Ironmaking

Modelling of multiphase flow in a blast furnace: Recent developments and future work (Review)

X.DONG et al.

An ironmaking blast furnace is a complex multiphase flow reactor involving gas, powder, liquid and solid phases. Understanding the flow behaviour of these phases is of paramount importance to the control and optimization of the process. Mathematical modelling, often coupled with physical modelling, plays an important role in this development. Yagi[1)] gave a comprehensive review of the early studies in this area in 1993. Significant progress has since been made, partially driven by the needs in research but mainly as a result of the rapid development of computer and computational technologies. This paper reviews these developments, covering the formulation, validation and application of mathematical models for gas–solid, gas–liquid, gas–powder and multiphase flows. The need for further developments is also discussed.

(cf. *ISIJ Int.*, **47** (2007), 1553)

Fundamentals of High Temperature Processes

Solidified structure comparison under imposition of oscillating electromagnetic force and DC electromagnetic force

M.USUI et al.

Experimental work has been done to investigate difference of structures solidified under the imposition of an oscillating electromagnetic force and that under the imposition of a DC electromagnetic force. For excitation of the oscillating electromagnetic force, a static magnetic field and an alternating current are simultaneously imposed on a Sn–10 mass% Pb alloy while the static magnetic field and a direct current are simultaneously imposed on the alloy for the excitation of the DC electromagnetic force. After the solidification, macrostructure is observed and it is concluded that both the electromagnetic forces have refining function of the solidified structure. Though magnitude of the DC force is weaker than that of the oscillating force, grain size solidified under the imposition of the DC force is smaller than that solidified under the imposition of the oscillating force. Nucleation is not induced under the imposition of the DC force while it is induced when the oscillating force is imposed on the alloy.

(cf. *ISIJ Int.*, **47** (2007), 1571)

Surface tension of liquid Fe–N–O–S alloy

J.RIIPI et al.

Surface tension and composition of gas–iron alloy interphase were calculated for Fe–N–S–O system using the modified form of Butler's equations and the derived values of the surface interaction parameters of the system. The calculated values are found to be in very good agreement with published experimental data in literature. Simulations showed that if contents of strong surface active elements such as sulphur and oxygen are low, nitrogen also works as a surface active element and decreases surface tension of melt. According to the calculations, the surface tension of steel in traditional BOF process changes from 1.73 to 1.1 N/m. Furthermore, it decreases due to high alloying of nitrogen and sulphur also during secondary metallurgical treatments although decrease is not as remarkable as during decarburization. Hence the surface tension cannot be assumed to be constant especially when fluid flows of BOF were studied.

(cf. *ISIJ Int.*, **47** (2007), 1575)

Chromites reduction reaction mechanisms in carbon–chromites composite agglomerates at 1 773 K

C.TAKANO et al.

Fe–Cr–C production is a very high electrical energy consuming process. When self-reducing agglomerates are used, it is expected to decrease up to 10% of this electrical energy. This paper presents the fundamental aspects of the reactions involved in reduction of chromites by use of self-reducing agglomerates. Brazilian chromite containing 41.2% Cr_2O_3 was mixed with petroleum coke and agglomerated with cement as the binder. The concept of "initial slag" was introduced and it was assumed that this "initial slag" is formed of fluxing agents, coke ash, silica formed, binder and dissolution of only 5% of the gangue from the chromite. This concept is important since the gangue of chromite is composed mainly by refractory oxides ($MgO+Al_2O_3$), which are difficult to dissolve into slag. The effects of "initial slag" composition, one with low liquidus temperature (~1 700 K) and the other with high liquidus temperature (~1 750 K) were investigated. The mixture was pelletized, dried and submitted at the temperature of 1 773 K until completion of the reactions and also the fractional reaction as a function of time was determined. The results showed that the pellets in which liquid slag phase was formed at high temperature presented significant better reduction behavior than the pellets in which the liquid slag phase was formed at low temperature. The microscopic analysis showed that a liquid phase was formed but the pellet did not collapse, and indicated that the coalescence of the metallic phase depended on the dissolution of the pre-reduced particles of the chromite into slag.

(cf. *ISIJ Int.*, **47** (2007), 1585)

Ironmaking

Characterizing swelling behaviour of iron oxides during solid state reduction for COREX application and their implications on fines generation

T.KANG et al.

Quality of iron feed source plays a critical role on the efficiency and productivity of advanced ironmaking processes such as COREX. A bench-scale study was conducted to characterize the effect gas composition on solid state reduction and swelling behaviour of pellets and lumpy state of iron ore for COREX application. Swelling and reduction behaviour of five commercials iron oxides were analysed in a horizontal tube furnace and a thermogravimetric analysis (TGA) reactor respectively by simulating the reducing gas composition and thermal profile of the reduction shaft of COREX process. The degree of reduction and swelling were related to the initial porosity of iron oxide samples. The study demonstrated the strong influence of the initial porosity of iron feed samples on both reduction and swelling characteristics such that high porosity pellets indicated faster reduction and less swelling when compared to low porosity pellets. However, cracks formed in the iron pellets during different stages of reduction could modify the degree of the influence of the initial porosity on the reduction rates due to modification of surface area growth. The compressive strength of samples was found to change non-linearly with progressive reduction such that the crushing strength of pellets declined continuously up to 30% reduction followed by rapid strength increase as the degree of reduction exceeds 50% which can be attributed to increasing sintering of metallic phases. The study implies that as far as physical properties are concerned, the initial porosity of iron feed samples can be used to optimize the reduction kinetics, the swelling tendency and the associated implications for the stability of COREX operations including fines generations in the reduction shaft.

(cf. *ISIJ Int.*, **47** (2007), 1590)

The influence of potassium on the boudouard reaction in manganese production

J.KACZOROWSKI et al.

The reactivity of selected, industrially applicable, carbonaceous materials towards CO_2 has been investigated. Metallurgical cokes from various locations, single source cokes, and eucalyptus charcoal have been tested for reactivity in a thermo-gravimetric furnace. A graphite sample was added to the experimental plan as a reference.

The effect of potassium on the CO_2 gasification rate for selected metallurgical cokes and single source cokes was studied after gaseous impregnation of the samples using potassium carbonate as a precursor. The deposited compound was then examined for chemical composition using EPMD technique.

Results from the reactivity measurements using non-impregnated samples were compared with properties of the carbons and the best correlation is illuminated. Also, activation energy of the cokes is presented and compared with the activation energy of the potassium impregnated samples.

The results showed that charcoal has the highest CO_2 reactivity, while graphite has the lowest reaction rate. The reactivity of different metallurgical cokes is similar and moderate, while cokes produced from single source coals exhibit strong variation in reactivity. Of the examined carbon properties, the alkali index showed the strongest influence on the reaction rate.

Studies on catalytic gasification showed that the reactivity of the laboratory impregnated samples is higher and that the increase is related to the initial reactivity of the original material. Following this it can be stated that potassium affects all the carbons used in this work equally.

(cf. *ISIJ Int.*, **47** (2007), 1599)

Steelmaking

Optimisation of the bottom tuyeres configuration for the BOF vessel using physical and mathematical modelling

V.SINGH et al.

An experimental perspex model of the BOF vessel was made to the scale of 1 : 6 on which mixing time measurements were done by injecting potassium chloride (KCl) at a certain point and measuring the conductivity of the solution with time. It was found that the mixing time in the vessel attained a minimum when the bottom nozzles (eight in number) were kept at a pitch circle diameter (PCD) ratio of 0.4 with combined blowing (top blowing as well as bottom blowing) but the mixing time became a minimum at a PCD of 0.5 when only bottom blowing was done. In order to get a finer position of the bottom nozzles so that the mixing time could still be minimized, a mathematical model was used (because experiment could not be done with so close placement of the nozzles in one setup) to simulate the flow in the vessel with the help of the two equation k–ε turbulence model along with a discrete phase model to simulate the air bubbles being injected in to the vessel. The mathematical model could predict the mixing time in the vessel to a very good degree of accuracy when compared with the experimental observations for the PCD of 0.5. From the mathematical model it was predicted that the mixing time in the vessel could still be lowered if the bottom nozzles were placed at a PCD of 0.56 instead of 0.5.

(cf. *ISIJ Int.*, **47** (2007), 1605)

Casting and Solidification

Optimization of alternating current imposing period on crystal alignment of Sn–Pb alloy subjected to a static magnetic field during solidification

M.USUI et al.

For optimization of alternating current imposing period in the crystal alignment process in which both a static magnetic field and an alternating current are imposed on an alloy during solidification, experimental work has been done using a Sn–10mass%Pb alloy. Index of crystal alignment decreases with increase in the imposing period of the alternating current because the electromagnetic torque induced in the sample disturbs the alignment of solid particles suspended in the liquid phase. Electromagnetic torque is dominant as resistance of the crystal rotation to magnetically preferred direction when the size of the crystal is 21 μm or larger. For the optimization of the crystal alignment in this process, imposing period of the electric current and the magnetic field should be controlled as follows. The electric current and the magnetic field are simultaneously imposed on the alloy only in the initial stage of the solidification. Then the electric current is turned off and only the magnetic field is imposed during the solidification.

(cf. *ISIJ Int.*, **47** (2007), 1613)

Basis for systematic hydrodynamic analysis of a multi-strand tundish

A.KUMAR et al.

Despite significant work done till date on single/dual strand tundish (those applied to slab casting) not much information on an equivalent multi-strand tundish (which are of significance to billet casting) is available regarding residence time distribution (RTD) measurements and its analysis. The proportions of various flow volumes estimation (*e.g.*, dead, plug, well mixed, *etc.*) on the basis of a single/dual strand tundish cannot be directly extrapolated to a multi-strand tundish from its individual strand data only. In the present study, therefore, the principle and the methodology underlying the derivation for concentration *vs.* time curves (C curves) of a multi-strand tundish is addressed to provide a basis for the evaluation of RTD parameters. To this end, several experiments in a four-strand water model tundish were carried out for RTD measurements and estimation of associated flow volumes. The tracer dispersion experiments were performed by injecting potassium chloride (20 mL solution) as a pulse into the submerged inlet stream and the variation of conductivity of water caused by the differential mixing of the injected tracer into the bath were recorded continuously at the exits of the water model tundish with a 75 L volume. These conductivity values of individual strands were converted into corresponding concentrations, and the dimensionless concentrations were plotted against dimensionless time to derive the characteristic C curves. The individual C curves effect the strand to strand variations whereas the overall C curve (average of individual C curves) is used to determine the flow volumes in a multi-strand tundish system.

(cf. *ISIJ Int.*, **47** (2007), 1618)

Kinetics evaluation of inclusions removal during levitation melting of steel in cold crucible

T.TOH et al.

Transport phenomena of inclusions during levitation melting of steel samples in a cold crucible are discussed by use of numerical simulation. Taking account of various forces acting on the inclusions during fusion, population balance simulation is performed within the framework of finite volume method (FVM) analysis for magnetohydrodynamics (MHD). The numerical results supported the experimental results that the inclusions size distribution does not change so much due to the agglomeration effect and the phenomena of inclusions removal to the sample surface are mainly caused by the electromagnetic reaction force and the flotation.

(cf. *ISIJ Int.*, **47** (2007), 1625)

Forming Processing and Thermomechanical Treatment

Dynamic recrystallization behavior in hypereutectoid steels with different carbon content

C.M.BAE et al.

The dynamic recrystallization behavior in hypereutectoid steels with different carbon content was determined by hot compression testing. Compression tests were performed using single hit schedules between 800 to 1 050°C, strain rates of 0.01 to 1 s^{-1}. It was found that the critical stress for the start of dynamic recrystallization is almost same as the steady state stress. The results also revealed that the carbon content has no effect on the activation energy of deformation.

(cf. *ISIJ Int.*, **47** (2007), 1633)

Influence of thermomechanical parameters on the competition between dynamic recrystallization and dynamic strain induced transformation in C–Mn and C–Mn–Nb steels deformed by hot torsion

J.L.FERREIRA et al.

The thermomechanical parameters have a great influence on the restoration processes of the steels and, consequently, on the grain size and morphology during and after deformation. At higher deformation temperatures the ferritic grain refinement may occur by dynamic recrystallization of austenite (DRX) and at lower temperatures, the operating mechanism might be dynamic strain-induced austenite–ferrite transformation (DSIT). In the present work, the effect of thermomechanical parameters on DSIT was investigated. In this study, after soaking at 1 200°C, the samples were cooled to 1 100°C submitted to hot torsion deformation to decrease the austenite grain size and then cooled to 900, 850 or 800°C for further hot torsion deformation, at strain rates of 1 s^{-1} and 5 s^{-1} and total strains of 1.5, 2.5 and 3.5. The steels were deformed by torsion in a 'Gleeble' thermomechanical simulator and water cooled immediately after deformation. In the steel without Nb, recrystallization occurred before enough deformation could be accumulated to induce ferrite formation, so DSIT would only occurred at the lowest temperature investigated, 800°C. In the Nb steel, Nb addition delayed austenite recrystallization allowing DSIT ferrite to form at higher temperatures than the steel without Nb, 850°C. The dynamic recrystallization of austenite at 850°C was retarded by the Nb addition thus allowing the occurrence of DSIT at this temperature. Variations in strain rate and amount of strain did not significantly change the dynamic mechanism of grain refinement, but did change the critical strain to start DRX and DSIT, as well as the fraction of the strain-induced transformed ferrite.

(cf. *ISIJ Int.*, **47** (2007), 1638)

Surface Treatment and Corrosion

Influence of Cu^{2+} on sulfate-reducing bacteria associated with magnesium alloy

S.J.FANG et al.

Influence of Cu^{2+} on sulfate-reducing bacteria associated with magnesium alloy was investigated. X-ray diffraction results reveal that the reaction products of magnesium alloy from the SRB and sterile medium containing Cu^{2+} consist of $Mg(OH)_2$ and Cu phases. Cu^{2+} can inhibit the growth of SRB, but it can not die out SRB cells in biofilm and medium. Cu^{2+} is a deleterious ion, which can form Cu–Mg micro-galvanic corrosion electrocircuits on substrate

surface leading to the severe corrosion of magnesium alloy. Although extracellular polymeric substances (EPS) of SRB have the ability to bind Cu^{2+}, severe micro-galvanic corrosion was still observed on magnesium alloy surface. This indicates that Cu^{2+} can not act as a sterilization reagent or a composition of sterilization reagent for SRB associated with magnesium alloy.

(cf. *ISIJ Int.*, **47** (2007), 1647)

Transformations and Microstructures

Ultrafine ferrite grains produced by tempering cold-rolled martensite in low carbon and microalloyed steels

H.F.LAN et al.

Ultrafine ferrite grains as small as a few hundred nano meters were obtained, without severe plastic deformation, by tempering cold-rolled martensite in a low carbon and a microalloyed steel. A multilevel subdivision mechanism responsible for the formation of ultrafine ferrite grains in cold-rolled martensite was discussed. It involves subdividing firstly a prior austenite grain into several martensite packets by phase transformation and then further subdividing the martensite structure into ultrafine cell blocks by plastic deformation. The relatively large misorientation between the ultrafine cell blocks achieved at a moderate strain level in martensite may be attributed to the interaction between the transformation introduced and the deformation introduced dislocations. Ultrafine ferrite grains were developed from the cell blocks during tempering at the temperature range from 500 to 600°C for 60 min. It was also demonstrated that the microalloying precipitates can effectively pin down the movement of dislocations and grain boundaries and thus, can increase the thermo stability of the ultrafine grained microstructure.

(cf. *ISIJ Int.*, **47** (2007), 1652)

Effects of nano precipitates in austenite on ferrite transformation start temperature during continuous cooling in Nb–Ti micro-alloyed steels

X.YUAN et al.

In the present paper, transformation behavior during continuous cooling in non-deformed and hot deformed Nb–Ti micro-alloyed steels was investigated by using the thermal dilation method. Ti content in Nb–Ti bearing steels varied from 0 to 0.031 mass% with Nb content being kept to be constant. Thermal dilation curves were measured at different cooling rates, from which continuous cooling transformation (CCT) curves were built up. For non-deformed Nb–Ti steels, it was observed that ferrite transformation start temperatures (A_{r3}) decreased with increasing Ti content up to 0.015 mass%, leveled off in the range of 0.015 to 0.027 mass% Ti, and drastically decreased thereafter. For hot deformed Nb–Ti steels, A_{r3} temperature did not exhibit significant difference with Ti addition lower than 0.027 mass%, and decreased drastically by further increasing Ti content. Austenite grain size (D_γ), Nb–Ti precipitates and residual strain were taken into account to explain the variation of A_{r3} temperatures. Based on the experimental results, mathematical models for the calculation of A_{r3} for non-deformed and hot deformed Nb–Ti micro-alloyed steels were developed.

(cf. *ISIJ Int.*, **47** (2007), 1658)

Magnetic properties and recrystallization texture evolutions of phosphorus-bearing non-oriented electrical steel sheets

I.TANAKA et al.

The effect of phosphorus (P) on magnetic properties and also on recrystallization texture of non-oriented electrical steel sheets has been investigated to develop core materials with low core loss and high permeability. Specimens containing different amounts of P were cold-rolled to various thicknesses, *i.e.* with various cold-rolling reductions, and annealed for recrystallization and grain growth. Magnetic induction of the steel with a large amount of P was higher than that of the steel with a small amount of P. Moreover, magnetic induction of the steel with a large amount of P slightly decreased with reduction of sheet thickness, *i.e.* with an increase in cold-rolling reduction, whereas magnetic induction of the steel with a small amount of P dramatically decreased. The most effective way to reduce core loss was to reduce thickness of electrical steel sheets. Therefore, P-bearing thin gauge non-oriented electrical steel sheets achieved low core loss and high permeability. The typical magnetic properties of P-bearing non-oriented electrical steel sheets with a thickness of 0.27 mm were 16.6 W/kg in W10/400 and 1.73 T in B50. These excellent magnetic properties were provided by the recrystallization texture control by P. $\{111\}\langle 112\rangle$ component in recrystallization texture, which deteriorates magnetic properties of electrical steel sheets, was suppressed during recrystallization. Furthermore, $\{\varphi_1, \Phi, \varphi_2\}=\{25°, 10–15°, 45°\}$ component significantly developed at the expense of $\{111\}\langle 112\rangle$ component during grain growth. P segregation at initial grain boundaries would be responsible for this texture evolution. Accordingly, P would greatly contribute to the improvement of magnetic properties of non-oriented electrical steel sheets through the recrystallization texture control.

(cf. *ISIJ Int.*, **47** (2007), 1666)

Isothermal precipitation behavior of copper sulfide in ultra low carbon steel

Z.LIU et al.

Copper and sulfur are typical residual elements or impurity elements in steel. Sufficient removal of them during steelmaking process is difficult for copper and costly for sulfur. Utilization of copper and sulfur in steel, especially in steel scrap, has been an important issue for a long period for metallurgists.

Copper and sulfur may combine to form a copper sulfide, which may provide a prospect to avoid the detrimental effects of copper and sulfur in steel. Unfortunately the formation mechanism of a copper sulfide in steel has not been completely clarified so far. In the present paper, solution treatment of samples containing copper and sulfur are firstly performed at 1 623 K for 2.7×10^3 s followed by quenching into water. The samples are then isothermally heat-treated at 673 K, 873 K, 1 073 K, 1 273 K and 1 373 K for different time followed by quenching into water again. The size, morphology, constituent and crystallography of sulfide precipitates in these samples are investigated by SEM and TEM equipped with EDS. Fine copper sulfides (less than 100 nm) are observed to co-exist with silicon oxide in samples even isothermally heat-treated at 1 373 K for 1.44×10^4 s; Film-like copper sulfides are generally observed to co-exist with iron sulfide in all samples; Plate-like copper sulfides are observed especially in sample isothermally heat-treated at 1 073 K for 1.44×10^4 s. The formation mechanisms of these copper sulfides have been discussed in detail.

(cf. *ISIJ Int.*, **47** (2007), 1672)

Effects of two-step annealing on texture and magnetic properties by addition of Co, Mo, or Ni in silicon steel

Y.B.CAI et al.

In 3Si–1.4Al electrical steel with addition of Co, Mo or Ni, the texture of hot bands is almost random except γ fiber which is dominant. After cold reduction, the texture shows the typical (111)//ND and (110)//RD fibers. When cold rolled sheets are annealed, it is clear that γ fiber of $\{111\}\langle 110\rangle$ and $\{111\}\langle 112\rangle$ decreases significantly, while, on the contrary, Goss texture increases but cube texture is not changed. Two-step annealing process was observed to be effective to increase grain size and decrease γ fiber texture resulting in lowering iron loss and its anisotropy. The combination of increasing grain size and decreasing γ texture by two-step annealing was able to improve magnetic properties.

(cf. *ISIJ Int.*, **47** (2007), 1680)

Mechanical Properties

Scattering in fatigue crack growth of thin pure copper sheet for smart stress memory patch

S.NAMBU et al.

A new sensing method called "smart stress memory patch" has been developed. This patch can estimate the number of cycles and the stress amplitude using its crack length. In this study, the scattering in the fatigue crack growth of the thin copper specimen was investigated to evaluate the error of estimated number of cycles. The rolled and the electrodeposited (ED) Cu with thin thickness were prepared. The fatigue test was performed to obtain the fatigue crack growth of each sample and the fatigue crack growth behaviors of specimens with large grain size demonstrated large scatter. The observed crack path and fracture surface indicated that large grain size affects scattering in crack growth. The effect of thickness and grain size on the scattering was also evaluated by the stochastic model. Furthermore, the error of estimated number of cycles demonstrated that the accuracy of measurement for memorized stress is improved using a specimen with small grain size such as as-received ED Cu for smart stress memory patch.

(cf. *ISIJ Int.*, **47** (2007), 1687)

Superplastic flow at elevated temperatures in As-rolled AZ91 sheet

S.FUDETANI et al.

An alternative processing method for superplastic magnesium alloys has been studied on the form of sheet of Mg–9Al–1Zn (AZ91) *via* large strain by ingot metallurgy with an isothermal-rolling. Constant initial strain rate tensile tests have been conducted at elevated temperatures for AZ91 sheets as rolled with reduction in area of 90%.

The values of total elongation exceeded over 50% at all strain rates and at all testing temperatures except 673 K, and the maximum total elongation exhibited 210%. The total elongation had a tendency to increase at low temperature side.

The strain rate sensitivity, m-values, exceeded over 0.5 at strain rates from 1.0×10^{-4} to $2.5\times10^{-4}\,s^{-1}$. The values of flow stress were lower than those of completely recrystallized AZ91 and did not depend so much on the tensile temperatures from 573 to 648 K at high strain rates.

The activation energy required for superplastic flow in the high-m-deformation was calculated to be 80–83 $kJ\cdot mol^{-1}$. This value was close to the grain boundary self-diffusion energy of Mg.

Anisotropic textures were no seen in X-ray (0002) pole figure analysis (XPFA) by Schulz's reflection method. It was suggested that the stress concentrations through grain boundaries or in grains could be relaxed during superplastic deformation process and the superplastic flow was more easily associated with boundary diffusion.

(cf. *ISIJ Int.*, **47** (2007), 1692)