Fundamentals of High Temperature Processes

Effect of thermal cycle on liquid structure of pure iron at just above its melting point

Q.ZHAI et al.

The effect of thermal cycle on liquid structure of pure iron was investigated by means of theta–theta type liquid metal X-ray diffractometer. The increase of thermal cycle times results in the reduction of the atomic cluster size and its atomic numbers, the expansion of the disorder areas, and the increase of the disorder degree of the liquid pure iron. The first sharp diffraction peak (FSDP) or pre-peak is found in the structure factor curve of liquid pure iron, which means there is medium-range order (MRO) in this melt. The FSDP or pre-peak directly relates to the correlation of Fe–Fe atoms on the MRO scale. It is concluded that the body-centered cubic (BCC) crystal structure of the previous δ-Fe is partly kept in the liquid pure iron, and the liquid pure iron is a mixture of atomic clusters and disorder areas.

(cf. *ISIJ Int.*, **44** (2004), 1279)

Ironmaking

Influence of basicity and FeO content on viscosity of blast furnace type slags containing FeO

Y.S.LEE et al.

The viscosities of $CaO–SiO_2–Al_2O_3–MgO–FeO$ slags were measured under conditions of C/S=1.15–1.6, 10–13 mass% Al_2O_3, 5–10 mass% MgO and 0–20 mass% FeO. Slag viscosity decreased with increasing FeO content at a fixed basicity (CaO/SiO_2) of slag. Slag viscosity at low FeO (<7.5 mass% FeO) exhibited a minimum value by increasing MgO content in slag. Viscosity decreased with increasing slag basicity up to 1.3 while it increased as slag basicity increased from 1.3 to 1.5. It was proposed that the driving force for the decrease of slag viscosity would be an increase in depolymerization of silicate network at C/S≤1.3, while the viscous behavior at C/S>1.3 would be increased with increasing the chemical potential of primary solid phase *e.g.* dicalcium silicate. A thermodynamic approach for the activity of primary solid phase in molten slags resulted in a reasonable relationship between viscosity and slag components. Therefore, it was confirmed that slag viscosity in basic slags (C/S>1.3) could be estimated by the chemical potential of dicalcium silicate.

(cf. *ISIJ Int.*, **44** (2004), 1283)

Influence of MgO and Al_2O_3 contents on viscosity of blast furnace type slags containing FeO

J.R.KIM et al.

The viscosities of $CaO–SiO_2–Al_2O_3–MgO–FeO$ slag were measured under conditions of C/S=1.35–1.45, 10–18 mass% Al_2O_3, 3.5–10 mass% MgO and 5 mass% FeO. The bosh slag with 10 mass% Al_2O_3 content had the lowest melting temperature and the widest solid-liquid coexisting region at about 5 mass% MgO, while in case of 14 mass% Al_2O_3, an increase in a MgO content from about 3.5 to 10 mass% raised the melting point of bosh slag. The viscosity of bosh slag also exhibited a minimum value at about 7 mass% MgO at temperatures above 1 723 K. However, it was not significantly changed with varying MgO content. On the hand, with increasing Al_2O_3 content, the viscosity of bosh slag increased at a fixed C/S and MgO content. Based on the melting temperature and the behavior of viscosity at a fixed temperature, it could be proposed that the MgO and Al_2O_3 contents in bosh slag should be maintained around 5 and 10 mass%, respectively, for high pulverized-coal ratio (PCR) and low slag volume operations in blast furnace.

(cf. *ISIJ Int.*, **44** (2004), 1291)

Prediction of raceway size in blast furnace from two dimensional experimental correlations

S.RAJNEESH et al.

It has been reported in the literature that raceway measurement made during the decreasing gas velocity is relevant to operating blast furnaces. However, no raceway correlation is available for decreasing gas velocity and none of the available correlations either in increasing or decreasing gas velocity take care of frictional properties of the material. Therefore, a systematic experimental study has been carried out on raceway hysteresis. Based on experimental data and using dimensional analysis, two raceway correlations, one each for increasing and decreasing gas velocity, have been developed. Results of these correlations have been compared with the data obtained from literature on the cold models and plant data along with some experimental data. A good agreement exists between the correlations and other data.

(cf. *ISIJ Int.*, **44** (2004), 1298)

Effect of iron ore particle assimilation on sinter structure

D.DEBRINCAT et al.

The properties of the melt generated during sintering determine the structure of the bonding phases formed. Melts that do not undergo reshaping and coalescence solidify into porous structures and this could have an adverse effect on sinter properties. The properties of melts, just prior to solidification, are highly dependent on the chemical composition of the adhering fines layer in granules and the assimilation behaviour of the nuclear particles. In this study, a carefully controlled bench-scale furnace was used to manufacture analogue sinters, which were characterized using optical microscopy and image analysis. Results show that altering the lime, and silica content of the adhering fines changed the structure of the analogue sinters formed because this altered the ability of the melt generated from the adhering fines, or primary melt, to react with iron oxide. The properties of the ore nuclear particles—in particular, porosity—have a significant influence on the proportion assimilated during the sintering period. The assimilation mechanism is different for porous ores because primary melts are highly mobile and readily penetrate into pores. Results also indicate that because of differences in assimilation mechanism, there are benefits in increasing the volume of primary melt (*i.e.* increased level of fines) when sintering blends containing high levels of porous ores. Maximum sintering temperature was also shown to be important because it influences assimilation rate and the viscosity of melts.

(cf. *ISIJ Int.*, **44** (2004), 1308)

Steelmaking

A new approach to using modelling for on-line prediction of sulphur and hydrogen removal during ladle refining

M.HALLBERG et al.

A simplified model has been developed for on-line determination of sulphur and hydrogen contents in the steel during vacuum degassing in an ASEA-SKF ladle furnace at Ovako Steel in Hofors, Sweden. The simplified model was developed based on results from fundamental mathematical model simulations of hydrogen and sulphur refining for a number of cases representing normal production situations. More specifically, mass-transfer coefficients were determined from the simulations and thereafter used to develop separate simplified models for sulphur and hydrogen refining. Predictions from using the simplified process models agreed well with sulphur and hydrogen data from full-scale plant trials. It was therefore concluded that the main purpose of the study, namely to achieve a less time-consuming model suitable for production applications, was fulfilled. The final part of the paper presents how the simplified models can provide engineers or operators with off-line or on-line guidelines on performing the vacuum degassing operation such that quality requirements regarding sulphur and hydrogen contents in the steel product are met.

(cf. *ISIJ Int.*, **44** (2004), 1318)

Dust formation by bubble-burst phenomenon at the surface of a liquid steel bath

A.G.GUÉZENNEC et al.

We have developed an experimental device for studying the main mechanism of dust formation in electric arc furnace steelmaking: the burst of gas bubbles at the liquid steel surface. As in the case of the air–water system, the bubble-burst process takes place in three steps: breaking of the film cap, projection of film drops, and projection of jet drops. The film break and the jet drop formation are observed with a high-speed video camera. The film drop aerosol enters a particle counter, which characterizes the drops in size and number. Results are presented and discussed. The quantification of both types of projections leads to the conclusion that the film drop projections represent the major source of dust. The amount of film drops greatly decreases with the parent bubble size. Bubbles with diameter under 4 mm theoretically do not produce film drops. Decreasing the CO-bubble size enough would therefore represent an effective solution for reducing drastically the electric arc furnace dust emission.

(cf. *ISIJ Int.*, **44** (2004), 1328)

An assessment of fluid flow modelling and residence time distribution phenomena in steelmaking tundish systems

A.KUMAR et al.

A summary of computational work reported in

the literature on tundish hydrodynamics has been presented wherein, it is shown that a diverse range of both computational (*e.g.*, nodal configurations, boundary conditions, inlet turbulence *etc.*) and physical parameters (*e.g.*, size, number of strands, inlet mass flow rates *etc.*) were applied. Accordingly, the conclusions drawn were found to vary from one study to another. In the present work, an attempt has therefore been made to assess computationally the role of various mathematical model parameters. To this end, mathematical model results were validated against experimental measurements on Residence Time Distribution (RTD) parameters derived from water model tundish.

Experimental measurements of RTD were carried out continuously by monitoring conductivity of water at the tundish exit port on a digital computer using a DAS interface. On the other hand, numerical calculations were carried out *via* the commercial CFD (Computational Fluid Dynamics) software FLUENT, 6.0. The combined experimental and computational study indicated that a sufficiently small grid resolution (control volume of the order of 10^{-6}m3) is necessary to arrive at a practical grid independent solution. Furthermore, Reynolds stress model was found to simulate RTD in the system somewhat superior to the standard coefficient k–ε model. Through comparison of the predicted results with experimental measurements, a set of optimal mathematical model configurations was deduced. It was demonstrated that mathematical model configured in this work is sufficiently reliable and robust as this leads to estimates of RTD parameters (*e.g.*, t_{min}, t_{max}, t_{mean}) close to experimental measurements in a tundish with and without flow modifiers.

(cf. *ISIJ Int.*, **44** (2004), 1334)

Simulation of oxygen penetration and decarburisation in EAF using supersonic injection system

F.Memoli et al.

The supersonic jet generated by a Laval nozzle in air or in steel has been modelled to vary degrees of complexity and with different goals.[1,2]

This paper describes the application of our model to an injection system based on fixed lances, placed in the furnace walls without the help of CFD simulation, which is certainly very precise, but very time consuming and useless for an on line control.

The approach followed here is energy-based and it allows estimating the depth reached by the O_2 during its penetration within the slag and steel. It can be used for an on line control and for the whole description of the injection process. The calculation of a theoretical interface surface allows investigating the chemical process and the mass transport phenomena induced by the injection itself.

This simulation can be used to investigate the required injection parameters to ensure the maximum mass exchange with the bath and to foresee new injection technologies performances.

Moreover, this model of the supersonic injection allows the construction of a decarburisation model that can evaluate the effects and the efficiency of the injection technology.

This article describes the jet-penetration model and the decarburisation model.

The validation of the model has been performed by the comparison with the experimental data of the Tenaris-Dalmine EAF and the KT Supersonic Injection System (the chemical package of Techint Technologies for the multi-point injection of oxygen, carbon and other fines into the EAF).

(cf. *ISIJ Int.*, **44** (2004), 1342)

Effect of silica in slag on inclusion compositions in 304 stainless steel deoxidized with aluminum

H.Todoroki et al.

Experiments were carried out to determine the effect of silica in the slag of CaO–SiO_2–Al_2O_3–MgO–F system on the formation of $MgO \cdot Al_2O_3$ spinel inclusion in 304 stainless steel deoxidized with Al. Immediately after the addition of Al into the molten steel, alumina clusters formed. Simultaneously, reduction of MgO in the slag occurred to raise Mg content in the steel. This resulted in the change in inclusion composition to $MgO \cdot Al_2O_3$ spinel which did not further change. In the previous experiments with CaO–Al_2O_3–MgO–F slag, however, spinel inclusions changed to MgO or liquid CaO–Al_2O_3–MgO system. The difference in behavior was caused by the existence of silica in the slag. Silica in the slag was considered to prevent the extensive reduction of MgO or CaO in the slag by Al to supply soluble Mg or Ca into the molten steel. A stability diagram of inclusions corresponding to Mg and Al contents in the steel was calculated employing available thermodynamic data. The inclusion compositions experimentally obtained well agreed with the diagram. This implies that spinel inclusions were the most stable in the molten 304 stainless steel deoxidized with Al under the presence of 10 mass% silica in the slag. As a result, it was concluded that silica in the slag enhanced the formation of spinel inclusions.

(cf. *ISIJ Int.*, **44** (2004), 1350)

Casting and Solidification

Effect of entrance nozzle design on the fluid flow in an ingot mold during filling

R.Eriksson et al.

Earlier studies have shown that the mold powder reacts with steel during filling of the mold during ingot casting of ball-bearing and tool steels, which results in formation of inclusions. Since all inclusions are bad for the material properties for these grades, this is a phenomenon that needs to be avoided. In this study, fundamental mathematical modeling of the filling of an ingot has been used to predict the fluid flow characteristics. A special effort has been made to model the effect of a modified inlet allowing for a larger volume flow. Predictions made by the presently used numerical model, indicates that a successive increase in the opening angle of the inlet nozzle leads to a gradual decrease in the disturbance of the free surface, during mold filling. Furthermore, the horizontal velocities are lower, which results in lower values of the Weber number which is an indication of less chances for mold powder entrapment into steel. It is concluded that both these improvements leads to decreased possibilities for the creation of inclusions in the steel due to interaction with the mold powder.

(cf. *ISIJ Int.*, **44** (2004), 1358)

Model experiment of particle engulfment into the solidifying shell under fluid flow

H.Yasuda et al.

A model experiment was performed to investigate movement of inclusions near the solid wall and engulfment into the solidifying front. Polystyrene particles (100 μm in diameter) were suspended in flowing melts (water, 20 mass% NaCl aqueous solution and succinonitrile). As the average flow velocity increased, number of the particles reaching the vicinity of the solid wall increased whereas the average stationary time of the particles near the wall decreased. Number of the particles engulfed into the solidifying shell deceased with increasing the flow velocity. Moreover, addition of 3 mass% acetone clearly reduced number of the engulfed particles. In this study, the stationary time and the capture time were introduced to consider the engulfment. The particle engulfment was qualitatively explained by considering changes of the stationary time and the capture time. According to the observation, probability of the engulfment for the particles reaching the solidifying front was 0.01 at most. Only the particles of which the stationary time was much longer than the average value were engulfed. The present study indicated that the particle engulfment under the melt flow should be considered as a probabilistic process.

(cf. *ISIJ Int.*, **44** (2004), 1366)

Numerical analysis of thermal-driven buoyancy flow in the steady macro-solidification process of a continuous slab caster

S.Qiu et al.

The role of thermal-driven buoyancy flow in the steady macro-solidification process of a continuous slab caster and its effect on the predicted flow and temperature distribution are discussed by combining the non-dimensional analysis and the predicted results obtained from a steady three-dimensional coupled fluid flow, heat transfer and macro-solidification model. Results show that the relative strength among the thermal-driven buoyancy flow, the forced flow caused by the SEN impinging jet and the fluid flow through the porous matrix of mushy-zone continuously changes. The strength of thermal-driven buoyancy flow in the mold and sub-mold zone of slab caster is dependent on the characteristic flow velocity, temperature difference and the porosity-permeability ratio relation. The convection flow caused by thermal buoyancy at liquidus temperature of steel can result in the occurrence of local turbulence. The obvious effect zone of the thermal buoyancy flow on the predicted flow and temperature is in the region where the forced flow has become inferior and the mushy porous flow does not play a dominant role.

(cf. *ISIJ Int.*, **44** (2004), 1376)

A DPIV study of liquid steel flow in a wide thin slab caster using four ports submerged entry nozzles

R.D.MORALES et al.

Influence of SEN design and its depth below the meniscus on liquid steel flow inside a large width thin slab mold was studied using a 1 : 1 scale water model. Fluid flow characterization was performed through Digital Particle Image Velocimetry techniques, measurements of bath oscillations and tracer dispersion experiments. Two designs of SEN with four ports (two lateral ports with two bottom ports) were investigated. SEN-1 has a wider bottom base and SEN-2 has a narrow one. Both SEN's provide fluid flows in the mold with upper and lower recirculating flows. Jets emerging from the lateral and bottom ports do not overlap although the surface area of the lateral jet of SEN-1 works inefficiently as compared with that of SEN-2. SEN-1 promotes higher bath oscillations than SEN-2 because the lateral jets travel almost horizontally toward the narrow face. This enhances fluid velocities along the narrow wall until the bath surface. A recirculating flow is formed close to the SEN-1 in the upper bath surface that provokes also high bath oscillations. Design of SEN-2 avoids these flow defects yielding more stable fluid flows. Rising the SEN depths alters negatively the flow characteristics, although SEN-2 is better than SEN-1. Generally speaking both designs yield complex turbulent and unsteady flows and a better SEN design is suggested.

(cf. *ISIJ Int.*, **44** (2004), 1384)

Mould temperature control in continuous casting for the reduction of surface defects

F.CAMISANI-CALZOLARI et al.

Temperature control in the continuous casting mould can have considerable implications for the eradication of surface defects that arise in the process. This paper presents auto regression with external inputs as a modelling tool to describe the effect of casting speed, mould level and water inlet temperatures on the temperature distribution in the mould. The accuracy of the modelling strategy is determined. The model can be used to design a closed-loop controller to maintain the mould temperature at a predefined value. The defects caused by temperature are therefore controlled implicitly through mould temperature, and the delay caused by measurement of defects is thus eliminated. Three controllers are designed and compared through simulation. It is found that an optimal regulator type controller delivers the best performance among the three controllers. Control of only one loop and a switching type controller show marginal improvements over the uncontrolled case.

(cf. *ISIJ Int.*, **44** (2004), 1393)

Unsteady pressure coefficient around an elliptic immersion nozzle

Y.UEDA et al.

An unsteady molten steel meniscus flow sometimes occurs in the continuous casting mold. When it impinges on the immersion nozzle, a severe vertical pressure difference is induced on the outer surface of the nozzle. Mold powder entrapment near the immersion nozzle is closely associated with the pressure difference. The use of an elliptic immersion nozzle is expected to effectively lower the difference, and accordingly, suppress the mold powder entrapment. The pressure difference around the elliptic immersion nozzle however is not quantitatively known yet. In this study it was numerically calculated by the vortex method over a wide aspect ratio range of the nozzle for two types of unsteady meniscus flows. The validity of the numerical results was confirmed from a comparison with previous results obtained from cold model experiments.

(cf. *ISIJ Int.*, **44** (2004), 1403)

Effect of operating parameters of an electromagnetic refining process on the solidified structure

K.SUGIURA et al.

Effect of operating parameters of a refining process on the solidified structure such as frequency and intensity of an alternating current has been experimentally examined by use of Sn–10mass%Pb alloy. In the refining process of a solidified structure in this manuscript, a static magnetic field and an alternating electrical current are simultaneously imposed on the local area of a metal or an alloy using copper electrodes. Concerning the intensity of the electrical current, threshold exists for the refining of the solidified structure, and the refined structure is mainly observed around the electrode in the case that the magnitude of the electrical current is around the threshold value. Imposition of the electromagnetic force in the initial stage of the solidification is crucial to obtain the refined structure in this process and the imposition in the middle stage has no refining function.

(cf. *ISIJ Int.*, **44** (2004), 1410)

Forming Processing and Thermomechanical Treatment

Modeling of austenite grain size distribution in Nb microalloyed steels processed by thin slab casting and direct rolling (TSDR) route

P.URANGA et al.

A mathematical model has been developed to predict the austenite microstructure evolution of Nb microalloyed steels during "Thin slab casting" and "Hot direct rolling" (TSDR) processing. The model is based on empirical equations specifically derived for the microstructural and processing features typical in these new technologies. Its main novelty is that it works with austenite grain size distributions instead of the typical mean values as used in conventional models to represent the microstructure. This fact is particularly important in working with as-cast austenite due to the wide range of grain sizes present in this microstructure. In the model the different softening and hardening mechanisms that can operate during hot working in austenite are considered: static, dynamic and metadynamic recrystallization, grain growth after recrystallization and Nb(C, N) strain induced precipitation. The model uses the initial austenite grain size distribution as input and provides the size distribution of recrystallized and unrecrystallized grains at the entry of any rolling pass. A validation of the model has been carried out in the laboratory by multipass torsion tests. The model is capable of predicting any heterogeneities that may appear in the final microstructure after this kind of processing and that are not well predicted by using conventional models based on mean values. Additionally, it can calculate the deformation history, in terms of the strain accumulated in the austenite, and stress behavior, in terms of the mean flow stress (MFS) corresponding to each deformation pass.

(cf. *ISIJ Int.*, **44** (2004), 1416)

Transformations and Microstructures

Strength anisotropy and residual stress in drawn pearlite steel wire

T.SUZUKI et al.

Strength anisotropy is found by tensile and compressive tests for a drawn pearlite steel wire, where the compressive tests are performed for prepared specimens along directions of 0, 45 and 90 degrees with respect to the drawing direction. The influence of annealing on such anisotropic strength is also examined. To make clear the origin of the strength anisotropy, texture and residual strain are measured using neutron diffraction. It is revealed that residual stresses in the ferrite and cementite phases are the cause of strength anisotropy.

(cf. *ISIJ Int.*, **44** (2004), 1426)

Role of combined addition of niobium and boron and of molybdenum and boron on hardenability in low carbon steels

T.HARA et al.

Effects of the combined addition of niobium (Nb) and boron (B) and of molybdenum (Mo) and B on hardenability were investigated using low carbon steels. Strength synergically increases due to the combined addition of Nb and B and that of Mo and B. It is thought that strength increases due to these combined additions because austenite (γ) to ferrite (α) transformation is retarded and bainite transformation is promoted due to the increase in the segregated B along the γ grain boundary before γ to α transformation. The mechanism for the increase in the segregated boron along the γ grain boundary by these combined additions is considered below. $Fe_{23}(C,B)_6$ precipitates formed along the γ grain boundary are suppressed by these combined additions because of the suppression of C diffusion towards the γ grain boundary due to the precipitation of the fine dispersive niobium-titanium carbonnitride (Nb, Ti)(C, N) or titanium-molybdenum carbonnitride (Ti, Mo)(C, N) and the formation of C clusters of Nb and Mo during rolling or during cooling after rolling. Therefore, the segregated B along the γ grain boundary increases and γ to α transformation is retarded. The combined addition of Nb and B or that of Mo and B in low C bainitic steel is effective for increasing strength without deteriorating low temperature toughness. It is clarified that the increments of hardenability by the combined addi-

tion of Nb and B is different from that of Mo and B due to the difference of the amount of carbide precipitates.

(cf. *ISIJ Int.*, **44** (2004), 1431)

Mechanical Properties

The effect of grain boundary cavities on the tertiary creep behavior and rupture life of 1.25Cr-0.5Mo steel welds

S.FUJIBAYASHI

In general, the ultimate creep failure mode of welds fabricated from low alloy ferritic steels can be considered to be Type IV cracking resultant from coalescence of grain boundary damage. Thus, observation of grain boundary feature using a replication technique has been one of the most common practices for the remnant life assessment of welds operated at high temperatures. The experimental results in the present work and those found in previous works, however, prove that the feature of grain boundary damage highly depends upon testing conditions. Therefore, the relationship between the extent of damage and remaining life would not necessarily be effective for the practical use if it were obtained under the extremely accelerated laboratory conditions.

In contrast, strain rate measurement predicted the rupture life with reasonable accuracy independently of the susceptibility to grain boundary cavitaion. The increase in the strain rate due to the presence of creep cavities was not observed in the experiments using heat treated specimens, which had the microstructure expected at the Intercritical HAZ in whole gauge length. This fact suggests the effectiveness of strain rate measurement for the life assessment and the necessity of reconsidering the physical meaning of grain boundary damage.

(cf. *ISIJ Int.*, **44** (2004), 1441)