Transformations and Microstructures

Annealing of cold-worked austenitic stainless steels (Review)
A.F.PADILHA et al.

This article reviews the phenomena involved during the annealing of cold worked austenitic stainless steels. Initially the cold worked state is discussed, with special emphasis on the formation of deformation induced martensites. Following, the phenomena of martensite reversion, recovery, recrystallization and grain growth are discussed. The interactions between primary recrystallization and precipitation and between precipitate dissolution and secondary recrystallization are dealt with in detail. Finally, the textures resulting from hot and cold working, and from primary and secondary recrystallization, are presented.

(cf. *ISIJ Int.*, **43** (2003), 135)

Fundamentals of High Temperature Processes

Thermodynamic assessment of liquid Mn–Fe–C system by unified interaction parameter model
Y.E.LEE

The present study assesses the available experimental data and proposes a model based on the Unified Interaction Parameter Formalism to describe the solution properties of the Mn–Fe–C system. The experimental information developed from the recent works by Katsnelson *et al.*, Fenstad, and Kim *et al.* defines the solution properties as the ratio of the activity of C to Mn in the Mn–Fe–C system. These data were used to determine the activity coefficient of carbon at infinite dilute solution of Mn in the Mn–C system at various temperatures.

$$\ln \gamma_C^\circ(Mn) = 0.32 - 2679/T\,(K) \quad (1628 - 1773\,K)$$

A determination of the individual activity of C and Mn from experimental data requires additional information. As it meets the necessary condition for the task by virtue of satisfying the Gibbs–Duhem relationship, the Unified Interaction Parameter (UIP) model was correlated with the experimental data of the Mn–Fe–C system. The interaction parameters of the UIP model were determined by multiple regression analysis of the correlated equations. The activity coefficients of carbon and manganese in reference to graphite and liquid Mn as respective standard states in the Mn–Fe–C system are determined as follows:

$$\ln \gamma_C = \ln \gamma_C^\circ(Mn) + \varepsilon_{CC}[x_C - 1/2\,x_C^2]$$
$$+ \varepsilon_{CFe}[x_{Fe} - x_C x_{Fe}] + \varepsilon_{FeFe}[-1/2\,x_{Fe}^2]$$
$$+ \varepsilon_{CCC}[x_C^2 - 2/3\,x_C^3] + \varepsilon_{CCFe}[2x_C x_{Fe} - 2x_C^2 x_{Fe}]$$
$$+ \varepsilon_{CFeFe}[x_{Fe}^2 - 2x_C x_{Fe}^2] + \varepsilon_{FeFeFe}[-2/3\,x_{Fe}^3]$$

$$\ln \gamma_{Mn} = \varepsilon_{CC}[-1/2\,x_C^2] + \varepsilon_{CFe}[-x_C x_{Fe}]$$
$$+ \varepsilon_{FeFe}[-1/2\,x_{Fe}^2] + \varepsilon_{CCC}[-2/3\,x_C^3]$$
$$+ \varepsilon_{CCFe}[-2x_C^2 x_{Fe}] + \varepsilon_{CFeFe}[-2x_C x_{Fe}^2]$$
$$+ \varepsilon_{FeFeFe}[-2/3\,x_{Fe}^3]$$

where $\varepsilon_{CC} = 9.24 - 16060/T$, $\varepsilon_{CCC} = -51.8 + 157800/T$, $\varepsilon_{CFe} = 7.52 - 7250/T$, $\varepsilon_{CCFe} = -8.39 + 16190/T$, $\varepsilon_{CFeFe} = -9.93 + 12790/T$, $\varepsilon_{FeFe} = 0$, and $\varepsilon_{FeFeFe} = 0$.

(cf. *ISIJ Int.*, **43** (2003), 144)

Ironmaking

Void formation and breaking in a packed bed
G.S.S.R.K.SASTRY et al.

An experimental study has been carried out to understand the void formation and breaking in a packed bed using two-dimensional glass models. No experimental data are available in the literature on void initiation and breaking which is essential to understand the aerodynamics of the packed bed reactors such as blast furnace, catalytic reformer and solid drying process. The effect of particle size, density, gas flow rate, bed height and model width on the formation of void and its breaking has been studied in detail. The effect of frictional properties of the particulate material on the void formation and breaking has also been studied using modified Janssen's equation. Pressure and velocity measurements have been taken using manometers and a hot wire anemometer to understand the void formation and breaking phenomena. Correlations have been proposed to predict the void formation and void breaking.

(cf. *ISIJ Int.*, **43** (2003), 153)

Effect of gas composition on the carbothermic reduction of manganese oxide
M.YASTREBOFF et al.

This paper examines the reduction of pure MnO, Groote Eylandt (Northern Australia) manganese ore, siliceous manganese fines and ferromanganese slag by graphite. Reduction was conducted in the stagnant atmosphere of argon, Ar–CO gas of varying composition and helium. The rate and extent of reduction were determined by thermo-gravimetric analysis and by monitoring CO and CO_2 concentrations in the gas phase. The rate of MnO reduction in Ar–CO gas increased with decreasing CO partial pressure. Reduction in helium was faster than in argon. Under given experimental conditions (stagnant gas atmosphere) the reduction rate was mix-controlled by CO mass transfer in the gas phase and chemical reaction.

(cf. *ISIJ Int.*, **43** (2003), 161)

All pellets operation in Kobe No. 3 blast furnace under intensive coal injection
Y.MATSUI et al.

In Kobe No. 3 blast furnace (third campaign) (inner volume: 1 845 m³; blown in on April 5, 1983), the use of pellets was begun as a result of suspended operation of the sintering plant in the end of May 1999 and Kobe 3BF began all pellets operation (pellet: 73%; lumpy ore: 27%) in the end of September 2001. This is dedicated to the advancement of all pellets operation under intensive coal injection with the bell-less blast furnace. A study has been made of the deepening of understanding on the phenomena of softening and melting properties by using the mixture of dolomite-fluxed pellets and low basicity pellets. In order to prevent the growth of cohesive zone root by using of low basicity pellets, the charging technique of time-series discharging based on model experiments was developed and applied to an actual furnace. To achieve the high accurate burden distribution control, the change of ore falling trajectory by fling-up of pellets inside the rotation chute was monitored and corrected. With respect to slag and metal chemistry under the low slag ratio operation with use of low basicity pellets, securing the slag fluidity and desulfurizing efficiency was designated as control points.

(cf. *ISIJ Int.*, **43** (2003), 166)

Effects of particle free space on hearth drainage efficiency
T.NOUCHI et al.

This paper presents an experimental and numerical study of the two-phase flow in a particle packed bed, under conditions related to a blast furnace hearth. In these models, drainage velocities, slag ratio, tapping time, and maximum slag level in hearth are studied. The coke free space formed at tap hole level forms a circumference slag flow and significantly improves the hearth drainage efficiency. When the coke free space surround a part of packed bed, the effect is in proportion to the surrounded packed bed size. Such a nonaxisymmetric coke free space causes the imbalances of tap time and slag ratio.

(cf. *ISIJ Int.*, **43** (2003), 175)

Recovery of nickel from selectively reduced laterite ore by sulphuric acid leaching
H.PURWATO et al.

The laterite ore with low nickel content deposits in Indonesia can be expected to be an alternative raw material of iron making due to its high iron content. One of the required processes is the separation of nickel and cobalt from the laterite ore by leaching it with H_2SO_4 at the atmospheric condition. The sample containing 50.88% iron, 0.03% cobalt and 0.30% nickel was selectively reduced with CO/CO_2 mixed gas to obtain metallic nickel and cobalt, as well as magnetite from hematite. Accordingly, in the leaching process metallic nickel and cobalt will be dissolved by controlling the iron dissolving. The effects of various parameters have been examined. These condition include leaching time, temperature (303–343 K), H_2SO_4 concentration (0.005–1.0 mol/l), as well as extraction rate of nickel.

The result of the analysis indicated that the influence of selective reduction could speed up the nickel extraction and obstructed the iron dissolution. The extraction rate of nickel was very high for small particle and slower for larger size. The optimal condition of the test was obtained at the leaching temperature of 343 K, 0.05 mol/l H_2SO_4 with a sample lower than 4.0 g/l. In 60 min after the test, about 93 mass% of nickel was extracted from the sample smaller than 44 μm. The nickel extraction would be higher by adding the leaching time. The rate of extraction was chemically controlled and the apparent activation energy was 42.2 kJ/mol. At the end of the leaching process, there was residual solid rich-magnetite and minimal nickel.

(cf. *ISIJ Int.*, **43** (2003), 181)

Solid flow caused by buoyancy force of heavy liquid

T.NOUCHI et al.

This paper presents an experimental and numerical study of the solid flow under conditions related to an ironmaking blast furnace. The flow of particles is driven by the downward gravitational and upward buoyancy forces. Consequently, the flow pattern and stagnant zone profile, strongly affected by the level of liquid and the position of discharging hole, are more complicated than those obtained when the gravitational force is the only force. DEM simulation can reproduce the experimental results well, which provides an effective way to simulate the solid flow and related complicated high temperature phenomena in a blast furnace hearth and understand the underlying physics.

(cf. *ISIJ Int.*, **43** (2003), 187)

Steelmaking

Corrosion mechanism and wear prediction of the sole of an electric arc furnace

L.F.VERDEJA et al.

There are many alternatives for the refractory lining in the sole of an electric arc furnace that produces refined ferromanganese, Fe–Mn (80% with low carbon content, %C<1.5). Empiric approaches have usually been used for the design. Even though they allowed increasing the number of tapping, they are not base in a quantitative prediction of the wearing from the knowledge of a corrosion mechanism.

This paper presents a quantitative prediction for the corrosion processes in two basic soles using the mathematical formulation of the Nodal Wear Model (NWM). In both cases, the equations that describe the corrosion are established and applied, according to the control mechanism of the corrosion, in each node of a Finite Element Model (FEM) grid of the refractory lining is in contact interface with the liquid ferroalloy.

When the sole formed by a magnesite castable refractory (with a minimum content of 95% periclase), the penetration of the molten phase through the open porosity of the refractory controls the corrosion. In the case of a dolomitic sole (75% MgO, 20% CaO, 0.60% SiO_2, 3.80% Fe_2O_3, Al_2O_3= 0.30%), the corrosion rate is controlled by the diffusion of silicon, one of the active components of the refractory matrix, from each interfacial node in the sole to the molten phase.

(cf. *ISIJ Int.*, **43** (2003), 192)

Deoxidation equilibria among Mg, Al and O in liquid iron in the presence of $MgO \cdot Al_2O_3$ spinel

W.-G.SEO et al.

The deoxidation equilibria among Mg, Al and O in liquid iron in the presence of $MgO \cdot Al_2O_3$ spinel was studied at 1 873 K by adding Al and Mg alloys into liquid iron in MgO and Al_2O_3 crucibles. From the experimental results, the equilibrium constant, K_{Mg}, for the reaction, $MgO(s)=$ $\underline{Mg}+\underline{O}$, and the first- and second-order interaction parameters including cross-product terms between

Mg and O have been determined. Using these thermodynamic parameters, the relations between a_{Mg} vs. a_O, a_{Mg} vs. a_{Al} in liquid iron could be well represented with respective oxide activities in $MgO \cdot Al_2O_3$ spinel. A stability diagram for MgO, $MgO \cdot Al_2O_3$ and Al_2O_3 phases was constructed at 1 873 K as a function of dissolved Mg, Al and O contents in liquid iron to examine the condition for the formation of $MgO \cdot Al_2O_3$ spinel during the deoxidation process.

(cf. *ISIJ Int.*, **43** (2003), 201)

Fluid flow analysis of jets from nozzles in top blown process

Y.TAGO et al.

It is important to know the behavior of jets from a top blown lance in order to control the refining and spitting phenomena of the converter in the steelmaking process. However, there are few theoretical studies on the characteristics of the jets from the nozzles.

In the present study, the characteristics of jets from single-nozzle and multi-nozzle lances were investigated by a fluid flow analysis based on fluid dynamics. The accuracy of the analysis was confirmed with the results of the cold model experiments.

As a result, it is clarified that the dynamic pressures of the jets from the single-nozzle or multi-nozzle lances are in a good agreement with those in the cold model experiments and are influenced by the nozzle geometry such as the inclination angle and the number of nozzles. It is also clarified that the jets from the nozzles proceed the different paths from those obtained geometrically due to coalescence between the jets.

(cf. *ISIJ Int.*, **43** (2003), 209)

Equilibrium of manganese and sulfur between liquid iron and $CaO–SiO_2–Fe_tO–MgO–MnO$ slags saturated with $2CaO \cdot SiO_2$ and MgO

S.-M.JUNG

The equilibrium of manganese and sulfur between liquid iron and $CaO–SiO_2–Fe_tO–MgO$ slags saturated with dicalcium silicate and MgO were studied in the temperature range of 1 823 to 1 923 K. The solubility of MgO decreases with increasing Fe_tO content. The values of (%MnO)/[%Mn] increase with increasing Fe_tO content and its relation was formulated by an empirical equation. The activity of Fe_tO for the present slag system almost stays unchanged with increasing Fe_tO content investigated. The oxygen content of metal in equilibrium with (39.9~49.9 mass%)CaO–(11.9~15.2 mass%)SiO_2 –(25.2~35.7 mass%)Fe_tO–6.1~7.0 mass%)MgO slags saturated with $2CaO \cdot SiO_2$ and MgO is expressed by the following equation.

$$\log[\text{mass\%O}]=-\frac{5\,690}{T}+0.011$$

The logarithm of the sulfide capacity for the present slags increases with increasing the theoretical optical basicity and its correlation was formulated. Using the relations obtained in this work and mass balance, the charging amount of Mn ore(MnO) for a final manganese content when adding MnO

to BOF was predicted and the desulfurized content affected by the addition of Mn ore was also estimated.

(cf. *ISIJ Int.*, **43** (2003), 216)

Casting and Solidification

Level meter for the electromagnetic continuous casting of steel billet

G.KIM et al.

A level measuring system has been investigated to work with the electromagnetic continuous casting of steel billet, based on the principle of electromagnetic induction. The basic idea of the development is the distinction of the magnetic field measured in the mold into the effect of the applied one and the effect of the level variation. Several candidates of induction type magnetic probes were devised and examined. It was seen that the so-called global sensor was the proper one from the viewpoint of sensing range, resolution of the signal, and robustness to the external perturbation. The level of the melt was successfully calculated from the sensor output by employing the reference voltage for the set current in the power supply as a measure of the applied magnetic field. The use of the global sensor associated with the electronic device and the program showed that the resolution of the measurement was within ±0.2 mm, the dynamic range of sensing the level was 0–300 mm below the top of the mold under the electromagnetic field at 20 kHz. In its application to commercial scale electromagnetic continuous casting at a billet caster of POSCO works, it worked well with the existing control device in supplying the molten steel to the mold. Particularly, its accuracy and promptness was sufficient to control the level at the initial stage of casting.

(cf. *ISIJ Int.*, **43** (2003), 224)

Instrumentation, Control and System Engineering

Control of lifting desired number of steel plates and automatic crane operation

H.-J.KIM et al.

This paper presents an automation scheme for an overhead magnet crane that is a critical component of thick steel plate storage yard automation. First, the load cells and magnetic flux sensors are introduced to detect the number of steel plates lifted using the magnet crane. Then a voltage control algorithm to lift the ordered number of steel plates is proposed and implemented by using the on-line tuning look-up table. Finally, the overall hardware and software description for automatic crane operation is presented. The results have been successfully implemented in POSCO's No. 2 thick steel plate storage yard.

(cf. *ISIJ Int.*, **43** (2003), 230)

Welding and Joining

Numerical modelling of resistance spot welding of aluminium alloy

A.DE et al.

An electro-thermal and mechanical coupled model is reported for analysing resistance spot welding process of aluminum alloys using curved face electrodes. An in-house software is developed based on finite element method that can predict in-process growth of nugget diameter, penetration and electrode–sheet contact diameter for different combinations of welding current, weld time, electrode force. Non-linear, temperature-dependent, thermophysical material properties as well as latent heat of fusion/solidification have been considered. An exponential decay of initial contact resistance is considered with different values of initial contact resistance for different surface conditions of aluminium alloys. It is observed that the formation of weld nugget is completed within the very first cycle considering a 50 Hz AC power supply. Increase of welding current enhances the area of molten zone substantially. Change in the initial value of contact resistance does not influence the overall nugget zone significantly. Overall, the present work indicates that such a simulation model can be very useful as an off-line monitoring tool to estimate the influence of process parameters on the final weld dimensions.

(cf. *ISIJ Int.*, **43** (2003), 238)

Transformations and Microstructures

Temperature dependence of grain boundary structure and grain growth in bulk silicon–iron
J.SIK et al.

Grain boundary shapes and grain growth in bulk

2.61 wt% silicon–iron have been studied by heat-treating at temperatures between 700 and 1 200°C. Initial microstructure with fairly uniform fine grains has been obtained by recrystallization at 800°C for 5 min after deformation. When subsequently heat-treated at 700 and 800°C, a fraction of the grain boundaries have hill-and-valley shapes with several facet planes or kinks. Some of these facet boundary segments are expected to be singular. Abnormal grain growth occurs at 700 and 800°C and is attributed to step growth of the boundaries. When heat-treated at 1 000°C, all grain boundaries are de-faceted with smoothly curved shapes, indicating that they are atomically rough. At temperatures above 1 000°C, normal grain growth occurs, because the rough grain boundaries move continuously. This correlation between grain boundary structure and grain growth is consistent with the earlier observations in other metals and oxides. It is thus shown that the abnormal grain growth in this alloy occurs at low temperatures because of the singular grain boundary structure.

(cf. *ISIJ Int.*, **43** (2003), 245)

Mechanical Properties

Initiation and growth behavior of creep voids in an austenitic steel with high ductility under multi-axial stresses
L.-B.NIU et al.

This study aims mainly to clarify the effects of the multi-axial stress components on the initiation and growth behavior of creep voids. For this purpose, creep tests, particularly creep interrupt tests are conducted in tension, torsion and in combined tension–torsion stress states at 700°C, using tubular specimens of the austenitic steel SUS310S with high ductility. Creep voids formed in the specimens are examined in detail by observation with the scanning electron micrographs. It is found that creep voids in the torsional creep specimens form easily to a certain size in the primary creep, but they grow difficultly to rupture. While from torsional stress state to tensile one, creep voids become easy to grow. The initiation and growth behaviors of creep voids under the multi-axial stress conditions are discussed. It is further suggested that the von Mises equivalent stress is a dominant component for the initiation of creep voids, and the mean stress component strongly promotes their growth.

(cf. *ISIJ Int.*, **43** (2003), 251)