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Fundamentals of High Temperature Processes

Effect of aluminum, titanium or silicon addition on nitrogen removal from molten iron

H.ONO-NAKAZATO et al.

There is a limit for lowering nitrogen in steel because of pickup from the atmosphere during and after degassing. Therefore, nitride capacity of various fluxes has been measured in order to examine the possibility of the nitrogen removal by using slag. In this study, nitrogen removal rate from molten iron to $CaO–Al_2O_3–CaF_2$ melt has been measured, and the effect of Al, Ti or Si addition into the metal has been examined at 1 873 K. From the results, it is found that nitrogen in molten iron can be removed effectively by the addition of aluminum, titanium, or silicon. It can be considered that the additives cause the effects on the oxygen partial pressure and the activity of nitrogen in the metal. For the nitrogen removal, it is most important to keep the oxygen partial pressure in the metal lower to raise the nitrogen distribution ratio. From this point, aluminum is the most effective of the additives investigated in the present work.

(cf. *ISIJ Int.*, **43** (2003), 975)

Generation of droplets in slag–metal emulsions through top gas blowing

SUBAGYO et al.

The behavior of metal droplets in a slag–metal–gas emulsion through impinging gas blowing was investigated experimentally using a cast iron–slag–nitrogen gas system at high temperatures. A mathematical model of the emulsification process for determining the generation rate, size distribution, and residence time of metal droplets has been developed and successfully validated using experimental data. From the present work, it was found that the generation rate and size distribution of metal droplets is strongly influenced by the ratio of the inertial force of blown gas to the surface tension and buoyancy forces of the liquid metal. A new dimensionless number, *i.e.* blowing number, which represents the ratio of inertial to surface tension and buoyancy forces and also the departure of the system from its stable condition defined by the Kelvin–Helmholtz criterion, is proposed. A functional relationship of generation rate and size distribution of metal droplets with the blowing number is proposed.

(cf. *ISIJ Int.*, **43** (2003), 983)

Ironmaking

A mathematical model of fluid flow phenomena for the liquid bath in smelting reduction processes

C.-W.CHEN et al.

This study established a mathematical model of fluid flow phenomena for the liquid bath in smelting reduction processes by the CFD (Computational Fluid Dynamic) software PHOENICS. The SEM (Scalar Equation Method) model was employed to treat the multi-phase flow, *viz.* liquid metal and injection gas. The Chen–Kim k–ε turbulent model which is suitable for gas-stirred system was imposed. An index named Mixtrg was defined to evaluate the mixing level of the injection gas to the liquid bath. The accuracy of the model was verified by comparing the theoretically predicted vertical velocity with the experimental data for the bubble-stirred air–water ladle.

Based on the standard operational condition, the influence of operational variables of simulated vessel was studied for the flow patterns of liquid bath. The calculated flow patterns of bath were helpful for understanding about distribution of injection gas, flow patterns of liquid bath, wave motion of liquid bath surface and the erosion conditions near the wall of furnace.

(cf. *ISIJ Int.*, **43** (2003), 990)

Exergy analysis of charcoal charging operation of blast furnace

H.NOGAMI et al.

Effective use of biomass resource is expected to be one of the solutions to the environmental problems, since a sort of biomass absorbs carbon dioxide through photosynthesis reaction. One of the possibilities to utilize such biomass resources is the replacement of coal and/or coke with charcoal. With nature of charcoal it is known that the hot metal quality can be improved as well as abatement of environmental impact through less slag generation and virtually no CO_2 and SO_2 emissions. This paper performed an exergy analysis on charcoal charged blast furnace. As a result, it is revealed that the charcoal system needs more enthalpy and exergy inputs than conventional ironmaking system while it produces more energy available in the other processes. This keeps exergy loss in charcoal system in the comparable level with the conventional system. The analysis shows that each process included in the system still has possibility to be improved. Thus the performance of the charcoal system is expected to be equivalent to or even better than the conventional system. Therefore ironmaking system with charcoal charged blast furnace is expected to be a key technology to contribute environmental issues.

(cf. *ISIJ Int.*, **43** (2003), 997)

Kinetics of silicon transfer from pulverized coal injected into blast furnace under intensive coal injection

Y.MATSUI et al.

With the progress of shifting to operation of intensive coal injection, Si in molten metal tends to increase, and this phenomenon cannot be explained by a conventional estimation model which does not distinguish between coke and pulverized coal on contribution to Si in molten metal. With respect to SiO gasification reactions from SiO_2 in pulverized coal, basic experiments were carried out on SiO(g) generation from pulverized coal char packed in a crucible under flow of reducing gas, and reaction rate was deduced with SiO_2 concentration in pulverized coal ash and slag composition taken into account. Furthermore, with respect to Si transfer in blast furnace, the SiO(g) generation rate derived from pulverized coal under intensive coal injection was evaluated and effects of pulverized coal on Si in molten metal were investigated. Consequently the molten metal [Si] variation associated with changes of pulverized coal brand in an actual furnace is become to be estimated.

(cf. *ISIJ Int.*, **43** (2003), 1004)

Effect of blast furnace profile on inner furnace states

T.INADA et al.

The effects of blast furnace profile on operation are investigated. The investigation is made by use of mathematical simulation models that are able to evaluate the operational conditions as follows: pressure drop, fuel rate and stability against channeling. The considerable number of furnace profiles are evaluated under the condition that inner volume, furnace height and hearth diameter have been given. In this investigation, geometrical parameters of furnace profile on furnace condition are clarified, and the better furnace profile for the furnace condition is shown.

(cf. *ISIJ Int.*, **43** (2003), 1010)

Casting and Solidification

Shrinkage of round iron–carbon ingots during solidification and subsequent cooling

K.HARSTE et al.

The shrinkage of round iron–carbon ingots during solidification and subsequent cooling has been investigated with hot model experiments involving round ingots of 50 kg of steel. Three motor driven sensors made it possible to measure the shrinkage without deformation of the shell starting a few seconds after casting.

The temperature distribution was computed with a thermal model. Thereafter, a mechanical model was applied to compute the shrinkage finding satisfactory agreement between the measured and computed shrinkage–time curves. Data are given on the effect of carbon content on the shrinkage of steel and it was confirmed that there is a shrinkage peak at about 0.1 mass% carbon.

(cf. *ISIJ Int.*, **43** (2003), 1018)

Effects of MnS on the heterogeneous nucleation of Cu precipitates in Fe–10 and –5mass%Cu alloys

H.HASEGAWA et al.

Copper in steel has been thought harmful because of the hot shortness at grain boundaries, but Cu precipitates finely distributed inside of each grain increase the strength. If the problem of hot shortness is solved, scrap recycling will become much easier and even Cu can be used as an important alloying element. It is therefore most important to investigate the behavior of Cu precipitation in Fe–Cu alloys at high temperatures. In this study, *in-situ* observation of the Cu precipitation on cooling in Fe–10mass%Cu and Fe–5mass%Cu alloys was made using a confocal scanning laser microscope. The precipitates were analyzed by SEM-EDX after *in-situ* observation experiments.

As a result the effect of MnS inclusion on the het-

erogeneous nucleation of Cu precipitate was made clear. In Fe–10 mass%Cu alloy containing MnS inclusions, the starting temperature of Cu precipitation became higher and its distribution became more uniform than the same alloy without MnS inclusions. In case of Fe–5mass%Cu alloy containing MnS inclusions, some of Cu precipitates appeared in γ phase before the γ/α phase transformation. In case of the same alloy without MnS inclusions, many fine Cu precipitates appeared in α phase after the γ/α phase transformation. The complex precipitate of MnS and Cu was also found indicating that Cu precipitated at MnS inclusion. The reason for these facts was explained by the heterogeneous nucleation theory. The undercooling for the Cu precipitation was estimated to be smaller in the alloy with MnS inclusions than in another case. Based on these results, if the nucleation sites such as MnS inclusions are finely distributed beforehand, the heterogeneous nucleation of Cu precipitates will be accelerated and its distribution will be made very fine.

(cf. *ISIJ Int.*, **43** (2003), 1028)

Forming Processing and Thermomechanical Treatment

Hot rolling of light gauge steel strip

P.C.ZAMBRANO et al.

Production of hot rolled thin gauge steel strip in a compact six-stand mill was studied by means of mathematical modelling and on site measurements. Data obtained during processing low carbon steel strip ranging from 1.06 to 2.68 mm in final outgoing thickness included speeds, reductions and separation forces at each of the six stands. The mean flow stress during rolling was calculated from the rolling loads, assuming adhesive conditions within the roll-gap, and by means of a mathematical model that accounts for strain hardening and the occurrence of various dynamic restoration phenomena during deformation. It was found that the values of the mean flow stress values, independently of the way they were obtained, varied as a function of both, strain rate and temperature, being possible to derive a unique formulation to describe their behaviour.

(cf. *ISIJ Int.*, **43** (2003), 1037)

Effect of thermal fatigue property of hot strip mill work roll materials on the rolled-in defects in the ultra-low carbon steel strips

J.-H.RYU et al.

This work was carried out to prevent the rolled-in defects originated from the roll surface deterioration through the investigation of the effect of the thermal fatigue property of hot strip mill work roll materials on the roll surface deterioration and subsequent surface defects in the cold-rolled ultra-low carbon steel strips. The thermal fatigue property was estimated by conducting the thermal fatigue test for an existing nickel-grain iron and a candidate high speed steel in the temperature range of 200 to 600°C, and its result was interpreted on the base of the microstructures, the mechanical and physical properties of the roll materials. It was found that the high speed steel had much better thermal fatigue property than the nickel-grain iron, which was attributed to a lower carbide content, a higher tensile and compressive strength and a higher thermal conductivity. And then, the effect of the roll materials on the rolled-in defects in the ultra-low car-bon steels was investigated by inspecting the work roll surface deterioration in actual hot strip mill and subsequent surface defects in cold-rolled strips. The high speed steel roll with an excellent thermal fatigue property showed much higher resistance against roll surface deterioration than the nickel-grain iron roll, which led to prevention of the surface defects in the cold-rolled ultra-low carbon steel strips.

(cf. *ISIJ Int.*, **43** (2003), 1043)

Grain growth modelling for continuous reheating process—a neural network-based approach

Y.Y.YANG et al.

An neural network-based modelling approach is employed to predict the grain growth behaviour during continuous reheating. Using a significant data set containing critical information on the grain growth, a neural network based model has been trained. A compact set of process variables has been selected as the model inputs, based on expert knowledge as well as data analysis techniques. Ensemble modelling techniques have been used to improve model performance as well as to provide error bounds for prediction confidence. The resulting neural network model gives an impressive prediction performance, with the prediction error very close to the maximal measurement standard deviation. The neural network model has been tested on new grain growth data with more divergence in the reheating patterns, and gives a satisfactory prediction on these data as well. It is concluded that the developed grain growth model is capable of providing the initial microstructures for an integrated thermomechanical model, with a very fast computing speed.

(cf. *ISIJ Int.*, **43** (2003), 1047)

Development of constitutive equations for a high carbon steel using additivity rule

S.SERAJZADEH

Flow behavior of a high carbon steel under hot deformation condition has been studied and a mathematical model for describing the flow stress under isothermal and constant strain rate as well as under non-isothermal and varied strain rates has been developed. For doing so, Bergstrom dislocation model together with the additivity rule for strain has been employed also, hot compression experiments at various temperatures and strain rates have been utilized to achieve the kinetics of dynamic recovery and recrystallization of the high carbon steel. The comparison between the predicted and experimental results under both isothermal and non-isothermal conditions verifies the validity of the proposed model.

(cf. *ISIJ Int.*, **43** (2003), 1057)

Stepped austempering of GGG 40 ductile cast iron

E.EL-KASHIF et al.

The effect of stepped austempering heat treatment (900°C, 60 min; 380°C, 15–120 min; 320°C, 60–360 min) on the microstructural and mechanical properties of an unalloyed ductile iron having a chemical composition of 3.86% C, 2.1% Si, 0.4% Mn, 0.042% Mg, 0.059% S and 0.07% P was studied. These properties were compared with those obtained by single austempering heat treatment (900°C, 60 min; 380°C, 60–360 min). Microstructure, hardness, Charpy impact V-notch and tensile properties were evaluated after each heat treatment cycle. The average austenite carbon content and retained austenite content have been evaluated by

X-ray diffraction. The fractography of tensile heat treated specimens was examined and evaluated using SEM. The results obtained showed that a stepped austempering treatment could be used to increase the strength without significant loss in ductility or impact energy compared with single austempering. The optimum combination of mechanical properties is obtained at first step austempering time of 45 min. For the other conditions, The UTS increases slightly by increasing the second step austempering time. The average austenite carbon content results indicate that stage II begins after 120 min of the second step austempering time which leads to reduction in ductility and impact toughness as a result of carbides precipitation. Decreasing the first austempering time, accelerates the stage I reaction in the second step treatment but causes a loss in the strength and hardness and an increase in ductility and impact energy. Analysis of fractured surfaces reveals that the fracture of stepped austempered ductile cast iron is a ductile fracture and this mode almost remains unchanged with different conditions.

(cf. *ISIJ Int.*, **43** (2003), 1063)

Grain refinement of as cast austenite by dynamic recrystallization in HSLA steels

N.FUJITA et al.

Recent progress of steel manufacturing process necessitates to refine an extremely coarse austenitic microstructure evolved in a strand cast steel. Grain refinement of as cast austenite by dynamic recrystallization in HSLA steels was studied by using a hot working simulator. The specimens were prepared from a strand cast slab and the hot rolled steel plate of 0.09%C–1.14%Mn–2.26Ni–0.54Mo–0.045%V steel supplied from a steel plant, and also laboratory heat ingots of 0.14%C–1.45%Mn and 0.14%C–1.45%Mn–0.018%Ti steels. Variations of the true stress–true strain curve and dynamically recrystallized grain size with the deformation temperature, strain rate and the initial γ grain size were investigated by hot compression test. It was confirmed that dynamically recrystallized grain size in as cast steels was determined simply by steady state flow stress or Zener–Hollomon parameter, but was not influenced by the initial grain size. Austenitic grain size variation with the reheating temperature in the as cast 0.09%C–2.26Ni–Mo–V steel was very small, and flow stress in the as cast Ti-bearing steel was markedly higher compared with those of the hot rolled plate of this steel or the C–Mn steel. These appeared to be caused by grain growth suppression due to the interdendritic phase enriched with carbon or alloying elements, and dispersion of the micro

segregation region with high hardness, respectively. Finally, the direct hot deformation experiment after levitation melting and solidification was conducted, where the Ti-bearing steel was reheated at the temperature from 1 743 to1 773 K and hot deformed by tensile strain at 1 523 K. It was confirmed that very coarse γ grain size in an order of mm was much refined down to 130 to170 μm by dynamic recrystallization.

(cf. *ISIJ Int.*, **43** (2003), 1070)

Transformations and Microstructures

Crystallographic analysis of $\{225\}_f$ martensite transformation in Fe–Cr–C alloy

X.LIN et al.

The microstructure of $\{225\}_f$ martensite transformation in Fe–Cr–C alloy was analyzed by means of transmission electron microscopy (TEM), and the habit plane rotation was predicted by means of Displacement Vector Theory, and its surface relief effect was observed and a mathematical model for the quantitative analysis of habit plane rotation of $\{225\}_f$ martensite transformation was established by means of atomic force microscopy (AFM). The experiment showed that the habit plane rotation of $\{225\}_f$ martensite transformation predicted by means of Displacement Vector Theory was 9.89°, which was incompatible with the concept of invariant plane strain (IPS); its surface relief revealed no character of IPS, that is, the formerly formed "surface relief packet" was irregular "N"-shaped, as well as one surface was planar, and the other surface was curved, and the latterly formed "surface relief packet" was irregular "N"-shaped, composed of layers of some small surface relives; the habit plane rotation of $\{225\}_f$ martensite transformation quantitatively analyzed (7.69°) by means of AFM was in agreement with the prediction of Displacement Vector Theory (7.98°), and it firmly confirmed the correctness of Displacement Vector Theory.

(cf. *ISIJ Int.*, **43** (2003), 1080)

Metadynamic and static recrystallization of hypereutectoid steel

A.M.ELWAZRI et al.

The metadynamic and static recrystallization behavior in hypereutectoid steel containing 1 % carbon was determined by hot compression testing. Compression tests were performed using double hit schedules at temperatures between 900 to 1 050°C, strain rates of 0.01 to $1s^{-1}$ and recrystallization times of 0.1 to 500 s. The characteristics of static and metadynamic recrystallization are distinctly different. Results show that the metadynamic kinetics was twice as fast as the static kinetics. These data were used to generate equations to predict the kinetics of static and metadynamic recrystallization, as well as the evolution of grain size, after recrystallization.

(cf. *ISIJ Int.*, **43** (2003), 1087)

Two-phase separation of primary MX carbonitride during tempering in creep resistant 9Cr1MoVNb steel

K.SUZUKI et al.

Precipitation behaviour during heat treatment has been investigated on 9Cr1MoVNb steel. Coarse primary and fine secondary MX carbonitrides are observed in the as normalized condition. On the other hand, coarse primary MX is not detected after tempering at 1 038 K, and Nb-rich and V-rich fine secondary MX carbonitrides and $M_{23}C_6$ carbide are observed in the as tempered condition. Variations of metallic elements concentrations of Nb-rich MX and V-rich MX in the as tempered condition are within the relatively small ranges. Average diameter of 34 nm for V-rich MX is slightly larger than that of 24 nm for Nb-rich MX in the as tempered condition. Both size and metallic elements concentrations of the fine secondary MX observed in the as normalized condition are almost the same as those of Nb-rich MX observed in the as tempered condition. A composition of metallic elements of the coarse primary MX varies along the line between those of Nb-rich MX and V-rich MX in a Cr–Nb–V ternary phase diagram. It has been considered that, at normalizing temperature of 1 323 K, Nb-rich MX and V-rich MX forms solid solution and composition of the primary MX varies along the tie line between those two phases. Two-phase separation of primary MX into Nb-rich MX and V-rich MX may be caused by the miscibility gap in primary MX and another two phases at the tempering temperature of 1 038 K.

(cf. *ISIJ Int.*, **43** (2003), 1096)

Computer simulation of 3-dimensional dendrite growth using modified phase field method

D.P.ZHAO et al.

Numerical simulation of three-dimensional dendritic growth is studied by using a macro–micro coupled method and a capturing liquid method. The dendritic growth is controlled by the solution of the phase field equation. Since it is difficult to compute the microstructure of a whole sample, a scheme is adopted that the temperature field is calculated on the whole sample, while the microstructure computation is carried out by selecting a macro-cell in the casting. Under the condition of not changing the Phase-field Model, a calculating method is advanced, which captures the liquid cells into the interface cells. In that method, every calculated micro-cell is endowed with a variable which identifies whether the cell is in the interface region and the phase field equation is only solved for the cells in that region. When the dendrite grows, the method captures the liquid cells into the interface ones and pushes the interface region forward. For the captured liquid cells, the values of the phase variable are modified. We apply the calculating method to accelerate the calculating speed, and realize the simulation of three-dimensional single grain and multiple grains for aluminum alloy. The simulation results are compared with those obtained experimentally.

(cf. *ISIJ Int.*, **43** (2003), 1102)

Mechanical Properties

Mechanism of toughening in ferritic iron by solute copper at low temperature

J.SYARIF et al.

The ductile-to-brittle transition (DBT) and plastic deformation behaviors were investigated in Fe–(0~2)mass%Cu alloys to understand the effect of solute Cu on the mechanical properties of ferritic iron. The DBT temperature of ferritic iron in Charpy impact test was lowered by the solute Cu although the hardness at room temperature was increased owing to solid solution hardening. Tensile tests revealed that the yield stress of the Fe–1mass%Cu alloy becomes smaller than that of the Fe–0mass%Cu alloy in the temperature range below 223 K through solid solution softening by Cu. The solid solution softening makes slip deformation easy to occur even at such a lower temperature and also at high strain rate. This leads to suppressing twin deformation which induces brittle fracture of ferritic iron at low temperature, and resulting in the shift of DBTT to lower side.

(cf. *ISIJ Int.*, **43** (2003), 1107)