Casting and Solidification

Perspectives of research on high-speed conventional slab continuous casting of carbon steels (Review)

M.SUZUKI et al.

Two decades ago the casting speed of the conventional slab continuous caster was increased stepwise to a level over 2 m/min. Henceforth, the casting speed has been remained a similar level. In this review the reasons for constraining the casting speed are discussed. As a result the constraints of the high-speed casting are thought mold powder entrapment and longitudinal facial crack occurring in high-speed casting.

Some measures to prevent the mold powder entrapment and the longitudinal facial crack are discussed. Resultantly the research issues we should develop are considered such as prevention of alumina built-up in a submerged entry nozzle, control of fluid flow in a mold and control of heat transfer through mold powder film interved between a solidifying shell and a mold wall. They are most important to realize the high-speed continuous casting of conventional slab.

(cf. *ISIJ Int.*, **41** (2001), 670)

Fundamentals of High Temperature Processes

numerical computation of electromagnetic fields in metals using a modified finite-difference time domain method

Z.-D.QIAN et al.

The Gandhi's scaled-frequency FDTD (finite-difference time domain) method for electromagnetic fields of low frequency was modified, and so can be adaptable to the numerical computation of electromagnetic phenomena in metals. The computational results by a simplified model agreed well with the analytical solutions. A new treatment for the interface of metal and dielectric was also presented, further how and why it is was explained. The low-frequency electromagnetic fields were computed successfully due to this treatment. The computational results are in excellent agreement with the experimental ones.

(cf. *ISIJ Int.*, **41** (2001), 683)

Suppression of the vortex in ladle by static magnetic field

J.W.SUH et al.

The vortex formation in draining the melt in ladle can be suppressed by the reduction of the tangential flow velocity of the melt. Two magnetic devices were designed in order to reduce the tangential flow velocity and tested with wood metal melt. One consists of 4 permanent magnets (PM device) and the other consists of an electromagnet (EM device). Magnetic flux density around each device was calculated and compared with the measured one. Induced body force in the melt was calculated with both of the calculated magnetic flux density and velocity profile. The dimensionless vortex formation height, where the vortex formation height is divided by orifice inner diameter, decreased from 1.7 down to 0.85 in both cases of the PM device and the EM device as the static magnetic field increased up to 0.17 T.

(cf. *ISIJ Int.*, **41** (2001), 689)

Evaporation of Fe and Cr from induction-stirred austenitic stainless steel. influence of the inert gas pressure

J.P.BELLOT et al.

In vacuum metallurgy, one of the purposes is the reduction (or at least the accurate prediction) of the evaporation losses. It is well known that the addition of an inert gas in a vacuum furnace increases the recondensation of the volatile elements and then reduces the evaporation losses. We may define the pressure $P_{1/2}$ required to halve the evaporation rate. The objective of this study is a theoretical and experimental evaluation of $P_{1/2}$ in the case of an austenitic stainless steel, and the analysis of the parameters which influence this value.

The experimental programme was carried out on an austenitic stainless steel to determine the net flux of evaporation from a well-mixed liquid in an ambient pressure of argon ranging from 0.03 to 133 Pa. $P_{1/2}$=30 Pa is estimated from the experimental curve.

The mechanisms of volatilization have been modeled using both a system based and a mechanistic approach, and the calculation of the pressure $P_{1/2}$ gives respectively 45 and 90 Pa. The numerical simulations (mechanistic approach) emphasize the strong expansion of the vapor from the high density regions close to the liquid surface. The macroscopic velocity of the vapor decreases as the argon pressure in the chamber increases since the average frequency of collision with the argon atoms increases.

We have set up a sensitivity study in order to analyse the effects of the geometry and scale of the furnace and of the liquid temperature on the factor $P_{1/2}$. Since geometry and temperature vary in large scales for the industrial applications, the use of the experimental value $P_{1/2}$=30 Pa obtained is discussed.

(cf. *ISIJ Int.*, **41** (2001), 696)

Effect of oxygen on the evaporation rate of lead from liquid copper under reduced pressure

T.YOSHIDA et al.

Previously, the present authors have investigated the effects of temperature and pressure on the evaporation rates of Pb and Zn from liquid copper under reduced pressure. Oxygen does easily contaminate molten metal during high temperature processing and is known as a strong surface active element. In this study, the effect of oxygen on the evaporation rate of Pb from liquid copper was discussed at 1 473 K and 1.3 kPa. The rate constant was supposed to be slower with oxygen content due to lowering the interfacial chemical reaction rate. However, the rate constant increased with oxygen content in the present experiment. Assuming that the acceleration of vaporization is due to the volatile lead oxide, the rate equation was derived for the evaporation of lead oxide together with that of metallic Pb. As a result of the analysis for the present experiment, it was found that Pb evaporated from copper melt containing higher oxygen in the form of PbO. The presence of PbO in the vapor phase was confirmed by the mass spectroscopy. The rate mechanism of vaporization of Sn and Cu from liquid steel containing oxygen have also been discussed.

(cf. *ISIJ Int.*, **41** (2001), 706)

The heating characteristics of $CaO–SiO_2–Fe_tO$ system slags under microwave irradiation

K.MORITA et al.

In order to develop an efficient heating process for the waste slag treatment, the heating behavior of the synthetic $CaO–SiO_2–Fe_tO$ slag under microwave irradiation was investigated. The heating rate of the slags was found to vary with the ratio of $Fe^{3+}/(Fe^{2+}+Fe^{3+})$ in the slags and the microwave energy was most efficiently absorbed when the value of $Fe^{3+}/(Fe^{2+}+Fe^{3+})$ was around 0.16 with the largest dielectric loss of the slag. Also the heating rate was benefited considerably from the presence of $CaFe_3O_5$ and magnetite phases in slags that have high value of dielectric loss. When the graphite powder was added to the slags, heating rate was drastically increased and the larger amount of carbon addition brought the higher value of heating rate.

(cf. *ISIJ Int.*, **41** (2001), 716)

Steelmaking

Viscosity measurements on some fayalite slags

N.N.VISWANATHAN et al.

In the present study, viscosity measurements on Fe–O–Si slags have been carried out using rotating cylinder method. The slag samples for viscosity measurement were prepared by pre-melting appropriate stoichiometric amounts of Fe, Fe_2O_3 and SiO_2 in an iron crucible under argon atmosphere, which ensured that Fe ions in the slag were predominantly in the valence state of +2. The viscosities of the pre-melted slag samples were measured in iron as well as nickel crucibles under argon atmosphere at different temperatures. The measured viscosity values obtained in the two kinds of crucibles were found to be in good agreement, indicating thereby that nickel crucibles can be successfully used for viscosity measurements. In order to investigate the effect of oxidation of Fe^{2+} to Fe^{3+}, the binary $Fe_nO–SiO_2$ slag was kept in a nickel crucible under oxidising conditions using a CO/CO_2 atmosphere and viscosity measurements were carried out dynamically as a function of time at 1 623 and 1 673 K. With time, Fe^{3+} concentration in the slag increased and hence the viscosity changed progressively. The rate controlling step for the oxidation reaction was considered to be the mass transfer of CO_2 in the gas stream to the slag–gas interface. A simple kinetic analysis was used to predict the concentration of Fe^{3+} in the slag with time. The measured viscosity with time indicated that the viscosity remains almost the same during initial period of oxidation. The viscosity raises sharply when the Fe^{3+} concentration in the slag, calculated as Fe_2O_3 reached

around 7 mass%.

(cf. *ISIJ Int.*, **41** (2001), 722)

Casting and Solidification

Precipitation behavior of TiN in Fe–10mass%Ni alloy during solidification and isothermal holding at 1 400°C

G.V.PERVUSHIN et al.

The precipitation of TiN during solidification and holding at 1 400°C has been studied in an Fe–10mass%Ni alloy as a function of initial contents of Ti and N and holding time. Dendritic and nondendritic (globular cell) zones are observed under the condition of the undercooling of 5 to 35°C. The number of particles per unit area, N_A, in nondendritic zone is significantly smaller than that in dendritic zone and the N_A values in both zones increase with holding time. The values for mean particle diameter, $\bar{d}_A$, remain unchanged in dendritic zone with holding time, while the $\bar{d}_A$ values decrease with holding time in nondendritic zone. In dendritic and nondendritic zones, the degree of precipitation of TiN particles increase with increasing area fraction of solid, f_S, and the degree of precipitation depends on initial contents of Ti and N. The $\bar{d}_A$ value in nondendritic zone, which is independent of f_S, is larger than that in dendritic zone at zero holding time for a given initial content.

(cf. *ISIJ Int.*, **41** (2001), 728)

Numerical simulation of microstructure evolution of Al alloys in centrifugal casting

S.R.CHANG et al.

A coupled stochastic model has been developed for the prediction of solidification grain structures in centrifugal casting. The present model consists of two schemes: the cellular automaton to simulate the evolution of solidification structure and the finite volume method to calculate the heat transfer. The present model has been applied to predict the evolution of solidification structures in centrifugal casting of Al alloys. The effects of mold rotation velocity, solute concentration, melt superheat and mold preheating temperature on solidification structures were investigated. In addition, the evolution of dendritic microstructures was also simulated using a modified cellular automaton model. The simulated results were in good agreement with those obtained experimentally.

(cf. *ISIJ Int.*, **41** (2001), 738)

Effect of primary deoxidation products of Al_2O_3, ZrO_2, Ce_2O_3 and MgO on TiN precipitation in Fe–10mass%Ni alloy

G.V.PERVUSHIN et al.

Effect of Al_2O_3, ZrO_2, Ce_2O_3 and MgO particles with mean diameter of 0.8 to 1.5 μm on the precipitation of TiN during solidification and holding at 1 400°C has been studied in an Fe–10mass%Ni alloy. The values for the number of particles per unit area, N_A, and the mean diameter, $\bar{d}_A$, of TiN and TiN+M_xO_y (M=Al, Zr, Ce, and Mg) particles have been measured as a function of initial contents of Ti (50 to 990 mass ppm) and N (200 to 290 mass ppm), and holding time (0 and 60 min). The N_A values of the TiN+MgO particles are considerably higher than those of the TiN+M_xO_y (M=Al, Zr, and Ce) particles, while the $\bar{d}_A$ values of the former particles, which are found to be independent of solidification mode, are smaller than those of the latter particles. The $\bar{d}_A$ values of TiN and TiN+M_xO_y (M=Al, Zr, and Ce) particles in dendritic solidification are smaller than those in nondendritic one, whereas an opposite trend is observed with respect to the N_A values. The $\bar{d}_A$ values of the TiN and TiN+M_xO_y particles were found to remain unchanged, but the N_A values tended to slightly increase with holding time.

(cf. *ISIJ Int.*, **41** (2001), 748)

Chemical and Physical Analysis

Quantitative analysis of total and insoluble elements and inclusion composition in metal by laser ablation ICP-MS method

A.V.KARASEV et al.

Total (M_{total}) and insoluble (M_{insol}) contents of element, and inclusion composition in metal samples have been analyzed quantitatively by using the laser ablation ICP-MS (LA-ICP-MS). The contents of M_{total} and M_{insol} in Fe–M, Fe–10mass%Ni–M, and Fe–0.2mass%C–M (M=Ti, Al, and Ce) alloys obtained by LA-ICP-MS are compared with those from chemical analysis. The compositions of synthetic particles (CA_2, CA, $C_{12}A_7$, C_3A, CAM, and MA; C=CaO, A=Al_2O_3, and M=MgO) and complex inclusions (Al_2O_3–TiN and Ce_2O_3–TiN) on a surface of glass or metal sample are analyzed by LA-ICP-MS, and these values are compared with those from EPMA and chemical analysis. It is found that LA-ICP-MS is an useful technique to the quantitative analysis of total and insoluble contents of elements and composition of inclusions in the range of particle diameter from 1 to 100 μm.

(cf. *ISIJ Int.*, **41** (2001), 757)

Forming Processing and Thermomechanical Treatment

Mathematical modeling of the recrystallization kinetics of Nb microalloyed steels

S.-H.CHO et al.

The recrystallization behavior of Nb microalloyed steels was studied using hot torsion testing with the aim of modeling the recrystallization processes taking place during hot rolling. Continuous and interrupted torsion tests were performed in the temperature range 850 to 1050°C at strain rates of 0.05 to 5/s on selected low carbon steels containing Cr, Mo, Nb, Ni and Ti. The kinetics of static and metadynamic recrystallization were characterized and appropriate expressions were formulated for the recrystallization kinetics. These are shown to depend on steel composition and the processing conditions. The rate of metadynamic recrystallization increases with strain rate and temperature and is observed to be independent of strain, in contrast to the observations for static recrystallization. By means of extrapolations to mill strain rates, it is shown that metadynamic recrystallization will always be more rapid than static recrystallization, even at the largest possible accumulated strains. These calculations support the view that the unexpected load drops occasionally observed in industrial mills (particularly in the final few passes) are probably due to strain accumulation leading to the initiation of dynamic recrystallization, followed by metadynamic recrystallization.

(cf. *ISIJ Int.*, **41** (2001), 766)

Transformations and Microstructures

Improved model for static recrystallization kinetics of hot deformed austenite in low alloy and Nb/V microalloyed steels

S.F.MEDINA et al.

Using torsion tests a improved model has been constructed to predict the static recrystallization kinetics of deformed austenite in low alloy and microalloyed steels. The model quantifies the influence of the most common elements (C, Si, Mn, Mo) in low alloy steels and the typical elements (V, Nb) in microalloyed steels, when they are in solution. Activation energy (Q) is the parameter sensitive to the content and nature of each alloying element, and an expression for Q is shown as a function of the percentage of each one. Nb is the element that contributes most to increasing the value of Q, and thus that which most delays recrystallization kinetics. C is seen to be the only alloying element that contributes to lowering the value of Q, and thus to accelerating recrystallization kinetics. Extrapolation of the expression of Q to pure iron in the austenitic phase gives a value of 148 637 J mol^{-1}, which is similar to other values found in the literature for the grain boundary self-diffusion energy of pure Fe_γ. Static recrystallization kinetics follow Avrami's law and expressions are given for the parameter $t_{0.5}$ and the exponent n.

(cf. *ISIJ Int.*, **41** (2001), 774)

Mechanical Properties

FEM Modeling of flow curves for ferrite/pearlite two-phase steels

D.-W.SUH et al.

Flow curves of ferrite/pearlite two-phase steels were simulated using finite element method (FEM) with regression equations for flow curves of each ferrite and pearlite phase proposed by Hiramatsu et al. and Furukawa *et al.* The calculated flow strength of ferrite/pearlite two-phase steel was lower than the experimentally measured one mainly due to the underestimation of flow strength of ferrite phase according to the yield elongation. To improve the simulation, the flow curves in homogeneous deformation range were considered. Microscopic observations revealed that most deformation was accumulated in the ferrite phase during yield elongation. Flow curves of ferrite phase were re-evaluated based on this observation and flow curves of ferrite/pearlite steels were also re-calculated. Re-calculated yield strength of ferrite/pearlite steels showed good

agreement with measured ones, however the work hardening rate of re-calculated flow curves is still lower than that of measured one. The simplicity of pearlite morphology for FEM analysis is thought to be responsible for lower work hardening behavior of calculated flow curve by FEM than that of measured one.

(cf. *ISIJ Int.*, **41** (2001), 782)

Study on the propagating shear fracture in high strength line pipes by partial-gas burst test

H.MAKINO et al.

In this paper, for the purpose of investigation on quantitative correlation between the partial-gas burst tests and the full-scale burst tests as a first step of establishing the evaluating method of crack arrestability in pipelines from partial-gas burst test results, the effects of the differences in test conditions on crack propagation behavior between both tests were evaluated. The partial-gas burst tests using high strength X80 pipes were carried out six times with varied gas ratio and failure pressure. The test results indicated that the crack propagation is much influenced by not only the failure pressure but also the gas ratio. After evaluation of the differences between the partial-gas burst tests and the full-scale burst tests, the simulating method of the propagating shear fracture in partial-gas burst tests were proposed. The crack propagation of the partial-gas burst tests was well simulated by this method and good agreement between the experimental data and the simulated results was obtained.

(cf. *ISIJ Int.*, **41** (2001), 788)

Prediction of stress–strain behaviors in steels using an integrated constitutive, FEM and ANN model

L.X.KONG et al.

Austenitic steels with a carbon content of 0.0037 to 0.79 wt% C are torsion tested and modeled using a physically based constitutive model and an Integrated Phenomenological and Artificial neural Network (IPANN) model. The prediction of both the constitutive and IPANN models on steel 0.017 wt% C is then evaluated using a finite element (FEM) code ABAQUS with different reduction in the thickness after rolling through one roll stand. It is found that during the rolling process, the prediction accuracy of the reaction force from FEM simulation for both constitutive and IPANN models depends on the strain achieved (average reduction in thickness). By integrating FEM into IPANN model and introducing the product of strain and stress as an input of the ANN model, the accuracy of this integrated FEM and IPANN model is higher than either the constitutive or IPANN model.

(cf. *ISIJ Int.*, **41** (2001), 795)

Social and Environmental Engineering

Recovery of the metals from pickling liquors of stainless steel by precipitation methods

J.DUFOUR et al.

Pickling liquors are still one of the main environmental concerns of the stainless steel industry. Most of the processes designed to recover these wastes focus on the recovery of their acid content (mixtures of HF and HNO_3), but also produce metals (iron, nickel, chromium and molybdenum) as a low quality by-product that sometimes must be treated as a residue. This paper presents the development of a process to obtain commercial products from the metal content of these liquors. To this end, three precipitation methods (total, sequential and modified) were tested. The proposed procedure is the last one, *i.e.*, modified precipitation. It consists of two stages each resulting in the recovery of solids. The first product is mainly composed of iron and chromium hydroxides and oxides, along with molybdate, while the second is mainly composed of nickel hydroxide. In addition, this method allows an almost total recovery of the acids.

(cf. *ISIJ Int.*, **41** (2001), 801)