Fundamentals of High Temperature Processes

Wetting characteristics of liquid Fe–19%Cr–10%Ni alloys on dense alumina substrates

M.Shin et al.

Using the sessile drop technique, the contact angle between a liquid Fe–19%Cr–10%Ni drops and a dense alumina substrate was measured under H_2 as well as CO_2–H_2 atmospheres in the temperature range of 1 753 to 1 823 K. The measurements were carried out both in the static mode and the dynamic mode. The static measurements in hydrogen showed that the contact angle decreased from 135 to 107° by increasing temperature from 1 753 to 1 823 K. In the dynamic mode, gas mixtures of different oxygen partial pressures were imposed on the system. At 1 753 K, the contact angle was decreased under the condition of oxide formation, whereas the contact angle was not changed under the condition of no oxide formation. At 1 823 K, the contact angle did not change regardless of the oxide formation. The time required for the surface oxide layer to fully cover the liquid metal drop was decreased by increasing the temperature.

(cf. *ISIJ Int.*, **48** (2008), 1665)

Ironmaking

Reaction behavior during heating waste plastic materials and iron oxide composites

Y.Ueki et al.

Effective utilization of waste plastic materials is one of key technologies for environmental protection. In this work, we conducted fundamental researches on production techniques of reduced iron and H_2 and CO gases from waste plastic materials (polyethylene and Refuse Derived Fuel) and iron oxide mixtures. The mixtures were heated up at the temperatures of 1 000–1 300°C in Ar gas stream. Concentrations of generated gases from samples were continuously measured by a quad-pole mass spectrometer.

Conversion ratios into H_2 from waste plastic materials reached 60–70% at 1 300°C both in thermal decomposition of the waste plastic materials and reduction of the mixture samples. In the reduction of the mixture samples, conversion ratios into CO reached 70–80% at 1 300°C. Final fractional reductions of samples containing RDF at 1 200°C and 1 300°C were 100%. When waste plastic materials are used as a reducing agent, plastics which contain large amount of fixed carbon are suitable to obtain a high fractional reduction.

(cf. *ISIJ Int.*, **48** (2008), 1670)

CFD modelling of liquid metal flow and heat transfer in blast furnace hearth

B.-Y.Guo et al.

An in-depth understanding of the liquid metal flow and heat transfer is essential in order to identify the key mechanisms for the hearth erosion of a blast furnace. In this study, a comprehensive computational fluid dynamics model is described which predicts the flow and temperature distributions of liquid iron in blast furnace hearth, and the temperature distribution in the refractories. The new model addresses conjugate heat transfer, natural convection and turbulent flow through porous media, with its main features including improved transport equations (a modified k–ε turbulence model and thermal dispersion term) and a three-dimensional, high-resolution grid. The new turbulence model and terms take account of the effect of microscopic flows around coke particles and allow unified treatment of coke bed and coke-free layer. The predicted results show a well-organized flow pattern: two large-scale recirculation zones are separated vertically at the taphole level. This flow pattern controls the temperature distribution in the liquid phase, so that the temperature remains nearly uniform in the upper zone, but changes mainly across the lower zone. The effects of several factors were examined, such as cases comparing fluid buoyancy with constant fluid density as well as the shape and position of the coke free zone (*i.e.* based on reported dissection studies). Natural convection is found to be most important for the liquid metal flow patterns observed. Comparison with the plant data shows that the refractory pad temperature is under-predicted when assuming intact hearth lining. The pad temperature is very sensitive to the erosion of protection layer in the hearth lining.

(cf. *ISIJ Int.*, **48** (2008), 1676)

Effect of different PCI practice on the texture obtained during reduction of iron oxide pellets

U.Leimalm et al.

In modern blast furnace ironmaking, producers continuously strive to reduce coke consumption by replacing coke with *e.g.*, an increased amount of injected pulverized coal. A change in pulverized coal injection rate (PCR) and injection coal type will influence the in-furnace conditions and thus the reduction of iron oxides. In the present study, the reduction behaviour of olivine pellets and textures formed were investigated in the LKAB Experimental Blast Furnace (EBF) and in laboratory scale. In the EBF, effects of injection of an low-volatile (LV) and an high-volatile (HV) coal type at different PCR while two types of oxygen supply methods were employed were investigated. The choice of injection coal type was conclusive for the Fe_{met} texture formed during reduction, extent of Fe_{met} carburization and K distribution in the pellets. The amount of volatile matters in the coal type had a greater effect on the reduction properties than the PCR and oxygen supply method. Laboratory experiments simulating PCR, based on measurements in the EBF, showed that the initial reduction conditions, in terms of temperature level and reduction gas composition, determined the pellet texture up to a reduction degree of at least 60%. The tests carried out in the EBF showed that the pellets were well suited for blast furnace reduction under all the investigated process conditions. The laboratory tests supported this conclusion.

(cf. *ISIJ Int.*, **48** (2008), 1686)

Validation of particle size segregation of sintered ore during flowing through laboratory-scale chute by discrete element method

H.Mio et al.

In this paper, the particle size segregation of sintered ore during flowing through a laboratory-scale chute was investigated to validate the simulated results. The chute angle, installation of a damper at the outlet of the chute or the particle mixing condition were changed. The particles were segregated during flowing through the chute. The smaller particles were at the bottom wall of the chute, and the larger ones were on the smaller particles. The particle discharging velocity decreased with increasing the rolling friction in DEM, and the velocity also became uniformly. The particle discharging behavior under the large rolling friction was not spread, this phenomenon was not comparable with the experimental one. The distributed coefficient of rolling friction was determined by the distribution of rolled distance of sintered ore particle, and every particle in DEM had the different value according to the distribution of rolled distance. This method was effective for the sintered ores' flow very much, and the simulated particle size segregation agreed with those of experimental very well, irrespective of chute angle, installation of a damper or particle conditions. Therefore, this simulation has been validated for the analysis of the granular flow in an ironmaking process.

(cf. *ISIJ Int.*, **48** (2008), 1696)

Steelmaking

Modeling of three-phase flows and behavior of slag/steel interface in an argon gas stirred ladle

B.Li et al.

A Mathematical model has been developed to analyze the transient three-dimensional and three-phase flow in an argon gas bottom stirring ladle with one and two off-centered porous plugs. Multiphase Volume of Fluid (VOF) method is used to simulate the behaviors of slag layer. Numerical simulation was conducted to clarify the transient phenomena of gas injection into the molten steel. When argon gas is injected into molten steel in a ladle, the gas rising passage is formed near the plug, and then bubbles are created in the molten steel. The rising gas bubbles impinge on the slag intermittently and break the slag layer to create the slag eye. Simultaneously, the wave at the slag–steel interface was formed and the wave frequency increases with the increase of argon gas flow rate for one off-centered plug case. The modeling simulations show that the diameter of slag eye changes from 0.43 to 0.81 m when the flow rate of argon gas varies from 100 to 300 NL/min for a 220 ton ladle. The relationship between non-dimensional areas of slag eye and the modified Froude number is in good agreement with the experimental data reported in literature. At the same total gas flow rate of 300 NL/min, the two-plugs generate two eyes with the diameters of around 0.6 m. Since the significant deformation of slag layer occurs during gas stirring operation, the thickness of slag becomes thin near the slag eye and thick near the ladle wall,

respectively. The downward flow velocity of steel at the slag eye periphery may be affected significantly by flow rate of Ar gas. Therefore, when the downward flow velocity would be larger, the more emulsification of slag could be expected.

(cf. *ISIJ Int.*, **48** (2008), 1704)

Casting and Solidification

Hydrodynamic and mathematical simulations of flow field and temperature profile in an asymmetrical T-type single-strand continuous casting tundish

S.-X.LIU et al.

To further remove mini-size nonmetallic inclusions and improve surface quality of stainless steel slab at No. 2 Steelmaking Plant of Shanxi Taigang Stainless Steel Company Limited, the flow field and temperature profile of molten stainless steel in an asymmetrical T-type single-strand continuous casting tundish with a capacity of 18–20 tons have been investigated by both hydrodynamic and mathematical simulations. The influences of height for low-wall of turbulence inhibitor, dam height, weir depth, distance between dam and weir, submerged depth of ladle shroud and casting speed on flow field in the tundish have been studied in a 1 : 3 reduced scale hydrodynamic model. The streamlines, velocity vector fields and temperature profiles are also mathematically simulated.

The hydrodynamic modelling results indicate that height for low-wall of turbulence inhibitor, dam height and weir depth are three important structural parameters on flow field of molten stainless steel in the tundish. The optimization of the three parameters can improve dispersed plug zone and reduce dead zone effectively. Changing casting speed can improve turbulent flow, and thus reduce dead zone of molten stainless steel in the tundish. As a result, five groups of optimized structural parameters of the tundish have been recommended, which can reduce volume fraction of dead zone down to 15–30% and increase volume fraction of dispersed plug zone to more than 20%. In addition, it is verified that the optimized groups of structural parameters of the tundish can maintain their advantage at different casting speed in a narrow range.

The mathematical modelling results suggest that heat losses around the tundish must be considered in order to accurately simulate the streamline, velocity vector field and temperature profile. The calculated temperature drop of molten stainless steel between inlet and outlet of the tundish is about 4.4 K; the maximum temperature drop in the whole tundish is about 10 K. The modification of flow filed by changing structural parameters of the tundish can slightly affect temperature profile of molten stainless steel in the tundish.

(cf. *ISIJ Int.*, **48** (2008), 1712)

Applying of real-time heat transfer and solidification model on the dynamic control system of billet continuous casting

J.MA et al.

In this paper, a real-time mathematical heat transfer model for billet continuous casting of low carbon steel has been presented and solved by finite volume method. This model can be used to simulate the casting conditions which vary frequently. As taking the variation of superheat of liquid steel into consideration in the water flow rate distribution, the fluctuation of billet surface temperature has been decreased. Meanwhile the fluctuation of measured temperature has been largely reduced when it is measured with thermal imager. The mathematical model has been validated by measuring shell thickness and surface temperature in industrial caster. The on-line model can monitor surface temperature and shell thickness along the caster machine in the casting process, and it has been applied on the dynamic control system to adjust the operation parameters. The billet defect has been decreased greatly and the quality of billet has been obviously improved.

(cf. *ISIJ Int.*, **48** (2008), 1722)

Numerical simulation of solidification structure formation in high Mn steel casting using cellular automaton method

H.ISHIDA et al.

Numerical simulation analysis was carried out to predict the solidification grain structure in commercial scale high Mn steel casting using the cellular automaton (CA) method, and the critical pouring temperature to produce fine equiaxed structure was examined. In the present simulation, heterogeneous nucleation in bulk liquid and the crystal multiplication due to the 'Big Bang' mechanism were taken into account. Fine equiaxed grain structure was formed in the simulation with low pouring temperature of 1 638 K and mixed structure with columnar and equiaxed crystals was formed with higher pouring temperature of 1 663 K. These simulated structures agreed with experimentally observed structures in real castings. To determine the critical pouring temperature to produce fine equiaxed crystal structure, CA simulations for several pouring temperatures were carried out and it was predicted that to obtain fine equiaxed grains in the high Mn steel casting, it will be required to cast with pouring temperature of less than 1 648 K.

(cf. *ISIJ Int.*, **48** (2008), 1728)

Instrumentation, Control and System Engineering

Wiener model identification of blast furnace ironmaking process

J.ZENG et al.

To account for the nonlinearity of blast furnace ironmaking process, a nonlinear Wiener model identification algorithm is presented. The system consists of a linear time invariant (LTI) subsystem followed by a static nonlinearity. The inverse of the nonlinearity is assumed to be a linear combination of known nonlinear basis functions and the linear subspace algorithm is used to identify the model. The inputs to the model are parameters regarded to be most responsible for the fluctuation of thermal state in blast furnace while the output to the model is silicon content in hot metal. The identified Wiener model is then tested on datasets obtained from No. 6 Blast Furnace from Baotou Steel. It is found that the blast furnace of concern is a short memory system, so that for each prediction the Wiener method is retrained. It is shown that the retrained model well improves the predictive accuracy.

(cf. *ISIJ Int.*, **48** (2008), 1734)

Forming Processing and Thermomechanical Treatment

Analysis of flange wrinkle in square-shell deep drawing of anisotropic sheet

T.OHWUE et al.

An FEM simulation utilizing a dynamic explicit code was conducted to investigate the flange wrinkle behavior of square shell deep drawing of anisotropic steel sheets. In the FEM simulation, anisotropy of the r-value is taken account of by using the Barlat–Lian '89 equation. The yield locus diagram and the influence of anisotropy were investigated by changing the combination of the R_{00}, R_{45} and R_{90} value. One quarter portion of the 75 mm square punch and 80 mm square die was used in the simulation and frictional coefficient $\mu=0$ (Teflon lubricant condition) was adopted. As a result, the greater the m-value of the yield locus, the greater the yield stress (YS) and the greater the ΔCL value $(R_{90}-R_{00})/R_{ave}$ become, the bigger the flange wrinkle.

(cf. *ISIJ Int.*, **48** (2008), 1739)

Formation of surface and subsurface oxides during ferritic, intercritical and austenitic annealing of CMnSi TRIP steel

Y.F.GONG et al.

The equilibrium external oxidation of CMnSi TRIP steel at different annealing temperatures in a low dew point N_2–10%H_2 atmosphere of −30°C was investigated for the first time by means of high resolution transmission electron microscopy of cross-sectional samples. Annealing in the ferrite stability temperature range below the Ae1 temperature resulted in the formation of 300–600 nm size crystalline internal MnO in the matrix. In the subsurface region, 10–20 nm size SiO_2 particles were detected. Large amorphous lens-shaped xMnO·SiO_2 oxides, with $x<0.5$, were present at the surface, and thin films of crystalline xMnO·SiO_2 oxides, with $1<x<2$, were formed between these large lens-shaped oxides. The amorphous lens-shaped xMnO·SiO_2 oxides were covered by a continuous thin layer of crystalline xMnO·SiO_2 oxide, with $x>2$. Amorphous 15–50 nm size internal SiO_2 particles covered with a thin layer of crystalline MnO·SiO_2 and MnO·Al_2O_3 oxides were found in the subsurface matrix region and at the grain boundaries after annealing in the intercritical and the fully austenitic temperature ranges. A discontinuous amorphous SiO_2 layer covered by a layer of crystalline 2MnO·SiO_2+MnO·SiO_2 mixed oxide was present at the surface after annealing in the intercritical Ae1–Ae3 temperature range. This changed to a continuous layer of amorphous SiO_2 on the steel surface covered by a continuous layer of crystalline 2MnO·SiO_2+MnO·SiO_2 mixed oxide after annealing in the austenitic stability range. The results

clearly show an increased tendency for the xMnO·SiO_2 and SiO_2 oxides to form two separate surface oxide films covering the entire steel surface during continuous annealing at the higher annealing temperatures used to process advanced high strength steels. The presence of these film-forming oxide layers will prevent the formation of the inhibition layer and its wetting by the liquid Zn, and cause galvanizing surface defects.

(cf. *ISIJ Int.*, **48** (2008), 1745)

Welding and Joining

Analysis of inclusion core under the weld pool of high strength and low alloy steel

H.TERASAKI et al.

Inclusion core in the weld pool of HSLA steel was directly observed by Time Resolved X-Ray Diffraction experiments. The aluminum concentration to oxide was changed from 0.48 to 1.52 through the experiments. The corundum alumina was identified in the weld pool and the population increased as the contents of aluminum increased. The results of TRXRD experiments was related to the direct observation of inclusion by TEM analysis and the formation process of inclusion in HSLA steel was summarized in the sense of overall microstructure evolution during welding. When an aluminum content was approaching stoichiometrical value to oxygen level, the corundum alumina reacted with glassy phase and spinel-type oxide was formed after solidification process of welding.

(cf. *ISIJ Int.*, **48** (2008), 1752)

Surface Treatment and Corrosion

Corrosion behavior under black deposit on low Cr bearing steels in NaCl completion fluid

H.TAKABE et al.

3% Cr steel has been developed as a tubing material for CO_2 oil well considering CO_2 corrosion resistance. However, an oil leakage problem occurred 6 months after the start of oil production in a CO_2 oil well which was completed by tubing of 3% Cr steel. 3% Cr steel was exposed to an alkaline NaCl completion fluid environment before exposed to the oil production environment. Corrosion under the black deposit, which developed locally on 3% Cr steel in the NaCl completion fluid, was identified to be a cause of oil leakage. The conditions of the black deposit formation on 1% Cr and 3% Cr steels were investigated by immersion test in a simulated NaCl completion fluid varying dissolved oxygen DO concentration, pH and temperature. 1% Cr steel is a representative Cr bearing steel and used as a comparable material. If the fluid was alkaline and DO concentration was above 77 ppb, the black deposit formed locally on 1% Cr and 3% Cr steels. Localized corrosion was observed just under the black deposit. If the DO concentration was equal to or less than 33 ppb, the black deposit did not form. Corrosion behavior of the specimens with the black deposit was also investigated in a simulated oil production environment. It is concluded that corrosion progress under the black deposit on 3% Cr steel in the production environment resulted in the oil leakage 6 months after the start of production. The black deposit was identified as Fe_3O_4 mainly by X-ray diffraction analysis. In order to prevent oil leakage on 3% Cr steels in the oil production environment, it is necessary to control the DO concentration in the alkaline NaCl completion fluid to or below 33 ppb that prevents formation of the black deposit.

(cf. *ISIJ Int.*, **48** (2008), 1758)

Microstructure and properties of purity high Mn steel crossing explosion hardened

F.ZHANG et al.

In this paper the effects of explosion hardening on the microstructure and the mechanical properties as well as the lifetime of purity high Mn steel crossing have been studied. The optimum explosion hardening technology of the purity high Mn steel crossing was proposed. That is the explosion by using cyclonite explosive in thickness of 4 mm. The new technology emphasizes the formation of a 25 mm-deep hardened layer with surface hardness of 360 HB. Upon the explosion impact, the deformation mechanism of the material is found to follow *in-situ* plastic deformation. The explosion hardening mechanism of the steel crossing are dislocation and twin hardenings. The explosion hardening enhances the mechanical properties of the material, included the deformation resistance, wear resistance and fatigue resistance, therefore, the lifetime of the purity high Mn steel crossing can be increased by ~40% through the explosion hardening treatment.

(cf. *ISIJ Int.*, **48** (2008), 1766)

Effects Of microstructure and texture on the formability character of the coatings in three industrial galvannealed steels

A.CHAKRABORTY et al.

The microstructural and textural aspects of the substrates and the coatings on three industrially galvannealed interstitial free, interstitial free high strength and low carbon high strength quality grade steels have been carefully evaluated to determine their effects on the powdering resistance behavior of the coatings. A high amount of delta phase and a non-basal $\{01.3\}\langle uv.w\rangle$ texture in the coating along with low Fe content have been found beneficial in this respect.

(cf. *ISIJ Int.*, **48** (2008), 1771)

Mechanical Properties

A simple method for prediction of shelf life of bake hardening steels

A.N.BHAGAT et al.

The shelf life of bake hardening (BH) steel is generally reported to be inferior to that of conventional grades due to presence of solute elements in the steel matrix. Hence the assessment of shelf life of BH steel is essential for automobile manufacturers to produce the components free from defects but a reliable method is not yet available to assess it in an industrial condition. Hence to formulate a simple method for assessing shelf life of BH steel, aging behavior of BH steels has been studied at various temperatures (50–100°C). Analysis of data showed higher activation energy (88–102 kJ/mol) than that of the diffusion of C or N in iron. Using the derived activation energy, K-value in Hundy equation was modified. The prediction of shelf life using earlier correlation was compared to that of modified equation. Based on the present analysis, a simple accelerated test has been presented for prediction of the shelf life applicable in an industrial practice.

(cf. *ISIJ Int.*, **48** (2008), 1781)

Evolution of texture and related magnetic properties in Fe–3%Si steel during single-step annealing

S.-M.SHIN et al.

Cold rolled Fe–3%Si steel sheets underwent a single-step annealing process, which included a decarburizing treatment. Crystallographic texture and magnetic properties were investigated after cold rolling and annealing for various times. Most of the Goss oriented grains were situated inside the shear bands of $\{111\}\langle 112\rangle$ oriented grains in the cold rolled samples. In the annealed samples, island grains were observed in the abnormally growing grains. The island grains had either low (<15°) or high (>45°) misorientations. The abnormally growing grains were surrounded by 25°–45° misorientation boundaries. The effects of crystallographic texture on magnetic properties were evaluated using a texture parameter, the ratio of the sum of Cube and Goss texture components fractions to γ fiber texture components fraction. The results show that iron losses decrease linearly with increasing texture parameter.

(cf. *ISIJ Int.*, **48** (2008), 1788)

Social and Environmental Engineering

Analysis of global demand for iron source by utility of stock hypothesis

S.KOZAWA et al.

To forecast iron source demand, the Intensity of Use hypothesis, which assumes that material consumption per capita is a function of GDP per capita, is the most dominant theory in existing studies. However, this hypothesis is not effective for a world one-region model of iron sources. Therefore, we focus our attention on utility, and we suppose that economic growth is a major driver to increase the utility. As the utility of steel sustains for ages after purchase, we formulate the Utility of Stock hypothesis, which assumes that the in-use steel stock is a function of GDP. In this study, the world steel stock was computed and the Utility of Stock hypothesis was tested. Clear correlation is found between the steel stock and the GDP. It leads to the estimation that the world demand for iron ore depends not on the volume of GDP but on the variation of GDP. For the first time with total world figures, the result enables us to rationalize the recent decoupling between the world growth of iron source demand and the economic growth.

(cf. *ISIJ Int.*, **48** (2008), 1795)