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Magnetohydrodynamic simulation of DC arc plasma under AC magnetic field

T.TOH et al.

Direct current (DC) thermal plasma, shape controlled by use of alternative current (AC) magnetic field enables the wide area of thermal treatment and has potentials of applications other than welding. In this paper, the behavior of DC plasma under AC magnetic field imposed perpendicular to the plasma current is discussed experimentally and theoretically by changing various parameters such as plasma electric current, nozzle diameter, argon flow rate and magnetic flux density including its wave form. As the theoretical study, DC plasma was mathematically modeled by use of three dimensional magnetohydrodynamics (MHD) theory and discussed through numerical simulations performed by full finite volume method approach. Then the DC arc plasma motion under sinusoidal AC magnetic field is discussed through MHD analysis. By these experimental and theoretical investigations, the controlling parameters of DC plasma by AC magnetic field have been made clear quantitatively.

(cf. *ISIJ Int.*, **45** (2005), 947)

Numerical simulation of a falling droplet of liquid metal into a liquid Layer in the presence of a uniform vertical magnetic field

T.TAGAWA

Dynamics of a falling droplet of liquid metal into a horizontal liquid layer in the presence of a uniform vertical magnetic field is numerically studied. Non-dimensional governing equations for an axisymmetric cylindrical coordinate system, which can simulate incompressible, immiscible two-phase flows like bubble, droplet and free-surface flows, have been derived and solved numerically with a finite difference method using the HSMAC algorithm. The numerical results reveal that the electromagnetic force simply opposes spreading of the disturbance after collision.

(cf. *ISIJ Int.*, **45** (2005), 954)

Refining mechanism of solidified structure of alloy by electromagnetically refining process

K.SUGIURA et al.

Refining mechanism of solidified structure in which a static magnetic field and an alternating electrical current are simultaneously imposed on the local area of a metal or an alloy, has been experimentally examined using a Sn–10mass%Pb alloy. The refining period of the structure was examined by changing the imposing period of the electromagnetic vibration on the sample and it was confirmed that the refining period was the initial stage of solidification. The refining region was specified to be around the electrodes by inserting a stainless steel wire net in the sample while it was independent of the inserting position of the electrodes. Convection was induced by the electromagnetic vibration because temperature difference in the sample drastically decreased as soon as the vibration was excited in the sample. From these experimental results, the estimated mechanism in this process is that dendrite tips around the electrodes are cut off by the electromagnetic vibration in the initial stage of the solidification and it spread to the whole area of the sample by the convection induced by the electromagnetic vibration. Furthermore, nucleation is induced by an intense electromagnetic vibration.

(cf. *ISIJ Int.*, **45** (2005), 962)

Refining of Si by the solidification of Si–Al melt with electromagnetic force

T.YOSHIKAWA et al.

Aiming at the development of Si solidification refining process with Si–Al melt, investigations on separation method of Si grains solidified from Si–Al melt and the laboratory scale refining test were carried out. By the use of electromagnetic force under the fixed alternating magnetic field, solidified Si grains were successfully agglomerated in the Si–Al alloy and the high Si density part was obtained, although the use of gravity force was not effective. Furthermore, the refining test with induction heating revealed the high purification ability of this refining.

(cf. *ISIJ Int.*, **45** (2005), 967)

Effect of rotating magnetic field on two-phase flow in RH vacuum degassing vessel

B.LI et al.

Rotating magnetic field is applied in up-leg of RH vessel to promote the removal of non- metallic inclusions of molten steel and to prolong the life of RH equipment. Physical and mathematical models have been developed to understand the two-phase turbulent flow considering the effect of the rotating magnetic field in the RH vacuum degassing vessel. Water model experiments verified that the gas bubbles can be moved toward the central zone of up-leg of RH vessel as the result of density difference between gas bubbles and liquid in the swirling flow. The larger circulation flow rate can be obtained in RH degassing vessel with the effect of swirling flow. A penetrating velocity, which does not change the equation characteristics but changes solution distribution, is proposed to revise the gas volume fraction conservation equation. A revised gas volume fraction conservation equation is successfully used to solve the gas distribution in RH vessel. If there is no swirling flow, the larger upward velocities and maximum of the gas volume fraction appear near wall of up-leg. If the rotating magnetic field is applied in up-leg, the larger upward velocities occur in the central zone of up-leg. These phenomena agree with the experimental observation. When the rotating electromagnetic force is applied, the numerical results showed that a swirling flow may be produced and extended into the vacuum chamber. As the occurrence of swirling flow in upper part of up-leg, the maximum of gas volume fraction moves toward the center zone of up-leg and the upward parabolic velocity distribution is also formed.

(cf. *ISIJ Int.*, **45** (2005), 972)

Free surface behavior of a liquid metal under the imposition of a high frequency magnetic field

M.SUDA et al.

Free surface behavior of a liquid metal under the imposition of a high frequency magnetic field has been examined. The high frequency magnetic field was generated by imposing a high frequency current on a coil surrounding the vessel filled with a liquid gallium. The magnetic field penetrated into a liquid gallium only from an upper surface due to the shielding effect of the copper vessel. A shallow standing wave on a free surface of a gallium was generated by a mechanical oscillator and its behavior was measured by a laser level sensor. The amplitude of the standing wave decreases with increase in the intensity and the frequency of the magnetic field. A damping behavior of the standing wave just after stopping the mechanical oscillation was also examined. The larger the intensity and the frequency of the magnetic field are, the more quickly the wave decays.

(cf. *ISIJ Int.*, **45** (2005), 979)

Inclusions behavior analysis during levitation melting of steel in cold crucible for application to cleanliness assessment

T.TOH et al.

Fusion of metals in a cold crucible is known as a clean melting method without contamination by refractory. For this reason, it is commonly applied to the fusion of high melting point metals or reactive materials. As the usage of the clean melting function, this technique is also applied to the cleanliness assessment method as an advanced technique of electron beam melting method.

In this paper, oxide inclusions behavior in a cold crucible levitation melting of steel is discussed through fundamental experiments and numerical simulations in order to clarify the inclusions behavior during the fusion. Experiments showed a rapid removal of oxides from the bulk molten metal to the sample surface without remarkable change in shape and size distribution of contained oxides. Numerical analyses revealed the dominant factors of this phenomenon, and explained the reason why the size distribution of oxides does not change during the fusion.

(cf. *ISIJ Int.*, **45** (2005), 984)

Investigation of the melt flow on solidified structure by a levitation technique using alternative and static magnetic fields

H.YASUDA et al.

A levitation method using the simultaneous imposition of an alternating field and a static magnetic field was applied to study effect of the melt flow on the microstructure of Cu, Cu–1at%Ag alloys, a middle carbon steel alloys and Fe–10at%Ni alloys solidified from the undercooled melt. Convection in the levitated melts was remarkably reduced when the imposed static magnetic field exceeded 1T. Reduction of the melt flow did not affect the nucleation temperature, but caused the morphological transition from the equiaxed grains to the columnar grains

for the Cu–Ag, the steel and the Fe–Ni alloys. The experimental results indicated that the melt flow in the mushy region caused the dendrite fragmentation and consequently resulted in formation of the equiaxed grains at the low undercooling region.

(cf. *ISIJ Int.*, **45** (2005), 991)

The crystal orientation taking account of gravity force under high magnetic field

C.WU et al.

High magnetic field is well known to have the function of crystal orientation, which is largely influenced by crystal size and shape to some extent. For crystals with large rod shape, the gravity force functions and affects the crystal orientation. In our experiment, different results were got when a high magnetic field was applied perpendicular and parallel to the gravity force. In this paper, the effect of the gravity force for crystal orientation under the high magnetic field is summarized and compared with the experiment result.

(cf. *ISIJ Int.*, **45** (2005), 997)

Phenomenological discussion of Fe and Co film electrodeposited in a magnetic field

H.MATSUSHIMA et al.

Fe and Co films were galvanostatically electrodeposited at 10 mA cm^{-2} on Cu substrate in sulfate aqueous solution with pH = 1.5. The amount of electricity of 150 C cm^{-2} was selected. The magnetic field (0–5 T) was superimposed parallel to the electrode plane. The superimposition of magnetic field to the electrodeposition process considerably decreased the current efficiency with increasing in the magnetic flux for Fe, while almost constant efficiency was maintained for Co. SEM images showed the smoother surface morphology of Fe film. Texture measurement demonstrated that Fe(110) plane was oriented to the magnetic field direction. On the other hand, the surface morphology of Co deposits was drastically changed from an angular to a platelike shape by superimposing the magnetic field. Comparing with the case of Fe texture evolution, Co texture variation with magnetic flux was not evident. The magnetohydrodynamic (MHD) effects on Fe and Co electrodeposited films are phenomenologically discussed.

(cf. *ISIJ Int.*, **45** (2005), 1001)

Management of water transport in the cathode of proton exchange membrane fuel cells using permanent magnet particles deposited in the cathode-side catalyst layer

L.B.WANG et al.

Recently, it was found that the performance of proton-exchange membrane (PEM) fuel cells was improved by the deposition of small magnet particles in the cathode-side catalyst layer. We developed a numerical simulation to clarify this effect, for a PEM fuel cell equipped with an interdigitated gas distributor. A two-dimensional, two-phase model was used. Cathode electrode consisted of gas diffusion layer and catalyst layer, and the latter was treated as a line. Darcy's law was used to describe the transport of the gas phase. The forces from the shear of the gas flow and of the capillary action move the liquid water through the porous cathode electrode. The magnetic field was modeled by using an equivalent magnetic field. Our numerical results show that the repulsive Kelvin forces acting on liquid water can control the liquid water flow through a porous gas diffusion layer. With increasing residual flux density of magnet particles, the velocity of liquid water near the interface of the catalyst/diffusion layers increases, the saturation of liquid water near the interface decreases, and increasing more pore space is freed for O_2 transport and reactions. Therefore, the mechanism of the improvement of the cell performance by magnet particles is clarified using such a numerical model. The use of permanent magnets will be especially useful for portable fuel cell in which there is no power to supply air.

(cf. *ISIJ Int.*, **45** (2005), 1005)

Fundamentals of High Temperature Processes

Effect of oxygen to silicon ratio on the viscosity of metallurgical slags

K.SANTHY et al.

Viscosity is an important physical property, which influences the performance of slags, in metallurgical processes such as iron making, steelmaking and continuous casting. Viscosity of slags is strongly influenced by the chemical composition and the temperature. Experimental measurement of slag viscosity requires high temperature equipment and is time consuming. Empirical relations/calculations using certain chemical parameters have been attempted to predict the viscosity, which may then be used for controlling metallurgical processes. Metallurgical slags used in the steel industry are made up of different oxides and fluorides, and may often be treated as silicates. The presence of silica, an inorganic polymer, in slags, has a major impact on "viscosity". It is convenient to describe the silicate slag structure in terms of the network character of silicates—either the Oxygen to Silicon ratio (O/Si ratio) or the Non Bridging Oxygen (NBO).

The effect of O/Si ratio (and temperature) on the viscosity of slags has been studied theoretically in this work. Data on composition and viscosities were taken from the literature and the trends have been analyzed in terms of Oxygen to Silicon ratio. Data on four different slag systems, consisting of 33 slags, covering a range of temperatures, have been used. In all cases, irrespective of the system and the temperature, the viscosity was found to decrease steadily with increasing Oxygen to Silicon ratio. This is due to the increased breaking of the silicate network. The suitability of this parameter for assessment of slags (viscosities) has been demonstrated.

(cf. *ISIJ Int.*, **45** (2005), 1014)

Phase equilibria in high MgO ferro-manganese and silico-manganese smelting slags

B.ZHAO et al.

Liquidus isotherms and phase equilibria have been determined experimentally for a pseudo-ternary section of the form "MnO"–(CaO+MgO)–(SiO_2+Al_2O_3) with a fixed Al_2O_3/SiO_2 weight ratio of 0.17 and MgO/CaO weight ratio of 0.17 for temperatures in the range 1 473–1 673 K.

The primary phase fields present for the section investigated include manganosite (Mn,Mg,Ca)O; dicalcium silicate α-2(Ca,Mg,Mn)O·SiO_2; merwinite 3CaO·((Mg,Mn)O·2SiO_2; wollastonite [(Ca,Mg,Mn)O·SiO_2]; diopside [(CaO,MgO,MnO,Al_2O_3)·SiO_2]; tridymite (SiO_2); tephroite [2(Mn,Mg)O·SiO_2]; rhodonite [(Mn,Mg)O·SiO_2] and melilite [2CaO·(MgO,MnO,Al_2O_3)·2(SiO_2,Al_2O_3)].

The liquidus temperatures relevant to ferro-manganese and silico-manganese smelting slags have been determined. The liquidus temperature is shown to be principally dependent on the modified basicity weight ratio (CaO+MgO)/(SiO_2+Al_2O_3) at low MnO concentrations, and dependent on the mole ratio (CaO+MgO+MnO)/(SiO_2+Al_2O_3) at higher MnO concentrations.

(cf. *ISIJ Int.*, **45** (2005), 1019)

Structure analysis of coke, wood charcoal and bamboo charcoal by Raman spectroscopy and their reaction rate with CO_2

M.KAWAKAMI et al.

In order to discuss the reactivity of carbonaceous materials with CO_2, the Raman spectroscopy analysis was carried out. Nine kinds of materials were examined. The Raman spectra of ordered materials could be assigned to the graphite structure and its defect, but those of disordered materials could not. New parameters were derived to evaluate the structure of the latter. Using the parameters, the structure change was followed during high temperature heat treatment. The disordered material consists of random structure, graphite structure and its defects. The random structure changes to the graphite structure with many defects and the defects decrease with the heat treatment temperature. The reaction rate constant is evaluated. It increases when the structure changes from the random structure to the graphite structure with many defects. After the change, it decreases with decreasing the defects in graphite structure. Thus, the most reactive material should consist of the graphite structure with many defects.

(cf. *ISIJ Int.*, **45** (2005), 1027)

Surface active effect of Na_2O on the rate of CO_2 dissociation on the surface of molten FeO_x–Na_2O and FeO_x–SiO_2–Na_2O systems

H.MATSUURA et al.

It is well known that P_2O_5 and Na_2O have strong surface active effect in the molten oxide systems and affect the rate of oxidation or reduction of melts. In the previous work, the effect of P_2O_5 addition on the rate of CO_2 dissociation on the surface of FeO_x (FeO and Fe_2O_3)-based molten oxides was investigated by isotope exchange technique and it was confirmed that P_2O_5 strongly disturbs CO_2 dissociation. In the present study, the effect of Na_2O addition on the rate of CO_2 dissociation on the surface of FeO_x–Na_2O and FeO_x–SiO_2–Na_2O (mol%FeO_x : mol%SiO_2 = 65 : 35) melts was measured at 1 773 K with P_{CO_2}/P_{CO} = 1 by isotope exchange technique. Reaction rate con-

stant drastically increased with increasing Na_2O content for the FeO_x–Na_2O system. On the other hand, rate constant gently increased for the FeO_x–SiO_2–Na_2O system. The Fe^{3+}/Fe^{2+} ratio of each system also slightly increased.

To estimate the rate constant from the composition of melts, the relationship between the rate constant and the Fe^{3+}/Fe^{2+} ratio for the FeO_x–CaO–SiO_2 system was also investigated. From the comparison of the estimated and observed rate constants, the strong promoting effect of Na_2O for CO_2 dissociation was confirmed in the FeO_x–Na_2O system.

The surface active effect of Na_2O was analyzed by "smoothed surface potential model", and the nature of molten oxide was discussed. From the obtained values, the surface tension of the molten oxide was estimated as a function of Na_2O concentration.

(cf. *ISIJ Int.*, **45** (2005), 1035)

Ironmaking

Degradation behaviour of a high CSR coke in an experimental blast furnace: Effect of carbon structure and alkali reactions

T.HILDING et al.

A high CSR coke was tested in the LKAB's Experimental Blast Furnace (EBF) at Luleå. The evolution of physical and chemical properties of the centre-line coke samples were analysed by Light Optical Microscopy (LOM), BET N_2 absorption and SEM/XRF/XRD. Alkali distribution in the EBF cokes was examined by XRF/SEM and EDS. Thermo Gravimetric Analysis (TGA) was used to measure isothermal and non-isothermal CO_2 reactivity of the cokes. The crystalline order of carbon and the concentration of alkalis were found to increase as the coke descended through thermal reserve zone to the cohesive zone of the EBF. The crystallite height (L_c) of EBF coke carbon displayed a linear correlation with the measured EBF temperatures demonstrating the strong effect of temperature on carbon structure of coke in the EBF. Alkali concentration of the coke was increased as it descended into the EBF, and was uniformly distributed throughout the coke matrix. The CO_2 reactivity of lower zone cokes was found to increase when compared to the reactivity of the upper zones cokes, and was related to the catalytic effect of increased alkalis concentration. The deterioration of coke quality particularly coke strength and abrasion propensity were related to coke graphitisation, alkalization and reactivity. Coke graphitisation is shown to have a strong influence on the coke degradation behaviour in the EBF.

(cf. *ISIJ Int.*, **45** (2005), 1041)

Casting and Solidification

Development of fluoride-free fluxes for billet casting

A.B.FOX et al.

More than 90% of the world's steel is produced using the continuous casting process, a method that has seen enormous advances over the last forty years. Mould fluxes play an important part in this process. These fluxes contain fluorides, which can volatilize at operational temperatures polluting both the plant air and cooling water. Airborne fluoride could potentially be a health and safety issue. Waterborne fluoride forms hydrofluoric acid (HF), which can cause plant corrosion, and may lead to contamination of watercourses necessitating water treatment schemes. This adds to production costs and may present potential environmental hazards. These concerns could be reduced or eliminated by removing fluoride from mould fluxes.

The present study examines the effect of different fluxing agents upon key mould flux properties. When substituting fluorides for alternative fluxing agents the key design properties of the fluoride-containing flux must be replicated; namely, (i) flux viscosity at 1 300°C, (ii) break temperature and (iii) percentage of crystallinity in the solid slag layer. This is to ensure 'optimal casting' where operational problems, such as sticker breakouts and defects such as longitudinal cracking, are minimized. In addition, the quality of the steel should not be affected by the substitution. Therefore, any substitute/additive or combination of additives would have to possess the capacity to replicate the effects that fluorine has on mould flux behaviour.

This study focuses on B_2O_3 and Na_2O as alternative substitutes for CaF_2 in billet fluxes. The new flux has been successfully tested in a plant trial on a continuous casting plant.

(cf. *ISIJ Int.*, **45** (2005), 1051)

Surface Treatment and Corrosion

Use of flow barriers to eliminate vortex in the flow field generated in a continuous galvanizing bath

S.K.DASH et al.

The Navier–Stokes equation has been solved numerically along with the two equations eddy diffusivity k–ε turbulence model in a continuous galvanizing bath of industrial size taking the details of the sink and the guide rolls into account where the strip speed and the width were kept constant. The main objective of the work was to eliminate the vortex formed between the strip and the sink roll, due to the movement of the strip over the sink and the guide rolls. This vortex feeds the dross particles back to the flow again so that the strip could pick up the dross over the time thus spoiling its own quality. Two alternative arrangements of placing a plate baffle (parallel and perpendicular) near the strip were tried, which could eliminate the vortex completely near the strip. The parallel plate baffle could eliminate the vortex as well as the perpendicular plate baffle but the flow field due to the perpendicular plate baffle seems to be more attractive than the one created due to the parallel plate baffle. So the choice of implementation remains with the plant personnel depending on the ease of fitting the plate to the galvanizing/zinc bath.

(cf. *ISIJ Int.*, **45** (2005), 1059)

Correlation of high-temperature steam oxidation with hydrogen dissolution in pure iron and ternary high-chromium ferritic steel

M.NAKAI et al.

The high-temperature oxidation in both air and steam was examined experimentally with pure iron and a Fe–10Cr–0.08C (mass%) ternary ferritic steel. In case of pure iron, the thickness of the oxide scale formed in steam at 923 K for 360 ks was comparable to that of the scale formed in air. On the other hand, in case of the ternary ferritic steel, the oxide scale formed was much thicker in steam than in air. Thus, the oxidation rate was nearly independent of the air and the steam atmosphere for pure iron, but was dependent for the ternary ferritic steel. In the present study, this difference was investigated from a viewpoint of the hydrogen dissolution in the oxide scale during the steam oxidation. The amount of dissolved hydrogen was measured using a thermal desorption spectroscopy (TDS). It was found that the amount of the dissolved hydrogen was much larger in the ternary ferritic steel than in pure iron. Also, it was shown that the hydrogen dissolution in the ternary ferritic steel was related to the presence of $(Fe,Cr)_3O_4$ in the oxide scale. The defect structure in this chromium-rich oxide was modified by hydrogen dissolution, so that the ionic diffusion could be enhanced in it, resulting in the more accelerated oxidation rate in steam.

(cf. *ISIJ Int.*, **45** (2005), 1066)