（＊掲載記事題目及び掲載頁は変更になる場合があります。）

Fundamentals of High Temperature Processes

Iron ore reduction in a laboratory-scale fluidized bed reactor—Effect of pre-reduction on final reduction degree

A.THURNHOFER et al.

Fluidized bed processes for iron ore reduction (*e.g.* FIOR®, FINMET®, FINEX®) operate in a continuous multi-staged countercurrent mode. To optimize iron ore reduction, different operating conditions occur in each stage.

Significant influence of the first reduction stage on the final reduction degree was observed in industrial plant. The iron ore particles seem to "memorize" the precursor autoclave conditions.

To optimize iron ore reduction, as well as to develop new reduction processes, it is necessary to understand this phenomenon. Industrial plants operate on pressures up to 12 bar and temperatures up to 900°C. So a laboratory-scale pressurized fluidized bed reactor was built to perform experiments similar to industrial conditions.

Two-stage experiments with Mt. Newman hematite ore from Western Australia at variable operating conditions show significant influences of temperature and residence time of the pre-reduction stage on the final reduction degree. Microscopical analysis showed the influence of mineralogy and texture on the reduction behavior of original respectively partly reduced iron ore. Formed magnetite in the pre-reduction stage causes a degradation of final reduction degree. Additionally the amount of newly formed magnetite depends on pre-reduction temperature, composition of the reducing gas and residence time.

(cf. *ISIJ Int.*, **45** (2005), 151)

The effect of B_2O_3 on dephosphorization of molten steel by FeO_x–CaO–$MgO_{satd.}$–SiO_2 slags at 1873K

T.HAMANO et al.

Reducing the exhaust amount of steelmaking slag is strongly required because of the view point of environmental conscious. CaO is often used for steelmaking slag but its high melting point prevents from reuse of slag as resources because free-CaO exists in the melt. Therefore highly dissolution of CaO is the key for reducing steelmaking slag. It was reported that B_2O_3 accelerates CaO dissolution into slag, however, few study about B_2O_3 containing slag has been conducted. The present work measured phosphorus partition ratio between liquid iron and MgO saturated FeO_x–CaO–$MgO_{satd.}$–SiO_2–B_2O_3 melts or MgO and CaO doubly saturated FeO_x–$CaO_{satd.}$–$MgO_{satd.}$–SiO_2–B_2O_3 melts at 1873K. If SiO_2 was replaced by B_2O_3, phosphorus partition ratio doesn't change. The maximum phosphate capacity is $10^{19.06}$ for MgO and CaO doubly saturated FeO_x–$CaO_{satd.}$–$MgO_{satd.}$–B_2O_3 system. The activity coefficient of $PO_{2.5}$ is calculated as a function of CaO content and following equation is derived for present experimental conditions.

$$\log \gamma_{PO_{2.5}} = -6.2 - 0.046 \times (\text{mass\%CaO})$$

(cf. *ISIJ Int.*, **45** (2005), 159)

Ironmaking

Theoretical analysis on the injection of H_2, CO, CH_4 rich gases into the blast furnace

D.ANDAHAZY et al.

The aim of this work is the determination of the combustion characteristics of two different fuel gases for their blast furnace utilization. The availability of gas from the coke production as well as from the basic oxygen furnace (BOF) process in an integrated metallurgical plant makes it possible to substitute reducing agents like oil. For a description of the varieties of the gases, coke oven gas (COG) and a mixture of COG and BOF gas, four independent modeling approaches were applied to cover all aspects. The different applied modeling approaches are the thermodynamic equilibrium, the plug flow reactor (PFR) model with detailed chemistry with or without, resp., consideration of the mixing time and computational fluid dynamics (CFD). This guarantees an improved understanding of the whole combustion process.

The earlier ignition of the COG/BOF gas mixture in comparison to the COG can be ascribed to the higher excess air ratio, in spite of the better ignition propensity of COG. The higher net calorific value of the COG results in higher combustion temperatures, which implicates a higher thermal strain on the tuyere. In addition, greater amounts on CO and H_2 in the raceway result from the COG combustion.

(cf. *ISIJ Int.*, **45** (2005), 166)

Steelmaking

The wear of tundish stopper refractories by inclusion slags at OneSteel

D.XIE et al.

Liquid inclusions in the steel may play an important role in the wear of the stopper tip refractories in tundish operations. In the present study, the attack and wear of the tundish stopper refractories by inclusion slags in OneSteel Whyalla billet product have been investigated.

Three stopper tip refractories, Al_2O_3–C, ZrO_2–C and MgO–C, have been tested with inclusion slags (SiO_2–Al_2O_3–CaO–MnO–FeO) under argon at 1570–1610°C for 1–4 h using an *in-situ* gravimetric technique. The *in-situ* gravimetric data, combined with autopsy of the samples after the tests, provide valuable insights into the dynamic processes of the slag–refractory interactions and the mechanisms for refractory wear.

It was found that the performance of the three refractories differed considerably and was determined predominantly by the resistance to the chemical attack by the liquid inclusions and the extent of internal carbon–oxide reactions. The FeO in the inclusion had a detrimental effect on the oxidation of carbon in the refractory, causing vigorous reaction and severe wear. The MnO in the slag also reacted with carbon, but to a much lesser extent, while severe wear only occurred when slag attacked the refractory grains. The weight loss, due to internal carbon–oxide reactions, appeared to be an important issue.

Of the refractories tested, the MgO–C performed the worst, suffering from severe inclusion attack on both the carbon and the periclase grains, and considerable weight loss due to internal carbon reaction. The ZrO_2–C showed a reasonable resistance to the chemical attack from the inclusion, with MnO up to 33 wt%; but showed extensive weight loss due to internal carbon reaction. The Al_2O_3–C was the best performer in terms of resistance to both the inclusion attack and internal carbon reaction. The results were found to be in broad agreement with plant experience and observations.

(cf. *ISIJ Int.*, **45** (2005), 175)

Casting and Solidification

Numerical simulation of grain structure evolution in solidification of an Al–5.0wt%Cu alloy under electromagnetic stirring and its experimental verification

Z.F.ZHANG et al.

A two-dimensional computational model, coupling a hmacroscopic heat and fluid flow analysis with a cellular automaton model under electromagnetic stirring, was developed. The dynamic evolution of solidification grain structures and transport phenomena during solidification were presented successfully. The Gaussian distribution was chosen to deal with nucleation events both on the mold wall and in the bulk melt. The KGT (Kurz–Giovanola–Trivedi) model, based on the calculated temperature field, was adopted to evaluate the growth velocity of a dendrite tip. The material used was an Al–5.0wt%Cu alloy. Both the computational and experimental results showed that grain refinement was improved remarkably with electromagnetic stirring. The fully equiaxed grain structures were obtained with a proper choosing of the casting process variables, such as pouring temperature, cooling rate and stirring intensity.

(cf. *ISIJ Int.*, **45** (2005), 183)

Solidification parameters dependent on interfacial heat transfer coefficient between aluminum casting and copper mold

H.-S.KIM et al.

The present study focused on the evaluation of the interfacial heat transfer coefficient as a function of the surface temperature of the casting material at the interface. The casting experiments of aluminum into a cylindrical copper mold were conducted. The thermal history during the experiment was used to solve the inverse heat conduction problem. The effects of coating and superheat on the interfacial heat transfer coefficient in the liquid state, during the solidification, and in the solid state were comparatively discussed. The interfacial heat transfer coefficient was categorized into three regimes according to the phase of the casting materials. In the liquid state, the interfacial heat transfer coefficient is affected by the roughness of the mold, the wettability of the casting on the mold surface, and the physical properties of the coating layer. At the initial stage of solidification, it drops to a certain value due to the abrupt surface deformation of the casting. After then it reduces again due to contraction of the casting. In the

solid state it depends only upon the thermal conductivity and the thickness of the air gap.

(cf. *ISIJ Int.*, **45** (2005), 192)

Forming Processing and Thermomechanical Treatment

Dimensional analysis of hot strip rolling for on-line prediction of thermo-mechanical behavior of roll–strip system

S.H.KIM et al.

General, dimensionless expressions are derived for the parameters describing the thermo-mechanical behavior of the roll–strip system, on the basis of the boundary value problem associated with hot strip rolling. Then, it is shown that, by conducting process simulation with an integrated finite element process model, the dimensionless expressions may be transformed into various on-line models which may be applied to precision process set-up and control. The validity of the proposed approach is examined through comparison with predictions from finite element process simulation.

(cf. *ISIJ Int.*, **45** (2005), 199)

Surface Treatment and Corrosion

Mathematical modelling of jet finishing process for hot-dip zinc coatings on steel strip

P.NAPHADE et al.

A mathematical model has been developed to predict the zinc coating thickness, and hence coating weight on a steel strip after passing it through a molten zinc pot, and wiping excess zinc from the surface of the strip using a pair of air wiping jets. The developed model predicts the coating weight as a function of different operating parameters such as strip velocity, jet nozzle pressure, nozzle-to-strip distance and nozzle slit opening. The required pressure and the shear stress profile on the strip surface were calculated through numerical simulations, carried out using FLUENT, a finite volume based commercial code. These were then correlated to the plant operating parameters through statistical regression analysis. Having been incorporated the developed correlations; the model was validated with the actual coating weight measured in CGL#2 of Tata Steel and also with the experimental results of J. M. Buchlin *et al.* The validated model was used to carry out the sensitivity analysis to determine the favourable operating regime for the air jet wiping process. It has been proposed that favourable operating regime should be chosen such that nozzle-to-strip distance is as small as possible and the nozzle pressure is as high as possible.

(cf. *ISIJ Int.*, **45** (2005), 209)

Numerical simulation of gas-jet wiping in steel strip galvanizing process

D.LACANETTE et al.

We have investigated the film thickness and thermal exchange occurring during the coating and cooling of a liquid film on a substrate. The aim of our study is to demonstrate the interest of Direct Numerical Simulation tools for Interfacial flows to understand, on the one hand, the mechanisms involved in the deposition of the film on the moving substrate, and on the other, to measure characteristic parameters of the process. The direct numerical simulation is presented here in two-dimensions based on the Navier-Stokes equations, generalized to free surface flows. They are approximated by VOF (Volume Of Fluid) methods . A Large Eddy Simulation (LES) model is used to take the turbulence into account. We attempt to define the governing parameters of the process and propose a description of the flow. The characteristic parameters of the wiping of the film and the associated thermal exchanges are presented in terms of wiping thickness, transfer coefficient, cooling rate and temperature gradient along the film.

(cf. *ISIJ Int.*, **45** (2005), 214)

Transformations and Microstructures

Modelling upper and lower bainite trasformation in steels

M.AZUMA et al.

Bainite is of considerable importance in the design of high strength steels. There are two types of morphologies, upper and lower bainite. In upper bainite, cementite forms between adjacent bainitic ferrite plates. In certain steels, however, the cementite reaction is suppressed so that carbon-enriched austenite remains untransformed between bainitic ferrite plates. In lower bainite, cementite also has the opportunity to precipitate within bainitic ferrite plates. In order to model the development of these microstructures, it is necessary to treat the simultaneous formation of both the ferritic and carbide components of the microstructure. A theory has been developed to do exactly this, enabling the estimation of the phase fractions, the cementite particle size and the transition from upper to lower bainite. The results have been compared against experimental data.

(cf. *ISIJ Int.*, **45** (2005), 221)

Neural network model for isothermal pearlite transformation. Part I: Interlamellar spacing

C.CAPDEVILA et al.

The present paper is the first of a two-part paper which deals with a neural network model to describe the isothermal pearlite formation. The isothermal austenite-to-pearlite transformation has been analyzed using a neural network technique within a Bayesian framework. In this framework, the pearlite interlamellar spacing and growth rate of pearlite can be represented as a general empirical function of variables such as Mn, Cr, Ni, Si and Mo alloying contents and temperature which are of great importance for the pearlite growth mechanisms. The method has limitations owing to its empirical character, but it has been demonstrated that it can be used in such way that the predicted trends make metallurgical sense. In this first part paper, the method has been used to examine the relative importance of the alloying elements on pearlite interlamellar spacing.

(cf. *ISIJ Int.*, **45** (2005), 229)

Neural network model for Isothermal parlite transformation. Part II: Growth rate model

C.CAPDEVILA et al.

The pearlite growth rate during the isothermal austenite-to-pearlite transformation has been analyzed using a neural network technique within a Bayesian framework. An extensive database consisting of the detailed chemical composition considering elements such as Mn, Cr, Ni, Si and Mo, and isothermal temperature was compiled for this purpose using data from the published literature. With the aim of modeling the pearlite growth rate during the austenite-to-pearlite transformation a neural network has been proposed. The model allows us to examine the relative importance of the alloying elements in pearlite growth. The results from the network analysis were consistent with those expected from phase transformation theory.

(cf. *ISIJ Int.*, **45** (2005), 238)

Deformation and recrystallization of tensile-deformed or rolled Fe–3%Si alloy single crystals

T.OKADA et al.

Fe–3%Si alloy single crystal samples with various tensile directions were deformed to strains of 0.25 to 0.65 and subsequently annealed. Necking occurred and work-hardening was very small in all tensile-deformed samples. After annealing, no recrystallized grain was formed. Fe–3%Si alloy single crystal sample of $\{111\}\langle 112\rangle$ orientation was lightly rolled to 25% and subsequently annealed. Many recrystallized grains were formed in the rolled sample. The orientation of recrystallized grains formed at the rolled surface was totally different from the orientation of those formed in the interior of the sample. These results are discussed based on the tendency for cross-slip and the dislocation network model for nucleus of recrystallized grain.

(cf. *ISIJ Int.*, **45** (2005), 248)

Image quality analysis: A new method of characterizing microstructures

J.WU et al.

Polycrystalline aggregates are comprised of three microstructural features: grain centers, grain boundaries, and regions affected by grain boundaries. It is these features that determine the mechanical properties, and any advanced understanding of microstructure–property relations requires their quantitative description. Traditionally, descriptions of microstructures have been based on visualization, *i.e.*, how grains appear in the optical or scanning electron microscope (SEM). While this may lead to classification systems that permit differentiation, it does not allow for quantification, especially in complex microstructures, and does not lend itself to either developing or applying structure–property relationships. The goal of this paper is to present a new approach to the characterization of complex microstructures, especially those found in advanced modern high strength steels. For such steels, the new approach employs the fact that different types of ferrite formed at different transformation temperatures have different dislocation or sub-grain bound-

ary densities. Hence, measuring the degree of lattice imperfection of the grain centers of the ferrite is one way of first identifying, then grouping, and finally quantifying, the different types or forms of ferrite. The index chosen in this study to distinguish the degree of lattice imperfection is the image quality (IQ). Finally, as part of the new approach a procedure has been developed to improve the accuracy of applying IQ measurements.

(cf. *ISIJ Int.*, **45** (2005), 254)

Mechanical Properties

A new evaluation method of hydrogen embrittlement fracture for high strength steel by local approach

S.TAKAGI et al.

An evaluation method for hydrogen embrittlement (HE) susceptibility for ultra high strength steel was studied. The study showed that the evaluation results obtained by the method were independent of the stress concentration factor and the dimension of the specimen. A commercial 0.40C–0.24Si–0.81Mn–1.03Cr–0.16Mo (mass%) steel with a tensile strength of 1400 MPa was used. The Local Approach, which was originally used for the evaluation of brittle fracture property, was applied to evaluate the HE susceptibility. The method was modified to consider the effect of hydrogen content to evaluate the HE susceptibility. The critical HE data, which were required in the modified Local Approach, were obtained by the stepwise test in which the stress increasing process and the stress holding process were alternatively repeated until the specimen fractured. The dimensions of the specimen used in the stepwise test consisted of a diameter of 10 mm and a stress concentration factor of 4.9. To evaluate the HE susceptibility for specimens with other dimensions, a critical hydrogen content for failure called Hc, which represents the maximum hydrogen content among the unfracture specimens on the HE test with constant loading, was used. It was found that the HE susceptibility could be evaluated by the modified Local Approach considering hydrogen content distribution in the specimens and that the probability of the HE fracture on the components could be designed by using the evaluation results.

(cf. *ISIJ Int.*, **45** (2005), 263)

Impact toughness and tensile properties improvement through microstructure control in hot forged Nb–V microalloyed steel

A.REZA et al.

The influence of thermomechanical processing parameters such as reheating temperature, deformation temperature, deformation percent and cooling rate on achieving high impact toughness properties was studied in a Nb–V microalloyed steel to be used as forged parts in automotive applications. 15 mm long and 65 mm diameter billets were forged using a 20 MN mechanical press. Tensile and Charpy impact tests specimens were machined out of the central part of the forged billets. The microstructure of the specimens was examined for each experimental condition using optical microscopy. Phase identification and distribution was studied using X-ray diffraction and orientation image microscopy techniques. The results indicate that, increasing the reheating temperature above the dissolution temperature of (Nb)(C, N) improved the impact energy values. By increasing the cooling rate from 0.3 to 3°C/s both tensile strength and impact toughness were improved. High elongation percent was also observed on samples reheated at higher temperature and/or cooled with the higher cooling rates. The obtained mechanical properties were related to the characteristics of microstructural components including acicular ferrite, retained austenite, pearlite and ferrite.

The interrelationship between thermomechanical processing parameters, microstructure development, and final mechanical properties were identified and optimized forging conditions to obtain high impact energy (>30 J) microalloyed forge steels were determined.

(cf. *ISIJ Int.*, **45** (2005), 272)

Tensile fracture behaviors in double-notched thin plates of a ductile steel

L.-B.NIU et al.

Tension tests are carried out on smooth and double-notched specimens of SPCC steel plates with various ligaments and notch root radii. By observing the tensile fracture processes, initial cracks are found to occur at the notch roots, the center and the 2 axi-symmetrical inner areas of ligaments for specimens with acute, obtuse and intermediate notches, respectively. In order to clarify the effect of multi-axial stresses on the ductile fracture mechanisms, distributions of multi-axial stress components in the notched specimens are calculated by finite element method. In a specimen undergoing the maximum load, the mean stress shows the largest value at the region where initial cracks just occur. This behavior is discussed with reference to the effects of multi-axial stress components on the initiation and growth of micro-cavities in specimens. The result suggests that the mean stress component should be a dominant factor influencing the fracture behaviors of the ductile steel plates.

(cf. *ISIJ Int.*, **45** (2005), 281)

Social and Environmental Engineering

Inadvertent melting of radioactive sources in BOF or EAF: Distribution of nuclides, monitoring, prevention

D.NEUSCHÜTZ et al.

This report lists the relevant nuclides presently or formerly in use as radiation sources and gives an account of their expected distribution between steel melt, slag, dust and off-gas upon inadvertent melt-down. Three groups of nuclides are identified, namely (a) strong γ-emitters (Co 60, Kr 85, Cs 137, Ir 192), (b) weak γ-emitters (Ra 226, Am 241), and (c) β- and α-emitters (Ni 63, Sr 90, Pm 147, Pu 238/239, and Cm 244). Equilibrium distributions based on thermodynamic calculations and experimental investigations are presented.

Combining the equilibrium partition ratios with process-specific effects leads to realistic distribution ratios: The steel melt is expected to contain about 98% of the radioactive Co, Ni, and Ir, while the dust will contain practically all the Cs and about 1% of all the other nuclides except Kr which should completely pass to the off-gas. The slag is expected to contain about 99% of the nuclides Sr, Pm, Ra, Am, Pu and Cm, and about 1% of Co, Ni and Ir dissolved in the suspended metal granules.

The strongly γ-emitting nuclides can be, and are increasingly, monitored quasi on-line on steel samples taken in the meltshop. The respective equipment operates reliably and efficiently. An on-line detection of weak γ-emitters and of α- and β-emitters is technically not possible at present. The steelworks can minimize the risks connected to the inadvertent melt-down of a radioactive γ-source by introducing three consecutive steps of measures: Prevention by inspection of incoming materials; Inhouse Scrap Monitoring by inspection during transport, and finally Product Control by monitoring of steel samples and in the bag-house.

(cf. *ISIJ Int.*, **45** (2005), 288)