Fundamentals of High Temperature Processes

Influence of sulfur content and temperature on the carbon boil and CO generation in Fe–C–S Drops

K. Gao et al.

Carbon boil in liquid iron has been studied as a function of some key parameters such as sulfur content (0.005–0.4%) and temperature (1 370–1 450°C) in a horizontal tube furnace. The metal–gas reactions and their time dependence, that is their dynamic nature, were observed *in-situ* at the temperature of interest. Experiments of Fe–C–S drops were also conducted in a vertical super-kanthal tube furnace to permit rapid quenching of metal drops and their subsequent analysis. The starting time of carbon boil phenomenon was determined using a CCD camera coupled with a time/date generator connected to a video recorder. The initiation time of carbon boil was in the range ~5 and ~20 sec under the conditions in this study. Mechanism for carbon boil has been proposed.

(cf. *ISIJ Int.*, **40** (2000), 301)

Isothermal reduction kinetics of Fe_2O_3 mixed with 1–10% Cr_2O_3 at 1 173–1 473 K

M.H. Khedr

Fired pure and 1–10% Cr_2O_3-doped Fe_2O_3 compacts, were isothermally reduced with H_2 at 1 173–1 473 K. Compacts are prepared by mixing chemically pure powders of Fe_2O_3 and Cr_2O_3 in the required ratios then pressed at 30 kN into cylindrical form of compacts before being fired at 1 473 K for 20 hr. The characteristics of the prepared compacts have been studied using X-ray diffraction analysis technique and reflected light microscope. The isothermal reduction curves obtained showed that Cr_2O_3 has a significant effect on the rate of reduction of Fe_2O_3. From the apparent activation energy and the gas–solid mathematical formulations, the rate controlling step in the reduction process was determined and proved to be the interfacial chemical reaction at the initial stages, while at the final stages, a combined mechanism of solid-state diffusion and interfacial chemical reaction was the rate controlling step.

(cf. *ISIJ Int.*, **40** (2000), 309)

Reaction kinetics of C_2H_6, CH_4–CO_2 and CO–CO_2–O_2 gases with liquid iron

K. Sekino et al.

The kinetics of several gas–metal reactions relevant to bath smelting have been investigated. The rate of carburization of liguid iron by C_2H_6 gas was measured between 1 400 and 1 600°C under conditions in which partial pressure of C_2H_6 was in the range of 0.016 to 0.04 atm and sulfur content in the iron was in the range of 0.003 to 0.5 wt%. The experimental results indicate that the rate is controlled by the dissociation of C_2H_6 on the surface of iron and gas phase mass transfer in series. The gas phase mass transfer can be corrected with reasonable accuracy and the chemical rate constants were obtained. The rate was retarded by sulfur in liquid iron and there was evidence of a large residual rate at high sulfur contents. The rate of carburization of pure liquid iron (a_s=0.01) by CH_4–CO_2 gas mixture was measured at 1 600°C under conditions at which the rate is controlled by gas phase mass transfer and chemical reaction in series. The gas was 6% CH_4 and up to 2.5% CO_2 in Ar. It was concluded that CH_4 and CO_2 reached the surface of the iron before they reacted with each other and carburization by CH_4 and decarburization by CO_2 occurred independently for the present experimental conditions. The rate of decarburization of carbon saturated liquid iron by CO–CO_2–O_2 gas mixture was measured at 1 600°C. The partial pressure of O_2 in 90%CO/10%CO_2 gas was in the range of 0 to 0.03 atm and sulfur content in the metal was 0.1 wt%. The measured rate shows that the gases reached the surface of metal before they reacted with each other and decarburization by CO_2 and O_2 proceeded independently at a high gas flow rate (5 l/min), but there may have been some gas phase reaction at lower flow rate (2 l/min).

(cf. *ISIJ Int.*, **40** (2000), 315)

Ironmaking

Sophisticated multi-phase multi-flow modeling of the blast furnace

S.A. Zaimi et al.

This article introduces an improvement of an existing blast furnace total model called the Four Fluid Flow Model, maintained by the last author. The derivation of solid phase motion in the former model is now replaced by an external numerical code, which implements a very specific granular flow theory called hypo-plasticity. The calculation method in the external solid flow model is based on the finite element method (FEM), and differs from the method used in the fluid flow model (finite volume method or FVM), hence their separation. Both models are run one after the other by exchanging data such as solid velocity field, drag forces and solid voidage, until convergence. One major issue of the additional solid flow model is its ability to calculate the shape of the dead man (the name of the stagnant zone inside the blast furnace), whereas its shape was prescribed in the fluid model. The solid flow model also introduces stress state dependence on voidage, and takes into account source and sink terms related to solid phase physical and chemical transformations.

(cf. *ISIJ Int.*, **40** (2000), 322)

Validation of a blast furnace solid flow model using reliable 3-D experimental results

S.A. Zaimi et al.

The finite element method (FEM) is used in conjunction with plasticity theory in granular materials to derive the stress field and velocity field inside a small experimental apparatus reproducing the blast furnace. The theory used, called hypo-plasticity, gave satisfactory agreement between numerical and experimental time lines, and was able to predict the shape of the stagnant region in the bottom part, the so called dead man, without any adjustable parameters. Specific numerical methods, like iterative remeshing, allowed it to reach steady flow conditions in an Eulerian frame. The stress field is characterized by a plastic active state in the upper part, and a plastic passive state in the lower part. The velocity field is characterized by a plug flow in the upper part, and a funnel flow in the lower part. This model can also simulate granular flows in all type of vessels, like silos. In modeling blast furnaces, its usefulness lies in its connection with a multi-phase total model.

(cf. *ISIJ Int.*, **40** (2000), 332)

Stabilization method for hot metal temperature in operation change of blast furnace

Y. Otsuka et al.

In blast furnace operation, the hot metal temperature is influenced by several operating factors, such as blast temperature, blast moisture and pulverized coal injection volume. In the case when an operating factor is changed intentionally in stepwise, one or more of the other operating factors are changed to compensate for the change so as to minimize the hot metal temperature deviation. Conventionally, in actual operation, the operating factors are changed in a trial-and-error fashion. This paper studies the operation planning method for a blast furnace which compensates for the hot metal temperature deviation accompanying a stepwise operation change with another stepwise operation change. First of all, a dynamic simulator for the blast furnace process is explained. Then the step responses of the hot metal temperature to several operation changes are analyzed. Next, switching operations of coke by PC operation and coke by blast temperature are planned. This is done using the simulated results to minimize the evaluation function which is defined as the integral of the square deviation of hot metal temperature. Satisfactory blast furnace operations are achieved based on this plan. Moreover, the unimodality of the evaluation function for such a switching operation of blast furnace is shown. The unimodal property means that the proposed operation planing method is applicable for construction of the furnace operation guidance system.

(cf. *ISIJ Int.*, **40** (2000), 342)

Steelmaking

Foaming characteristics of BOF slags

S.M. Jung et al.

Slag foaming measurements were carried out for BOF type slags that exist during the first half of the blowing period in order to better understand slopping of slag. The foam index (Σ) decreases with increasing FeO up to about 20% FeO content and is almost constant for FeO from 20 to 32% FeO. This is believed to be because above about 25% FeO, the viscosity is nearly constant. The foam index shows a minimum value at basicity[=(CaO+MgO)/(SiO_2+Al_2O_3)] of 1.4 at 1 713 K; it increases at higher basicities due to the precipitates such as $2CaOSiO_2$ or (Fe,Mg)O which stabilizes the foam. The effect of TiO_2 and MgO on foam index was also evaluated. An empirical equation for the foam index obtained by the previous researchers was applied to the present experimental results. The foaming during the first half of the blowing in BOF process was described based on the empirical relationship and the foam height was estimated for a BOS converter as a function of decarburization rate.

(cf. *ISIJ Int.*, **40** (2000), 348)

Casting and Solidification

Mechanical behavior of carbon steels in the temperature range of mushy zone

D.J.Seol et al.

Tensile strength and ductility of carbon steels have been measured in the temperature range of mushy zone by the *in-situ* melting tensile test technique with Gleeble system. The specimen was melted and cooled to the test temperature before the tensile deformation in order to get the mechanical properties subject to the continuous casting process. During hot tensile test, a ceramic fiber tube was used to reduce the radial temperature gradient in the heated specimen. Tensile strength of carbon steels in the temperature range of mushy zone increased with decreasing test temperature, and was well described by the modified yield criterion for porous metals. The measured zero strength temperature (ZST) and zero ductility temperature (ZDT) were related to the solid fractions evaluated by the numerical simulation of microsegregation developed by Ueshima *et al.* The characteristic solid fractions of ZST and ZDT which corresponded to 0.75 and 0.99, respectively, were well described by the prediction equation on ZST and ZDT at given steel compositions and cooling rates.

(cf. *ISIJ Int.*, **40** (2000), 356)

In-situ observed pore formation during solidification of aluminium

H.Yin et al.

Incidental porosity formation during pure aluminium solidification was visualized in real-time with an X-ray radioscopic facility. The dynamic growth process of a 10-mm pore is observed. Its growth is divided into two sequential stages. In the first stage, the radius of the pore increased very fast, with time to the power of 0.52. In the second stage, the growth slowed as the pore radius changed with time to the power of 0.25. Theoretical analysis of the pore growth based on the present observation shows that, in the initial stage, the growth is primarily controlled by a hydrogen diffusion mechanism; and in the second stage, growth is controlled primarily by volume shrinkage during solidification.

(cf. *ISIJ Int.*, **40** (2000), 346)

Forming Processing and Thermomechanical Treatment

Modelling of rolling of strips with longitudinal ribs by 3-D rigid visco-plastic finite element method

Z.Jing et al.

A main feature of special shape strips is the local residual deformation on a normal flat. This paper considers a numerical simulation of the rolling of strips with longitudinal ribs as an example, to analyse the influence of friction variation on the convergence and results of simulation such as rolling force, rib height and forward slip by a 3-D rigid visco-plastic Finite Element Method (FEM). The effects of mesh division and the number of elements on the precision, stability and convergence of simulation are also discussed. This investigation shows that a frictional stress model with a variation in the deformation zone can provide satisfactory results. Suitable mesh division can improve the precision and convergence of simulation. The simulation coupled with temperature field is also discussed, and the results are in good agreement with experimental values.

(cf. *ISIJ Int.*, **40** (2000), 373)

Tensile properties of simulated thin slab cast and direct rolled low-carbon steel microalloyed with Nb, V and Ti

J.S.Park et al.

The hot direct rolling of thin slab cast microalloyed, low-carbon steels was simulated on a laboratory scale. The carbon content of the steels ranged from 0.026 to 0.11 wt%. In steels microalloyed with niobium, a significant loss of yield and tensile strength occurred when the carbon content exceeded approximately 0.07 wt%. Large, eutectic NbCN precipitates, which formed during solidification, were observed at higher carbon contents. It was concluded that when the carbon content of the steel exceeded a critical level, segregation of niobium to the liquid phase during solidification of the castings resulted in the presence of the eutectic NbCN. This effectively removed a significant fraction of the niobium from being able to participate in precipitation strengthening. The addition of up to 0.09 wt% V, and of V plus up to 0.025 wt% Ti, to steel containing 0.04 wt% Nb failed to increase yield or tensile strength.

(cf. *ISIJ Int.*, **40** (2000), 380)

Transformations and Microstructures

Critical temperature range in spheroidal graphite cast irons

V.Gerval et al.

A literature review of the effect of scanning heating or cooling rate and alloying elements on the eutectoid reaction in spheroidal graphite cast irons is made. These data are used to verify the potentialities of a previous description of the conditions for the start of the transformation during direct and reverse eutectoid reaction. At finite cooling rate as used in practical heat treatments, the direct eutectoid transformation starts at the lowest temperature limit of the relevant three phase field, either stable or metastable. Upon heating, decomposition of a ferritic matrix starts at the highest temperature of the stable three-phase field, while the reference temperature for the start of the transformation for alloys with a pearlitic matrix is the same upon cooling and heating.

(cf. *ISIJ Int.*, **40** (2000), 386)

Effect of internal stresses in cold rolled IF steel on the orientations of recrystallized grains

Y.B.Park et al.

The residual stress remaining in deformed matrix is evaluated on the basis of the active slip systems and the dislocations necessary for flow. The orientations of the recrystallized grains that are expected to grow preferentially in the internally stressed matrix are predicted by means of a new recrystallization model. The model involves two principles: i) a strain energy release maximization theory and ii) growth by {110} plane matching. The predictions obtained in this way are compared with experimental results and discussed in terms of the possible effect of the internal stresses produced by cold rolling on the recrystallization texture.

(cf. *ISIJ Int.*, **40** (2000), 393)

Effect of hot-band annealing condition on secondary recrystallization in grain-oriented 2.3%Si–1.7%Mn steel

T.Fukagawa et al.

The effect of hot-band annealing temperature on secondary recrystallization was investigated using the hot-rolled steel sheets containing ultra-low C–2.3%Si–1.7%Mn–0.01%sol.Al of 2.3 mm thickness. The followings were found.

When the hot-bands doesn't recrystallize after the hot-band annealing at 600 and 625°C, secondary recrystallization of the {110}⟨001⟩ orientation mixed with the {211}⟨011⟩ orientation forms. This is because the {110}⟨001⟩ orientation density is too weak in the primary recrystallization texture. That also occurs when the inhibitor is too weak in the secondary recrystallization stage. Fully recrystallized hot-band after annealing at 700°C leads to no secondary recrystallization. The reason is that very coarse primary recrystallized grains at the center layer prevent secondary recrystallization. Secondary recrystallization of the {110}⟨001⟩ orientation evolves completely when only near surface layer but not the center layer of the hot-band recrystallize after the hot-band annealing at 650 and 675°C. The reason is because amount of {110}⟨001⟩ component in the primary texture, the inhibitor intensity and the primary matrix grain size structure are satisfied.

(cf. *ISIJ Int.*, **40** (2000), 402)

Mechanical Properties

Change in earing of low-carbon aluminum-killed steel sheets with hot- and cold-rolling conditions

H.Murakami et al.

Experiments have been conducted to investigate the effect of hot- and cold-rolling conditions on earing. It was shown that the earing of cold-rolled and annealed sheets increases with an increase in cold-rolling reduction. On the other hand, the earing decreases with a finishing temperature below Ar3 temperature in hot rolling, the effect of the finishing temperature below Ar3 being minimal in connection with a hot-rolling reduction. The earing increases as the hot-rolling reduction increases and a finishing temperature below Ar3 decreases. With a lower coiling temperature, a deformed structure remains in hot-rolled band and the earing is increased. These increases or decreases in earing depend on the growth or suppression of 45° earing arising from the texture of RD//⟨110⟩±20°. The texture development is affected by the initial texture and initial grain size before cold-rolling, and the earing is controlled by the effect of a balance between the same.

(cf. *ISIJ Int.*, **40** (2000), 409)