Fundamentals of High Temperature Processes

Deviation from local thermodynamic equilibrium state in thermal plasma
T.KITAMURA et al.

Spectroscopic analysis of AR–H₂ and Ar–N₂ plasmas revealed that the population density of the excited states of each species (Ar, H and N) followed a Boltzmann distribution, but each species had its own respective excitation temperature. The temperature of the argon was lower than that of the hydrogen in the plasma of AR–H₂ mixture. The temperature of the nitrogen was close to that of the argon in the plasma of Ar–N₂ mixture under one atmospheric pressure. The estimation of the temperatures defined by the velocity distribution functions from the experimental conditions indicate that there are the possibilities to have higher temperatures for the hydrogen than that for the argon in the plasma. These results suggest that there is a deviation from local thermodynamic equilibrium (LTE) in these plasmas under one atmospheric pressure.

The deviations from LTE in these plasmas is explained by the differences in the energy flow in the plasmas. The energy flows of these plasmas are considered as follows from the estimated relaxation times of energy distributions for each species. As for the AR–H₂ plasma, the electric energy is transferred to the electrons and then the energy of electrons is transferred to the hydrogen atoms. The argon atoms are mainly heated by collisions with the hydrogen atoms. In the case of the Ar–N₂ plasma, both the argon atoms and the nitrogen atoms are heated by collisions with the electrons which obtain the electric energy. As a result, the temperature state of $T_e \fallingdotseq T_H > T_{Ar}$ and $T_e > T_{Ar} \fallingdotseq T_N$ could exist in the plasma.

Sulphide capacities in some multi component slag systems
M.M.NZOTTA et al.

Experimental measurements have been carried out to determine the sulphide capacities of some slags in the Al₂O₃–MnO, Al₂O₃–MgO–MnO, Al₂O₃–CaO–MgO–MnO, Al₂O₃–CaO–MgO–SiO₂, Al₂O₃–CaO–MnO–SiO₂, and Al₂O₃–CaO–MgO–MnO–SiO₂ systems in the temperature range of 1 773–1 923 K. The gas–slag equilibration technique has been employed using the gas mixtures of Ar–CO–CO₂–SO₂. Repetition of the measurements has revealed very good reproducibility of the experimental results. The measured sulphide capacities have been used to examine the reliability of a sulphide capacity model developed earlier in the present laboratory. The model predictions based on the model parameters up to ternary interactions obtained in the corresponding lower order systems have shown good agreement with the experimental data. Model parameters necessary for the calculation of sulphide capacities of the above mentioned systems have been provided.

Flow establishment time of a water bath contained in a cylindrical vessel set in sudden rotation
M.IGUCHI et al.

A cylindrical reactor of material processing systems is sometimes rotated about its axis or an offset axis in order to enhance mixing and homogenize temperature and chemical compositions. As a simplified model for this kind of flow field, a water bath contained in a cylindrical vessel suddenly set in rotation about its axis was taken up. The flow establishment time of the water flow in the bath, defined as a period till the instantaneous tangential velocity component exceeded 95 % of its final steady state value, was determined experimentally. Two different boundary conditions were imposed on the top part of the bath. One was covered with a flat circular disk and the other was free surface. The flow establishment time thus determined was correlated as a function of the angular frequency of rotation, the diameter and depth of the bath, and the kinematic viscosity of liquid. The existence of the top wall shortened the flow establishment time significantly.

The least number of chemical reactions to describe the oxidation and the carburization of liquid iron in irreversible processes
TAO Xiaojie et al.

Kinetics of reactions between CO–CO₂ mixtures and liquid iron were investigated at 1 843 K using the cold crucible technique and the concentration changes of C and O were analyzed using non-linear kinetic equations based upon independent reactions in the system. The carbon or oxygen concentration changed against the chemical potential gradient in the initial stage of the reactions. It was proved that such concentration changes were controlled only by interfacial reactions. The concentration changes in the whole process were successfully reproduced by nonlinear equations based upon the two independent reactions in which the nonlinear reaction CO(g)= $\underline{C}+\underline{O}$ was included. It has been shown that there are always some combinations of independent reactions which can describe the chemical changes in irreversible processes from the macroscopic point of view.

Ironmaking and Reduction

Effect of iron ore shape on gaseous reduction rate
H.W.KANG et al.

In order to clarify the effect of particle shape on the gaseous reduction rate of iron ores, iron oxide pellets of various shapes including the long cylindrical- and the disc shape are reduced with 10%CO–90%CO₂ gas mixture. Experimental results show that the reduction rate of the disc-shaped particle is the fastest among all and the long cylindrical particle follows. The experimental data are analyzed by the unreacted-core model for non-spherical particle proposed by authors in the previous paper. According to the analysis, this model is applicable for the non-spherical iron ore of the cylindrical shape within the ratio range of the height to the cylindrical diameter from 0.5 to 2 while the particles of the long

cylindrical- and disc-shaped particle out of this range are problematic applying the model. Based on the review of the experimental- and analysis results, the kinetic behavior concept for the non-spherical particle including the long cylindrical- and disc-shaped particles is discussed.

Steelmaking and Refining

Physical model studies on slag foaming
S.S.GHAG et al.

A physical modelling investigation has been undertaken to determine the relationship between the physico-chemical properties of the liquid phase, the gas bubble size, the gas flux, and the residence times of gas in spherical foams. The testwork was conducted in a 107 mm diameter glass column in a temperature controlled environment. The foams were generated by the injection of compressed air into solutions of distilled water and glycerol. Water glycerol solutions were used to obtain a wide range of liquid viscosities. The strongly adsorbing surfactant, sodium dodecylbenzene sulphonate, was added to the water-glycerol solutions so that the surface tensions of the solutions could also be controlled.

The experimental results show that the residence times of gas bubbles in the foam increase with increasing liquid viscosity and increasing surface tension depression, and with decreasing gas bubble size. Furthermore, a transition from a foaming to a non-foaming regime was observed as the mean gas bubble diameter increased above 5 mm.

Model development of slag foaming
S.S.GHAG et al.

A general model of foaming has been developed which relates the structure of a foam stabilised by viscoelastic forces to the bubble rupturing processes. For the specific case of negligible bubble coalescence within the foam it has been shown that, in the region of linearity between the foam height and gas flux, the residence time of gas in the foam (Σ) is solely a function of the bubble diameter (d), the liquid phase density (ρ) and viscosity (μ), and the effective elasticity (E_{eff}) resulting from the dynamic adsorption of surface active species:

$$\Sigma = 1 \times 10^6 \left(\frac{\mu \cdot E_{eff}}{(\rho g)^2 d^3} \right)$$

The model, which shows that the gas bubble diameter has the greatest effect on the retention of gas bubbles within the foam, has been found to be applicable to a range of system in which foams are stabilised by viscoelastic forces.

The prediction of gas residence times in foaming CaO–SiO₂–FeO slags
S.S.GHAG et al.

A dynamic, non-equilibrium model of foaming:

$$\Sigma = 1 \times 10^6 \left(\frac{\mu \cdot E_{eff}}{(\rho g)^2 d^3} \right)$$

which relates the residence times of gas bubbles in foams (Σ) to the viscosity of the liquid phase (μ); the effective elasticity (E_{eff}) resulting from the dynamic adsorption of surface active species; the liquid phase density (ρ); and the mean bubble diameter (d); has been applied to foaming in the CaO–SiO–FeO system at 1 823 K.

In agreement with industrial observations, the model shows a transition from a foaming regime to a non-foaming regime as the slag basicity increase above 1.5. This is due to poor surface elasticity resulting from the negligible adsorption of silica in this region.

Dynamic model of slag foaming in oxygen steel-making converters
P.MISRA et al.

The foaming and emulsification of steelmaking slags can be analyzed in terms of an emulsion number which is defined as the ratio of the velocity of gas bubbles and that of metal droplets present in slag at any given stage of the blow. An improved procedure is suggested to evaluate the viscosity of gas–slag foam at high gas void fractions. The calculated velocity of gas bubbles in foaming slags is verified using the experimental results reported in literature. A critical comparison is also made with the other approaches available in the literature. It is shown that the emulsion number is directly related to foaming conditions. A dynamic model of slag foaming is developed on the basis of the bubble and droplet velocities, changing slag composition and temperature and the continuous reduction of iron oxide content of slag during the main blow period. Combined effects of lance nozzle design and blowing regime on slag foaming are discussed.

Break-up phenomena of liquid drops impacting on immiscible liquids
K.-Y.LEE et al.

Experimental studies investigating the break-up of liquid drops impacting on immiscible target liquids have been undertaken. High speed photography has been used to elucidate the mechanisms of drop break-up. Three distinct regimes were identified, *i.e.*, a regime in which drops never break, a regime in which drops show a variable behaviour from no break-up to break-up into multiple droplets, and a regime in which drops always break. The sequence of events that occur on impact can be divided into six stages, namely, impact, spread, contraction, re-bound, recovery and penetration. Three different break-up mechanisms were identified, namely, the break-up at the maximum spread of the drop on the cavity floor (perimeter break-up), the break-up at the maximum rebound of the drop (rebounding-jet break-up) and the break-up during penetration through the cavity floor (cavity-pulled break-up).

Critical falling heights for the first break-up of liquid drops impacting on immiscible liquids
K.-Y. LEE et al.

Experimental studies investigating the break-up of liquid drops impacting on immiscible target liq-

uids have been undertaken. The critical falling height at which the first break-up occurs has been found to be proportional to the drop mass to the power of -0.65 ± 0.05, irrespective of change in physical properties of either drop or target liquid, and can be related to the drop mass by the following equation:

$$H_{cr}=k_c W^n$$

where H_{cr} is the critical falling height, k_c is the proportionality constant, W is the mass of liquid drop, and n is the power (-0.65 ± 0.05). The value of k_c varies with change in physical properties of drop or target liquid, and hence the critical falling height is dependent on the physical properties of both drop and target liquids. The mechanism of the first break-up changes from the cavity-pulled to the rebounding-jet break-up as the viscosity of either the drop or target liquid increases.

Modelling of break-up of liquid drops impacting on immiscible liquids
K.-Y.LEE et al.

Break-up phenomena of liquid drops impacting on immiscible liquids have been investigated. Oscillation of falling drops was found to play an important role in break-up in a certain range of falling height. Criteria for break-up were discussed, and it was found that either Reynolds or Weber number was not adequate in describing the criteria of break-up of a liquid drop impacting on an immiscible liquid target. From the experimental results of the present study, empirical models have been formulated, which enables to predict the critical falling height for the first break-up of a drop. Conditions for break-up of liquid iron drops impacting on a liquid slag were predicted using the models. The prediction showed that the majority of metal drops propelled to the top space of an intensive reactor should suffer break-up during the fall through the slag layer.

Forming Processing and Construction

Influences of piercing ratio, expansion ratio, feed, cross and skew angles on available piercing size range in rotary piercing process
C.HAYASHI et al.

A cone-type piercing mill was developed by the authors for materials with poor hot workability. This piercing mill is called "the super piercer" in Europe and America. This mill has a pair of cone-type main rolls supported at both ends with their roll axes inclined and crossed so as to enable piercing at high feed and cross angles. In order to ensure the best performance of the rotary piercing, disc rolls are adopted instead of plate guide shoes. The super piercer was put into practice at the small-diameter seamless tube plant operated in 1983. The recent progress in our research and development on the super piercer has resulted in the concept of "the new super piercer", which allows expansion piercing. Namely, the development of the skewing technology for disc roll axes and its application to the cone-type piercing technology has realized remarkable in-

crease in the expansion ratio. The new super piercer was adopted as the core technology of the new medium-diameter seamless tube plant operated in 1997. In this paper, studied in detail were the influences of the piercing ratio, expansion ratio, feed and cross angles for main roll axes and skew angle for disc roll axes on the available piercing size range.

Finite element analysis of hot rolled coil cooling
S.-J.PARK et al.

A new unit layer model for the equivalent thermal conductivity of layered steel strips has been proposed. The equivalent thermal conductivity is a function of strip thickness, surface characteristics and compressive stress. The modeled equivalent thermal conductivity corresponds well to the experimental data. Finite element analyses (FEM) for cooling of hot rolled coil have been carried out under various cooling conditions using the equivalent thermal conductivity as the thermal conductivity in radial direction of hot rolled coil. A new calculation procedure using ABAQUS has been developed, where the radial compressive thermal stress is taken into account for calculation of the equivalent thermal conductivity, or the orthotropic stress dependent thermal conductivity. The calculated cooling curves using the orthotropic stress dependent thermal conductivity have been compared with data calculated using isotropic and orthtropic stress independent conductivity and with experimental data. The cooling curves calculated using equivalent thermal conductivity as radial thermal conductivity are in better agreement with experimental data.

Microstructure

Effects of rare earth element on isothermal and martensitic transformations in low carbon steels
T.Y.HSU (XU Zuyao)

Rare earth elements (RE) may segregate at the grain boundaries of austenite, lead to form carbide and refine the austenite grain. In case of no change of grain size and carbon content of austenite, an addition of RE is beneficial to the hardenability of steels. In case of a marked refinement of austenite grain, addition of RE will deteriorate the hardenability. The incubation period of the proeutectoid ferrite can expressed as a function of grain boundary energy, grain size, activation energy for growth and the driving force for transformation and the calculated results are in good agreement with the experimental data. RE may retard the isothermal pearlitic transformation, because RE diminishes the diffusion coefficient of carbon as well as tends to segregate at Fe_3C/α interface, showing a pinning effect on the transformation. RE reduces the lamella spacing of the pearlite owning to lowering the interfacial energy, *e.g.*, from 0.7 to 0.53 J/m^2 in 0.27C–1Cr–RE steel. RE tends to segregate at ferrite/island interface in the granular bainite. In grain refined steel, at the earlier stage of bainite formation, the transformation rate is high while at later stage it becomes sluggish. The activation energies of pearlitic and bainitic transformations increase by the addition of RE. The segregation of RE at ferrite/island interface

may act as a drag effect. A drag factor α is expressed as a function of transformation fraction and calculated in a 0.27–1Cr–RE steel. RE segregates at the grain boundary of austenite and this kind of distribution will not be changed during the martensitic transformation. It is reasonable to predict that RE will lower the martensite/austenite interface energy, resulting in the formation of a finer lath structure. RE lowers M_s, decreases the amount of the retained austenite and retards the autotempering process. It is emphasized that the amount of the retained austenite, γ, in quenched low carbon steel depends on not only the M_s and the temperature of quenching medium, T_q, but also the influence of alloying elements on the carbon diffusion during quenching. A general equation modified from the Magee's equation is derived as $\gamma = \exp\{\alpha(C_1 - C_0) - \beta(M_s - T_q)\}$ where C_0 and C_1 are carbon concentrations in austenite before and after quenching respectively, α and β are constants. RE decreases M_s but also lowers C_1 so as to reduce the amount of the retained austenite.

A quantitative characterization of austenite microstructure after deformation in nonrecrystallization region and its influence on ferrite microstructure after transformation

T.KVAČKAJ et al.

A mathematical description of austenite structure after deformation in nonrecrystallization region is given. The essential characteristic of austenite grain, after recrystallization before deformation in the nonrecrystallization region is the effective nucleation area of austenite grain boundaries. Theoretical results are compared with experimental values for a C–Mn–Nb–V steel. The connection of austenite microstructure state before phase transformation and the ferrite microstructure after transformation is given too.

Thermal mechanisms of grain and packet refinement in a lath martensitic steel

H.J.KIM et al.

This work was done to clarify the metallurgical mechanisms that are used in thermal treatments to refine the effective grain size of lath martensitic steels. The alloy chosen for this work was Fe–12Ni–0.25Ti, which provides a well-defined lath martensite structure in the as-quenched condition. The alloy was given four prototypic heat treatments: (1) an anneal-and-quench treatment, (2) an intercritical anneal, (3) a single or double anneal in the austenite range, and (4) a single or double reversion to austenite at a rapid heating rate. Two effective grain sizes were identified for each heat treatment: the packet size, or dimension over which adjacent martensite laths have a common crystallographic orientation, and the prior austenite grain size. The former controls the ductile–brittle transition temperature (DBTT), the latter controls intergranular embrittlement. The different heat treatments suppress the DBTT and increase resistance to intergranular embrittlement to the extent that they decrease the relevant grain size. Rapid reversion is the most successful of the heat treatments since it destroys the alignment of laths within a packet. Rapid reversion readily yields an effective grain size near 1 μm, leading to a very low ductile–brittle transition temperature and a substantial resistance to temper or hydrogen embrittlement.