. The reaction is between Al and SiO2 that is the major component in the mold flux system. Intensive efforts have been conducted to optimize the mold flux and a CaO–Al2O3-based mold flux system has been proposed, which shows the potential to be applied for the casting process of AHSS. The latest developments for this new mold flux system were summarized with the aim to offer technical guidance for the design of new generation mold flux system for the casting of AHSS.

**A comparative study of fluid flow and mass transfer in a trumpet-shaped ladle shroud using large eddy simulation.** J. Zhang, J. Li, Y. Yan, Z. Chen, S. Yang, J. Zhao, Z. Jiang

The advantages of trumpet-shaped ladle shrouds (TLS) have been frequently demonstrated over conventional straight-bore ladle shrouds (CLS) with respect to production efficiency and molten steel quality in continuous casting practices. The present study is to shed some lights on why the TLS are better than the CLS design by examining the fluid dynamics and mass transfer using large eddy simulation. The obtained numerical results were validated with particle imaging velocimetry experiments. Flow velocity, deformation, turbulent energy dissipation, and mixing kinetics of tracer were discussed. The results showed that the entering jet of the CLS flowed straight down into the tundish with a relatively high speed (average at 0.710 to 0.815 m/s) and turbulent kinetic energy. However, the trumpet section of a TLS intensified velocity differences, strain rates, and vortices, and promoted an increase on turbulence dissipation rate in the interior of the ladle shroud. The average speed of the entering jet to the tundish was decreased to 0.270 to 0.410 m/s from the 0.708 m/s of the inlet speed. The entering jet from the TLS swung, twisted and well mixed with surrounding fluid in the tundish, and dissipated its kinetic energy. Consequently, the turbulence of the whole flow field as well as the mean skin friction coefficient of tundish wall and the velocity of free liquid surface were reduced. A tracer experiment was carried out to study mass transfer and flow mixing behavior, and the results demonstrated that the use of the TLS increased the plug volume and decreased the dead zone, thereby enhancing inclusion flotation.

**Metallurgical and Materials Transactions A, February 2016**

**In situ measurement and prediction of stresses and strains during casting of steel.** D. Galles, C. Beckermann

Modeling the thermo-mechanical behavior of steel during casting is of great importance for the prediction of distortions and cracks. In this study, an elasto–visco–plastic constitutive law is calibrated with mechanical measurements from casting experiments. A steel bar is solidified in a sand mold and strained by applying a force to bolts that are embedded in the two ends of the bar. The temporal evolutions of the
restraint force and the bar’s length change are measured in situ. The experiments are simulated by inputting calculated transient temperature fields into a finite element stress analysis that employs the measured forces as boundary conditions. The thermal strain predictions are validated using data from experiments without a restraint. Initial estimates of the constitutive model parameters are obtained from available mechanical test data involving reheated steel specimens. The temperature dependence of the strain rate sensitivity exponent is then adjusted until the measured and predicted length changes of the strained bars agree. The resulting calibrated mechanical property dataset is valid for the high-temperature austenite phase of steel. The data reveal a significantly different mechanical behavior during casting compared to what the stress-strain data from reheated specimens show.

ISIJ International, January 2016
Structure and properties of slags used in the continuous casting of steel: Part 1 conventional mould powders. K. Mills
The physical properties of mould slags are key to their performance in the continuous casting process. The magnitudes of key properties (viscosity, break temperature, fcryst and optical properties) are determined by the mould dimensions, casting conditions and the steel grade being cast. However, a range of other properties (e.g. interfacial tension, density) are needed to minimise defects and process problems. The extant data for thermo-physical properties of conventional mould slags are reviewed here and those for specialist powders (e.g. F-free or for casting TRIP steels) are reviewed in Part 2. It was concluded that there is a need for (i) resolution of the huge differences in thermal conductivity of mould slags for T>1 050 K obtained with the LP and THW methods (ii) more data for some properties (e.g. Cp and density) and more accuracy for others (viscosity, surface tension) (iii) standardised procedures for the determination of fcryst and (iv) characterisation of the porosity in slag films. It was also concluded that (i) gaseous convection makes a significant contribution to the heat transfer in the powder bed and (ii) glassy slag films are probably optically-thin.

Structure and properties of slags used in the continuous casting of steel: Part 2 specialist mould powders. K. Mills
In Part 1, the thermo-physical properties of conventional mould slags used in the continuous casting of steel were reviewed. In Part 2, the properties of mould slags used in specialised continuous casting are collated and examined. The following types of slag have been studied (i) Fluoride-free (ii) Carbon-free (iii) non-Newtonian slags used to cast (iv) high Al steels (v) Ti-stabilised stainless steels (vi) thin-slabs at high speeds and (vii) round billets. The casting problems encountered with each type of slag are outlined and the characteristics of the developed slags described. The empirical rules developed for conventional casting apply to these specialised continuous casting covered here. So values of the viscosity, break temperature and fraction crystalline phase are determined by the mould dimensions, casting conditions and steel grade. Consequently, much of these data were produced in “New powder versus Conventional powder” and tend to have similar property values. However, some systematic studies have been carried out but there are no published values of the density, surface tension and thermal conductivity. The use of non-Newtonian slags provides a new method of improving steel cleanliness and many of the casting problems encountered in the casting of high Al steels have been reduced using calcium aluminate-based slags; however, some further developments are still needed in both cases.

Surface tension of molten ionic mixtures such as slag is an important physical property related directly to various surface or interfacial phenomena in high-temperature
industrial processes. In particular, surface tension of oxide–fluoride melts is of interest to understand interfacial phenomena in continuous casting in steelmaking. However, the composition dependence of surface tension in reciprocal ionic melts has not been well understood because of its complexity related to the reciprocal reaction between input components in the melt. In this study, we measured the surface tension of reciprocal oxide–fluoride melts in a Si–Ca–Na–O–F multicomponent system, to evaluate its composition dependence. We used a maximum bubble pressure method to determine the surface tension of these melts with high accuracy. Our results indicate that (1) the surface tension of the SiO2–CaO melt decreases by NaF addition more steeply than by Na2O addition, and (2) the surface tension of the SiO2–CaO–CaF2 melt decreases with Na2O addition but depends on NaF formation because of the reciprocal reaction CaF2 + Na2O = CaO + 2 NaF. When this reaction is taken into account, the surface tension of the SiO2–CaO–CaF2–Na2O melt matches that of the SiO2–CaO–NaF melt with increased CaO concentration from the above melt composition.

Analysis of factors affecting free surface vortex formation during steel teeming. H. Li, Q. Wang, J. Jiang, H. Lei, Z. Guo, J. He
To suppress slag entrapment by vortexes during steel teeming, and to improve steel cleanliness, key factors affecting free surface vortex formation have been analyzed in this study. It was found that Coriolis forces have little effect on vortex formation. The initial tangential disturbance is the main factor for vortex formation. And when the nozzle position is central or eccentric, the effects of initial tangential velocity, nozzle diameter on the critical height are different. Physical properties of liquid steel have a small effect on the critical height. A formula for calculating the height was discussed.

Analysis of two-phase flow and bubbles behavior in a continuous casting mold using a mathematical model considering the interaction of bubbles. T. Zhang, Z. Luo, H. Zhou, B. Ni, Z. Zou
A new mathematical model considering the process of bubbles interaction has been developed to simulate the transient fluid flow, dispersed bubbles motion and transport process in the slab continuous casting mold. Rather than prescribing a constant bubbles size in previous work, this model allow us to calculate the constantly changed daughter particles size distribution after the process of bubbles collision and breakup. In this paper, using the new model to study the effect of some parameters such as gas flow, casting speed, and the depth of submerged entry nozzle (SEN) on the fluid flow pattern, the gas volume fraction, the distribution of bubbles and so on. The predictions of gas bubble distribution and fluid flow pattern are in good agreement with the water model experimental observations. Meanwhile, the model has successfully reproduced many known phenomena and other new predictions, including the process of bubbles collision and breakup. The simulation results show that the important factors that influence the size and quantity distribution range of bubbles are casting speed and argon gas flow rate and depth of SEN. Through the statistical analysis of bubbles behavior, the effects of blowing argon on porosity defects under different operating conditions can be obtained.

Liquid Metal Processing & Casting Conference, September 2015, Leoben, Austria
Comparison of different methods to model transient turbulent magnetohydrodynamic flow in continuous casting molds C Kratzsch, A Asad, R Schwarze.
Modeling of the processes in the continuous casting mold engaged many scientist once the computer-technology was able to accomplish that task. Despite that, CFD modeling of the fluid flow is still challenging. The methods allow deeper and deeper inside views into transient flow processes. Mostly two kinds of methods are applied for this purpose. URANS simulations are used for a coarse overview of the transient behavior
on scales determined by the big rollers inside the mold. Besides, LES were done to study the processes on smaller scales. Unfortunately, the effort to set up a LES is orders of magnitude higher in time and space compared to URANS. Often, the flow determining processes take place in small areas inside the flow domain. Hence, scale resolving methods (SRS) came up, which resolve the turbulence in some amount in these regions, whereas they go back to URANS in the regions of less importance. It becomes more complex when dealing with magnetic fields in terms of EMBr devices. The impact of electromagnetically forces changes the flow structure remarkably. Many important effects occur, e.g. MHD turbulence, which are attributable to processes on large turbulent scales. To understand the underlying phenomena in detail, SRS allows a good inside view by resolving these processes partially. This study compares two of these methods, namely the Scale Adaptive Simulation (SAS) and the Delayed Detached Eddy Simulation (DDES), with respect to rendition of the results known from experiments and URANS simulation. The results show, that the SAS as well as the DDES are able to deliver good results with higher mesh resolutions in important regions in the flow domain.

Ironmaking & Steelmaking, October 2015

Prediction model for steel/slag interfacial instability in continuous casting process. L. Zhang, Y. Li, Q. Wang, C. Yan

In a continuous casting process, mould powder is typically adopted to cover molten steel, which prevents liquid steel from oxidation by air, preserves heat for the top layer of liquid steel, lubricates the initial shell and so on. However, mould powder may deteriorate the quality of the final product if the entrapment of mould powder forms, which is usually caused by the instability of the steel/slag interface. In the current work, a model to predict the critical point of interfacial instability for liquid–liquid stratified flow was developed based on the Kelvin–Helmholtz instability. To prove the validity of the prediction model, a water model experiment was carried out in a rectangular container. In this experiment, oil and water were used to simulate slag and molten steel respectively. The results of the water model prove that the prediction model is correct. Applying the prediction model to a steel–slag system, the critical velocity of molten steel for mould powder entrapment is 0.463–0.541 m s⁻¹. When considering the most severe chemical reaction, the critical velocity decreases to 0.29 m s⁻¹. The lowest critical velocity of molten steel is 0.264 m s⁻¹ when the viscosity of the slag and steel/slag interfacial tension is extremely low.

Effect of CaO/Al₂O₃ ratio on viscosity and crystallisation behaviour of mould flux for high Al non-magnetic steel. W. Yan, W. Chen, Y. Yang, C. Lippold, A. McLean

In order to facilitate the development of CaO–Al₂O₃ based mould flux for casting high aluminium, non-magnetic steel, the effect of CaO/Al₂O₃ ratios from 0.6 to 3.2 on viscosity and crystallization characteristics were investigated with the aid of a rotational viscometer, Fourier transform infrared spectroscopy, a single hot thermocouple technique and X-ray diffraction analysis. The results showed that, at temperatures above 1543 K (1270°C), the viscosity first decreased and then became stable with increase in the CaO/Al₂O₃ ratio. At temperatures below 1543 K (1270°C), the viscosity again first decreased but then increased, with the CaO/Al₂O₃ ratio. This viscosity behaviour can be attributed to changes in the network structure characteristics and the precipitation of solid particles within the liquid flux. Increase in the CaO/Al₂O₃ ratio also first inhibited and then enhanced crystallisation as demonstrated by the changes in initial crystallisation temperatures and incubation times. The X-ray diffraction results confirmed that, at both low and high CaO/Al₂O₃ ratios, the dominant precipitates were compounds with high melting points. On the other hand, with CaO/Al₂O₃ ratios in the midrange, the dominant precipitates were compounds with relatively low melting temperatures. It is concluded that mould flux with a CaO/Al₂O₃ ratio in the range 1.1–1.6 is the most appropriate for casting high aluminium, non-magnetic steels.
Archives of Metallurgy and Materials, August 2015
Numerical and physical simulation of liquid steel behaviour in one strand tundish with subflux turbulence controller. A. Cwudziński
This paper presents the results of computer simulations (Ansys-Fluent) and laboratory experiments (physical water model) carried out to describe the motion of steel flow in the tundish. The facility under investigation is a single-nozzle slab tundish. The internal geometry of the object was changed by flow control device i.e. subflux turbulence controller (STC). In order to obtain a complete hydrodynamic picture in the tundish, laboratory experiments (physical modeling) were performed for both isothermal and non-isothermal conditions. From the performed computer simulations and laboratory experiments (physical modeling) it can be found that, the non-isothermal conditions occurring during continuous steel casting will definitely influence the hydrodynamic pattern forming in the tundishes with STC.

METEC & 2nd ESTAD, June 2015
Mold flow optimization for casting narrow section in CSP at BPSL – India. R Arasu, D. Mahanty, J. Richaud
In order to cater to the product demands, narrow slabs are being cast in 800mm wide CSP funnel mold at Bhushan Power and Steel Limited (BPSL). Further to remain competitive in the market, long casting sequence has become the need of the day while maintaining high quality standards. A new refractory Sub-Entry-Nozzle (SEN) was developed by Vesuvius design team to achieve long casting sequence in tundish. Numerical simulation supported by water modeling were conducted with the objectives of achieving better mold flow stability, enhanced mold powder melting for optimal lubrication. Due to a challenging small mold cavity inside which the SEN has to fit with a desired mold clearance, high erosion resistance material is used in the mold slag line region. To increase sequence length, the mold flow behavior has to remain stable regardless of the large nozzle immersion range achieved by ramping both mold level and tundish car position. The new design, R3S is achieving these goals, 30 heats are regularly cast with mold level fluctuations remaining below 1 mm range. BPSL has optimized all process and practices to achieve these long casting duration, such as preheating, ramping practice and casting parameters.

Automatic virtual optimization of ingot and continuous casting processes. I. Hahn, E. Hepp, M. Schneider
Simulation technology today makes it easily possible to carry out three-dimensional simulations of the teeming and solidification of ingots as well as of the flow and solidification in continuous casting processes. Quick and reliable virtual casting trials in the computer can be performed considering all relevant process parameters. During casting, numerous complex physical phenomena occur simultaneously that are coupled with each other. Changes of one process parameter usually lead to a change of many quality-relevant properties of the product. A coupling of casting process simulation with statistical design of experiments allows the virtual exploration and evaluation of the effects of process changes on all relevant quality characteristics. Automatic virtual optimization, which is focused on the fulfillment of several targets at the same time, provides a promising approach for defining robust casting processes and finding operating points that build a best compromise between competing objectives. This paper will show examples of the application of these methodologies for continuous and ingot casting processes and gives an insight into how process development benefits from them.

Quantification of martensitic banded microstructure in dual phase steels and its application at ArcelorMittal Dofasco’s No.1 continuous caster. S. Alibeigi, J. Sengupta, E. Biro
A simple technique was developed to quantify the level of banding using automatic image analysis. The proposed method is based on computing a banding severity index (BSI) in optical microscopic images by measuring band dimensions such as bands length and average bands thickness. LePera’s and 4% picral etchants were used to reveal martensite and bainite/pearlite bands, respectively. BSI is in qualitative agreement with the microstructures. The method was used to study the effect of continuous casting parameters and hot mill coiling temperature on banding severity in hot rolled dual phase samples. It indicated that increasing the superheat and coiling temperature resulted in higher level of banding in the microstructure. No correlation between casting speed and banding severity was observed.

**A model for sequencing and optimizing steel melt shop operations using discrete event system simulation.** A. Mukherjee, A. Adak

This paper presents how steelmaking throughput improvement study using simulation helped to identify the bottlenecks causing capacity loss and experiment with options to redesign the system by suggesting mechanisms for improvement and additional facilities and logistical resources. From a unit optimization perspective, it is essential that the BOF does not have any wait time other than the preparation time. Liquid steel is moved to the casters from the BOF via LRF and for some grades VD, such that the heat sequences for different grades are maintained while maximizing the utilization of the casters. The simulation model of the steel-melting-shop unit included all these elements and constraints to reflect the behaviour of the unit in operation. Based on the objective of maintaining the sequence continuity in the casters while maximizing its utilization, our simulation model helped discover the bottleneck due to BOF delays and the number of existing LRFs. Redesigning and simulating again yielded the changes in BOF, optimal number of LRF units, the optimal number of hot metal ladles and steel ladles in active circulation and also ensured maximum possible capacity utilization and throughput in the melt shop.

**Technological and automation upgrade for CSP plant TKSE Bruckhausen.** M. Thomasky, S. Burger, R. Leitner, M. Lasslberger

In July 2011, ThyssenKrupp Steel Europe (TKSE) in Bruckhausen, Germany, awarded a contract to Primetals Technologies for the modernization of the existing automation system in the casting section of their Compact Strip Production (CSP) plant. The solutions are based on proven CC automation packages from VAI. The scope of supply comprised the replacement of the process-control and visualization system with a new PCS7-based automation package, as well as the installation of technological control packages that included DynaWidth moldwidth adjustment, DynaFlex oscillator control and LevCon mold level control for improved quality, as well as the breakout-prevention system Mold Expert for increased plant availability. This paper discusses the technical concept of the time-critical system upgrade that was carried out without additional interruptions to the production process. The results of the installed packages LevCon, DynaWith, DynaFlex and Mold Expert after the successful completion of the acceptance tests are presented. Feedback from TKSE after two years of operation with the new technological and automation systems rounds off this topic.

**Innovation highlights in continuous casting automation.** W. Oberaigner, R. Leitner

This capability is impressively demonstrated by recent advancements in automation solutions from Primetals Technologies that include: DynaPhase, Dynacs 3D, and DynaGap. This state-of-the-art suite of dynamic secondary cooling and soft-reduction packages take into account thermodynamic effects such as shrinkage and phase transitions, and thereby significantly contribute to direct quality improvements during the solidification phase in the continuous casting process. Speed Expert calculates an optimum casting speed for every casting situation, and additionally recommends a strand speed so that the point of final solidification is positioned at the end of a
segment for optimum soft reduction. Nozzle Expert is a completely new model that detects clogged nozzles and broken hoses in secondary cooling systems. The first installations were highly successful and customers are pleased with impressive reductions in maintenance costs and improved steel quality. In the case of steel grade changes, the Intermix model precisely calculates the chemical properties of the mixed steel, thereby minimizing losses due to deviations from required specifications. Furthermore, a completely new human-machine interface (HMI) for the Level 2 automation system has been developed and successfully installed in recent projects. These solutions and operational results are described, and an outlook on future developments is presented.

**Comprehensive process optimization system for JSW Steel Toranagallu.** R. Hubmer, J. Weiss, N. Desai

The JSW Steel Ltd has become India’s largest private sector steel company with an installed capacity of 14.3 MTPA. The JSW Steel Vijayanagar plant in Toranagallu is the first integrated steel plant in India to reach 10 MTPA capacity in a single location. In October 2013 JSW Steel decided to place an order to Primetals Technologies Austria (former Siemens VAI Metals Technologies) for the installation of a comprehensive Level 2 process optimization system for more than 20 existing production facilities of various suppliers. For SMS-I new L2 systems are provided for two hot metal pretreatment stations, three hot metal desulphurization stations, three ladle furnaces, two 1-strand slab casters, a ladle tracking system as well as a shop supervisory system. Additionally the existing L2 system for one 1-strand slab caster is being upgraded in the course of the project. In SMS-II new L2 systems for the 7 hot metal desulphurization stations, 4 ladle furnaces, 1 new RH vacuum degasser, ladle tracking system and a shop supervisory system are supplied. Following the challenging time frame from JSW Steel Ltd the acceptance test has been passed in July 2014 and the commissioning of the single facilities started within less than 12 month after contract effectiveness. This paper describes the installed Primetals Technologies process optimization systems and their integration into the JSW automation environment. Furthermore it gives a characterization of the course of the project and focuses on achieved results.