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Fundamentals of High Temperature Processes

Formation of titanium carbonitride from hot metal

Y.Li et al.

Studies on the formation of TiC and Ti(C,N) from hot metal were preformed to determine the conditions required for the formation of a protective layer rich in titanium carbonitride on the refractories in the blast furnace hearth. *In situ* observations of the formation of TiC and Ti(C,N) from carbon-saturated iron containing 0.07 to 1.3 mass% titanium were made at 1 673 to 1 873 K using a confocal scanning laser microscope equipped with an infrared image furnace. In order to measure the activity coefficient of titanium, the solubility of titanium in carbon-saturated iron was measured and found to be 1.3, 1.0, and 0.3 mass% at temperatures of 1 798, 1 772, and 1 670 K, respectively. The activity coefficient of titanium in carbon-saturated iron is expressed as $\log f_{Ti} = -5.41 + 6\,890/T$. Based on the results the conditions for Ti(C,N) formation and the amount of TiO_2 addition to a blast furnace were calculated. At 1 773 K and 1.0 atm of nitrogen, the minimum titanium in hot metal to form Ti(C,N) was determined to be 0.2 mass%. Under typical blast furnace operation conditions, a titanium load of 3.6–5.2 kg TiO_2/tHM is required. It was conclude that *in situ* observation using confocal scanning laser microscope provided us a unique and reliable technique to study thermodynamic of some molten metal systems.

(cf. *ISIJ Int.*, **41** (2001), 1417)

Feasibility of rotary cup atomizer for slag granulation

T.Mizuochi et al.

At the present molten slag from a blast furnace (B.F.) is granulated by impinging much water without any recovery of its much sensible heat (1 823 K), polluting water and atmosphere. To solve these problems, we studied the dry granulation of molten slag by Rotary Cup Atomizer (RCA), in which the influence of the rotating speed of the RCA on slag drop size was mainly examined. In the experiment, the molten B.F. slag was supplied to the center of RCA with air blast. Slag drops flown from the cup lip due to centrifugal force were collected and examined from viewpoints of shape, dimension and the flown distance of the drop.

Most significantly, molten slag was successfully granulated under the dry conditions without water impingement. The rotating speed of the RCA influenced the diameter and shape of slag drop very strongly. The higher rotating speed made the slag drops smaller, more spherical and more uniform. Drops with 5 to 6 mm of average dimension were obtained at the rotating speed of 15 rps (900 rpm), and drops with less than 1 mm, at that of 50 rps (3 000 rpm). In the former case, the shape of drop obtained was distributed, changing from sphere to stick at the further place from the center of RCA. The results revealed a possibility of alternative, new slag granulation process with many benefits.

(cf. *ISIJ Int.*, **41** (2001), 1423)

The melting properties of tuyere slags with and without flux injection into the blast furnace

L.S.Ökvist

A laboratory study concerning the melting properties of tuyere slags has been conducted. The melting-point measurements of various specimens, consisting of coke ash, coal ash and fluxes (BOF slag, burnt lime and burnt dolomite), corresponding to the tuyere slags formed in front of the tuyeres with or without flux injection, have been performed in a high-temperature microscope. Theoretical estimations of melting points have been made based on the chemical composition of the tuyere slag specimens.

The results have shown that injection of fluxes has quite a positive effect on the melting properties of the tuyere slag. The melting point of the tuyere slag decreases and the temperature interval between softening and complete melting of the tuyere slag becomes narrower. Compared to the injection of burnt lime and burnt dolomite, the injection of BOF slag will result in still better tuyere slag properties in terms of lower flow point and narrower temperature interval between softening and melting. The differences in melting behaviour in the tuyere slag specimens indicate that injection of BOF slag will also give the tuyere slag a lower viscosity compared to injection of burnt lime or burnt dolomite at the same levels of slag basicity B2.

(cf. *ISIJ Int.*, **41** (2001), 1429)

Steelmaking

Fluid flow and mixing in a six strand billet caster tundish: A parametric study

P.K.Jha et al.

Mixing phenomena in a six strand billet caster tundish has been studied by numerically solving the Navier Stokes equations along with the species concentration equation in a boundary fitted coordinate system comprising the geometry of the tundish. The solution of the species concentration equation has been utilized to compute the mix, dead and plug volume of the tundish under different flow conditions. The numerical procedure and solution algorithm has been first verified by comparing the numerically obtained residence time distribution curve, which agree well with that of the experiments done for a single strand bare tundish by Singh and Koria.[44] It has been observed that the ratio of the mix to dead volume for the six strand tundish has a maximum value for a particular position of the outlets. At that particular position of the outlets (where mixing is best), an APB is placed on the bottom of the tundish surrounding the incoming inlet jet and the height of the APB has been varied to see the effect on mixing in the tundish. It has been observed that the ratio of mix to dead volume further increases with the use of APB and attains a peak value after which it decreases with the increase of the height of the APB signifying the existence of an optimum APB height. At this optimum height of the APB, the shroud immersion depth was made to change from 0 to 400 mm. It was also observed that there exists an optimum immersion depth of the shroud where the ratio of mix to dead volume still attains another peak signifying still better mixing. However, increasing the immersion depth to higher values spoils mixing significantly.

(cf. *ISIJ Int.*, **41** (2001), 1437)

Thermodynamics of titanium oxide in ladle slags

S.-M.Jung et al.

It is necessary to have information on the thermodynamic behavior of titanium oxide in ladle type slags in order to control the titanium content in several grades of steel. In the present study, the thermodynamics was determined from the equilibrium between Fe–C_{sat}–Ti and CaO–SiO_2–30%Al_2O_3–MgO–TiOx slags in equilibrium with CO and from the equilibrium between Fe–C_{sat}–(16～18)%Cr–Si–Ti and CaO–SiO_2–20%Al_2O_3–MgO–TiOx slags in equilibrium with CO. From the experiment with Fe–C_{sat}–Ti alloy, the activity coefficients of $TiO_{1.5}$ and TiO_2 vary with basicity from 0.3 to 1.5 and from 0.5 to 2.3, respectively. And from the experiment with Fe–C_{sat}–(16～18)%Cr–Si–Ti alloy, the activity coefficients of $TiO_{1.5}$ and TiO_2 vary with basicity from 0.4 to 1.4 and from 0.6 to 3.5, respectively. The results obtained from the equilibrium between Fe–C_{sat}–(16～18)%Cr–Si–Ti and CaO–SiO_2–20%Al_2O_3–MgO–TiOx slags were used to estimate the titanium content of silicon-added stainless steel. Experiments were also conducted using Fe–Al–Ti melts in equilibrium with CaO–SiO_2–Al_2O_3–TiO_x slags saturated with MgO. In this case most of the titanium in the slag is present as TiO_2(Ti^{4+}). The present results were used to predict the titanium content of aluminum-killed steel in equilibrium with ladle slags containing titanium oxide and the predictions agreed with plant data.

(cf. *ISIJ Int.*, **41** (2001), 1447)

Effect of lance design on jet behavior and spitting rate in top blown process

Y.Higuchi et al.

It is important to know the behavior of jets from a top-blown lance in order to control the spitting phenomena in the converter. However, there are few studies on the characteristics of jets from nozzles and effects of them on spitting rates.

In this study, the characteristics of jets from multihole lance and the effects of them on spitting behavior were investigated by cold and hot model experiments. Furthermore, lances were proposed and evaluated which have newly designed 6-hole nozzles with different diameters and inclination angles.

As a result, spitting rates were found to be influenced by maximum dynamic pressure of jets and distance of pressure peak from the lance axis. And lances with newly designed nozzle arrangement were confirmed to be effective to decrease the spitting rate.

(cf. *ISIJ Int.*, **41** (2001), 1454)

Sulfide capacity and phase equilibria of MnO–TiO_2–MnS system at 1 723 K

T.G.Kim et al.

The sulfide capacity and the activity of MnO in the MnO–TiO_2 system were measured at 1 723 K. Also, the phase equilibria of the MnO–TiO_2–MnS

system were estimated by measuring the solubility of MnS in the melts. The thermodynamic behavior of MnO and TiO_2 in the MnO–TiO_2 system exhibits a negative deviation from ideality at 1 723 K. The sulfide capacity increases and the activity coefficient of MnS decreases with increasing MnO content in the MnO–TiO_2 system. The solubility of MnS in the MnO–TiO_2 system increases with increasing MnO content up to about 50 mol%, followed by nearly constant value of about 80 mass% MnS. The solubility of MnS equilibrated with MnO is in good correspondence with the value obtained from the phase diagram of the MnO–MnS binary system. Compared with the phase diagram of the MnO–SiO_2–MnS system, a homogeneous liquid region in the MnO–TiO_2–MnS system is found to be wider at the same temperature. The activity of MnS increases with increasing MnS content at a fixed MnO/TiO_2 ratio in the MnO–TiO_2–MnS system. Also, the activity slightly decreases with increasing TiO_2 content at a fixed MnS/MnO ratio, whilst MnS activity rapidly decreases by increasing the content of MnO at a constant TiO_2/MnS ratio.

(cf. *ISIJ Int.*, **41** (2001), 1460)

Casting and Solidification

Water modeling evaluation of metal delivery in a twin roll strip caster using pool level and residence time distribution measurements

D.BOUCHARD et al.

A quantitative methodology that uses a water model to evaluate fluid flow of delivery systems under various operating conditions in the pool of a twin roll strip caster is presented. The measurements of two parameters are involved: level fluctuations of the pool and residence time distribution (RTD) of the fluid near the free surface. It is shown that a nozzle geometry that produces small level fluctuations and short residence times can be identified.

(cf. *ISIJ Int.*, **41** (2001), 1465)

Prediction and analysis on formation of internal cracks in continuously cast slabs by mathematical models

Z.HAN et al.

The formation of internal cracks in continuously cast slabs is mainly attributed to the strain status and microsegregation near the solidifying front of the slabs. Based on this understanding, the effects of the strain status at solidifying front and the chemical composition of liquid steel on the internal cracks were studied using a strain analysis model and a microsegregation model developed in the present study. The tensile strains at the solidifying front caused by bulging, unbending, and misalignment of supporting rolls in a four-point-unbending bow caster were calculated. The roll gap in the caster was measured for the calculation of the strains caused by the misalignment of the supporting rolls. The calculated strain status near the solidifying front was used to predict the internal cracks. Critical strains based on some experimental data were adopted as the crack criteria. Sulfur prints of the slab transverse sections were used to verify the model predictions. The enrichment of chemical compositions in the interdendritic liquid and its effect on the freezing temperature of the liquid were studied with the microsegregation model, in which the transition of ferritic/austenitic solidification and the precipitation of MnS were taken into account. S and P were revealed to strongly accumulate at the columnar grain boundaries, and the segregation of P increases significantly when C content increases from 0.1% to 0.2%. With the accumulation of P and S in the interdendritic liquid, the freezing temperature of the liquid decreases obviously, thus the internal crack tendency is greatly increased.

(cf. *ISIJ Int.*, **41** (2001), 1473)

Numerical study of effect of cooling rate on double-diffusive convection and macrosegregation in iron–carbon system

A.K.SINGH et al.

The present study is aimed at understanding the effect of rate of heat extraction on macrosegregation during solidification of binary Fe–1wt%C alloy. For a constant superheat and geometry, the effect of cooling rate is studied by imposing constant heat fluxes, along the vertical wall of a rectangular cavity, in the range of 5 kW/m^2 to 6 000 kW/m^2. The effect of variation of heat flux on various transport fields such as double-diffusive convection, thermal and solutal fields and resultant solutal in-homogeneity are analyzed in detail. Its effect on final macrosegregation is discussed in terms of global extent of segregation (GES) and overall macrosegregation pattern in the casting. GES initially decreases with an increase in heat flux up to 10 kW/m^2. Between heat flux of 10 and 100 kW/m^2, GES goes through a maximum. Beyond 100 kW/m^2, GES decreases with an increase in heat flux. The variation in GES with heat flux is explained in terms of thermo-solutal convection, mush structure and solidification time.

(cf. *ISIJ Int.*, **41** (2001), 1481)

Chemical and Physical Analysis

Enhancement factor in the emission intensities excited by radiofrequency-powered glow discharge plasma associated with bias-current introduction

K.WAGATSUMA et al.

The introduction of a d.c. bias current to an r.f. glow discharge plasma led to enhancement in the intensities of particular emission lines. Atomic emission lines having the excitation energy of 3–4 eV were commonly enhanced 10–20 times by conducting the bias current of 20–30 mA. The enhancement factor strongly depended upon both the pressure of the plasma gas and the r.f. applied power. The intensities of atomic emission lines having the excitation energy of c.a. 5.7 eV were much more elevated and their enhancement factors exceeded 50. However, little increases for emission lines having the excitation energy more than 7 eV were observed regardless of the plasma conditions.

(cf. *ISIJ Int.*, **41** (2001), 1488)

Suface Treatment and Corrosion

Effects of chemical composition and oxidation temperature on the adhesion of scale in plain carbon steels

T.KIZU et al.

Effects of chemical composition and oxidation temperature on blistering and delaminating of scales formed on steels were investigated. The scale blistering occurred for steels with P content above 0.005 mass%. Low carbon steels with 0.01mass%Si–0.2mass%Mn–0.01mass%P showed pronounced blistering at 1 223 K. The temperature at which the time to blistering is the shortest, the prominent temperature, decreased with increasing Mn and P contents and deceasing Si content in steels. There was no effect of C, S and sol. Al contents on the such specific temperature. The blistering was promoted by increasing C, Mn and P contents and suppressed by increasing S content at any temperature. The blistering was suppressed at 1 223 K by increasing Si content but promoted at 1 323 K. Sol. Al showed no effect on the acceleration of blistering. The blistering would be correlated to scale texture and segregation of minor elements at the interface between scale and substrate. {111} and {110} oriented crystals in {100} matrix of FeO, that were preferable with increased Si, Mn and P contents, decreased S content and oxidation temperature, accelerated the blistering. The segregated P promoted by increasing P content and decreasing oxidation temperature accelerated the blistering, whereas the segregated Si promoted by increasing Si content and decreasing oxidation temperature suppressed it.

(cf. *ISIJ Int.*, **41** (2001), 1494)

Transformations and Microstructures

Effect of Ti and Nb on the formation of carbides and the mechanical properties in as-cast AISI-M7 high-speed steel

S.KHEIRANDISH

In this research, the carbides of as-cast AISI M7 high-speed steel, in which different amounts of V and W were replaced by equivalent Ti and Nb, were investigated using light and electron microscope. EDX and WDX analysers were used in order to recognize the type and formulae of carbides. The volume fractions of each type of carbides are determined using especial etchant, so that the effects of Nb and Ti on the carbides types, shapes and volume percentages could be understand.

The results show that Nb and Ti increase the volume fraction of MC instead of M_2C or M_6C and decrease the volume fractions of total carbides. It is also found that, the volume fractions of M_2C decrease and M_6C increase with increasing Nb percentage.

(cf. *ISIJ Int.*, **41** (2001), 1502)

The analysis of phase transformation for the prediction of microstructure change after hot forming

J.LIU et al.

A new model of phase transformation for contin-

uous cooling after hot forming is proposed. It is based on incremental formulation of conventional nucleation and grain growth theory, and dislocation density is introduced to describe the effect of hot forming to phase transformation. Upsetting experiments under different cooling rates, plastic strains and deformation temperatures are performed to validate the accuracy of the proposed model. The proposed model has been applied to simulate phase transformation and final microstructure after 4-pass bar rolling.

(cf. *ISIJ Int.*, **41** (2001), 1510)

Development of grain interior strain localizations during plane strain deformation of a deep drawing quality sheet steel

V.M.NANDEDKAR et al.

Development of dislocation substructures was characterized in an aluminum killed deep drawing quality steel at four different plane strain deformations. At and above 20% reduction, the most significant substructural feature was micro bands (MBs). MBs appeared as paired dislocation walls of 0.2–0.4 μm thickness and were always at an angle of approximately 37° with rolling direction (RD). As the traces of the MBs were more than 5° of {110} and {112}, closed packed planes of the bcc system,—they were termed as first generation[1] or non-crystallographic using the convention[16] commonly used in fcc metals. Other than the pre-deformation high angle boundaries, MBs were the only feature with large enough misorientations necessary for optical visibility. At least for the range of strain and strain path used in the present study, the first generation MBs can be considered as the so-called grain interior strain localizations. Relative presence and effectiveness of MBs were quantified in different microtexture components from the MB spacings along TD (λ) and the average misorientation across MBs (θ_{MB}) and these appear to determine the stored energies of different microtexture components.

(cf. *ISIJ Int.*, **41** (2001), 1517)

Physical Properties

Thermal diffusivity of iron at high temperature in both the liquid and solid states

B.J.MONAGHAN et al.

Thermal diffusivity measurements of pure iron have been made using a laser flash apparatus (LFA) over the temperature range 25 to 1 640°C. These measurements are compared with existing data and recommended values are given. In the γ-Fe phase region the thermal diffusivity can be represented by $a=6\times10^{-6}+3.13\times10^{-9}\times(T-911)$. In the δ-Fe phase region the thermal diffusivity can be represented by the constant $0.07\times10^{-4}\,m^2\,s^{-1}$. In the liquid region up to 1 640°C, the thermal diffusivity can be represented by $a=6.2\times10^{-6}+1.79\times10^{-9}\times(T-1\,538)$. T in both equations is temperature in Celsius and the thermal diffusivity equation units are $m^2\,s^{-1}$.

To improve the LFA measurement characteristics of a metal, it is often coated with graphite. Unfortunately, due to the solubility of carbon in iron, at high temperatures, the coating does not remain on the surface of the iron. The effect of using a zirconia coating as opposed to a graphite coating was tested. The efficacy of this change was evaluated by comparing thermal diffusivity measurements on Cu using both coating materials.

(cf. *ISIJ Int.*, **41** (2001), 1524)