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Fundamentals of High Temperature Processes

Slag composition variations causing variations in steel dephosphorisation and desulphurisation in oxygen steelmaking (Review)

E.T.TURKDOGAN

Study of plant analytica data for BOS and OBM processes revealed that the iron oxide content of slag has a decisive effect on the extent of steel dephosphorisation and desulphurisation. The slag/metal distribution ratios (%P)/[%P] and (%S)/[%S] from the plant data are scattered about the calculated equilibrium values for the slag–metal reactions involving the iron oxide content of the slag. The data also revealed consistent interrelations between the concentrations of FeO, CaO and SiO_2 in the slag at the end of oxygen blowing. However, there are variations in the slag composition in the interrelations between the oxide contents: 5 to 6% FeO and 4 to 5% CaO or SiO_2 between the low and high values. These unpredictable variations in slag composition from one heat to the next bring about variations in the extent of steel dephosphorisation and desulphurisation. Consequently, the observed distribution ratios (%P)/[%P] and (%S)/[%S] are scattered within a slag composition range, bordered by the equilibrium curves for the low and high iron oxide contents with the corresponding CaO and SiO_2 contents of the slag.

(cf. *ISIJ Int.*, **40** (2000), 827)

Carbothermic reduction in the combustion bed packed with composite pellets of iron oxide and coal

E.KASAI et al.

Process feasibility has been experimentally studied on a new reduction concept using the composite pellets of iron ore and coal powders in their combustion bed. A key to realize this concept will be a method to prevent reoxidation of metallic iron formed during the process. To examine the optimum measure, reduction experiment using a single composite tablet was first conducted. Coating the tablet with a CaO bearing material, *i.e.*, $Ca(OH)_2$ or $CaCO_3$ powder, gives a certain suppression effect on the reoxidation at high temperature. On the basis of this result, reduction experiment in the combustion bed packed with the composite pellets were carried out under various conditions. An proper condition could not be found to perfectly prevent the reoxidation of metallic iron. However, the reoxidation was significantly suppressed by the admixing of CaO bearing material to the mixture or the coating it around the composite pellets. The maximum reduction and metallization degrees obtained were 72 and 64%, respectively. It suggests that the proposed process has a potential to produce partially-reduced iron burdens to a subsequent reduction/melting process such as the blast furnace.

(cf. *ISIJ Int.*, **40** (2000), 842)

Manganese and silicon distribution between slag and metal in silicomanganese production

W.DING et al.

Laboratory measurements have been carried out to investigate the equilibrium distribution of manganese and silicon between slag and metal in silicomanganese production. Graphite crucibles have been used to study equilibrium between Mn–Si–C_{sat} alloys and MnO–SiO_2–CaO–Al_2O_3–MgO slags in CO gas at 1 600°C, 1 650°C and 1 700°C.

The equilibrium content of Si in the metal is mainly controlled by the temperature, the silica content of the slag and the mass ratio R=(CaO+MgO)/Al_2O_3. The silicon content increases with the temperature and the silica content, and decreases with increasing R-ratio. The silicon content remains approximately the same when some MgO replaces CaO in the slag.

The equilibrium content of MnO in silicomanganese slags is primarily controlled by the temperature and the silica content of the slag. Addition of Al_2O_3 to acid slags will result in somewhat lower MnO contents, and addition to more basic slags has the opposite effect. The equilibrium content of MnO in the slag is slightly increased when some CaO is replaced by MgO.

(cf. *ISIJ Int.*, **40** (2000), 850)

Ironmaking

Influence of properties of fluxing materials on the flow of melt formed in the sintering process

E.KASAI et al.

Partial melting of raw materials and flow of the formed melt are essential phenomena for the agglomeration in the sintering bed of iron ores. A new experimental technique has been proposed which enables us to detect the macroscopic flow of melt formed during heating. Using this technique, the effects of the kind and particle size of fluxing materials and basicity of the mixture of raw materials were examined. Especially, it lays emphasis on the dolomite addition which will be effective to lower the slag ratio in the blast furnace operation by its replacement of serpentine. The present paper mainly describes the results of the melt-formation behavior in the cases using different types and particle sizes of dolomite samples comparing to those using serpentine. Further, a noteworthy phenomenon is pointed out that CaO component separated from MgO during heating course of dolomite tends to react with hematite and forms melt at lower temperature under certain conditions.

(cf. *ISIJ Int.*, **40** (2000), 857)

Steelmaking

Fluid flow and mixing process in a bottom stirring electrical arc furnace with multi-plug

B.LI

Fluid flow and mixing process in a bottom stirring electrical arc furnace (EAF) with the single- and multi-plug are experimentally and numerically studied. A homogeneous fluid with a spatially variable density is used to model the gas–liquid flow. k–ε turbulence model is employed to calculate the effective viscosity. The five layouts are selected to examine the mixing times. The mixing time is defined as the function of the diameter, number, location of plugs and the tracer injection point. The results show that the variation of mixing time is not obvious with the increasing of plug diameter, but the stirring efficiency is getting better when plug number is increased and distributed in deep and off-central region in vessel. This is because the angular velocities occur and the more stirring energy is obtained in such layouts.

(cf. *ISIJ Int.*, **40** (2000), 863)

Casting and Solidification

Our understanding of macrosegregation: past and present (Review)

M.C.FLEMINGS

Macrosegregation has long been a topic of engineering importance, with recorded publications on the subject extending back nearly half a millennium. The phenomenon has assumed new importance in recent decades with the advent of new casting processes including continuous casting. This lecture reviews our current understanding of macrosegregation, with particular reference of carbon steel ingots and continuous castings. Aspects of the problem are noted where our understanding remains weak.

(cf. *ISIJ Int.*, **40** (2000), 833)

Phase-field model for solidification of ternary alloys

M.ODE et al.

The phase-field model for dilute ternary alloys is proposed and the relationships between phase-field parameters and material properties are derived at a thin interface limit. One-dimensional and two-dimensional numerical simulations show that the model reproduces the equilibrium conditions including Gibbs–Thomson effect. We apply the model for ternary alloys to micro-segregation analysis in Fe–C–P alloy and the results are compared with analytical models. The results show good agreement with those of Clyne–Kurz equation. For two-dimensional computations, isothermal dendritic growth is simulated for Fe–C and Fe–C–P alloys. The change in phosphorous concentration affects significantly the interface velocity and the dendrite shape even when the phosphorous concentration is much lower than that of carbon because of the small diffusivity of phosphorous.

(cf. *ISIJ Int.*, **40** (2000), 870)

In situ observation of the role of alumina particles on the crystallization behavior of slags

C.ORRLING et al.

The confocal laser scanning microscope (CLSM) allows crystallization behavior in liquid slags to be observed *in situ* at high temperatures. Slags in the lime–silica–alumina–magnesia system are easily under cooled and it is possible to construct time temperature transformation (TTT) diagrams for this system. The presence of solid alumina particles in these liquid slags was studied to determine if these particles act as heterogeneous nucleation sites that cause the precipitation of solid material within slags. The introduction of alumina particles reduced

the incubation time for the onset of crystallization and increased the temperature at which crystallization was observed in the slags to close to the liquidus temperature for the slag. Crystal growth rates are in a good agreement with Ivantsov's solution of the problem of diffusion controlled dendritic growth. Alumina appears to be a potent nucleating agent in the slag systems that were studied.

(cf. *ISIJ Int.*, **40** (2000), 877)

Numerical analysis of fluid flow and heat transfer in the funnel type mold of a thin slab caster

H.NAM et al.

Thin slab casting is an emerging technology offering many economic benefits. In the case of a thin slab caster, the control of fluid flow in a mold is particularly difficult due to the high casting speed and large aspect ratio of the mold. In addition, the knowledge of the transport phenomena is important because melt delivery is directly related to the problems of non-uniform shell growth, surface turbulence and mold powder entrapment. In this study, a 3-dimensional mathematical model has been developed for the coupled analysis of fluid flow, heat transfer and solidification in the funnel type mold using finite volume method based on the body fitted coordinate. The characteristics of transport phenomena in the mold of a thin slab caster were analyzed by numerical simulation. As a result of the simulation, the basic flow pattern could be characterized and the heat transfer calculations could accurately predict the areas where the mold is susceptible to cracking as a result of thermal stress. The predicted shell thickness showed good agreement with the measured thickness at the solidified shell of the break-out products.

(cf. *ISIJ Int.*, **40** (2000), 886)

Forming Processing and Thermomechanical Treatment

Static recrystallization behaviour of a wide range of austenite grain sizes in microalloyed steels

A.I.FERNÁNDEZ et al.

The static recrystallization kinetics of four steels microalloyed with Nb, Ti and Nb–Ti have been investigated, covering conventional and hot direct rolling conditions. The influence of the grain size on the recrystallization time has been studied for a wide range of grain sizes (20–1000 μm). For the same deformation conditions it has been observed that the quadratic dependence on grain size works well in the range of finer grain sizes (<160 μm). In contrast, the recrystallization times measured at coarse grain sizes are significantly lower than those predicted by this dependence. However, when the whole grain size range analysed is considered, a linear dependence on grain size gives the best fit to experimental data. The effect of strain on the recrystallization kinetics has been also analysed for different initial grain sizes. It has been observed that the time to reach a 50% recrystallized fraction ($t_{0.5}$) shows a dependence on strain of the type $t_{0.5} \propto \varepsilon^{-p}$, the exponent being influenced by the initial grain size. A unique equation has been proposed to describe the static recrystallization kinetics of Nb, Ti and Nb–Ti microalloyed steels. The predictions of the equations have been compared to previously published data on similar steels.

(cf. *ISIJ Int.*, **40** (2000), 893)

Transformations and Microstructures

Retained austenite characteristics and tensile properties in a TRIP type bainitic sheet steel

K.SUGIMOTO et al.

Retained austenite characteristics and tensile properties in a 0.2C–1.5Si–1.5Mn, mass%, high-strength cold-rolled "TRIP type bainitic steel" which was associated with the transformation induced plasticity (TRIP) of the retained austenite were investigated. The steel mainly consisted of bainitic ferrite lath matrix, blocky martensites and stable retained austenite films of 5–12 vol%. When austempered at temperatures above M_S temperature, the steel possessed high tensile strength of 900 MPa, large total elongation of 15–20% and large reduction of area of 40–60%. The good ductility was mainly owing to uniform fine lath structure, initial martensite and the TRIP effect of retained austenite, as well as a small contribution of long range internal stress resulting from untransformed retained austenite films.

(cf. *ISIJ Int.*, **40** (2000), 902)

Rotations involved in tensile deformation and recrystallization in Fe–11Cr–19Ni alloy single crystal

T.OKADA et al.

An Fe–11Cr–19Ni alloy single crystal having an initial orientation close to $\langle 011 \rangle \{511\}$ was deformed in tension. The uniformly deformed portion (*i.e.* matrix) of the crystal was rotated about a $\langle 110 \rangle$ axis in the counterclockwise direction as tensile deformation proceeded. The rotation suggests that not only the slip systems on the primary slip plane but also those on the critical slip plane were involved in the deformation. After annealing, the matrix almost completely recrystallized. Orientation relationships were found between the deformed matrix and the recrystallized grains. The majority of the recrystallized grains was related to the matrix orientation by rotation about $\langle 111 \rangle$ axes. Among such recrystallized grains, those rotated about the conjugate-slip plane normal and those rotated about the cross-slip plane normal outnumbered the others. The rotation occurred in the clockwise direction, opposite to the deformation-induced rotation of the matrix.

(cf. *ISIJ Int.*, **40** (2000), 909)

Numerical simulation of phase separation in Fe–Cr binary and Fe–Cr–Mo ternary alloys with use of the Cahn–Hilliard equation

M.HONJO et al.

The Cahn–Hilliard nonlinear diffusion equation for a binary alloy system was extended to a ternary system. Numerical model based on the Cahn–Hilliard equation for multicomponent system was applied to the prediction of microstructural evolutions in Fe–Cr binary and Fe–Cr–Mo ternary alloys. The free energy of the system was approximated by the regular solution model. In an Fe–40at%Cr binary alloy, the Cr composition profile at 800 K shows a modulated structure with the wave length of about 4 nm. This result is consistent with those of reported Atom-probe FIM analyses. In an Fe–40at%Cr–3at%Mo ternary alloys, the wave lengths of Cr and Mo composition profiles were similar to that for the binary alloy. However, the decrease in the Mo composition was observed at the peak position of Cr composition because of the repulsive interaction of Cr and Mo atoms.

(cf. *ISIJ Int.*, **40** (2000), 914)

Mechanical Properties

Stretch-flangeability of a high-strength TRIP type bainitic sheet steel

K.SUGIMOTO et al.

The stretch-flangeability of a newly developed high-strength bainitic sheet steel which is associated with the transformation-induced plasticity (TRIP) of retained austenite, or "TRIP type bainitic steel" was investigated for the automotive applications. An excellent stretch-flangeability was completed in the steel composing of bainitic ferrite matrix and interlath retained austenite films without initial blocky martensite. In this case, the stable or carbon-enriched retained austenite films enhanced the stretch-flangeability due to the reducion of the surface damage on hole-punching and the promotion of the TRIP effect on hole-expanding. Also, uniform fine bainitic ferrite lath structure contributed to improving the stretch-flangeability due to the increased localized ductility and development of severe plastic flow.

(cf. *ISIJ Int.*, **40** (2000), 920)

Deep-drawable thin-gauge hot strip of steel as a substitution for cold strip

A.TOMITZ et al.

In a conventional production of deep-drawable steel sheets, a hot rolling in austenite and a cold rolling at room temperature together with a subsequent recrystallization annealing are applied to achieve a desired texture in the final cold strip. As a cost saving replacement for this, a thin-gauge hot strip with a required deep-drawability can be employed by applying the ferritic rolling with the finishing shifted down into the temperatures below Ar_1. To optimize the process parameters, laboratory tests on an IF steel were carried out by using the hot deformation simulator WUMSI. By the measurements of the texture development as well as by the computing of r-values, the texture formation in a hot strip after ferritic rolling could be optimized achieving a deep-drawability in hot strips comparable to that of a cold strip.

(cf. *ISIJ Int.*, **40** (2000), 927)