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Fundamentals of High Temperature Processes

Liquid metal cleanliness analyzer (LiMCA) in molten aluminum

M.Li et al.

A mathematical model was developed to describe the motion of inclusions within melts of aluminum passing through the electric sensing zone (ESZ) of a LiMCA (Liquid Metal Cleanliness Analyzer) system. The fluid flow field within the ESZ was obtained by solving the Navier-Stokes equations. The trajectories of entrained particles were calculated using the equations for motion of particles. The motion of particles within the parabolic shaped ESZ orifice was shown to be affected by particle conductivity, density and size. The numerical results prove that particles in molten aluminum are distinguishable by LiMCA system. On the other hand, the study of the fluid flow generated during the "conditioning operation" (corresponding to high amperage transiently passing through the ESZ) suggests that the dramatically increased fluid velocity thereby generated near the sidewalls of the ESZ during the current surge helps to clear any build-up of the inclusions prior to a sampling of inclusions within melts of aluminum.

(cf. *ISIJ Int.*, **41** (2001), 101)

Effects of slag compositions on the rate of methane–steam reaction

T.Shimada et al.

For the effective heat recovery from molten slag by utilizing a chemical reaction, rates of the methane–steam reaction on the slag surface were studied for thirteen slag samples, in which effects of mass ratio of CaO to SiO_2 (CaO/SiO_2 ratio), and concentrations of wustite (FeO) and sulfur in slag on the reaction rate were systematically examined in the slag temperature range from 1 473 to 1 823 K.

The results showed that the higher CaO/SiO_2 ratio, meaning the weaker network structure of molten slag, gives rise to the higher rate of methane–steam reaction. In contrast, the FeO addition to slag brings about the lower reaction rate than that for the slag without FeO, indicating the inhibitory effect of FeO on the reaction. The higher FeO concentration proportionally provides the stronger inhibitory effect over the slag temperature of 1 773 K, while it is independent on both of the slag temperature and the FeO concentration under the temperature of 1 673 K. The results also revealed that the sulfur contained in slag has the inhibitory effect on the methane-steam reaction, which is much larger than the equi-mass of FeO over 1 673 K. This inhibitory effect of sulfur increases with increasing the sulfur concentration from 0.5 to 1.0 mass%, whereas it is insignificantly enhanced by the further increase in the sulfur concentration.

(cf. *ISIJ Int.*, **41** (2001), 111)

Decomposition of Na_2CO_3 by interaction with SiO_2 in mold flux of steel continuous casting

J.W.Kim et al.

The effect of SiO_2 addition on the decomposition of Na_2CO_3 was investigated using the thermo-gravimetric and differential scanning calorimetric method (TG-DSC). Addition of SiO_2 greatly enhanced the decomposition of Na_2CO_3. The main decomposition reaction began to take place at a eutectic temperature of the Na_2O–SiO_2 system (800°C). The initial decomposition product was identified as Na_2SiO_3, irrespective of the mixing ratio of Na_2CO_3 to SiO_2. The governing reaction of the decomposition was concluded to be $Na_2CO_3+SiO_2=Na_2SiO_3(s)+CO_2(g)$. The decomposition rate was independent of the Na_2CO_3/SiO_2 mixing ratio until either one has completely been exhausted and hence was not available any more for the above reaction. If surplus Na_2CO_3 exists after formation of Na_2SiO_3 by reacting with all SiO_2, the remaining Na_2CO_3 decomposes partly by reacting with Na_2SiO_3 to form $Na_6Si_2O_7$ and partly by thermal self-decomposition. A liquid layer that was formed at the carbonate/additive interface facilitated the decomposition of the carbonates. The melting behavior of a mold flux was greatly influenced by the lowest eutectic temperature that a mold flux system can exhibit. The apparent activation energy of the decomposition of Na_2CO_3 in existence with SiO_2 was estimated to be 426 $kJ \cdot mol^{-1}$.

(cf. *ISIJ Int.*, **41** (2001), 116)

Effect of swirl motion on mixing time in water bath agitated by upward gas injection

Y.Takatsuka et al.

Mixing time in a cylindrical water bath agitated by upward gas injection through a single-hole bottom nozzle and a J-shaped top lance was experimentally investigated in the presence of swirl motion of the bath. This gas injection process is regarded as one of models for steel refining processes. Measured values of the mixing time could not be predicted by empirical equations derived previously in the absence of the swirl motion. The effect of the swirl motion on the mixing time was significant, *i.e.*, the mixing time was highly shortened in the presence of the swirl motion. An empirical equation was newly proposed for the mixing time as a function of the injection distance from the nozzle tip to the bath surface, gas flow rate, bath diameter, bath depth, and kinematic viscosity of liquid.

(cf. *ISIJ Int.*, **41** (2001), 124)

Ironmaking

Leaching dicalcium silicates from iron ore sinter to remove phosphorus and other contaminants

T.R.C.Patrick et al.

Although dicalcium silicates can constitute up to 10 vol% of many modern hematite/goethite iron ore sinters, traditional mineralogical investigations of such sinters have largely overlooked this phase and focused on the more abundant iron oxides and ferrites. However, dicalcium silicates have a range of properties that make them unique in sinter parageneses. These properties may contribute significantly to bulk sinter properties and also make dicalcium silicates potentially exploitable in novel upgrading processes. Analyses on a pot grate test sinter have shown that phosphorous (and possibly other elements including potassium and chromium) was heavily concentrated in the dicalcium silicates. A series of etch tests have demonstrated that dicalcium silicates can be selectively removed from the surface of polished sinter samples using weak acids. In addition, bulk leaching trials showed that the phase can also be removed from powdered and coarser (−5 mm) sinter in mild acids. These leaches resulted in a >90% reduction in phosphorous with a 7% improvement in iron grade for the powdered material and a 70% reduction in phosphorous with a 5% improvement in iron grade for the coarser material. Two novel processes are proposed to exploit the leachability of contaminated dicalcium silicates from sinter: one being a potential route to a high-grade iron product, the other being a return fines washing circuit.

(cf. *ISIJ Int.*, **41** (2001), 128)

Fundamental reaction characteristics of pulverized coal at high temperature

Khairil et al.

In order to enhance the overall thermal efficiency in blast furnace system as well as coal gasifiers, it is necessary to elucidate fundamental reaction characteristics of pulverized coal at high temperature. The experiments were carried out using a horizontal pulverized coal reactor with a pre-combustor to produce vitiated air at high temperature and high-oxygen concentration. The reaction behavior of coal during combustion and/or gasification are elucidated by means of sampling and analyzing both reacting particles and reaction gases as well as optical measurement of the instantaneous particle temperature. Evolution rate of the volatile matter for various types of coal at high temperature is obtained from the Arrhenius plots.

As a result, the volatile matter is rapidly evolved as soon as coal particles are introduced into the furnace since temperature of the vitiated air increases sufficiently. Result shows that the evolution rate of volatile matter does not depend on coal types. Activation energy and frequency factor of the evolution rate of volatile matter for various types of coal remain almost constant in the particle temperature range of 2 200 to 2 700 K, even when other experimental conditions were varied. In the char combustion region, char structure was found to affect the reaction rate of fixed carbon. It is observed that coal, which forms a network-type of char, indicated reaction rate of fixed carbon which did not always increase even when the vitiated air temperature was high enough. For a balloon-type char, on the other hand, the reaction rate of fixed carbon decreased with an increase of the vitiated air temperature.

(cf. *ISIJ Int.*, **41** (2001), 136)

Neural network model of burden layer formation dynamics in the blast furnace

J.Hinnelä et al.

A model of the thickness of burden layers in the ironmaking blast furnace is presented. Local layer thickness estimates are calculated on the basis of signals from stockrods that measure the burden (stock) level in the furnace. These estimates are

used in developing a model for the relation between the layer thickness and variables such as stock level and movable armor settings. Because of the nonlinear dependence of the variables, the models are based on feedforward or recurrent neural networks. The network size is carefully selected based on a cross-validation procedure. The resulting neural model is first studied by analyzing its predictions for different inputs. By further introducing a simplified scheme for considering the practical constraints of the charging process, an autonomous model, where the neural network plays an important role, is formed. This hybrid model is applied to yield insight into the dynamics of the layer formation process; the effect of movable armor settings, stock level and burden descent rate are analyzed and compared with practical experience.

(cf. *ISIJ Int.*, **41** (2001), 142)

Steelmaking

Cold model study on inclusion removal from liquid steel using fine gas bubbles

J.-S.CHO et al.

A water model study was undertaken to investigate inclusion removal from liquid steel using fine gas bubbles, which were created by injecting air into a shroud nozzle just underneath the slide gate. The water flow rate was varied in the range of 2.0–3.2 $m^{3}hr-1$, which is equivalent to 1.77–2.83 $m\,s^{-1}$ of the linear velocity at the exit of the shroud nozzle. The ratio of gas to liquid flow rates was varied in the range of 0–12% by volume. Polyethylene, PVC and ABS particles were used to imitate the inclusion. The characteristics of the bubble formation varied with the gas inlet position along the shroud: the closer the slide gate, the better the mixing between the gas and liquid phases. This was dependent on the slide gate opening: the smaller the opening, the more turbulence and hence the better mixing of the gas and the liquid. The relative removal efficiency was fairly independent of such variables as liquid flow rate, *i.e.*, linear velocity, the slide gate opening (up to 58% by area), and inclusion concentration. However, this was greatly affected by the wettability, *i.e.*, contact angle of the inclusion with the liquid: the larger the contact angle, the higher the efficiency. It is concluded that the governing factor which determines the removal efficiency of the inclusion from liquid steel is the wettability of the inclusion with the steel, and the idea proposed in the present study should be an effective means for production of clean steels.

(cf. *ISIJ Int.*, **41** (2001), 151)

Casting and Solidification

An analytical model of microsegregation in alloy solidification

Y.H.Shin et al.

An analytical model has been developed for modeling microsegregation in the secondary arm spacings of binary alloys. The present model includes the dilution effects both of back-diffusion and coarsening on microsegregation of solute in solidification of binary alloys. When the dilution effect of coarsening is not considered, the present model approaches to the Kobayashi model, whilst it approaches to the Mortensen model in the absence of back-diffusion. The present model was verified by the comparison with other previous analytical models, and successfully applied to the prediction of eutectic fractions in directional solidification of an Al–4.9wt%Cu alloy. The predicted eutectic fractions by the present model are in good agreement with the measured ones. It was found that the present microsegregation model is one of the most appropriate analytical models to account for both the effects of back-diffusion and coarsening.

(cf. *ISIJ Int.*, **41** (2001), 158)

Welding and Joining

Plasma-arc welding sound signature for on-line quality control

Y.WANG et al.

On-line quality control in automated welding operations is an important factor contributing to higher productivity, lower costs and greater reliability of the welded components. The sound signal of plasma arc welding was acquired at high speed and investigated with the aid of computers. It is shown that the amplitude of the sound signal greatly varies with the variation of the statuses of the weld pool. The analysis of frequency domain indicated that the area below the curve of the low frequency band of the power density spectra, which may reflect the oscillation properties of the weld pool, is largest on the transition phase. The high frequency dominant peaks of the sound signal, which may relate to the plasma jet pulsation, is highest on the keyhole-formed phase. The method for detecting the behaviors of the weld pool keyhole was developed. The experimental results indicate that the acoustic emission is a usable, practical information source in the penetration quality detection of plasma arc welding.

(cf. *ISIJ Int.*, **41** (2001), 164)

Surface Treatment and Corrosion

Hydrodynamic effects on galvanising of high strength steels

L.BORDIGNON

A modification of the laboratory galvanisation equipment was made to reproduce the zinc movement along the strip as it is the case industrially during hot dipping. The galvanisation tests in baths containing between 0.24 wt% and 0.28 wt% of aluminium show an improvement of the zinc wettability on high strength steel to the same level as on industrial lines. The same kind of defects (small bare spots) can also be observed when high strength steels with large amounts of alloying elements are galvanised. Comparable inhibition layer and coating adhesion are however obtained with or without a bath stirring.

For galvannealing baths where the aluminium content is smaller (0.135% Al_{eff}), the aluminium depletion obtained at the steel/liquid zinc interface is more important in the non-stirred baths. That depletion of aluminium is no more compensated by the long dipping time (3s) and a thinner inhibition layer is formed on the steel surface with static baths. The thicker inhibition layer, more representative of industrial conditions, induces an increase of the galvannealing temperature to completely transform the coating.

(cf. *ISIJ Int.*, **41** (2001), 168)

Transformations and Microstructures

Calculation of phase equilibria between austenite and (Nb, Ti, V)(C, N) in microalloyed steels

K.INOUE et al.

Thermodynamic calculations of the phase equilibria between austenite (γ) and complex carbonitrides containing Nb, Ti and V, (Nb, Ti, V)(C, N), were performed. The solubility product and formation energy of each carbide and nitride as well as the interaction parameters between components were evaluated. Experimental investigation on phase separation in the complex carbonitrides was also carried out using STEM-EDX and X-ray diffraction. The immiscibility of carbonitride was found to strongly affect the phase equilibria even when the content of microalloying elements in IF steels was very low.

(cf. *ISIJ Int.*, **41** (2001), 175)

Mechanical Properties

Size dependence of delamination of high-carbon steel wire

K.SHIMIZU et al.

In order to find out major causes to produce the wire-size dependence of delamination, comparative experiments were performed with high-carbon steel wires. A large-size wire and a small-size wire were patented, drawn, and blued under almost the same conditions and the resultant wires were compared quantitatively. Consequently, the experiments showed that even when the wire-making processes were controlled equivalently between the two different sizes, the delamination of the large-size wire tended to be less reduced than the small-size wire. An analysis with torsion tests revealed that the observed size dependence was not substantially associated with applied shear stress in torsion, while the yield shear stress had a significant effect on delamination occurrence. Close observation with SEM showed that significantly large microvoids form in the large-size delaminated wires, but not in the small-size non-delaminated wires. Microvoids were found to be nucleated preferentially at the interface between a fragmented cementite particle and relatively thick ferrite. The difference in the stress intensity factor between the different size wires seems to be one of the major causes bringing about the size dependence. Another finding that the as-patented large-size wire had a larger volume of proeutectoid ferrite than the as-patented small-size wire suggests the strong likelihood of proeutectoid ferrite being associated with void formation.

(cf. *ISIJ Int.*, **41** (2001), 183)

Degradation of impact toughness due to formation of R phase in high nitrogen 25Cr–7Ni–Mo duplex stainless steels

J.CUI et al.

Influences of the formation behavior of the R phase on the hardness and the impact toughness were experimentally studied for high nitrogen duplex stainless steels containing 25 mass% of Cr, 7 mass% of Ni, 3 to 5 mass% of Mo, 0.14 to 0.27 mass% of N, and 0.02 mass% of C. The steels were solution heat treated at 1 323 K for 3.6 ks, and then aged at 873 K for various times between 1.0 and 1.08×10^4 ks. For the aged steels, the hardness and the impact toughness were examined with a Vickers hardness test and a Charpy impact test, respectively, whereas the microstructure was observed by transmission electron microscopy as well as by optical microscopy. The experimental results indicate that thin and fine platelet precipitates of the R phase are formed along the {110} planes of body-centered cubic (b.c.c) ferrite (α phase) at early stages of the aging. The formation of the platelet precipitates of the R phase causes the brittle fracture of the α phase and thus the significant degradation of the impact toughness.

(cf. *ISIJ Int.*, **41** (2001), 192)

Precipitation Kinetics and Strengthening of a Fe–0.8wt%Cu Alloy

A.DESCHAMPS et al.

Precipitation kinetics and strengthening have been investigated for a Fe–0.8wt%Cu alloy. Microstructure evolution during aging at 500°C has been studied by a combination of Transmission Electron Microscopy and Small-Angle X-ray Scattering to provide information on the nature and location of the precipitates as well as a quantitative estimate of their size and volume fraction. The associated mechanical properties have been studied by hardness and tensile tests.

The precipitation kinetics measured in this study are fully compatible with results reported for alloys with higher Cu levels. Nucleation of Cu precipitates is promoted by the presence of dislocations whereas coarsening rates in the later stages of aging appear to be not affected by fast diffusion paths along dislocations.

The strength of individual precipitates increases with precipitate size based on the analysis of the mechanical test results. However, the strength of the largest precipitates observed remains approximately half of the strength required for the Orowan by-passing mechanism. The Russell-Brown model for modulus strengthening has successfully been applied to the current data.

Study of the plastic behavior shows that the maximum initial hardening rate is related to the highest strength of the material. This unusual result may be explained by a dynamic strained-induced phase transformation of the precipitates from the bcc to the 9R structure. Consequently, the hardening potential of Fe–Cu alloys is associated with good plastic properties close to peak strength thereby indicating the excellent potential of copper as hardening element for the development of novel high strength interstitial free (IF) steels.

(cf. *ISIJ Int.*, **41** (2001), 196)