Liquid Metal Processing & Casting Conference - LMPC 2024

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Book of Abstracts

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Session 10 / 1

Formablity at room temperature of twin-roll cast Mg-Al-Zn-Sn alloy applied pre-strain and solution heat treatment

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A twin-roll cast material of Mg-9.0 mass%Al-0.72 mass%Zn-1.85 mass% Sn-0.21 mass%Mn (AZT912) with 2.4 mm thick and 100 mm width that was given pre-strain after solution heat treatment was tested by V-bending at room temperature.
The purpose of this study is to fabricate a thin sheet plate for the practical use of plastic forming in room temperature by using twin-roll cast Mg-9mass%Al-1 mass%Zn-2 mass% Sn alloy, which have possibilities to improve mechanical properties and corrosion resistance by applying heat treatment after twin-roll casting. Pre-strain to the solution-treated twin-roll cast material was given and annealing was performed. A V-bending test has been conducted in order to estimate cold formability at room temperature.

Speaker Country:

Japan

Session 10 / 2

Bonding magnesium alloy andpolymer applied by silane coupling and atmosphere pressure plasma

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In order to advance the development of innovative lightweight materials, it has been clarified the effects of heat treatment of magnesium alloys and silane coupling conditions on the bonding strength of the laminated Mg alloy/polymer material. Effects of silane coupling condition on bonding have been mainly discussed on laminated Mg alloy/polymer material.
It has been considered that the proposed research will contribute to the formation of an environmentally friendly manufacturing technology that can respond to the reduction of greenhouse gas emissions such as CO2.

Speaker Country:

Japan

Session 1 / 3

THE DEVELOPMENT OF SIMULATORS FOR THE ESR AND VAR REMELT PROCESSES

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ABSTRACT
Mathematical modelling studies of the remelt processes afford valuable insights into the solidification processes, but they generally present an instantaneous snapshot of conditions in the liquid pool rather than a global view of the entire process. This paper describes the development of simulators for the ESR (round and slab) and VAR remelt processes in different production configurations. Each predicts the behaviour of the remelt process from start to finish of melting, including calculation of solidification conditions, heat balances, and voltage/current/electromagnetic field distributions within the furnace and the ingot.
Key to the development of these simulators is the formulation of a model for the energy source in each process. This source model enables the top ingot boundary condition to be calculated from the furnace operating parameters (voltage, current or melt rate, arc gap or swing depth), process parameters (electrode/crucible dimensions) and furnace characteristics (furnace resistance, current flows). Additional data describing the physical characteristics of the furnace and the boundary conditions for the process are incorporated into the models. The details of each simulator for the ESR and VAR processes are described.

Speaker Country:

Canada

Session 1 / 5

The Role of Solidification Irregularities in Freckle Formation

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Several detailed models have been developed to account for the formation of freckles in conventional ingots, remelted ingots and in single crystal castings, accounting for the effect in titanium alloys, steels, superalloys and aluminium alloys as well as in model laboratory systems based on aqueous solutions or low melting point alloys. They are based on the concepts of inter-dendritic fluid flow through the solidifying dendrite network, driven by buoyancy forces developed by the density differences in the liquid arising from segregation of the alloy elements. In some models the formation process is held to be assisted by fluid flow in the liquid ahead of the liquidus. Following experimental verifications in laboratory conditions they have been used for both alloy design proposals and in establishing melting and casting parameters for industrial processes. In this work we examine the result of applying the models to industrially remelted ingots in various alloy compositions. The conclusions indicate that whilst the models produce satisfactory indications of freckle flow in the ideal solidification structures, the solidification irregularities formed the local deviations in process parameters generally present in industrial practice play an overriding role in determining the presence or absence of freckles in the final ingot product

Speaker Country:

Canada

Session 2 / 6

Segregation in vacuum arc remelted ingots of titanium alloys

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Segregation in titanium alloy ingots has largely been treated as a macro-segregation problem. The alpha/beta alloy Grade 5 (“6/4”), for example, is sensitive to macro-variations in Al content due to the precise property requirements of the heat-treated structures. In VAR practice, the problem is mitigated through the use of multiple melting techniques, high quality alloys being remelted three successive times with ingot reversal. The mechanisms and outcomes in ingot composition changes have been modelled with the assumption that the solidification is always in a columnar-dendritic mode. However, in most melting practices, the energy input necessary to maintain a good ingot surface causes a substantial fraction of the ingot to solidify equiaxially. The practical and modelling consequences of this change are examined.

Some of the near-beta alloys (e.g. 10-2-3, Ti17, Beta-CEZ) are also sensitive to micro-segregation issues, principally freckle formation. The freckle problem, unlike the same issue in lower melting-point alloys, is not one of locally excessive primary precipitate formation. Instead it is instead one of composition variations which lead to transition temperature changes resulting in deleterious beta phase retention after heat treatment. Present freckle models do not appear to explain this phenomenon in titanium alloys. It is proposed that freckle formation in this alloy system is largely controlled by process instability deriving from the arc characteristics of the VAR furnace.

Speaker Country:

Canada

Session 8 / 7

Modelling the physical properties of electrofluxes through the lens of experimental data

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Electroslag remelting (ESR) and vacuum arc remelting (VAR) are widely employed techniques for producing defect-free ingots in ferroalloys, nonferrous metals, and superalloys. These technologies find applications in sectors like military, aerospace, and aeronautics, where high performance is of paramount importance. Given the critical nature of these applications, a comprehensive understanding of the smelting process is imperative. Therefore, developing precise models for predicting the physical properties of the involved slag is crucial, as it enables operators to simulate and optimize process parameters effectively. This study comprehensively modelled three premelted commercial electrofluxes from Wacker and compared these models with experimental data. Key properties such as viscosity, density, electrical conductivity, specific heat (Cp), heat of fusion, and linear and volumetric thermal expansion coefficients was modelled through precise mathematical expressions, which can be subsequently integrated into process simulations. Moreover, the Roscoe-Einstein expression, traditionally used for correcting viscosity during solid-liquid phase transitions, was adapted to model electrical conductivity across the entire temperature range, from solid to fully liquid. Models demonstrated a strong correlation with the experimental data, providing operators with reliable and accurate information about Wacker Electrofluxes in their production processes.

Speaker Country:

Deutschland

Session 4 / 8

Simulation and optimization of electromagnetic stirring and braking in slab continuous casting mold

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With increasing demands regarding efficiency and product quality, flow control by electromagnetic fields is becoming the state-of-the-art in continuous slab casting technology. In such systems, the flow is controlled by Lorentz forces, which arise from the interaction between liquid steel flow and externally applied magnetic field. Static magnetic fields generated by Electromagnetic Braking (EMBr) systems serve to stabilize the flow. Conversely, traveling magnetic field systems, like the Electromagnetic Level Accelerator (EMLA), provide more active control over the liquid steel flow. Proper application of combined electromagnetic stirring and breaking within the mold results in a favorable flow behavior, which leads to an increased internal strand quality even at high casting speeds. Therefore, understanding and optimizing the interplay of electromagnetic fields with casting parameters is essential. The complexity of these systems calls for a numerical investigation. A substantial number of simulations is required to conduct a comprehensive parametric study and optimize the performance of the electromagnetic flow control system. In this work, a system equipped with AC and DC coils, which can generate combined electromagnetic fields, is presented. Using Computational Fluid Dynamics (CFD) simulations, we examined the impact of EMBr and EMLA on mold flow patterns across a range of casting parameters, including casting speed, width, and sub-entry nozzle immersion depths commonly used in the casting process.

Speaker Country:

Austria

Session 3 / 9

A comprehensive numerical modelling of Plasma Arc Melting (PAM) process and simulation of inclusions removal

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Titanium alloys are increasingly used in aeronautical applications, a sector that requires highly controlled materials. In particular, inclusion cleanliness is a necessary and mandatory condition for safe use of aeronautical components. During the production and processing of titanium alloys, inclusions could appear, with two distinguishable types: low density inclusions (LDI) and high-density inclusions (HDI). LDIs result from the contamination of titanium by oxygen or nitrogen during production stages, while HDIs originate from refractory metals such as molybdenum or tungsten carbide.

Plasma Arc Melting Cold Hearth Remelting (PAMCHR) is one of the most effective recycling and refining process for titanium alloys. The furnace comprises three parts; a melting crucible where raw materials are loaded and melted, a refining crucible where the elimination of the inclusions must be completely, and finally, an ingot mold where the secondary ingot grows and solidifies. Firstly, this work reports the thermal modeling of the melting of raw materials in the melting crucible as well as a complete 3D numerical simulation of the thermo-hydrodynamic behavior of the metal flow in the PAMCHR furnace, based on the software Ansys-Fluent CFD. Simulation results are presented for a pilot furnace with a comparison between the measured and calculated pool profiles that shows a satisfactory agreement. Additionally, a numerical analysis of the residence time distribution (RTD) is presented. A RTD trial was carried out where a copper tracer is introduced into the feed material flow (Dirac function), and the profile of the mass fraction is measured in the secondary ingot. Perfectly stirred reactors (PSR) accurately model the flow in each of the crucibles of the pilot furnace.
A Lagrangian calculation of particle trajectories in the liquid metal pool is also performed. The effects of critical parameters such as particle size, density, injection location and plasma torch trajectory on particle residence time are evaluated. The calculated rates of inclusions are then compared to an experimental injection in the pilot furnace.

Speaker Country:

France

Session 2 / 10

3D Transient Numerical Modelling of Vacuum Arc Remelting Process and its implication on 2D Axisymmetric Model

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Computational modeling of the Vacuum Arc Remelting (VAR) Process has been developed to provide a deeper physical and metallurgical understanding and assist in the reliable and efficient manufacture of defect-free ingots. While 3D VAR models with transient (time varying) arc behavior have been developed, 2D axisymmetric models with steady-state arc boundary conditions remain the primary tool in industrial applications due to their computational efficiency and the accepted representation of fundamental physical phenomena. In this study, a multi-physics computational model was established in ANSYS Fluent to simulate the VAR process for Inconel 718 in 3D with a transient arc. The model accounts for critical aspects, including magnetohydrodynamics, heat transfer, fluid dynamics, as well as melting and solidification, facilitated through highly customizable user-defined functions. Using widely accepted assumptions from existing literature, the 3D transient model was validated against experimentally measured melt pool geometry. Further, numerical experiments were conducted with a verified 2D axisymmetric VAR model to explore its efficacy and accuracy under identical boundary conditions as the 3D transient model, varying only the profiles of the current density distribution. The melt pool morphology, flow pattern, and solidification environments from the 2D mode, including the commonly adopted Gaussian distribution for arc behavior, were compared with those obtained from the 3D transient model. In order to bridge the gap between 2D and 3D representations, the feasibility of using novel temporally averaged arc distributions in 2D to reproduce the effects of the actual arc behavior in a 3D context is explored.

Speaker Country:

United States

Session 1 / 11

Segregation sensitivity study of Ni-based superalloys for turbine discs application

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Ni-based superalloy are sensitive to segregation during solidification and special care must be taken to control final chemistry on billet. Especially, some alloys are very sensitive to the formation of freckle type defect. Thus, the prediction of the evolution of the liquid phase composition and density during solidification is necessary to develop the corresponding melting conditions. Microsegregation of the as cast ingot shall also be reduced by heat treatment. Cycle duration and temperature must be adapted to the as-cast dendrite arm spacing. In this work we investigate the use of DTA sample to study the segregation sensitivity of different Ni-base superalloys. EPMA analyses were used to measure the effective partition coefficient for each alloying element. Some back diffusion is observed for the high segregating alloying elements like Nb and a correction is suggested to predict equilibrium partition coefficient. The correction method is validated for the IN718 alloy by comparison with Thermocalc© Scheil prediction and measured spot segregation. The same methodology was used for high alloyed Ni base superalloys for which the thermodynamic databases are not as accurate. In particular, the partition of W and Al does not match experimental measurements. Freckle sensitivity was investigated based on measured partition coefficients and compared for various superalloys. Finally, the homogenization heat treatment of the as-cast alloy was studied. Diffusion modelling prediction was compared to industrial results. It is concluded that it is necessary to consider the dendrite arm spacing distribution in addition to the average distance to reproduce the experimental results.

Speaker Country:

France

Session 8 / 12

A Novel Approach for Measuring the Electrical Conductivity of Molten ESR Slag Systems

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Energy expenditures for slag and metal melting primarily drive production expenses of electrometallurgical smelting processes. In Electroslag remelting (ESR), the thermal energy is directly generated by resistance heating of the slag system. Therefore, exact knowledge of the electrical conductivity of the molten slag is vital for regulating the process temperature and energy costs during smelting. However, to date, electrical conductivity measurements of ESR slags show substantial deviations due to method- and technique-related errors, such as the neglection of electrical fringe fields and interfacial effects between slag and electrodes, demanding an exact and reliable measurement procedure. In this study, a new high-accuracy approach for measuring the electrical conductivity of molten slag systems is validated in aqueous salt solutions at room temperature. The approach is then tested on a low, medium, and high conductive ESR slag with varying contents in CaF2, Al2O3, and CaO from Wacker Chemie AG within a temperature range of 1,500 to 1,700 ℃. The method uses a calibration-free differential technique with a coaxial electrode geometry to overcome fringe field distortions. Electrochemical Impedance Spectroscopy (EIS) is used to generate an equivalent circuit model for the simulation of the electrochemical cell, allowing the extraction of the electrical slag resistance from interfacial influences. Validation investigations in salt solutions at room temperature correlate well with comparable, highly accurate experimental data. Results with high reproducibility can be achieved for the three tested ESR slags.

Speaker Country:

Germany

Session 10 / **15**

Improving AISI 431 stainless steel ingot cleanliness by optimizing the refining and casting process

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Large inclusions (size ≥ 100μm) deteriorated the cleanliness of AISI 431 stainless steel ingots fabricated by a Chinese steel mill, resulting in the formation of defects that can be visually observed on the surface of the oil pump. Here, we revealed the Al contents and inclusion evolution route in the process of "AOD refining - LF refining - Casting - Rolling" by analyzing samples obtained during production. It was found that inclusion removal in the LF refining process is not enough owing to inappropriate LF slag composition. Reoxidation during casting and mold flux entrapment were considered as two main sources for the formation of large inclusions in ingots because the dissolved Al content decreases obviously and large inclusions form newly after casting and the composition consists of two main types of inclusion: Al2O3 and complex oxide inclusion with Na2O. The optimization of refining and casting process was proposed and utilized: (a) the LF refining slag with R=5.5 and Al2O3 content of 25% was designed for enhancing inclusion absorbing ability of slag, and the soft Ar blowing time at the end of LF refining must exceed 20 minutes, (b) the distance between the ladle nozzle and the central casting pipe should be minimized as much as possible to avoid reoxidation, (c) the Ar flow rate should be appropriately controlled for guaranteeing the stability of liquid steel flow during casting. (d) the height of placing mold flux before casting was adjusted. After optimization, the cleanliness of steel ingots improved because large inclusions decreased significantly.

Speaker Country:

China

Session 8 / **16**

Microstructural evolution and dynamic phase transformation of micro-alloyed steel during hot deformation and its impact on the 2nd ductility minimum

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Continuous casting of steel is widely used to manufacture semi-finished long or flat products. Various stresses are present during slab casting: the stress caused by the friction between the mould wall and the solidified shell, thermal stresses acting on the strand surface, and the stresses due to the bending and straightening operations. During casting, the combination of the temperature and deformation velocities may provoke ductility losses of the material. Steels present a minimum ductility point during continuous casting in the solid-state condition. In this work, we aim to answer the metallurgical reasons for the occurrence of the ductility minimum in a micro-alloyed steel by investigating the microstructural evolution. The samples are in situ melted via induction heating in the BETA250-5® thermomechanical simulator machine, followed by hot tensile tests conducted at different temperatures and strain rates. The ductility drop is analysed in the range of 650℃-1100℃ at different strain rates, 10-2 s-1 to 10-3 s-1. Furthermore, the study investigated the development of the ferrite phase at the prior austenite grain boundaries, the fraction and thickness of ferrite, dynamic phase transformation, and the influence of the test conditions on these parameters. The grain size, fracture mechanism, and ferrite fraction are determined from metallography investigations using optical microscopy (OM) and scanning electron microscopy (SEM). Finally, the microstructural changes are correlated to the ductility minimum using the measured results.

Speaker Country:

Austria

Session 1 / **17**

Development of an optimized SEM-EDS testing method for non-metallic inclusions and its application to evaluate the cleaning effect of different ESR-slags

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Non-metallic inclusions (NMI) are an essential quality criterion for electro-slag remelted products. Besides standardized testing methods such as ASTM E45, SEM-EDX-based methods have gained widespread application, as they provide not only information on shapes, sizes and numbers of NMI, but also about their chemical composition. Therefore, they are a useful tool not only for quality control but also for the investigation of the impact of process parameters and slag compositions on the cleaning effect during electro-slag remelting (ESR). However, the investigation method is quite time consuming and therefor often restricted to a small detection area, thereby limiting the significance of its results, especially regarding statistically rare, larger inclusion. Using a double raster-technique with a ten-time larger detection area, the probability range for medium size NMI

could be significantly extended. As a result of this procedure, a better differentiation between NMIs newly formed during the solidification of the remelted material and such NMI, which did not dissolve and are therefore remnants of the electrode deoxidation, becomes possible. With this tool in hand, the opportunity was opened up to better understand and differentiate the cleaning effect of various ESR-slags. Laboratory ESR trials were therefore conducted, using several commercial slags with different CaF2-content and double-raster SEM-EDX measurements were applied on the remelted and deformed ingots as well as on the electrode material. The results extend the previous knowledge on the significant effect of the slag composition on the type, respective chemical composition of newly formed NMI, by a clearer differentiation of the cleaning effect of these slags regarding the remnant NMI from the electrode. Besides providing a better understanding of these two different influencing factors of the slag composition on NMI in ESR, the method offers also a useful tool for the optimization and development of new slag compositions with higher cleaning potential.

Speaker Country:

Austria

Session 1 / 18

A Metamodel for VAR Processing of Alloy 718

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Modelling the Vacuum-Arc-Remelting (VAR) of NiFe-Based alloys like alloy 718 is motivated by its potential role in the further development of the process. It offers insight in the complex interaction of fluid mechanics and thermodynamics in a process which is experimentally hard to monitor. Nonetheless the numerical description itself requires a full definition of relevant boundary conditions which are not known per se and have to be estimated or determined by inverse modelling like e.g. parameters which determine the heat extraction from the ingot to the crucible. This makes it especially hard to model the process with a variation of the process parameters as boundary conditions are potentially and likely influenced by it.

The development of a metamodel for the remelting of alloy 718 by VAR therefore attempts to derive suitable boundary conditions and to provide a comprehensive numerical description in dependency of processing parameters. The development is based on the experimental investigation of a set of industrial sized VAR-ingots produced with different melt rates and varying helium cooling conditions. Individual calculations for each parameter set have been carried out using the commercially available software MeltFlow-VAR. Relevant parameters like the ones concerning the extraction of heat are determined by inverse modelling and validating the results against experimentally pool profiles which are evaluated from the part of the ingot processed in the steady state. The individually obtained parameters form the base of the metamodel that relates them to the set process parameters. The summarizing cross-validation of the metamodel with the individual pool profiles results in good agreement within the available data set.

Speaker Country:

Deutschland

Session 2 / 19

Consumable electrode vacuum arc remelting of gamma-TiAl with online feeding

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Vacuum arc remelting is widely recognized for its ability to produce high quality ingots for demanding applications. Since its introduction in the 1940s, great efforts have been undertaken to increase productivity, reliability and furnace safety by different iterations of furnace design accompanied by improvements in process data acquisition and interpretation to allow remelting behavior simulation. However, essential challenges regarding the heat extraction remain to this day, due to the direct coupling of melt rate, melt power, gap distance, furnace geometry, cooling capabilities and physical properties of the material when using a conventional vacuum arc remelting setup with consumable electrode. These parameters define achievable temperature gradients and heat transfer limits in the system, thus dictate the microstructure formation as well as segregation effects. To overcome these limitations, a novel approach is introduced at IME RWTH University, which uses a continuous online feeding of same sort metal powder into the melt pool during the remelting process, to increase heat extraction and nucleation density. In this study the successful introduction of metal powder into the pool via online feeding during vacuum arc remelting with consumable electrode is presented together with its influence on the process behavior and remelting result.

Speaker Country:

Germany

Session 1 / 20

Effect of Si Content in Electrode and SiO2 Additions to the Slag during Electroslag Remelting

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Evolution of Si concentration in 316 stainless steel electrodes was observed during a melting campaign consisting of recycling electroslag remelted (ESR) ingots to make new electrodes using vacuum induction melting (VIM). This campaign consisted of iterations of VIM + ESR operations to optimize melting parameters. The effect of Si content on the melt parameters and ingot quality was further evaluated and additions of SiO2 to the slag chemistry were studied using research-scale experiments, x-ray fluorescence (XRF), visual inspections and computational tools. The Si concentration was found to decrease by approximately 600 ppm following ESR of 150 lb. research-scale electrodes. Eventually, this led to failure of the slag skin and direct ingot/crucible contact. Additions of SiO2 to the slag at levels matching the calculated Si loss resulted in significant decrease in slag resistivity (measured) and the current during steady state increased to maintain a constant melt rate. By lowering the SiO2 addition by an order of magnitude the resistivity was closer to the baseline ESR condition and slag skin failure was again observed. Computational fluid dynamics simulations were performed to model the ESR process under the various slag conditions and elucidate the relationships between slag properties and melt characteristics.

Speaker Country:

United States

Session 3 / 22

VIM B52 For Superalloy Barstick Production – Design Features Of An Innovative Furnace Concept

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In 2022 and 2023, for the needs of company Feinguss Blank GmbH, DANIELI developed and built an innovative middle size VIM for the remelting of Ni- and Co-based superalloy scrap from investment casting into barsticks. Several technical challenges, particularly unfavorable scrap geometry, its back-charging etc. were solved. The furnace realizes both, direct pouring and pouring via tundish. Some break-through solutions in process, providing a high level of automation have been found and realized. This new furnace concept sets a milestone in economic and environment-friendly recycling of the high-value superalloys used and processed in investment casting. The paper describes the main design innovations and gives an overview on production results achieved.

Speaker Country:

Austria

Session 8 / 23

Effect of deoxidizing elements on inclusions in vacuum refining of stainless steel

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Stainless steel is widely used in extreme environments due to its high corrosion resistance. In particular, materials for applications requiring high reliability such as medical devices and etching equipment are produced with EBM, ESR, or VAR to reduce inclusions. These processes do not use refractory materials and thus provide better cleanliness than conventional melting methods. Especially VAR provides the best cleanliness because strong carbon deoxidation occurs under its high vacuum atmosphere.

However, the factors affecting carbon deoxidation under high vacuum on the cleanliness of stainless steel have not been fully investigated. For example, the effect of the initial composition of inclusions is not well-known. Thus in this study, to evaluate the effect of initial inclusions, Si-killed and Al-killed AISI-316L steels were remelted in a high vacuum cold crucible furnace and the inclusions were investigated.

After vacuum refining, CaO-SiO2 inclusions were observed in Si-killed material, while CaO-SiO2-Al2O3 inclusions were observed in Al-killed material. Inclusion sizes were similar, despite the large difference in initial oxygen concentrations. On the contrast, number density in Al-killed material was smaller than that of Si-killed material which suggests that initial Al-killing is beneficial for higher cleanliness after vacuum refining.

Speaker Country:

Japan

Session 4 / 24

Interface tracking in modeling of nozzle clogging in steel continuous casting

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A common problem in continuous casting of steel is clogging of submerged entry nozzle (SEN) that occurs due to the continuous build-up of solid material. Clogging reduces productivity of the process and quality of the final product. The authors have developed a volume average model for particulate clogging of the nozzle. In this model, clog is treated as a developing porous medium due to the continuous deposition of solid non-metallic inclusions (NMIs) on the nozzle wall. With development of the clog, wall boundary conditions are not valid anymore and it is necessary to introduce proper conditions at the clog-melt interface to mimic the porous nature of the clog. In the present work, a new front tracking model is introduced to the clogging model using piecewise linear interface calculation (PLIC) approach. The main advantage of the PLIC model is more accurate calculation of the turbulent flow in partially clogged computational cells where the interface between clog and melt flow is defined. To verify the model, two similar cases were prepared for a predefined clog geometry on the nozzle wall: in one case the clog geometry was created by porous medium and in the other case, the clog interface was formed by deforming the nozzle wall geometry. The comparison of the results of two cases showed that the PLIC treatment in the volume average model can reproduce conditions at the porous clog-melt interface properly.

Speaker Country:

Austria

Session 1 / 25

Effects of Size on Characteristics of Electroslag Remelted (ESR) HAYNES®282® alloy ingots

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ESR ingots of varying sizes – 4”, 6” and 8” diameter laboratory scale ingots and commercial scale 20” diameter and 10”x42” slab ingots were produced using stabilized processes. Process control steps needed to stabilize the ESR process used to produce the laboratory 6” and 8” diameter ingots will be discussed, with attention to how the process was modified based on outcomes of employed trials. Variations in ingot microstructure characteristics (primary / secondary dendrite arm spacings) across the spatial extents of the ingots of the aforementioned sizes were obtained by metallographic analysis. These results will be compared with predictions from simulations of the ESR process using the commercial software package MeltFlow-ESR. Results for other simulation predicted ingot characteristics, such as local solidification time and the likelihood for freckle formation based on the Suzuki-Yang criterion will also be presented. It was found that the ESR simulations, reasonably accurately, captured the variation in dendrite arm spacings across the ingots of the discussed sizes. The observed changes in ingot characteristics as the ingot sizes are increased will be presented and their implication for down-stream ingot processing and for ingot soundness will be discussed.

Speaker Country:

United States of America

Session 8 / 28

Surface tension and viscosity measurements on laser heated liquid gallium droplets using acoustic levitation and oscillations methods

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Advanced techniques for liquid metal processing and casting, such as monocrystalline casting, atomization for powder metallurgy, metallic additive manufacturing, welding or ingots refining processes, are complex to master. Developing and controlling industrial equipment is costly and so manufacturers are promoting digital design methods. But numerical models rely on accurate knowledge of thermophysical properties, such as surface tension and viscosity, to be effectively representative of real processes. Due to the strong chemical reactivity of liquid alloys at high temperatures (> 1000℃), measurements with contact are easily biased. We have developed a non-contact laser-powered melting furnace, based on the acoustic levitation phenomenon, to perform these measurements on samples in liquid form. Current stable levitation conditions allowed us to carry measurements on molten gallium up to 500℃. Influence of samples temperature and shape, as well as oxygen content of the surrounding atmosphere, on the properties magnitude is emphasized. Perspectives for measurements on high melting point reactive alloys are discussed.

Speaker Country:

France

Session 6 / 29

Using CFD to study freeze-lining formation: a collaborative research project between academia and industry

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The formation of freeze lining (FL), a protective layer of solidified slag, holds significant economic value in industrial processes by safeguarding furnace reactors and refractories from corrosive molten slag and providing a thermal barrier that minimizes energy consumption. To deepen our comprehension of FL formation, a collaborative research project has been undertaken, bringing together academic partners from the University of Leoben (Austria) and the University of Leuven (Belgium), alongside industrial partners RHI Magnesita and Aurubis-Beerse.
This collaboration has led to the development of a novel CFD model framework capable of simulating FL formation across a broad range of applications. The model has undergone rigorous testing in various settings, ranging from controlled laboratory experiments to industrial processes.
Laboratory experiments were conducted to investigate FL formation under controlled conditions, providing a valuable foundation for model development. The model's ability to accurately replicate these experimental results demonstrated its capability to predict FL dynamics under well-defined conditions. In industrial applications, the model was employed to simulate FL formation in an electric smelting furnace and a slag fuming furnace. The electric smelting furnace simulation highlighted the intricate interplay between heat transfer and fluid flow dynamics in shaping FL formation. For the slag fuming furnace simulation, model predictions were validated against industrial data, exhibiting a remarkable agreement regarding both FL thickness and heat fluxes across the furnace.
These comprehensive testing procedures have validated the robustness and applicability of the newly developed model framework. Moreover, the model has proven to be versatile and accurate across diverse industrial processes. These qualities make it a valuable tool for optimizing reactor design, enhancing energy efficiency, extending the lifespan of the reactor and refractory materials, and improving overall sustainability.

Speaker Country:

Austria

Session 1 / 30

Influence mechanism of feeding on the removal of inclusions and shrinkage cavity defect during electroslag remelting process

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The implementation of the feeding is a crucial and effective technique for preventing the accumulation of inclusions and the formation of shrinkage cavity at the top of electroslag ingot. In this study, a whole process model of electromagnetic-magnetic-flow-thermal inclusion removal with the full coupling of electroslag remelting of H13 die steel was established. The accuracy of the model was verified by comparing the radial distribution of inclusions and the droplet size with the experimental results of 2t H13 electroslag ingot. Based on the analysis of the influence of melt droplet collection, necking and dripping process on the electromagnetic-magnetic-flow-thermal physical field during the electroslag remelting process, combined with the research on the removal and trapping behavior of inclusions, the influence mechanism of the feeding on the trajectory and macroscopic distribution of inclusions was elucidated. Compared to the fact that inclusions are concentrated at the top of the electroslag ingot, there are more inclusions at the edges after feeding. Meanwhile, the position of the molten pool zone that solidifies increased after feeding, ultimately leading to an increase in the

position of the shrinkage cavity in the electroslag ingot, which improved the quality of electroslag ingot and further enriched the control theory of electroslag remelting cleanliness.

Speaker Country:

China

Session 1 / **32**

On the Generation Mechanism of Large-size CaO•Al2O3 Inclusions in Die Steel during the Electroslag Remelting Process: at Atomic Scale

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It is generally believed that electroslag remelting can effectively reduce the number of large-size non-metallic inclusions in steel and improve solidification structure, thus electroslag remelting (ESR) has become the main method to produce high quality die steel. However, large-size inclusions (D and Ds type) have been aperiodically detected in the production-scale ESR die steels. The detection results indicate that majority large inclusions are CaO•Al2O3 inclusions and reducing calcium content in die steel is important to control D and Ds inclusions. In this work, we have focused on the generation mechanism of large-size CaO•Al2O3 inclusions in die steel during the electroslag remelting process. It was proposed that the concentration of free Ca2 + ions (calcium activity) in ESR slags was the key parameter that determines the calcium content and CaO•Al2O3 inclusions in ESR die steels. Considering various CaF2-containing slags (CaF2-CaO-Al2O3-SiO2-MgO), the bond configuration and mean square displacement of Ca2+ ions were studied based on molecular dynamics simulation. Combined with ion and molecular coexistence theory (IMCT), we established a model to calculate the calcium activity. The model indicated that CaF2 component in slags significantly determine the calcium activity since Ca2+ ions provided by CaF2 could move freely and hard to be incorporated into complex molecular cluster. A novel ESR slag with low CaF2 content has been developed and applied in the industrial production of die steel, calcium content and large-size CaO•Al2O3 inclusions been successfully reduced, validating the reliability of the theoretical analysis. This work has established the intrinsic relationship between large-size inclusion in ESR die steel and microscopic atomic structure of ESR slag. This is of great significance to optimize the ESR slag composition to improve the metallurgy quality of ESR die steels.

Speaker Country:

China

Session 10 / **33**

Mechanism of improving solidification structure of super austenitic stainless steel by feeding strip in a laboratory simulator for continuous casting

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Feeding steel strip into molten steel in the mold is an effective technique for refining the solidification structure of steel (especially high-alloy steel) during the continuous casting process. This study experimentally investigated the effects of feeding strip on the solidification structure of super austenitic stainless steel S32654 and clarified the relative mechanism by combining numerical simulation. The results revealed that feeding strip noticeably increased the proportion of equiaxed grains, refined the dendritic structure, and improved Mo segregation and the precipitation of σ phase. Feeding strip promoted the formation and survival of a large number of floating dendrites by cooling the molten steel. As the temperature decreased, these floating dendrites underwent repeated splitting, thereby sharply increasing their quantity. Subsequently, these floating dendrites acted as nucleation particles for the equiaxed grains, thus significantly increasing the proportion of equiaxed grains and refining the dendritic structure. Besides, feeding strip apparently reduced the microsegregation of Mo element, which lowered the precipitation temperature and growth time of σ phases. Under such a condition, the σ phases mainly nucleated and grew after complete solidification rather than in the residual liquid phase. Therefore, the slower diffusion and insufficient supply of the Mo element were not conducive to the nucleation and growth of the σ phase. Meanwhile, the dendrite refinement further limited the growth space of the σ phases. Finally, the σ phases in S32654 steel fed with strip were significantly reduced and became finer and more dispersed.

Speaker Country:

China

Session 8 / 35

A Review of Nitrogen Solubility in Nickel-based Alloys

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Compared with liquid iron, pure liquid nickel has a relatively limited solubility for nitrogen. Studies that have measured solubility have found values ranging from literally zero in one case to 35 ppm at 1600 C at the high end. Studies that examined the effect of temperature found the reaction to be endothermic with solubility increasing with temperature. Solubility predictions based on studies that determined free energy equations of solution generally range from 5-20 ppm over a temperature range of 1480-1700 C. Studies of solubility in nickel alloys found that most alloying elements increase nitrogen solubility (Al and Cu are possible exceptions) and that Sievert's Law was followed up to very high pressures with exceptions for Ni-Cr and Ni-W alloys above a certain alloying level. Both chromium and niobium were found to change the solubility reaction to exothermic and reverse the temperature dependence. Interaction parameters reported from these specific studies were constants, however, rather than functions dependent on temperature as with stainless steels. As a result, using these constants to calculate solubility could give the incorrect trend with temperature. These parameters were reevaluated to include the temperature effect. For Ni-based superalloys with high Ti levels, nitrogen solubility may become limited by the formation of titanium nitride. One known published experimental work on nitrogen solubility in high titanium superalloys was reexamined to develop a regression equation for solubility based on a chromium equivalence term and temperature. By comparison, when predictions of solubility using interaction parameters with the free energy of the titanium nitride reaction were extended to high titanium levels, substantially higher solubility levels for nitrogen were predicted. Further fundamental research may be needed for these types of alloys to address the difference in solubility predictions from low to high titanium levels and the effect of other alloying elements.

Speaker Country:

United States

Session 1 / 36

Monitoring the internal processes of electroslag remelting through an external array of magnetic field sensors

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This paper presents the results of laboratory and industrial scale investigations into the internal processes of electroslag remelting (ESR) facilitated by an external array of magnetic field sensors. Electroslag remelting is a crucial metallurgical process employed for the refinement and production of high-quality metal ingots, particularly in the context of alloy manufacturing. Real-time monitoring of the internal dynamics has remained elusive due to the prohibitive environment inside the ESR furnace. Here, we investigate the applicability of passive magnetic field sensors in measuring such key operational conditions as electrode immersion depth, slag depth, current partition, and the identification of any internal arcing, including the arc location, within the ESR. The approach is based upon 20 years of experience in the use of magnetic field measurements during vacuum arc remelting, however additional signal processing techniques were utilized to analyze the data obtained because of the AC nature of the power. Initial investigations indicate that the use of the magnetic signature of the AC current can be utilized to ascertain clear process condition signatures as outlined. The goal of this work is to enhance our understanding of melt dynamics, fluid flow patterns, and solidification behavior during ESR processing.

Speaker Country:

United States

Session 1 / 37

Statistical Evaluation of Arc Dynamics Measured During an Industrial VAR Melt of IN718 Under Various Arc Gaps

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An industrial scale experiment on the impacts of process variations on ingot quality of IN718 was carried out by monitoring the associated magnetic fields by VARmetric. The test performed monitored operational variations during the processing of the ingot when different arc gaps were maintained. A short, medium, long, and extra-long arc gap were chosen during the melt, the system was allowed to operate for approximately 1 hour at each arc gap before readjusting to the next arc gap. Magnetic field measurements were used to continuously determine the arc centroid position during the melt. A detailed analysis of the arc position measurements was conducted employing quantitative and statistical tools to assess the overall impact of process variations on the distribution of arcs. The arc rotation and spread were characterized for different arc gaps which clearly shows the transition from a diffuse to a constricted arc mode. A strong correlation was observed between the arc radius and arc gap which may be able to be used to monitor arc gap size in lieu of drop shorts.

Speaker Country:

United States

Session 2 / 38

Improvements to Ingot Quality of Industrial-Scale Vacuum Arc Remelted Ti6Al4V by Application of Magnetic Sensing and Controls

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External transverse magnetic fields were applied during the vacuum arc remelting of 900 mm and 1000 mm Ti6Al4V ingots in order to control the arc dynamics. The overall goal of the industrial experiments were to provide a known arc distribution throughout the melt, including startup and hot topping, that optimizes solidification. Magnetic field sensors (VARmetric) were deployed to continuously monitor the arc position during the experiments, while electromagnets (ARControl) were utilized to control the location and distribution characteristics of the arc. The vertical position of the electromagnet system was automatically repositioned throughout the melt to move with the arc gap location, which was determined by magnetic arc gap tracking. Feedback from magnetic arc position sensing was also used in real time to ensure safety during the experiment through side arc detection. The result(s) of the application of transverse magnetic fields was to broaden the arc distribution, shallowing the melt pool and reduce uncontrolled variation in the arc location. An additional benefit was an improvement in the ingot skin quality. Overall results in the increase in yield and product quality are addressed.

Speaker Country:

United States

Session 1 / 39

Effect of double circuits electroslag remelting process on the ingot quality and corrosion resistance of S136 steel

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This paper investigates the effect of different electroslag remelting processes on the solidification quality and corrosion resistance of S136 steel. The results show that the double circuits process can reduce the mass fraction of oxygen in the ingot and effectively improve the cleanliness of the ingot. Analyzing the solidification quality of ingots, it can be seen that the secondary dendrite spacing in the ingot heart position obtained by the double circuits process can be reduced by 46.04 μm compared with the traditional electroslag remelting process, and the segregation of C and Cr elements in the ingot can be effectively reduced. The average diameter of inclusions in the ingots obtained by the double circuits process was reduced by 0.18 μm (0.5 R), the number of inclusions was reduced by 38.63 % (0.25 R), and the integral number of inclusions was reduced by 41.83 % (0 R) compared to the traditional process. Electrochemical experiments on experimental steel in the tempered state, the experimental steel pitting pits obtained from the double circuits process are smaller in size and more diffuse in distribution, the depth of the pits is reduced, and the corrosion resistance is improved.

Speaker Country:

China

Session 3 / 40

From Concept to Reality: Exploring the Potentials of Hydrogen Plasma Smelting Reduction

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The iron and steel industry is undergoing significant changes due to global efforts to combat climate change, like the Paris Agreement and the European Green Deal. These initiatives aim for the European Union to become carbon neutral by 2050 and significantly reduce greenhouse gas emissions by 2030. This is a big challenge for the industry, which produced 1.95 billion tons of crude steel in 2021, mostly using the energy-intensive blast furnace and basic oxygen furnace (BF-BOF) process.
The paper introduces Carbon Direct Avoidance (CDA) as a promising pathway for reducing emissions, focusing on the Hydrogen Plasma Smelting Reduction (HPSR) approach. This technique, which uses electrical energy and hydrogen for reduction, is being developed at the Montanuniversitaet Leoben at laboratory scale and at a demonstration plant operated by K1-MET GmbH. Due to the generation of exited hydrogen species (atomic and ionized) and high temperatures in the arc's focal spot, the reduction process is favoured both thermodynamically and kinetically.
The study delves into laboratory-scale experiments demonstrating the significant influence of cathode geometry, plasma gas composition, and iron ore feed rate on arc stability and reduction rate in the HPSR process. It also examines how iron ores of varying degrees of pre-reduction affect hydrogen utilization and overall process time while maintaining consistent product microstructure. The research aims to identify optimal combinations of pre-reduction states and plasma gas composition to maximize hydrogen utilization. The results contribute to the iron and steel industry's efforts to reduce greenhouse gas emissions and achieve international sustainability goals.

Speaker Country:

Austria

Session 2 / 43

A numerical study on the solidification shrinkage of the ingot in vacuum arc remelting (VAR) process

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The Vacuum Arc Remelting (VAR) process is employed in the production of Nickel-based alloys, including Alloy 718. However, challenges arise during the process due to solidification shrinkage, leading to the loss of contact between the ingot and the mold. This phenomenon diminishes the cooling efficiency of the system, resulting in a deeper melt pool and a decline in ingot quality as heat removal becomes less effective. To comprehensively investigate the implications of solidification shrinkage, we introduce a sophisticated 2D axisymmetric Magnetohydrodynamics (MHD) model. This model incorporates calculations for electromagnetic, thermal, and flow fields. Also, the MHD model is fully coupled with a thermal stress-strain model, enabling the computation of solid mechanical parameters like stress, strain, and deformation within the ingot. Our coupled model provides essential insights, including the width of the air gap along the ingot, the precise position of contact between the ingot and mold, and the profile of the melt pool, among other critical parameters. Ultimately, the model's accuracy is verified through rigorous validation against experimental data, enhancing our understanding of the VAR process and its impact on the alloy quality.

Speaker Country:

Czech republic

Session 2 / 44

Magnethohydrodynamics (MHD) analysis of the molten pool in Vacuum Arc Remelting (VAR) of Alloy 718 utilizing Gaussian distribution

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This paper conducts an analysis of the Vacuum Arc Remelting (VAR) process to manufacture steel, examining the interplay of factors such as side-arcing, arc distribution types, thermal radiation, magnetohydrodynamics (MHD), and ingot solidification. The proposed numerical model explores how these factors influence the molten metal pool profile, which is a critical aspect in ensuring the production of ingots with minimal solidification defects. Simulation results demonstrate that the diffusive

arc yields a shallower melt pool compared to the constricted arc; Increased side-arcing leads to a reduction in pool depth.
Moreover, we conducted a practical experiment in a dedicated melt shop to remelt a steel electrode using the VAR process. This experiment allowed us to extract crucial data, including the pool profile, water coolant temperature, etc. In alignment with the model, we maintained consistent input parameters during the experiment, including melt rate, electric current, voltage, etc. To validate our findings, we compare the simulation result with the experimental data, aiming to improve our understanding of MHD effects within the melt pool in VAR.

Speaker Country:

Austria

Session 8 / **45**

Influence of forced convection and variation of composition on the forming of iron-rich phases in an A226 alloy

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In Al casting alloys, iron (Fe) is known as an impurity that forms during solidification as a β-Al4.5FeSi phase, a brittle, plate-like structural component. This β-phase leads to negative influences on the mechanical and casting properties. Its presence favors stress concentrations at the plate edges. It can also promote shrinkage porosity and a reduction in feeding performance.
Fe is enriched through the use of recycled material in the global material recycling process. The usage of secondary Al alloys is much more energy efficient than the production of primary aluminum, resulting in energy and CO2 emission savings of about 95 %. The solubility of Fe in molten Al is approximately 2.5 wt% at 700 °C and increases with higher temperature to 5.0 wt% Fe (at 800 °C). Currently, the reduction of Fe in molten Al is achieved by downcycling with primary material.
A more beneficial way to reduce the Fe content is to filter the material. The variation of the chemical composition with the addition of other elements such as manganese and chromium can achieve a change in morphology, which prevents a negative influence on the mechanical properties and which can be separated with adequate efficiency by filtration.
The present study provides an overview of the influence of forced convection on the shape, morphology and size of Fe-containing intermetallic phases using electromagnetic fields as a convenient tool on primary phase formation. The appropriate adjustment of the intensity and shape of the flow leads to the formation of an Fe-rich enrichment zone, whereby the Fe content in the Fe-depleted residual zone can be reduced from the original 0.9 wt% to below 0.3 wt%. Through forced convection and variation of the chemical composition, an average Fe reduction of 66 % can be achieved.

Speaker Country:

Germany

Session 2 / **46**

Numerical Simulation of Asymmetric Cooling in Vacuum Arc Remelting Furnace

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In the field of metallurgy, the optimization of the process has driven the integration of advanced numerical simulations to enhance the efficiency and reliability of industrial systems. This article focuses on the application of 3D numerical simulations to investigate the cooling system of a Vacuum Arc Remelting (VAR) furnace, an essential component in the production of high-quality alloys. The study not only focuses on the fundamental aspects of VAR furnace cooling but also explores the coupling between asymmetric cooling and thermo-mechanical deformation of the ingot.
The development of the model involves the creation of a 3D simulation using COMSOL Multiphysics to simulate the cooling system dynamics during the VAR process. This model facilitates the computation of heat flows on the crucible walls through thermo-fluidic coupling, providing a detailed representation of the thermal behavior within the cooling system and therefore in the crucible and the ingot.
To assess the impact of asymmetric cooling in critical cases, one of the four outlets of the cooling system is selectively closed, enabling a focused study on the resultant effects on the cooling process. Through systematic investigation, the article aims to predict the temperature distributions and heat transfer patterns caused by this modification to the cooling system.
The derived heat flows from the 3D simulation serve as a crucial tool to explore the effects of asymmetric cooling on the VAR process. To study those effects, the heat flows are extracted from the 3D model and integrated as boundary conditions into a 2D axisymmetric thermo-mechanical model of the ingot. The results presented in this article contribute to the fundamental understanding of VAR process but also provide actionable insights for the security of the furnace and the practical enhancement of alloy production and quality control.
COMSOL is a registered trademark of COMSOL AB.

Speaker Country:

France

Session 6 / 47

Fast simulation of a multiphase tundish flow by using recurrence CFD

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Abstract

Simulating the inclusion removal process in a tundish requires the consideration of large range of time and length scales.**[1.]** Because of both the steel and argon inlet, small timesteps as well as a fine mesh are required due to turbulence. On the other hand, the cleaning process itself takes comparatively long times to reach a steady state and consequently large computational costs are required for a full simulation.

However, the recurrent nature of the turbulent flow allows to approximate its evolution in an efficient, physically sound way called recurrence CFD.**[2., 3.]** Starting from a short high-fidelity time series, further predictions are made based on iteration of the method of analogues, i.e. it is assumed that similar states evolve in a similar fashion. This also holds for the cell-to-cell transport behavior of the flow, **[4.]** which makes it possible to describe the dynamics of passive species without the need to solve the Navier-Stokes equations. Hence, computational costs are massively reduced and process-relevant durations may be simulated.

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Speaker Country:

Austria

Session 4 / 48

Formation of segregated channels in a rotating geometry during the solidification of steel alloy

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A two-phase columnar solidification model considering fluid flow, heat, and solute transport is applied to simulate the solidification in a 3D rotating geometry using the finite volume method. Molten steel alloy is confined within a rectangular cavity, initially at a temperature above the liquidus, with distinct hot and cold surfaces at the top and bottom, respectively. A slow cooling rate of CR = 0.1 K/s was applied to the bottom surface, allowing for the phase transformation as the temperature decreased below the liquidus. The simulated domain is in a rotating frame of reference, rotating about a fixed axis of the original frame with r = 0.9 m radius of rotation. The rotating geometry undergoes a change in rotation speed, therefore, Coriolis, Centrifugal, and Euler are the simulated fictitious forces. Also, a rotating gravity vector, rotating with the frame, is implemented. This study aims to examine the effect of the Coriolis and Euler forces on centrifugal buoyancy-driven convection in a rotating geometry. The key features of solidification phenomena in this process, including solute transport, thermo-solutal convection of the melt, flow driven by buoyancy, Centrifugal forces, and formation of macro-segregation, are simulated. As a result, it is predicted that segregated channels were formed in the vertical direction during the rotation. After the full solidification, segregated cells were developed at different horizontal cut planes of the samples. The formation mechanism of this segregation pattern is discussed. This study provides insights into the underlying mechanisms governing the observed segregation patterns. Furthermore, it delves into the impact of rotation on both flow and segregation patterns, offering valuable insights applicable to a range of industrial processes.

Speaker Country:

Austria

Session 1 / 49

Validation of electroslag remelting process simulation of an industrial scale martensitic stainless tool steel ingot

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A martensitic stainless tool steel was remelted by a Pressure Electroslag Remelting (PESR) process with deliberate cancellation of the remelting just before normal hot-topping operation. Enabling evaluation of the ingots melt pool profile, dendrite angle and spacing, and macrosegregation during normal remelting conditions. A longitudinal cross section (500x500 mm) from the top of the 500 mm diameter cylindrical ingot was extracted from its transverse midpoint and macro-etched. Microstructural characterization of the solidification structure was carried out using light optical microscopy, supplemented by scanning electron microscopy, and macro segregation by optical emission spectroscopy and combustion infrared detection. The results from the ingot cross section were compared with predictions made by the commercially available modelling software package, MeltFlow-ESR™.

Speaker Country:

Sweden

Session 6 / 50

On Performance of Data Models and ML Routines for Simulations of Casting Processes

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Abstract

The performance of data models and their associated machine-learning routines for simulations of multi-physical continuous casting processes are scrutinised in this research work. Data science techniques have already started to have a significant impact on optimisation and controlling of manufacturing processes by providing fast and real-time predictive-corrective tools. These techniques employ data analytics, data training\learning, and deterministic\statistical methods to create fast and real-time models to improve manufacturing processes. In this research work, data reduced models and machine learning (ML) routines are developed to predict the influence of various process parameters on direct chill casting processes. These data models represent the essential features of the multi-physical casting processes, while significantly reducing the simulation time and efforts.

Hence, the computational fluid dynamics (CFD) simulations are initially used to create a comprehensive database where variations of major process parameters are considered using carefully-sampled snapshot matrices. These matrices are employed to capture the most important aspects of the processing parameters including melt temperature, cooling and casting speed. Furthermore, the resulting data models are thoroughly examined for their accuracy and reliability using some selected design of experiments (DOEs).

Keywords: data models, real-time modelling, data training, machine learning, direct chill casting, continuous casting process

Speaker Country:

Austria

Session 8 / 51

Laser ultrasound for in line and in situ measurements during casting and rolling.

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Laser ultrasound, a non-contact technique utilizing lasers for both excitation and detection of ultrasonic waves, offers an approach to assess structural and elastic properties in hot steel. This method employs an excitation laser emitting 7ns pulses at typically 10 to 100Hz repetition rate to generate ultrasonic waves through thermoelastic expansion and ablation. Detection is achieved via an interferometer, capturing reflected waves at the point of measurement. Both excitation- and detection-system are available for industrial use. For imaging, the lasers are scanned across the steel's surface, where preparatory treatment is only necessary where coarse scale has formed on the surface.
Our study introduces a laser ultrasonic system used in steel casting to determine the solid-fluid interface in strands at a surface temperature of 1150℃ and a core temperature of approximately 1500℃. Comparisons with solidification process models reveal a strong correlation in estimated shell thicknesses. Additionally, we applied this system to hot steel ingots during rolling, detecting non-metallic inclusions at around 1000℃ surface temperature.
Laser ultrasonic methods extend beyond interface reflections and obstacle detection, such as oxides or pores, they can also provide insights into elastic properties. This is achieved by correlating sound speeds with the metal's Young's modulus, shear modulus, mass density, and Poisson's ratio. In plate-like structures like rolled sheet steel, laser ultrasound can excite and analyze local resonances, offering valuable data on microstructural changes during thermal treatments. We present in situ measurement results on samples in a thermal simulator, showing recrystallization at different isothermal holding temperatures.
The application of Laser Ultrasound directly in line or in laboratory settings offers a high throughput advantage, a feature crucial to comply to high quality requirements at varying raw materials. This aspect becomes particularly significant during the transition to more sustainable steel production methods using increasing amounts of scrap. Alongside the demonstrations mentioned above, we will address the experimental and theoretical foundations of laser ultrasound. Our goal is to provide a foundation that not only explains current methods, but also stimulates interest in new studies and applications in this evolving field.

Speaker Country:

Österreich

Session 8 / 52

Integrated Numerical and Experimental Analysis of Refractory Erosion: A Case Study on Alumina with CAS and CASM Slags

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Erosion in refractories plays a dominant role in the wear of these materials which is of significant relevance to the metallurgical industry. Not only is the lifespan of these materials affected by erosion but also steel quality can be reduced through the introduction of exogenous inclusions. In their application these materials are exposed to aggressive melts and intense flow conditions. The infiltration and internal corrosion of the refractory weakens the matrix-grain bonds and facilitates grain erosion under applied flow shear forces. To comprehensibly understand and characterize the erosion process, a computational fluid dynamics model was developed. In this model, the flow field of the corrosive melt is resolved and the refractory represents a dynamic boundary to the simulation domain. The erosion rate is based on a function of the applied shear stress, characterized by three erosion parameters: detachment rate, critical shear stress and an exponent. The dynamic behavior of the boundary is governed by this law and is applied through user defined functions to the refractory nodes according to the calculated erosion rate while the mesh quality is maintained through additional automated smoothing and remeshing methods. Coupling of the model to experimental finger test is used to inversely calculate the unknown erosion parameters. Experiments with coarse grain alumina samples with slags in the calcia-alumina-silica (CAS) system and calcia-alumina-silica-magnesia (CASM) were performed at temperatures of 1450 and 1500°C. Cylindrical samples were immersed in isothermal slag baths and rotated at constant speed. Next, the eroded surfaces were laser scanned and the obtained raw data processed into an axisymmetric erosion profile. These profiles are compared to the simulated erosion profiles in an automated calculated routine, where the erosion parameters are obtained as solution to the nonlinear least-squares problem. The results showed the suitability of the model in depicting the erosion of refractories within the investigated systems, revealing reasonable tendencies in the calculated erosion parameters. The detachment rate was notably higher for CASM slags due to higher degree of basicity, and increased with temperature. Conversely, the critical shear stress, an indicator of the minimum forces necessary for erosion, decreased with rising temperature, aligning with expectations. These findings emphasize the applicability of the presented method in further exploring refractory erosion in different melt systems.

Speaker Country:

Austria

Session 4 / 53

On Modelling Electromagnetic Braking in Thin Slab Continuous Casting: fundamentals, applications, and outlooks

Author: Alexander Vakhrushev[1]

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Continuous casting (CC) became the world-leading technology for steel production. The thin slab casting (TSC) features a slab shape close to the final products, which are cast at high speeds and rapid solidification rates. The quality of the thin slabs is defined by the turbulent flow pattern and superheat distribution influencing the growing solid shell. To control the fresh melt feeding through the submerged entry nozzle (SEN), electromagnetic brake (EMBr) technology is commonly applied. Numerical modelling is a perfect tool to investigate the EMBr effects during the TSC process. In the presented work we gather results from the long-term studies, which are mandatory to correctly tackle considered multiphase phenomena: (i) interaction of a turbulent jet with the DC magnetic field; (ii) coupling the turbulent flow, heat transfer and solidification with the effects of magneto-hydrodynamics (MHD) in the CC mold; (iii) influence of the conductive solid shell presence on the induced electric current distribution and action of the Lorentz force; (iv) flow regimes and superheat transport under growing Hartmann number, (v) outlooks on the adjustable flow controls and solidification using EMBr technique. The presented studies are performed using an in-house implementation of the MHD model using the open-source CFD package OpenFOAM®.

Speaker Country:

Austria

Session 8 / 54

Non-metallic inclusion capture at the steel-slag interface in tundish simulations

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Non-metallic inclusion have a strong impact on the final product quality in steel production. Thus, inclusion removal from the melt is an important aspect of achieving the intended steel properties. In continuous casters the tundish can be utilized to enhance inclusion removal. One method to promote inclusion removal within the tundish is the installation of an argon bubble curtain.

The aim of this work was to implement a model for inclusion removal within the CFD framework of Ansys Fluent. This inclusion flotation model considers a possible entrapment of inclusions at the steel-slag interface. The underlying CFD model is an Euler-Lagrangian model, which models the steel and slag phases using a VOF model. The non-metallic inclusions are modelled using the discrete phase model. Argon bubble flotation is considered in the model as well.

This work demonstrates the implementation of an interface-capture model for non-metallic inclusion in a full tundish simulation. This model was developed by Zhang et al. from detailed simulations of a spherical non-metallic inclusion at the steel-slag interface.

During model development, simplified simulation cases were used to demonstrate basic model capabilities and a generic tundish simulation was created to showcase the full model by comparing inclusion removal with and without argon bubbling.

References

Zhang, X., Pirker, S. and Saeedipour, M. (2023), Investigation of Inclusion Removal at Steel–Slag Interface toward a Small-Scale Criterion for Particle Separation. steel research int., 94: 2200842. https://doi.org/10.1002/srin.202200842

Speaker Country:

Austria

Session 10 / 55

Control technology of homogenization during Solidification of high-end continuous casting slab

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For low carbon content personalized steel grades, the corresponding relationship between the banded microstructure at the typical position of 1/4 width of hot rolled steel coil and the W shape of the solidification end point of the cast slab was revealed. The influence of hereditary laws such as casting solidification structure and element distribution on banded microstructure was clarified. The soft reduction technology considering the reduction efficiency at the solidification end was developed, and the idea of two-stage uneven reduction at the solidification end was proposed to solve the problem of uneven W-shaped solidification at the transverse 1/4 position of the cast slab, effectively improving the proportion of steel coils with a banded microstructure less than C 2.0.

Speaker Country:

China

Session 8 / 56

Experimental observation and CFD study on inclusion particle behavior at a slag/argon interface

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This study highlights a dissolution experiment conducted by high-temperature confocal laser scanning microscopy (HT-CLSM). Besides providing essential information on particle dissolution inside slag, this experiment constitutes a slag-argon multiphase environment and reveals particle behavior in the vicinity of the interface. It is observed that after the slag melts, the particle initially placed on the slag surface moves into the slag rapidly, then intends to settle at the interface, followed by the final detachment from the interface. The corresponding scenario of particle/interface interaction is further investigated by CFD simulations. We use the volume of fluid (VOF) method and the dynamic overset grid technique in combination with the 6DOF solver to account for particle motion near the slag-argon interface. The results indicate that the capillary action and viscous effect could induce

particle entrapment, and the settling position estimated by simulation shows consistency with experimental measurements. Simulations further evaluate if the dissolution-induced solute Marangoni convection is responsible for the final detachment. The results imply the contribution of both particle movement and dissolution on its detachment from a fluid-fluid interface. The findings can be highly relevant to particle separation at the steel-slag interface, which is essential for clean steel production.

Speaker Country:

Austria

Session 8 / **57**

Steel and slag combined in HT-CSLM: A new approach for the in-situ investigation of non-metallic inclusions

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The High-Temperature Confocal Scanning Laser Microscope (HT-CSLM) is a powerful tool for in-situ investigations of surface phenomena and has proven its suitability for metallurgical processes. It is widely used to observe phase transformations, melting behavior, agglomeration of non-metallic inclusions (NMIs), or dissolution of particles in slags. However, these processes have been studied as stand-alone experiments until now. In this work the authors describe the development of a set-up for the combined investigation of steel, slag, and NMIs in-situ in the HT-CSLM to observe agglomeration, movement towards the slag, detachment, and dissolution of NMIs in a single experimental set-up. The developed procedure takes geometrical, chemical, and physical aspects into account and includes safeguards to prevent leaking of liquid steel or slag into the furnace chamber by using a dual crucible approach. As the slag (partially) covers the steel it must be transparent which leads to limitation in composition of both steel and slag. The focus of this work is on different steel/slag combinations of medium-carbon steels with different alloying elements and deoxidation concepts. The slags used are low melting CaO-Al₂O₃-SiO₂ slags. For some experiments, alkali oxides were added to the slags to decrease their melting point and viscosity.

Speaker Country:

Austria

Session 3 / **58**

Insights into Electric Arc Furnace Behavior: A Practical Simulation Approach

Authors: Mohamad Al Nasser[1]; abdellah kharicha[2]; Christian Redl[3]; Harald Holzgruber[3]; Anton Ishmurzin[4]; Gernot Hackl[4]; Nikolaus Voller[4]

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The Electric Arc Furnace (EAF) has become increasingly popular in the industrial metal production sector in recent decades, undergoing substantial growth. At present, over 30% of steel production relies on electric arc furnace technology. In light of the harsh conditions surrounding the electric arc, numerical modeling emerges as a valuable tool for examining its behavior throughout the process. The objective of numerical modeling is to bring industrial enhancements in furnace design and facilitate the integration of new, environmentally friendly technologies, such as the utilization of hydrogen within the EAF.
The current study presents a model capable of simulating the thermal and flow dynamics of an industrial-scale EAF. The model couples the very rapid dynamics of the arc with flow inside liquid slag and metal. The model possesses the capability to forecast the behavior of the electric arc, including its interaction with the liquid pool underneath and its impact on the furnace's refractories thermally through radiation and mechanically through arc shear flow, all at an industrial scale. The arc shear flow and the electro-vortex flow inside the slag and liquid metal ensure sufficient mixing inside the slag layer and liquid metal. The model predicts the slag temperature to be higher than the liquid metal temperature which is in line with experimental measurements. The presence of an external axial magnetic field alters the flow and produces flow in the azimuthal direction. For a low axial magnetic field in a range of the earth's magnetic field, a rope tornado flow can be observed. With the increase in axial magnetic field, the flow transitions into a tornado-like flow. These simulations play a crucial role in advancing our comprehension of the electric arc furnace process. Additionally, they offer valuable insights into phenomena occurring inside EAF such as heat transfer to refractory walls and the erosion rate.

Speaker Country:

Austria

Session 4 / 59

Advanced Level 2 Software Integration for Enhanced Temperature Control from Meltshop to Casting

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As part of its commitment to environmental sustainability, the steel industry constantly seeks to enhance operational efficiency. A significant area of focus is the optimization of temperature control in meltshops, a process traditionally constrained by the limitations inherent in Level 2 systems. These systems, characterized by static optimization and compartmentalized operations, lack a comprehensive integration of production planning and process control.

To address these challenges, we present a modular software system tailored for meltshops and casters. This system innovatively merges the functionalities of traditional process control with advanced production planning techniques, thereby facilitating a seamless transition between Level 2 and Level 3 systems. Central to this approach is a real-time data platform that underpins both metallurgical models and sophisticated data-driven models.

The efficacy of our system is illustrated by demonstrating the implementation in the meltshop at Cleveland Cliffs Burns Harbor, which highlights significant improvements in temperature guidance across various stages of steel production, including BOF, SLD, LTS, and VD. The system utilizes a combination of global recommendation models and local prediction models, all functioning effectively in real-time. These models are designed to consider a comprehensive range of parameters, from energy inputs and chemical additives to treatment processes, transport durations, and the thermal states of ladles and tundishes.

This case study proves that our system not only enhances the efficiency and precision of temperature control in steel production but also aligns with the industry's environmental sustainability goals. By integrating advanced data management and process modeling techniques, the system marks a significant step forward in the technological advancement of meltshop operations.

Speaker Country:

United States

Session 6 / 60

Study on the Influence of Neutral Gas Fraction in the AOD Process using a 3D Two-Phase CFD Model

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The AOD (Argon Oxygen Decarburization) converter process is a dominant process step in the production of high-quality stainless steel, with gas injection playing a critical role in influencing process efficiency and product quality. This paper focuses on developing a mathematical model for gas injection in the AOD converter process, utilizing advanced Computational Fluid Dynamics (CFD) simulations. The primary objective is to investigate the impact of the argon to oxygen gas ratio on key process parameters, specifically emphasizing jet penetration length, bubble column behaviors, and local steel-gas interactions around the tuyere, all impacting the efficiency of decarburization. The developed AOD model incorporates separate mass, momentum and energy transport equations for the steel and gas phases. Additionally, the model addresses the heat generated from the carbon oxidation reaction effectively estimating variations in gas properties (e.g. gas density) due to this reaction. Notably, this study represents the first consideration of the impact of the argon-oxygen ratio on gas phase properties, including gas-steel interfacial tension and the drag force. This approach can be utilized to simulate the initial state of each decarburization stage during the transition to the subsequent stage. This research brings new knowledge to a gap especially within the framework of the multi-stage gas injection in the AOD decarburization process.

Speaker Country:

Belgium

Session 4 / 61

Grain refinement of high-Mn wear-resistant cast steel by means of heterogeneous nucleation

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The understanding and controlling of the primary solidification, particularly the formation of first grains, is of significant relevance. Generally, high-Mn steels exhibit a coarse-grained microstructure in the millimeter range and are known for their high strain hardening ability and thus, excellent cyclic deformation resistance. In order to further improve the cyclic mechanical properties, this study aims to increase the strength of the alloy via grain refinement.

From a comprehensive literature research, the nonmetallic inclusions AlCeO3 and Ce2O3 were identified as the most promising particles for the heterogeneous nucleation of austenite. Based on this literature review, various grain refining agents were evaluated, and test melts were carried out. With the grain refining agent from ELKEM (WearSeed), it was possible to reduce the grain size by over 80% (from 1550ym to 285ym). However, the process window for a successful grain refinement is only very small. Extensive thermodynamic calculations with FactSage on the interaction of O-S-Ce-Al in high-Mn steel melts, and particle analyses of the potential nuclei by automated SEM-EDS were carried out.

The framework conditions for a successful grain refinement were systematically developed depending on the casting temperature, dissolved O and S, and the addition of Al and Ce. Finally, the static and cyclic mechanical properties of the grain refined high-Mn steel cast were determined using tensile and low cycle fatigue testing and showed very promising results.

Speaker Country:

Austria

Session 10 / 63

A System for Evaluating the Interior of a Crucible

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High performance alloys for Aerospace applications are cast in cylindrical copper crucibles. Maintaining the appropriate crucible taper and diameter is critical to a quality casting. The use of micrometers, feeler rods, visual inspection is popular for a quick assessment of crucible diameter and condition. In this work, a sensor is used to measure the crucible diameter, and video camera to record. Both units are mounted on a linear drive, that can traverse longitudinally and rotate around the axis. Preliminary results from a laboratory scale setup will be presented, along with thoughts on scale up.

Speaker Country:

US

Session 4 / 65

Experimental evaluation of MHD modeling and engineering applications

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Electromagnetic stirring (EMS) has been recognized as a mature technique in steel industry to control the as-cast structure of steel continuous casting, and computational magnetohydrodynamic (MHD) methods have been applied to study the EMS efficiency. Most MHD methods de-coupled the calculations of electromagnetic and flow fields or simplifications were made for the flow-electromagnetic interactions. However, the experimental validations of the MHD modeling have been rarely reported or very limited. In our previous work [Zhang et al., Metall. Mater. Trans. B, 53, 2022. 2166-2181], we have presented a benchmark, i.e., a series of laboratory experiments, to evaluate the MHD methods. The magnetic field distribution within the magnetic inductor, the torque experienced by solid casting under a rotating magnetic field (RMF), and the RMF-induced rotational flow of the liquid melt (Ga75In25) were experimentally measured to validate MHD modeling. The MHD calculation is performed by coupling ANSYS Maxwell and ANSYS Fluent. Various MHD calculation methods and coupling schemes are investigated. The Lorentz force, as calculated by analytical equations, ANSYS Fluent addon MHD module, and external electromagnetic solver, is added as the source term in Navier–Stokes equation. By comparing the simulation results with the benchmark experiments, the calculation accuracy with different coupling methods and modification strategies is evaluated. Based on this, a necessary simplification strategy of the MHD method is established. This contribution will demonstrate some engineering applications, including the unidirectional solidification of aluminum-based casting, and continuous and semi-continuous casting processes of steel.

Speaker Country:

Austria

Session 3 / 66

DEVELOPMENT OF A NEW TYPE OF VACUUM ARC COLD HEARTH SKULL MELTING FURNACE & PROCESS

Authors: Alexander Scheriau[1]; Uwe Haissl[1]; Harald Korbel[1]; Harald Holzgruber[2]

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This paper describes the development of a new type of Vacuum Arc Cold Hearth Skull Melting & Casting (VA CH SM) process and design concept which is based on the well-established Skull Melting & Casting process and industrial proven cold hearth technologies.
Driven by the current challenges on the titanium and raw materials market and in line with the global target of reducing carbon emissions, the trend for titanium producers to increase the recycling rates in their production processes is on the rise. Following this demand of the industry, INTECO has developed a new plant design concept which allows the semi-continuous feeding of scrap or other raw material (e.g., compacted chips, Master alloys, Titanium sponge) into the melting and casting process without breaking the vacuum between the melting and casting cycles. Two different casting techniques (static and dynamic casting) can be applied, allowing highest flexibility in production.
With this new concept, recycling rates of up to 100% can be achieved as the process is able to produce its own melting electrode out of scrap, thus providing its own melting feedstock.
The new INTECO VA CH SM plant which has been developed with one of the leading titanium producers is currently in hot commissioning phase and first insights and promising results are presented.
An outlook and extended functionality of the new VA CH SM design is presented.

Speaker Country:

Austria

Session 4 / 67

Influence of the rotation parameters on the solidification conditions during mechanical stirring

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The concept of the mechanical stirring technology was developed by INTECO to investigate the influence of mechanical rotation conditions on the solidification structure and to evaluate whether a similar or greater positive effect can be achieved than with electromagnetic stirring (EMS). The great advantage of the mechanical stirring effect compared to the EMS system is that forced convection occurs at the solid-liquid interface at every point in the strand or ingot over the entire length, regardless of the size dimensions, right into the centre. In the production of larger dimensions, electromagnetic stirring to some extend reaches its technical limits, as extremely high electrical power must be installed to achieve a sufficient stirring effect, especially if a stirring effect is to be achieved in the core.
This paper describes the mechanical stirring process including innovative technological key features and provides an overview over two series of trials with two different materials and a total of 12 tests Furthermore, first laboratory results of section sizes of 194,1 mm dia. are discussed and presented.

Speaker Country:

Austria

Invited talk / 68

Update on the World Market for Special Steels & Powder Metallurgy – Remelted Steels or Titanium or Powder Metallurgy - friend or foe?

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The presentation will highlight the recent developments in the world of remelted steels, titanium and powder metallurgical as well as will give an overview about end-user demand and structures of these special materials and also summarize the actual status of installations on a global scale. The speech will also focus on the production and especially its associated production technologies and how they compete or complement each other. As they are and will become key future core technologies for a number of demanding products and thus for the usage in different associated industries. The presentation will also highlight the actual supply and demand situation and will introduce leading manufacturers and summarizes installed capacity and new capacity that is on the way and how China has developed itself compared to the rest of the world.

Speaker Country:

Austria

Session 8 / 69

Reducing the risk of blowholes in heavy steel plates: causes to consider

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The comprehensive metallographic analysis and statistical big-data analysis of blowhole appearance in heavy plate manufacturing gave no exact cause of defect formation but indicated differences in the chemical composition of defective and clean heavy plates and, above all, high content of residual elements. The rare BHs were found in the largest width ingot and on thinner plates that can be connected with open of blowholes after a thick layer of scale is removed after reheating. Non-metal inclusions in areola around blowholes have a higher content of silicon and manganese, possibly forming by casting mixture particles entrapping and dissolved by liquid steel at pouring. The copper-enriched phases were found in the formed scale and on the interface between metal and scale making them characteristic of hot-shortness defects which difficult to differentiate from blowholes. The ways to eliminate the risk of blowhole formation and ensure the highest quality and efficiency of cast ingots are proposed.

Speaker Country:

Ukraine

Session 1 / 70

Simulation of Remelting Processes: Challenges and Emerging Perspectives

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coming soon…

Speaker Country:

Austria