（＊掲載記事題目及び掲載頁は変更になる場合があります。）

Fundamentals of High Temperature Processes

The preferable growth direction of iron nuclei on wüstite surface during reduction

Y.SASAKI et al.

Effects of the surface grain's orientation on iron nucleation process during wüstite reduction at 1 073 K have been studied. Wüstite samples initially equilibrated for 432 ks with 50%CO–CO_2 gas mixture at 1 073 K are reduced by using 75%CO–CO_2 gas mixture with varying reaction time. The surface orientation of each grain is determined by using Electron Back Scattering Diffraction (EBSD) technique, and the surface morphology and the development of iron nuclei are examined by FE-SEM.

The apparent reduction rate of wustite is about 1.78×10^{-8} mol/cm^2/s and contrlled by the interfacial chemical reaction. For the reaction time of more than 90 s, the iron nuclei are detected on the wüstite sample and their magnitudes are gradually increased with time. The shape of developed iron nuclei is a pyramidal shape with a square base. The iron nuclei grow preferentially on the rearranged (100) surface of wüstite. This is because that the Fe nuclei can be easily formed on the (100) wüstite surface since there is a negligibly small mismatch between Fe and wüstite lattices. It has been found that the surface energy as well as the interface energy between Fe and wüstite affect the shape of iron nucleus.

(cf. *ISIJ Int.*, **45** (2005), 1077)

Heating efficiency of twin torch plasma arc

T.IWAO et al.

The twin torch plasma arc has a higher temperature arc column. For that reason, it can generate high temperature and treat non-conducting material, even though it is a non-transfer type. Therefore, the twin torch plasma arc is a more effective device for treatment of hazardous waste. However, the arc mode is not easy to control in the twin torch plasma arc. In this paper, a twin torch plasma arc with a rated current of 40 to 100 A is described such as arc mode, voltage as function of current and length, heating efficiency, and running cost for hazardous waste. The high temperature region of the twin torch plasma arc is larger than that of a conventional single plasma torch. The plasma arc length can be changed as a function of the plasma gas flow rate. The arc voltage is also variable as a function of the current and plasma gas flow rate. The temperature of twin torch plasma was measured to be about 10 000 K near the cathode and anode, and 8 900 K at the center point between the electrodes at 100 A. The neutral bar received heat power of the amount of 280–500 W, and the fraction of the total power transferred to the neutral bar is 12–18%.

(cf. *ISIJ Int.*, **45** (2005), 1084)

Model study of the rupture phenomena of a metal droplet growing on a slag–metal interface

T.KAGAWA et al.

Cold model experiments were carried out to understand the behavior of a molten steel droplet growing on a slag and molten steel interface due to coalescence with other molten steel droplets. Water, silicone oil, and n-pentane were used as the working fluids. A water droplet was generated from a single-hole nozzle placed just above a silicone oil and water interface or an n-pentane and water interface. The droplet grew in contact with the interface and then ruptured. An empirical equation was proposed for the volume of the droplet. The flow fields in and around the droplet were visualized with a CCD camera and the velocity vectors were determined with particle image velocimetry (PIV). The flow pattern near the interface was correlated in terms of the Weber number similitude.

(cf. *ISIJ Int.*, **45** (2005), 1088)

Phase equilibria in the olivine primary phase field in the MgO–"FeO"–SiO_2 system in equilibrium with metallic iron

S.CHEN et al.

Liquidus isotherms and phase equilibria have been measured in the olivine primary phase field of the MgO–"FeO"–SiO_2 system in equilibrium with metallic iron. Liquidus isotherms have been determined in the temperature range from 1523 to 1 898 K. The tie lines between liquid and olivine solid solutions have been determined and the results were compared with those obtained in previous studies.

(cf. *ISIJ Int.*, **45** (2005), 1095)

Effects of Al_2O_3 on phase equilibria in the olivine primary phase field of the MgO–"FeO"–SiO_2–Al_2O_3 system in equilibrium with metallic iron

S.CHEN et al.

Liquidus temperatures and phase equilibria have been determined in the olivine primary phase field of the MgO–"FeO"–SiO_2–Al_2O_3 system. Liquidus isotherms have been determined in the temperature range from 1 748 to 1 873 K. The results are presented in the form of pseudo-ternary sections of the MgO–"FeO"–SiO_2 with 2 and 3 wt% Al_2O_3 in the liquid. The study enables the liquidus to be described for a range of SiO_2/MgO ratios. It was found that liquidus temperatures in the olivine primary phase field decrease with the addition of Al_2O_3.

(cf. *ISIJ Int.*, **45** (2005), 1101)

Thermodynamics of TiN formation in Fe–Cr melts

J.-J.PAK et al.

The equilibrium solubility of titanium and nitrogen in Fe–Cr melts was measured in the presence of pure solid TiN under various nitrogen pressures. The activity coefficients of titanium and nitrogen relative to 1 mass% standard state in liquid iron were calculated from the experimental results in the temperature range of 1 843–1 923 K. The first and second order interaction parameters of chromium on titanium and nitrogen were determined as a function of temperature. The validity of thermodynamic parameters determined in the present study was examined by constructing the stability diagram of TiN for Fe–Cr melts and by observing the formation of primary and secondary TiN inclusions at controlled titanium and nitrogen contents in the melt.

(cf. *ISIJ Int.*, **45** (2005), 1106)

Ironmaking

Segregation behavior for fine particles of sintered ores and coke supplied at the top of a two dimensional cold model of blast furnace

H.KAWAI et al.

The segregation and accumulation behavior for the fines of sintered ore and coke was investigated experimentally with a two-dimensional cold model of blast furnace, charging the fines at the top of the equipment together with coarse particles. The fine particle was 0.5 mm in diameter and alumina sphere, 2.6 mm in diameter, was used as a coarse material. The following elemental motions govern the fines behavior. (1) The fines fall down through the space between the coarse particles. This permeation is due to the continuous change of the packing structure of the coarse particle bed during the descending motion and the fluidization of the fines. (2) The fines are blown up by the gas flow through the space between the coarse particles. In the peripheral charging method for the fines of sintered ore, there is little fines accumulation in the central part of the shaft and the permeation of fines going ahead of the coarse particles is very quick near the walls. This charging method is effective to secure the central stream of gas. In the horizontal uniform and center charges, the fines accumulation increases in the central part of the shaft and deadman surface. In the case of the fine coke of low density, a critical velocity over which the fines begin to move upward by elutriation is successfully estimated on the basis of the regular cubic arrangement of equal spheres. In the horizontal uniform charge, the bridging over between the walls appears when the accumulated fines layer grows to a certain critical thickness with repeating fines charge.

(cf. *ISIJ Int.*, **45** (2005), 1112)

Heat transfer analysis and estimation of refractory wear in an iron blast furnace hearth using finite element method

S.KUMAR

The wear of hearth refractory by hot metal penetration and mechanical erosion is the limiting factor in the life of a blast furnace and their control and minimisation result in a direct benefit in an extended campaign. At the same time, it is difficult to directly measure the amount and location of hearth erosion during any campaign. Heat transfer mathematical model is an appropriate tool to quantify the amount of erosion based on the prediction of temperature profile particularly 1 150°C freeze line isotherm in the hearth.

In the present investigation, an axisymmetric conductive heat transfer model based on finite element method has been formulated and computer software is developed. Using the model and the computer code, temperature profile is predicted in the hearth zone of two different designs of industrial blast furnaces and maximum (worst) hearth wear has been estimated. The erosion pattern is calculated on the basis of worst-case location of 1 150°C isotherm that can occur during the furnace campaign. Effects of hot metal temperature, cooling conditions and

coke-bed states (floating and sitting) on temperature profile and refractory wear are also investigated.

(cf. *ISIJ Int.*, **45** (2005), 1122)

Steelmaking

Modeling the effects of a swirling flow on temperature stratification of liquid steel and flotation of inclusions in a tundish

G.Solorio-Diaz et al.

A conventional ladle shroud (LS) is compared with a swirling ladle shroud (SLS) from the points of view of fluid flow dynamics and removal ratio of inclusions from liquid steel flowing through a tundish using water modeling and fluid dynamics approaches. In this tundish the LS generates vortexing flows at the tundish outlets that disappear with the existence of high temperature gradients inside the liquid phase. On the other hand, the SLS avoids efficiently the formation of vortexes and recirculating flows either under isothermal and non-isothermal conditions. Buoyancy forces generated by changes of liquid density enhance upward velocities enhancing the flotation rate of inclusions. The conventional shroud does not promote this effect due to the existence of the vortexing flows. Eventually the LS would drive the fluid toward the bath surface forming entrainment of slag particles by liquid steel while the SLS yields a low turbulent entry jet. The SLS is a good alternative to substitute the current flow control devices available in the market.

(cf. *ISIJ Int.*, **45** (2005), 1129)

Mathematical model for removal of inclusion in molten steel by injecting gas at ladle shroud

L.T.Wang et al.

A three-dimensional mathematical model has been developed to predict steady flow field, pressure distribution inside the shroud and efficiency of inclusion removal in tundish after argon gas injection at the shroud. Effects of the different opening of the slide gate and gas injection on velocity and pressure have been analyzed. The results show that the molten steel velocity gradually decreases and the pressure increases as the opening of the slide plane becomes larger. The velocity increases and the pressure decreases after gas injection. Bubble adhesion plays an important role in inclusion removal. Smaller bubbles and larger inclusions are favorable for inclusions removal. The larger flow rate of gas is, the greater number of bubbles generated is. Thereby the amount of removed inclusion increases. But local boiling will occur in the case of larger rate of gas, so the flow rate of gas should be strictly controlled in practice.

(cf. *ISIJ Int.*, **45** (2005), 1138)

Promotion of uniform dispersion of fine particles into a mechanically agitated steel bath

T.Sukawa et al.

Water model experiments were carried out to promote uniform dispersion of fine particles into a molten steel bath contained in a cylindrical vessel. Fine particles were initially placed on the surface of a water bath. The bath was mechanically agitated by means of an impeller settled on the centerline of the vessel. The dispersion of the particles into the bath was highly promoted by immersing a cylinder slightly into the bath at an offset radial position. The effects of the shape and size of the cylinder and impeller on the dispersion characteristics were investigated to reveal an optimum condition for the uniform dispersion.

(cf. *ISIJ Int.*, **45** (2005), 1145)

Casting and Solidification

The effects of thermosolutal convection on macrosegregation during alloy solidification

J.Lee et al.

A new combined numerical model of the BFC (Boundary Fitted Coordinate) system and moving boundary technique has been developed for the analysis of macrosegregation phenomena during alloy solidification. This new model is applied to a Pb–Sn alloy solidification process in a two-dimensional confined rectangular mold to study the effects of thermosolutal convection on the formation of macrosegregation. The basic equations are solved using the Continuum Model theory with the SIMPLE algorithm adopting the new combined method of time-dependent and boundary-fitted coordinate system to treat the moving (possibly irregular shaped) interface. Not only the effect of the buoyancy-driven flow due to temperature and liquid composition gradients but also the effects of the cooling condition, magnitude of gravity, and interaction between liquid and mushy zones on the macrosegregation are examined using the new combined model.

(cf. *ISIJ Int.*, **45** (2005), 1151)

Cold model study of the effects of density difference and blockage factor on mold powder entrapment

J.Yoshida et al.

Cold model experiments were carried out to understand the effects of the density difference between mold powder and molten steel and of the blockage factor for the immersion nozzle on the mold powder entrapment in the continuous casting mold. Water, salt water, fluorinert, and mercury were used as the working fluids. A seesaw type vessel was used as a model for the mold and it was inclined for generating an uneven flow approaching the immersion nozzle of poor wettability. The meniscus descended along the outer surface of the immersion nozzle due to a pressure difference induced along the immersion nozzle. The pressure difference was caused through an effect of abrupt arrival of the uneven flow. The penetration depth of the meniscus is closely associated with the mold powder entrapment at the nozzle ports. An empirical equation was proposed for the penetration depth. An increase in the blockage factor promoted the penetration of the meniscus.

(cf. *ISIJ Int.*, **45** (2005), 1160)

Instrumentation, Control and System Engineering

Robust molten steel level control in a strip-casting process

D.S.Lee et al.

A robust molten steel level controller is developed for a strip-casting process by using the quantitative feedback theory (QFT). The plant model for the molten steel level system is first developed as a linear time-invariant system with parametric uncertainties. The parametric uncertainties reflect the uncertain discharge coefficients of the immersion nozzle and the stopper, the uncertain transport delay of the molten steel supply system, and the various hot strip production rate of the strip-casting process. In this paper, the robust stability requirement, reference tracking capability, and disturbance rejection capability at the plant input are specified in terms of the bounds on the magnitude of the closed-loop transfer function. Then the loop shaping technique is used to design a robust QFT controller in such a way that the nominal loop transmission can meet the constraints. The simulation and experimental results show that the performance of the closed-loop system with the proposed controller is better than that with a conventional PID controller.

(cf. *ISIJ Int.*, **45** (2005), 1165)

Forming Processing and Thermomechanical Treatment

Mathematical model for the thin strip cold rolling and temper rolling process with the influence function method

Y.Liu et al.

A mathematical model for the thin strip cold and temper rolling process has been developed using the influence function method. By solving the equations describing the roll gap phenomena in a unique procedure and considering more influence factors, the model offers significant improvements in accuracy, robustness and generality of the solution for the thin strip cold and temper rolling conditions. The relationship between the shape of the roll profile and the roll force was also discussed. Calculation results show that any change increasing the roll force may result in or enlarge the central flat region in the deformation zone. Applied to the temper rolling process, the model can well predict not only the rolling load but also the large forward slip. Therefore, the measured forward slip, together with the measured roll force, was used to calibrate the model. The model was installed in the setup computer of a temper rolling mill to make parallel setup calculations. The calculation results showed good agreement with the measured data and the validity and precision of the model were proven.

(cf. *ISIJ Int.*, **45** (2005), 1173)

Characterization of internal voids and cracks in cold heading of dual phase steel

A.Sabih et al.

In this work, the mechanism of void and microc-

rack formation along the adiabatic shear bands (ASB) was studied for processing dual phase steel by cold heading. Experimental investigation along with finite element simulation has confirmed that this mechanism depends on two types of instabilities, namely geometrical and thermal instabilities. The geometric instability occurs in the presence of second phase particles (inclusions) and in relation to the material flow orientation, whilst the thermal softening arises due to the localized plastic deformation inside the ASB. Progressive deformation was observed to cause the elongation of voids in the direction of shearing that formed microcracks in the ASB of the cold headed specimen. In addition, transformed bands were observed in the highly deformed zones as a result of the temperature in the ASB exceeding the Ac_3 transformation temperature 847°C. The superposition of the location of the ASB region containing the voids and micro-cracks with the phase transformation zone indicates that the development of optimized processing conditions is particularly critical for preventing fracture during cold heading of dual phase steels.

(cf. *ISIJ Int.*, **45** (2005), 1179)

The coupled model of a microstructure evolution and a flow stress based on the dislocation theory

D.S.SVYETLICHNYY

A coupled mathematical model has been developed that predicts a microstructure evolution and a flow stress during and after the process of deformation. A part of the model, which is responsible for the microstructure evolution, consists of models of a recrystallization and a grain growth. A dynamic, static and metadynamic recrystallization is considered as a whole. The flow stress is calculated on the basis of the dislocation theory. Changes of the dislocation density during the deformation are described by model considered the hardening, the recovery and the recrystallization. In pauses between deformation process, the recrystallization is the only process taken into account as a softening one. The results of the simulation are demonstrated.

(cf. *ISIJ Int.*, **45** (2005), 1187)

Transformations and Microstructures

Microstructure and formability of aluminum bearing TRIP-aided steels with annealed martensite matrix

K.SUGIMOTO et al.

The effects of aluminum content on microstructure, ductility and formability of advanced high strength low alloy TRIP (Transformation-Induced Plasticity)-aided ferrous sheet steels with annealed martensite matrix (or TRIP-aided annealed martensitic steel) were investigated in order to realize hot-dip galvanization. Aluminum addition of 0.5–1.0 mass% (and simultaneous silicon removal of the same amount) to a 0.2C–1.5Si–1.5Mn–0.04Al (mass%) steel refined the matrix structure and retained austenite needles and increased carbon concentration of retained austenite. It also brought on an excellent total elongation, stretch-flangeability and bendability, although the tensile strength decreased. Optimum austempering temperature for the total elongation increased to 450–475°C, due to the increased carbon concentration of retained austenite. On the other hand, optimum austempering temperatures for the stretch-flangeability and bendability were maintained at 350–400°C, mainly due to uniform fine lath matrix and retained austenite needles. If only large total elongation is required for the TRIP-aided steel, it is expected that hot-dip galvanizing immediately after continuous intercritical annealing can be realized.

(cf. *ISIJ Int.*, **45** (2005), 1194)

Mechanical Properties

Mechanical properties and microstructures of Zr-microalloyed cast steel

H.A.AKBARZADEH et al.

Microalloyed cast steels are a group of microalloyed steels, in which reliable mechanical properties could be achieved by heat treatment. In addition, Thermochemical data indicate that Zr has high affinity for oxygen, nitrogen and carbon.

The aim of present work was to investigate on the role of Zr, as a microalloying element, on mechanical property and microstructure of microalloyed cast steel. After casting of the steels with various Zr content, heat treatments were carried out.

Results show that Zr between 0.005–0.01 percent has the effects on increasing hardness and impact toughness of steel. Also the formation of Zr precipitates was confirmed by SEM and XRD.

(cf. *ISIJ Int.*, **45** (2005), 1201)

Effect of microstructural features on ductility of drawn pearlitic carbon steels

W.J.NAM et al.

The effect of microstructural features on ductility of cold drawn pearlitic steels containing 0.52–0.92 wt% C was investigated. The relationship between ductility and microstructural features of interlamellar spacing, ferrite thickness and cementite thickness, was closely examined, compared with that with drawing strain. The variations of reduction of area (RA) with drawing strain well reflected the microstructural evolution occurred during wire drawing; RA increased initially with the progressive realignment of randomly oriented cementite, showed a maximum peak due to the completion of the alignment of most cementite, and decreased with thinning or fragmentation of the aligned cementite. Among factors on ductility, cementite thickness was found to be the most dominant microstructural feature for RA of drawn pearlitic wires, regardless of transformation temperature and carbon content in steels. Additionally, the presence of the specific cementite thickness for the maximum RA in drawn steel wires was observed as about 0.006–0.009 μm.

(cf. *ISIJ Int.*, **45** (2005), 1205)

Social and Environmental Engineering

Model study on a swirl motion of a bubbling jet generated in a wastewater bath covered with top oil layer

T.Tamamori et al.

Experimental investigation was carried out on a swirl motion of a bottom blown bubbling jet in the presence of a top oil layer. Water was used as the lower liquid and silicone oil was used as the top oil. The kinematic viscosity of the silicone oil was changed over a wide range. The occurrence region of the swirl motion became narrow as the kinematic viscosity of the silicone oil, ν_o, increased. Silicone oil did not affect the period of swirl motion, T_s. As ν_o increased, the starting time of the swirl motion, $T_{s,s}$, increased, whereas the amplitude, A, and the damping time of the swirl motion, $T_{s,d}$, decreased. An apparent kinematic viscosity, ν_{app}, was introduced for correlating A, $T_{s,s}$ and $T_{s,d}$. Empirical equations were proposed for these quantities as functions of ν_{app}.

(cf. *ISIJ Int.*, **45** (2005), 1211)