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Fundamentals of High Temperature Processes

Macroscopic models for gas stirred ladles (Review)

D.MAZUMDAR et al.

Considerable efforts have been made during the past two decades to develop reliable and effective macroscopic process models for inert gas stirred ladles. The primary objective of these has been to develop simplified equations/expressions embodying a set of key operating variables such as ladle dimensions, gas flow rate, nozzle/tuyère dimension and so on for hydrodynamics, scaling criterion, structure and profiles of the gas–liquid two phase plume, mixing, heat and mass transfer between solids and bulk liquid *etc.* An exhaustive literature search on the subject indicates that both fundamental as well as empirical approaches were adopted by investigators to develop these simplified process models. It was further noted that a vast majority of these studies applied aqueous model of gas stirred ladle systems as a means to arrive at or validate such models. Parallel to this, limited available evidence within the literature also suggests that macroscopic models, despite being simplistic have a sound basis and therefore can form a reasonably reliable predictive framework, particularly in the absence of any elaborate computer solutions, for first hand analysis of rate processes in gas stirred ladles.

(cf. *ISIJ Int.*, **44** (2004), 447)

Reduction behaviour of iron ore fluxed pellets under load at 1 023–1 273 K

A.A.EL-GEASSY et al.

Commercially, high grade acidic and basic fluxed iron ore pellets were isothermally reduced at 1 023–1 273 K under different load values ranging from 0.0 up to 0.0559 MPa. The reduction was carried out with synthetic gas mixture containing 55 vol% H_2, 36 vol% CO, 5 vol% H_2O, 3 vol% CO_2 and 1 vol% N_2. The oxygen weight loss resulted from the reduction of Fe_2O_3 to lower oxides or to metallic iron was continuously recorded as function of time. X-ray phase analysis, optical microscope, high-pressure mercury porosimeter were used to characterise fluxed and reduced pellets. The different parameters affecting the reduction of these pellets were studied and correlated. It was found that the bascity of pellets $(CaO+MgO)/(SiO_2+Al_2O_3)$. At early and intermediate stages, the reduction increased gradually with temperature showing a significant increase in the rate at >1 173 K. At later reduction stages, the load had a measurable effect on the reduction due to the sintering of freshly reduced metallic iron that increased with temperature and reduction extent. The internal structure was correlated with the reduction kinetics to predict the corresponding mechanism. The inter-relating effect of temperature and load on the reduction kinetics of fluxed pellets was also given.

(cf. *ISIJ Int.*, **44** (2004), 462)

Influence of lime/limestone addition on the SO_2 and NO formation during the combustion of coke pellet

M.-S.LEE et al.

Isothermal combustion experiments of coke pellet mixed with lime/limestone had been performed to investigate the effect of lime/limestone addition on the reduction of NO and SO_2 emission. The coke pellets were combusted between 700°C and 1 300°C under pure oxygen atmosphere. Combustion kinetics and conversion data of SO_2 and NO were obtained from the thermogravimetry of coke pellet and gas analysis data. Adsorption of NO by lime mixed with coke was not occurred in the experimental ranges. It was possible to reduce most of SO_2 emission below 900°C by adding lime/limestone to coke. However, the reduction efficiency of SO_2 by the addition of lime/limestone decreased with increasing temperature due to the decomposition reaction of $CaSO_4$. The variation of the conversion to NO and SO_2 with the combustion conditions during the combustion of coke pellet was compared with the results of thermodynamic calculation.

(cf. *ISIJ Int.*, **44** (2004), 470)

Phase equilibria of two-liquid CaO–MgO–Fe_tO–P_2O_5 slag saturated with (Mg, Fe)O

T.TAMURA et al.

Phase equilibria of two-liquid CaO–MgO–Fe_tO–P_2O_5 slag saturated with (Mg, Fe)O solid solution and the distribution ratio of phosphorus between the slag and liquid iron were measured at steelmaking temperatures by chemical equilibration. It is known that this slag system has wide liquid miscibility gap at steelmaking temperature and this two-liquid phase slag has many advantages, such as high activities of both Fe_tO and CaO and high amount of phosphoric oxide. It was made clear that the phosphorus distribution ratio between the slag system and molten iron was higher than that of the $CaO_{sat.}$–Fe_tO–P_2O_5 system and the two-liquid slag phase was very useful for dephosphorization of molten steel and reduction of slag volume.

(cf. *ISIJ Int.*, **44** (2004), 476)

Ironmaking

Swelling behaviour of cement-bonded briquettes-proposed model

M.SINGH et al.

The cement-bonded agglomeration process is an alternative to the traditional balling-sintering process for recycling iron-rich by-products generated in iron and steel plants back to the blast furnaces. It has been observed that, under certain conditions, the briquettes containing pellet-fines show a tendency to swell catastrophically when reduced. This swelling is dependent upon a number of factors like: reducing temperature, composition of briquettes, particle size of raw material, amount of cement and composition of reducing gas. The SEM and optical micrographs do not show the formation of iron whiskers as the cause of swelling; instead, the swelling is due to the movement of reduced iron particles away from each other. It has been proposed that the swelling takes place in three steps: (a) fragmentation of weak pellet-fines particles during reduction to wustite; (b) formation of liquid slag due to reaction between CaO, MgO, FeO, SiO_2 and Al_2O_3; (c) generation of high gas pressure due to formation and subsequent oxidation of metastable iron carbide.

(cf. *ISIJ Int.*, **44** (2004), 482)

Modeling of combustion and heat transfer in an iron ore sintering bed with considerations of multiple solid phases

W.YANG et al.

The iron ore sintering was characterized as a relatively uniform process of solid material, coke combustion, various modes of heat transfer, and the complicated physical changes of solid particles. The sintering bed was modeled as an unsteady one-dimensional process of the solid materials with multiple solid phases, which confers a phase on each kind of solid material. Each solid phase had a specific particle size and compositions. Drying, condensation, coke combustion, limestone decomposition, generation of the macroscopic internal pore and shrinking of the bed were considered. Complicated modes of heat transfer including conduction, convection and radiation were considered. Numerical simulations of the condition in the iron ore sintering bed were carried out for various parameters: coke contents and air suction rates, along with some other parameters of the model. Calculation results were compared with the results of the sintering pot test. The temperature profiles and gas compositions showed a good agreement with the experimental data.

(cf. *ISIJ Int.*, **44** (2004), 492)

Numerical investigation on effects of deadman structure and powder properties on gas and powder flows in lower part of blast furnace

H.NOGAMI et al.

Deposition of excessive amount of fine powder in the lower part of blast furnace deteriorates permeability of packed bed for reacting gas and liquid products, and causes operation instability. Powder behavior in the lower part of blast furnace has been attracting technical and scientific interests with increase in injection rate of pulverized coal into blast furnace. This study performed numerical experiments on effects of deadman structure and properties of generated powder on gas and powder flow behavior in the lower part of blast furnace by using two-dimensional axisymmetric mathematical model for flow and heat transfer in blast furnace based on multi-fluid theory. Among the packed bed properties, voidage has greater effect than coke diameter on penetration of high temperature gas and powder into the deadman zone and pressure drop in the furnace. The deadman having extremely low voidage is possibly to cause formation of low temperature zone in the deadman. Thus it is preferable to repress powder accumulation within deadman packed bed to keep its permeability. Increase in powder diameter raises the maximum value of volume fraction of powder within the deadman, and heavier particles tend to leave from the gas stream. Such particles are considered easy to accumulate in the deadman. Therefore decrease in generation of larger and heavier particles and increase in their consumption are effective to realize permeable deadman.

(cf. *ISIJ Int.*, **44** (2004), 500)

Numerical analysis on charging carbon composite agglomerates into blast furnace

M.CHU et al.

The carbon composite agglomerates have been numerically examined. The previously presented multi-fluid blast furnace model is modified to simulate blast furnace operation with carbon composite agglomerates charging. The model considers the behavior of carbon composite agglomerates, namely, conservation equations of chemical species contained in this material including chemical reactions and phase transformations are newly added. A series of simulating calculations are performed to examine the effect of charging carbon composite agglomerates. The result reveals that with increase in carbon composite agglomerates charging ratio in-furnace temperature level tends to decrease, the location of cohesive zone shifts downward, and the reductions of carbon composite agglomerates and sinter are delayed. On the other hand, the productivity tends to increase while coke rate and total reducing agent rate show decrease. The energy consumption for unit production of hot metal is lowered. The performance of blast furnace is improved in the tested range mainly due to the decrease in heat requirements for solution loss, sinter reduction and silicon transfer reactions, heat outflow by top gas and wall heat loss.

(cf. *ISIJ Int.*, **44** (2004), 510)

Mathematical model of gas flow distribution in a scale model of a blast furnace shaft

J.JIMENEZ et al.

The mutual influence between gas flow and burden distribution in the upper part of a blast furnace has been studied employing a simplified mathematical model to estimate burden distribution and a gas flow model based on Ergun's equation.

Experiments carried out on a 1/10 scale cold model of Aceralia's blast furnace B were compared with results obtained from these mathematical models. Results corroborate that changes in burden distribution during the charging process have a strong influence on gas distribution, which also affects the burden layer profiles. These interrelations should be taken into account when the blast furnace charging patterns are designed

(cf. *ISIJ Int.*, **44** (2004), 518)

Steelmaking

Computer applications of thermodynamic databases to inclusion engineering

I.-H.JUNG et al.

Computerized thermodynamic databases for solid and liquid steel, slags and solid oxide solutions, for large numbers of components, have been developed over the last two decades by critical evaluation/optimization of all available phase equilibrium and thermodynamic data. The databases contain parameters of models specifically developed for molten slags; liquid and solid steel; and solid oxide solutions such as spinels. With user friendly software, which accesses these databases, complex equilibria involving slag, steel, inclusions, refractories and gases simultaneously, can be calculated for systems with many components, over wide ranges of temperature, oxygen potential and pressure. In the present article, several case studies will be presented, illustrating applications to complex steelmaking processes such as: Ca injection processes (Fe–Ca–Al–O inclusion diagram), corrosion of refractories, Mn/Si deoxidation, Ti/Al deoxidation (Fe–Al–Ti–O inclusion diagram), spinel formation (Fe–Mg–Al–O inclusion diagram), (Ti,N)(N,C) inclusion formation, oxide metallurgy.

(cf. *ISIJ Int.*, **44** (2004), 527)

Numerical investigation on role of bottom gas stirring in controlling thermal stratification in steel ladles

S.GANGULY et al.

A two dimensional Computational Fluid Dynamics (CFD) model was developed to simulate the fluid flow and heat transfer of the molten steel in a ladle during the holding time, with gas purging from the bottom. Transient analysis of the temperature and the velocity distribution of the liquid steel during ladle standing and subsequent gas stirring was conducted, by employing a pressure-based fully-implicit finite volume approach. Stratification, which can adversely affect the quality of steel products, was seen to develop due to natural convection. Therefore, particular attention was paid to study the effect of bottom gas stirring in minimizing the thermal stratification. This was accomplished by introducing a novel approach of coupling the effects of natural convection and axisymmetric bottom gas injection. Various parametric studies was undertaken to examine the effects of standing time, gas flow rate and geometry of the ladle on the resultant thermal field. It was observed that bottom purging situation induces a strong recirculatory flow in the molten steel bath, with an increase in the order of turbulence giving rise to thermal homogenization. The results indicate that the thermal stratification can be effectively eliminated by a relatively gentle agitation. Homogenization takes place at a faster rate with an increase in the amount of bottom gas flow. The effect of ladle size was found to be inconsequential, in comparison to other parameters.

(cf. *ISIJ Int.*, **44** (2004), 537)

Casting and Solidification

Analysis on refinement of columnar γ grain by phosphorus in continuously cast 0.1 mass% carbon steel

N.YOSHIDA et al.

Based on a grain growth model, this paper discusses the γ grain refinement by phosphorus (P) in as cast 0.1 mass% C slabs. Two important factors, the starting temperature of the rapid grain growth (T_{rg}) and the grain growth rate, are especially focused in the model. Local Equilibrium Mapping (LEM), an analytical method with local equilibrium calculations in the micro-segregation maps determined by EPMA, is carried out to evaluate the local transformation temperature and the γ phase fraction. The LEM analysis shows that the micro-segregation of P extends the δ/γ transformation temperature range to a lower temperature and retains the δ phase at a lower temperature. The Classical Grain Growth Model (CGM) based on a theory by Burke (1949) and Turnbull (1951) is derived, which assumes a normal grain growth with a parabolic law. The CGM successfully evaluates the γ grain growth curve in the as cast 0.1 mass% carbon steels considering the rapid growth after the δ/γ transformation and the change of the growth rate during cooling. The CGM analysis predicts the decrease of both T_{rg} and growth rate by the P addition. The decrease of T_{rg} was determined to be 160–170 K and agrees with the extension of the δ/γ transformation temperature range evaluated by the LEM analysis. Hence, the grain growth curves can be predicted by considering the extension of the δ/γ transformation temperature range due to the P addition and its micro-segregation.

(cf. *ISIJ Int.*, **44** (2004), 547)

Numerical simulation of molten steel flow under a magnetic field with argon gas bubbling in a continuous casting mold

N.KUBO et al.

In a continuous casting process, it is essential to prevent the surface defects which are caused by the entrapments of both mold powder and argon gas bubbles. It is well known through experiments that the decrease in the molten steel flow velocity just under the free surface is one of the most effective methods for the prevention of mold powder entrapments. For this purpose, we have already employed the electromagnetic force by the ElectroMagnetic Level Stabilizer (EMLS) system, which applies a low frequency alternating magnetic field that moves from the narrow face of the mold to the mold center below the nozzle exits. In this study, the molten steel flow in a mold was numerically analyzed to optimize the conditions for the prevention of the deteriorating phenomena: optimization of electromagnetic force with argon gas bubbling.

Simulation results indicate that argon gas bubbles ascend near the nozzle due to their buoyancy, and ascending argon bubbles induce the upstream of the molten steel. Due to the electromagnetic force, the molten steel is forced to flow toward the magnetic field traveling direction in the region where the magnetic field is imposed. Consequently, the molten steel flows toward the mold center near the free surface with a smaller imposed magnetic field, and it flows toward the narrow face with a larger imposed magnetic filed. A suitable imposed magnetic filed with argon gas bubbling can be chosen to minimize the flow velocity and also the amount of mold powder entrapments.

(cf. *ISIJ Int.*, **44** (2004), 556)

Concentric solidification for high temperature laser scanning confocal microscopy

M.REID et al.

A new experimental technique defined as concentric solidification has been developed to improve *in-situ* observations of solidification and high tempera-

ture phase transformations using laser scanning confocal microscopy (LSCM). The technique consists of applying a radial thermal gradient across a 10 mm diameter sample such that the maximum temperature is focused in the centre of the specimen. Careful control over the sample thickness, heating rate and peak temperature results in the formation of a liquid pool in the centre of the specimen. Surface tension balance between solid, liquid, gas and crucible result in minimal meniscus formation on the liquid pool, leading to a greatly enhanced *in-situ* observations. Examples of the range of observations possible as well as unique observations of segregation related phenomena are presented.

(cf. *ISIJ Int.*, **44** (2004), 565)

Instrumentation, Control and System Engineering

Blast furnace hot metal temperture prediction through neural networks-based models.

J.JIMENEZ et al.

Blast furnace hot metal temperature prediction, by mean of mathematical models, plays an interesting role in blast furnace control, helping plant operators to give a faster and more accurate answer to changes in blast furnace state. In this work, the development of parametric models based on neural networks is shown. Time has been included as an implicit variable to improve consistency. The model has been developed departing from actual plant data supplied by Aceralia from its steel works located in Gijón.

(cf. *ISIJ Int.*, **44** (2004), 573)

Welding and Joining

Creep behavior of 2.25Cr–1Mo steel shield metal arc weldment

S.FUJIBAYASHI et al.

In order to guarantee the safety of high temperature components and prevent unscheduled outage, remnant life assessment for creep is quite important. The experiences in actual components reveal that almost all the problems relating to creep are generated at the weldment, which contains microstructures with different creep properties from those presumed in the parent material. Nowadays, it is generally accepted that a terminal failure mode of low alloy ferritic steels or tempered martensitic steels become Type IV, taking place at the Intercritical HAZ or Fine Grained HAZ. However, in the present work using 2.25Cr–1Mo steel welds fabricated with basic coated Shield Metal Arc Weld (SMAW) consumables, the most prevalent failure mode was Type I in the center of weld metal rather than Type IV. And this tendency was more pronounced at low stresses, suggesting the possibility of Type I cracking in actual components. It was concluded that poor creep strength of 2.25Cr–1Mo weld metal was ascribed to its fully bainitic microstructure in which carbides evolution was accelerated and M_2C depletion took place earlier than base metal.

(cf. *ISIJ Int.*, **44** (2004), 581)

Transformations and Microstructures

Effect of the hot band grain size and intermediate annealing on the deformation and recrystallization textures in low silicon electrical steels

M.F.deCAMPOS et al.

The effect of hot band grain size on the texture of low silicon steels was investigated. In spite of different hot band grain sizes (22, 125 and 500 μm), the deformation texture is formed by the fibers ⟨111⟩//ND and ⟨110⟩//RD. Nevertheless the recrystallization texture is strongly affected. Increasing the hot band grain size, from 22 to 125 μm, the intensity of the Goss component in the recrystallized material increases and {111} components decreases. The further increase to 500 μm does not increase Goss, but increases cube on face component. When the hot band grain size is sufficiently large (~500 μm) the deformed grains tend to recrystallize independently, originating regions (clusters) of grains with same orientation. There is no apparent effect of an intermediate recovery (after deformation ε=0.7 annealing at 500°C during 1 h) on the deformation or recrystallization textures.

(cf. *ISIJ Int.*, **44** (2004), 591)

Mechanical Properties

Improvement of cutting tool life by AlN deposition on the tool

H.YAGUCHI et al.

SCM415 steel was machined with carbide tools in as hot rolled condition and after normalizing heat treatment. In the as-rolled sample, a significant amount of Al and N existed as solid solution; whereas, in the normalized sample, Al and N existed as AlN precipitates. Reduction of tool wear for the as-rolled sample was observed. On the rake face of the tool machined for the as-rolled sample, the presence of AlN deposit was observed. It is believed that Al and N in solid solution form AlN deposit on the tool face due to temperature rise during machining, and that the deposition of the AlN layer on the tool face prevents diffusion between the tool and chip and reduces tool wear.

(cf. *ISIJ Int.*, **44** (2004), 598)

Effects of microstructure on stretch-flange-formability of 980 MPa grade cold-rolled ultra high strength steel sheets

K.HASEGAWA et al.

Stretch-flange-formability is an important property for ultra high strength steel (UHSS) sheets for press-forming. In this study, microscopic deformation behaviors during punching and following stretch-flange-forming were investigated using three types of 980 MPa grade UHSS sheets with either two ferrite/martensite dual-phase structures or a martensite single-phase structure in order to clarify how the microstructure affects the stretch-flange-formability of UHSS sheets. The results of this investigation revealed following conclusions. Microscopic plastic-flow or micro-void density generated by punching is not the dominant factor of the stretch-flange-formability of UHSS sheets. During hole-expanding, cracks were mainly initiated at the fractured surface part and the cracks became longer and deeper from the punched surface with the increase of hole-expanding ratio. Deep cracking resistance in this process is important to improve the stretch-flange-formability. The existence of strain gradient induced by hole punching is considered to be one of the reason for the highest hole-expanding ratio of the martensite single phase steel. During hole-expanding, the micro-cracks propagate mostly along the phase interfaces in the dual-phase steel sheets in the case of poor stretch-flange-formability, while the micro-cracks are tend to propagate through ferrite and martensite phases in the case of high stretch-flange-formability. The analysis of the hardness of ferrite and martensite suggests that the difference in hardness is the dominant factor of the stretch-flange-formability of the dual-phase steel. In addition, the volume fractions of phases also influence the formability.

(cf. *ISIJ Int.*, **44** (2004), 603)

Ductile–brittle transition temperature of ultrafine ferrite/cementite microstructure in a low carbon steel controlled by effective grain size

T.HANAMURA et al.

To analyze the good toughness of ultrafine ferrite/cementite steels, the concept of effective grain size (d_{EFF}) is applied to ductile-to-brittle transition temperature, DBTT, for ultrafine ferrite/cementite (Uf-F/C), ferrite/pearlite (F/P), quenched (Q), and quench-and-tempered (QT) microstructures in a low carbon steel. The d_{EFF} is determined to be 8, 20, 100, and 25 μm for Uf-F/C, F/P, Q, and QT, respectively. In F/P and Q, it is in accordance with the ferrite grain size and the prior austenite grain size, respectively. In QT, the d_{EFF} fits the martensite packet size. In Uf-F/C, the ferrite grain size has a bimodal distribution and the larger grain size corresponds to the d_{EFF}, which is the smallest among the four microstructures. In terms of the relationship between d_{EFF} and DBTT, the Uf-F/C, Q, and QT microstructures can be placed into the same group and the F/P to a different one. Furthermore, the Uf-F/C has the highest estimated fracture stress among the four microstructures. These might be the result of the difference in the surface energy of fracture, namely the former is estimated to have a surface energy of 34.6 J/m^2 and latter a surface energy of 7.7 J/m^2. Thus, the excellent toughness of the ultrafine ferrite/cementite steel can be attributed to the small d_{EFF} and the high surface energy of fracture.

(cf. *ISIJ Int.*, **44** (2004), 610)

Physical Properties

Decarburization kinetics during annealing of a semi-processed electrical steel

K.M.MARRA et al.

Semi-processed, non-oriented electrical steels used in motor and transformer cores have their magnetic properties optimized by means of a heat treatment performed under a moistened nitrogen atmosphere containing small amounts of hydrogen. The

oxidation of carbon on the steel surface by the oxidizing gases present in this atmosphere decreases the carbon content of the steel. The consequent reduction in the amount of soluble carbon and in the volume fraction of carbides reduces magnetic losses and the susceptibility of the steel to magnetic aging. In this work, a cold-rolled, semi-processed electrical steel was submitted to six thermal treatments covering the most usual conditions employed in industry, combining two types of atmosphere (mixtures of nitrogen with 5% and 10% H_2) and three dew points (10, 20 and 30°C). The treatments were carried out in a pilot electrical oven especially adapted to simulate the thermal cycle and the moistened atmospheres employed in industry. The results obtained show that, at the beginning of the process, the decarburization rate is controlled by the chemical reaction of carbon on the steel surface. Later, an oxide layer may build up, depending on the humidity level of the atmosphere, reducing the rate of decarburization.

(cf. *ISIJ Int.*, **44** (2004), 618)

Social and Environmental Engineering

Dissolution mechanism of fluorine in aqueous solution from fluorine containing synthetic slag

H.MIZUKAMI et al.

The behavior of dissolution of fluorine from the fluorine containing synthetic slag was clarified by the shaking test under various experimental conditions. The fluorine containing minerals were cuspidine, fluorapatite and fluorite. The amount of fluorine dissolved from the slag increased with an increasing of the concentration of fluorine in the slag and an decreasing of the size of slag particles. The amount of fluorine dissolved from the slag could be estimated from the size distribution of slag particle and the concentration of slag for the shaking test. The amount of fluorine dissolved from the slag decreased with an increasing of the basicity of slag and the concentration of alumina. The amount of fluorine from the slag increased with increasing the cooling rate during solidification because the slag became amorphous. The dissolution of fluorine from the slag was controlled by the mass transfer in the liquid layer which was formed near the surface of slag.

(cf. *ISIJ Int.*, **44** (2004), 623)

Immobilization mechanism of fluorine in aqueous solution from road material containing synthetic hot metal pretreatment slag by shaking test

H.MIZUKAMI et al.

The ability of immobilization of fluorine dissolved from the fluorine containing slag with the calcium compound was evaluated by the shaking test. In the calcium compounds which have the ability of immobilization of fluorine, the $12CaO \cdot 7Al_2O_3$ was found to be the largest ability. From the results of evaluating the stability of immobilization with $12CaO \cdot 7Al_2O_3$, it was shown that the dissolved fluorine from slag was immobilized for 100 h in shaking time. It was confirmed from the experimental results of X-ray analysis and the equilibrium thermodynamic calculation for aqueous solution that the generation of fluorite which was hard to dissolve in aqueous solution enabled the immobilization of fluorine dissolved from slag. Moreover, the $12CaO \cdot 7Al_2O_3$ of 5–15 mass% could be used for the road construction material which consisted of fluorine containing slag and blast furnace slag and as a result the immobilization of fluorine was confirmed.

(cf. *ISIJ Int.*, **44** (2004), 630)