Technology Relating to Lorentz Ferce

Free surface controlled by magnetic fields (Review)

Y.FAUTRELLE et al.

In metallurgy it is needed to master the shape or the motion of the liquid metal free surface. The present paper reviews some effects of a magnetic field on the behaviour of liquid metal free surfaces. First, the various effects associated with A.C. fields are presented, static dome shaping, dome oscillation, instability, emulsion. Then, the case of a DC magnetic field is presented. Such field is generally stabilising. Nevertheless, in particular case, its application may promote low frequency oscillations. Finally, the effects of magnetic field exhibiting more than one frequency are presented. All these cases are illustrated by photographies produced in the EPM-Madylam laboratory.

(cf. *ISIJ Int.*, **43** (2003), 801)

Initial solidification control of continuous casting using electromagnetic oscillation method

I.SUMI et al.

An initial solidification control technology, called the Electromagnetic Oscillation Method, intermittently applying high frequency magnetic field was developed aiming to reduce the friction between mold and initial solidified shell and to perform high speed casting for producing cast having excellent surface properties. According to the method, a high frequency magnetic field is applied synchronizing with the mold oscillation, applying a horizontal and inward electromagnetic force from outside the mold during the positive strip period, while applying a downward electromagnetic force from above the mold during the negative strip period. The method was investigated in terms of influence on the surface properties of cast and other variables by applying the method to laboratory scale continuous steel casting. The experiment was given by casting round billets having 100 mm in diameter at casting speeds of 0.5 to 1.6 mm/min, applying high frequency magnetic fields of 1 to 9.8 kHz. The flux film thickness in the mold increased by applying horizontal electromagnetic force during the positive strip period, and the surface properties of the cast improved. By applying downward electromagnetic force during the negative strip period, the strength of initial solidified shell increased to prevent the occurrence of breakout.

(cf. *ISIJ Int.*, **43** (2003), 807)

Continuous casting of steel billet with high frequency electromagnetic field

J.PARK et al.

The electromagnetic continuous casting technology has been investigated in commercial scale casting experiments at a billet caster of POSCO works. A set of facility composed of coil & mold with a specially devised molten metal level meter, and software for casting monitoring were well suited to No. 2 billet caster of POSCO. The devised EMC facility and software proved well working and good enough for commercial production in the viewpoint of cooling capability of the mold, control of molten steel level. The major observations with the electromagnetic continuous casting operations include that the oscillation mark was improved a lot to its nominal depth of less than 0.1 [mm], and that the solidified shell thickness at the mold bottom was increased 10%. It was also seen that the mold powder consumption increased up to 30%, and that a continuous casting without mold oscillation was possible with excellent surface quality of the billet. The billet surfaces to the various amounts of mold flux consumption suggested that the choice of the mold flux be one of the important elements to enjoy the electromagnetic effects. Finally, it is worthwhile to emphasize that the electromagnetic continuous casting can help to prevent breakouts and to relieve the mold oscillation, besides the well-known effects of surface improvement.

(cf. *ISIJ Int.*, **43** (2003), 813)

Electromagnetic separation of nonmetallic inclusion from liquid metal by imposition of high frequency magnetic field

K.TAKAHASHI et al.

In this study, a method is investigated for separating inclusion particles from liquid metal by the electromagnetic force generated by an alternating magnetic field. To make clear the characteristics of the inclusion separation, a model experiment has been performed by the use of a SiC-liquid aluminum system in a high frequency induction furnace. The thickness of particle-accumulated layer formed on the side wall and its area fraction of particles are measured from the micrographs of the cross section of solidified aluminum sample. It is found that the growth of the particle-accumulated layer is completed in a short time (ten and several seconds), and that the thickness of the layer becomes smaller and the particle fraction in the layer becomes larger with increasing coil current. Mechanical stirring is found to retard particle separation in the case of small coil current. The maximum thickness of the particle-accumulated layer obtained for the 3 mass% addition of particle is almost same as the skin depth. To investigate the electromagnetic separation in the present system, a complete mixing model is made, which takes into account the effect of the particle-accumulated layer on the electromagnetic force distribution. This model is based on the Lavers' theory with a simple modification of the change in apparent electric conductivity in the particle-accumulated layer. The estimated results of the change in particle concentration and the growth of particle-accumulated layer are in good agreement with the observed results.

(cf. *ISIJ Int.*, **43** (2003), 820)

Promotion of desulphurization in ladle through slag emulsification by stirring with stationary AC electromagnetic field

T.INOMOTO et al.

Strong electromagnetic stirring enables promotion of interfacial reaction between slag and metal in ladle refining processes. This study elucidates the interfacial phenomena through plant scale experiments by using stationary alternative current (AC) electromagnetic field, cold models to make clear the hydrodynamic behavior of fluids, and the numerical simulation of the magnetohydrodynamic (MHD) and chemical reaction analyses. They revealed that the enhancement of the interfacial reaction is strongly related to the state of the slag–metal interface and that there exist critical values of the intensity of electromagnetic power supply, which govern the reaction rate.

(cf. *ISIJ Int.*, **43** (2003), 828)

Non-contact sensor for the measurement of meniscus velocity of molten metal flow

M.IGUCHI et al.

An electromagnetic non-contact sensor was developed to measure the meniscus velocity of molten metal flow. Wave motions were generated on the surface of a molten metal bath by applying a Lorentz force periodically. The meniscus velocity was obtained by detecting a difference between the propagation times of the waves to the upstream and downstream level sensors. This is because the propagation time difference depends on the meniscus velocity of molten metal flow. The effects of the frequency of the electric source, excitation frequency, and the existence of mold powder on the accuracy of the meniscus flow measurements were investigated based on cold model experiments using molten Wood's metal and silicone oil. The accuracy was satisfactory under the experimental conditions considered.

(cf. *ISIJ Int.*, **43** (2003), 836)

Solidified structure of Al alloys by a local imposition of an electromagnetic oscillationg force

T.TAKAGI et al.

Refinement of a solidified structure of aluminum alloys by an electromagnetic method in which oscillation was locally imposed by a simultaneous imposition of a static magnetic field and an alternating current has been investigated. In the viewpoint of potential energy, stable positions of a primary solid particle precipitated during solidification were theoretically predicted under the consideration of the gravitational force and the magnetization force acting on the particle, and furthermore, moving time of the primary particle in a melt was derived. In the experiment, a refined structure was obtained for an Al–6mass%Si by imposing the electromagnetic vibration while a macro-structure of an Al–15mass%Si was not refined by this method. The primary phase of β precipitated in the liquid Al–15mass%Si was mainly observed at the theoretically predicted positions. But the primary phase of α in the Al–6mass%Si was observed in the whole area of the sample though the theoretically stable position was the bottom in the sample. The discrepancy between the theoretical prediction and the experimental result can be explained by the moving time of primary particles, which is not enough in the experiment to reach the stable position in the case of the Al–6mass%Si.

(cf. *ISIJ Int.*, **43** (2003), 842)

Visual system experiment of MHD pump using rotating twisted magnetic field applicable to high-temperature molten metals

T.ANDO et al.

A new type MHD pump, applicable to high-temperature molten metal in cylindrical ducts, is proposed. A rotating twisted magnetic field is generated by a stator with three pairs of helical windings. Axial thrust, as well as rotational torque, acts on the secondary conductor. Experiment with a transparent duct system was performed to confirm that this induction machine works as a pump, and it is verified that the thrust is actually obtained on experiments with a prototype stator and liquid gallium. This experiment shows the thrust is proportional to the square of the primary current.

(cf. *ISIJ Int.*, **43** (2003), 849)

Relating to Intense Magnetic Field

The control of crystal orientation in non-magnetic metals by imposition of a high magnetic field

T.SUGIYAMA et al.

High magnetic filed can affect not only ferromagnetic materials but also non-magnetic ones. In general, materials have a crystal magnetic anisotropy where a magnetic susceptibility is different in each crystal direction. So that the utilization of this property can control the crystal orientation by imposition of the high magnetic field. Up to now, the possibility of magnetic orientation by imposition of the high magnetic field has been studied, it was said that existence of crystal magnetic anisotropy and a low viscosity are essential. Then, substance which has crystal magnetic anisotropy can control the crystal orientation by heating up to liquid and solid zone which is a low viscosity.

It is found that the high magnetic field can control the crystal orientation of Zinc or Bismuth–Tin alloy, non-magnetic material, by reheating in a solidification process. These experimental results can be explained by taking into account of a magnetic energies due to the crystal magnetic anisotropy. And, we discuss a theoretical analysis on the magnetic rotation of non-magnetic metal crystals by taking account of Lorenz force which acts in of molten metals.

(cf. *ISIJ Int.*, **43** (2003), 855)

Electromagnetic flow around two non-conducting particles and the interaction forces — different diameter cases —

T.OGASAWARA et al.

In this study, electromagnetic (em) migration forces exerted to two non-conducting particles having different diameters are investigated, which are in conducting liquid with imposition of DC em field. The electromagnetically-driven flow (em-flow) around the particles was analyzed numerically. Its influence on the interaction force between the particles and on the magnitude of em migration forces (Gc) were examined for the two particles in three configurations; Direction of two particles in a row is either parallel to the current (Case 1), or to the magnetic field (Case 2), or to the em force (Case 3).

Four circulating flows were formed around the two particles. Strong penetrating flow between the particles existed in Case 1 and 2, but they had different flow directions. In Case 3, the penetration flow was weak. The migration force exerted to the small particle was influenced markedly. In Case 1, Gc of small particle is larger than that of the large particle twice as much. In Case 2, the direction of em migration force was opposite to the large particle. These relative differences in em migration force correspond to the repulsive interaction between the particles. Interaction forces along directions of the particles in the row were negligibly small in all three cases.

Nature of generating interaction forces between the particles was discussed by considering the pressure distribution on the particle surface.

(cf. *ISIJ Int.*, **43** (2003), 862)

Shape anisotropy evolution of Co grains in Cu–30at%Co alloy by annealing under magnetic field

H.YASUDA et al.

The shape change of the fcc-Co grains during the coarsening process was examined by using the Cu–30at%Co alloys. The fine Co-rich particles were uniformly distributed in the rapidly solidified alloys when the cooling rate was sufficiently large to prevent the dendritic growth of the primary Co phase. The influence of the magnetic field on the shape change of the Co grains was clearly observed when the rapidly solidified particles were annealed at 1 173 K under 10 T. The average angle between the long-axis and the magnetic field direction at 10 T is 15 degrees smaller than the average value at 0 T. The coarsening model suggested that the shape magnetic anisotropy energy acts as a driving force of the coarsening in the region that the Co grain size is several μm. The static magnetic energy due to the shape anisotropy has an alternative potential to produce the aligned structure.

(cf. *ISIJ Int.*, **43** (2003), 869)

Effects of strong magnetic fields on natural convection in the vicinity of a growing cubic protein crystal

L.B.WANG et al.

Recently, better quality protein crystals have been obtained by using a superconducting magnet. One of important factors that determine crystal quality is natural convection in the fluid where the crystals are grown. This paper presents a comprehensive, comparative numerical study of natural convection around a growing protein crystal when a vertical magnetization force caused by a gradient magnetic field acts on protein aqueous solution and the viscosity of the solution increases. The study shows that natural convection around a crystal can be damped most effectively and the crystal growth rate is reduced when an upward magnetization acts on a protein solution and the viscosity increases. The decrease of crystal growth is thought to contribute to the improvement of crystal quality. The technique of obtaining low gravity environments and damping natural convection in electric low- and non-conducting fluid will be useful for the preparation of many materials.

(cf. *ISIJ Int.*, **43** (2003), 877)

Effect of magnetic convection on metal substitution reaction under intense magnetic field

T.KOZUKA et al.

Metal substitution reaction between solid metal and ionic solution occurs according to ionization tendency. In these reactions, the micro MHD effect and magnetic convection can affect the reaction rate under imposition of an intense magnetic field.

In this study, the effects of a magnetic field up to 5 T and its gradient on the metal substitution reaction of copper(II) sulfate solution with solid iron or solid zinc were investigated. Both the micro MHD effect and magnetic convection can affect the reaction rate. The micro MHD effect, which promotes the metal substitution reaction, appears more strongly for zinc than for iron, because the ionization tendency of zinc is higher than that of iron. Magnetic convection can promote or suppress the natural convection around the metal surface in the solution. For the system of solid iron in the solution, natural convection, which is induced by the buoyancy of iron-rich solution around the solid iron, is suppressed by downward magnetic convection, because iron ions are paramagnetic, and is promoted by upward magnetic convection. In contrast, zinc ions are diamagnetic, and the effect of magnetic convection around solid zinc is opposite the effect around solid iron.

(cf. *ISIJ Int.*, **43** (2003), 884)

Numerical Simulation Techniques

Modelling electromagnetically levitated liquid droplet oscillations

V.BOJAREVICS et al.

This work comprises accurate computational analysis of levitated liquid droplet oscillations in AC and DC magnetic fields. The AC magnetic field interacting with the induced electric current within the liquid metal droplet generates intense fluid flow and the coupled free surface oscillations. The pseudo-spectral technique is used to solve the turbulent fluid flow equations for the continuously dynamically transformed axisymmetric fluid volume. The volume electromagnetic force distribution is updated with the shape and position change. We start with the ideal fluid test case for undamped Rayleigh frequency oscillations in the absence of gravity, and then add the viscous and the DC magnetic field damping. The oscillation frequency spectra are further analysed for droplets levitated against gravity in AC and DC magnetic fields at various combinations. In the extreme case electrically poorly conducting, diamagnetic droplet (water) levitation dynamics are simulated. Applications are aimed at pure electromagnetic material processing techniques and the material properties measurements in uncontaminated conditions.

(cf. *ISIJ Int.*, **43** (2003), 890)

3-D free surface simulation in the electromagnetic dam

K.MORITA et al.

A method to study the physical phenomena of the molten metal under the AC magnetic field has been

required to design the electromagnetic (EM) dam system. This confines a side of the molten metal by Lorentz force without contact between the side wall and the molten metal. In this work, we have developed a numerical analysis method to predict the 3-D phenomena of the molten metal considering the free surface. To evaluate steady the state of the molten metal including the free surface, the integrated computational errors are eliminated after certain iteration step. This process avoids the solution diverged and provides the converged steady state solution. However, although the error elimination process neglects the physical phenomena of smaller scale than the elimination time step related, this method could predict slowly varying the surface shape obtained by the experiment. By using this method, the effects of magnetic field direction and the EM boundary condition on the surface shape are investigated. The profile of Lorentz force corresponding to the direction of magnetic field and boundary condition was found to affect the flow pattern resulting in the change of the steady state surface shape.

(cf. *ISIJ Int.*, **43** (2003), 899)

Numerical computation for the melt convection of the model system of continuous steel casting with various magnetic fields

K.EZAKI et al.

Melt flow in the model system of continuous steel casting process was numerically computed with an application of various magnetic fields. The model geometry is $1\times1\times2$ which is not in accordance with the current shape employed in a practical industry. Electric coil to produce a magnetic field was either vertical, horizontal and parallel, or perpendicular to the nozzle jet from the tandish. Detailed melt flow in the mold is graphically presented. The axial magnetic field appears to suppress the jet flow most effectively.

(cf. *ISIJ Int.*, **43** (2003), 907)

Effects of electromagnetic brake and meniscus electromagnetic stirrer on transient molten steel flow at meniscus in a continuous casting mold

K.TAKATANI

On the molten steel flow in the mold of the slab-type continuous caster, the analysis by the unsteady and three-dimensional mathematical model is carried out from the viewpoint of the meniscus behavior. As flow control methods at meniscus in the mold, electromagnetic brake and meniscus electromagnetic stirrer are chosen, and those flow control characteristics are investigated and results are as follows.

1) The electromagnetic brake makes the molten steel flow two-dimensional, and the turbulence of fluid flow is suppressed, and the electromagnetic brake has suppression of the fluctuation of the fluid flow just under the meniscus and remarkable effect of temperature rising at meniscus.

2) Flow control is possible with the interference of the electromagnetic force by the meniscus electromagnetic stirrer with the molten steel flow through the immersion nozzle, and meniscus electromagnetic stirrer emphasizes the fluctuation of molten steel flow in front of solidified shell and has slight temperature rising effect at meniscus.

3) Selection of discharge angle of immersion nozzle is important for these flow control devices by the electromagnetic field. These flow control devices have no effect or have the opposite effect in some cases by the wrong selection of discharge angle.

(cf. *ISIJ Int.*, **43** (2003), 915)

Numerical estimation of the effect of the magnetic field application on the motion of inclusion in continuous casting of steel

B.LI et al.

Numerical estimation has been conducted to analyze the motion of inclusion considering the effects of argon gas injection and magnetic field application in the continuous casting of slab. The fluid velocity field was obtained by solving the Navier–Stokes equations with electromagnetic force, and the trajectories of inclusion particles are calculated based on the computed velocity field. A reasonable agreement between numerical and experimental trajectory for single sphere was obtained using the water model. The movements of particles are traced in cases with and without the magnetic field and argon gas injection. The results show that some particles after spiral movements re-enter the jet zone of molten steel, and then enter the opposite circulation zone. Inclusions in the upper circulation zone are easily removed. Argon gas injection increases the removal rate of inclusions. The spiral trajectories of inclusion particles disappear when the magnetic field is applied, and the particle velocities decrease significantly. The argon gas injection and magnetic field application are effective for the control of the inclusions.

(cf. *ISIJ Int.*, **43** (2003), 923)

Numerical analysis of thermo-electrically conducting fluids in a cubic cavity using vector finite element method for induction equations

M.MATSUMOTO et al.

he purpose of this study is to apply vector finite element method to magnetohydrodynamics. Vector finite element method is one of the popular methods in the field of electromagnetism. Two types interpolation functions are defined. One is facet element and another is edge element. In applying vector finite element method to the Inductions equations solenoidal condition is satisfied automatically without iterative corrections. But classical finite element method like B method by Oki *et al.* needs to solve Poisson equations to satisfy the solenoidal condition. In the present study Induction equations are numerically analyzed with vector finite element method. Flow field and temperature field are analyzed using GSMAC finite element method. We call this analysis technique GSMAC-VFEM (generalized simplified marker and cell vector finite element method). Three-dimensional natural convection in a cavity under a constant magnetic field is analyzed to determine the accuracy and the efficiency of the method. Computational results are compared with B method to verify this numerical scheme. Since the numerical results obtained here agreed well with other numerical results, the new numerical method for solving Induction equations using vector finite element method was verified. Calculation time of new numerical scheme was faster than the other numerical method. The reason is that using vector finite element method for solving Induction equations solenoidal condition for magnetic flux density satisfies automatically.

(cf. *ISIJ Int.*, **43** (2003), 932)

Effect of magnetic field on solidification in Cu–Pb monotectic alloys

H.YASUDA et al.

Two phases produced through the liquid–liquid separation gravitationally segregate during solidification of the monotectic alloys. This paper examined reduction of the gravity segregation for the Cu–Pb monotectic alloys by imposing a static magnetic field up to 10 T. The Cu–Pb alloys with compositions ranging from 15.5 to 84.5 at% Pb solidified at a cooling rate of 10 K/s under a magnetic field. The effect of the magnetic field on the macrosegregation was clearly recognized for the Cu–Pb alloys with compositions ranging from 65 to 70 at% Pb, while the magnetic field did not become a dominant factor of the segregation behavior in the other compositions. Furthermore, diameter of the Cu-rich liquid drops under 10 T was smaller than that under 0 T. The static magnetic field reduced not only the rising velocity of the Cu-rich drops but also the coalescence rate of the liquid drops, resulting in the reduction of the macrosegregation. The magnetohydrodynamic estimation suggested that the terminal velocity of the Cu-rich particles with typical diameters is significantly reduced by the imposed static magnetic field. The difficulty of the particle movement due to the electromagnetic force resulted in the homogenous solidified structure for the Cu–Pb alloys.

(cf. *ISIJ Int.*, **43** (2003), 942)

Performance evaluation of arc–electrodes systems for high temperature materials processing by computational simulation

H.NISHIYAMA et al.

Thermofluid analysis of an arc flow and the evaluation of the cathode lifetime have been conducted by a computational simulation for the performance improvement of arc–electrodes systems. The effects of arc current, electrode gap, inlet gas flow rate and cathode vertex angle on the temperature and velocity fields of an arc flow are clarified by parametric computations to optimize the operating conditions and torch geometry. The temperature field by an arc flow model shows the quantitative agreement with the available experimental data in the local thermodynamic equilibrium (LTE) region. The cathode lifetime is evaluated successfully by coupling with the computated thermofluid field of an arc flow. The effects of different operating conditions on the cathode lifetime are also discussed for longer lifetime of the arc–electrodes systems.

(cf. *ISIJ Int.*, **43** (2003), 950)