（＊掲載記事題目及び掲載頁は変更になる場合があります。）

Fundamentals of High Temperature Processes

Estimation of surface tension of molten silicates using neural network computation

M.NAKAMOTO et al.

Neural network computation was applied to the estimation of surface tension in ternary silicate melts. In addition, the criterion for designing the units in the middle layer of the layer-type neural network computation was discussed. It was found that the C_p-criterion modified by considering the degrees of freedom in the neural network computation was useful for determining the number of units in the middle layer, which gives an optimal estimation. The surface tension calculated by neural network computation using units determined by the C_p-criterion virtually reproduced the experimental data in molten ternary silicates with high precision.

(cf. *ISIJ Int.*, **47** (2007), 1075)

Thermodynamics of titanium, nitrogen and TiN formation in liquid iron

W.-Y.KIM et al.

Thermodynamics of titanium, nitrogen and TiN formation in liquid iron was investigated using the metal–nitride–gas equilibration under different nitrogen partial pressures in the temperature range of 1 873–1 973 K. The nitrogen solubility in liquid iron increased with increasing titanium content. Pure solid TiN was formed at critical contents of titanium and nitrogen in liquid iron. The experimental results were thermodynamically analyzed using Wagner's interaction parameter formalism to determine the first-order interaction parameter between titanium and nitrogen, the first-order self interaction parameter of titanium, and the equilibrium constant for the dissolution of pure solid TiN in liquid iron given as follows.

$$e_N^{Ti} = -8\,507/T + 4.18, \quad e_{Ti}^{N} = -29\,110/T + 14.3$$

$$e_{Ti}^{Ti} = 0.048 \ (1\,873\text{–}1\,973\ \mathrm{K})$$

$$\mathrm{TiN\,(s)} = \underline{\mathrm{Ti}} + \underline{\mathrm{N}}$$

$$\log K_{TiN} = -15\,780/T + 5.63$$

(cf. *ISIJ Int.*, **47** (2007), 1082)

Viscosity of highly basic slags

S.-H.SEOK et al.

The viscous behavior of $CaO–SiO_2–FeO–MgO$ slags saturated with dicalcium silicate ($2CaO \cdot SiO_2$) with 8 mass% MgO at 1 873 K, and $CaO–SiO_2–FeO–Al_2O_3–MgO$ slags are measured under the conditions of highly basic slag compositions with regard to the fluidity of BOF slag and slag coating technology. The experiment shows that slag viscosities increase with decreasing temperature for almost all the slags that have been investigated over a range of temperature range, and the slag viscosity has exhibited different behavior in the temperature range lower and higher than 1 773 K. The viscosity of the present slag systems has decreased with increasing FeO content. The viscosities depended on Al_2O_3 and FeO contents more strongly than on MgO content. The slag basicity has a more significant effect on increasing slag viscosity. A thermodynamic approach for the constants of the Einstein–Roscoe equation has resulted in a reasonable relationship between the relative viscosity and the volume fractions of solid phases estimated from the slag compositions. Thus, the present study confirms that the viscosities of highly basic slags can be estimated in terms of the slag compositions by predicting the fraction of solid phases in the slags for the stable BOF operation and the reliable coating of vessel lining.

(cf. *ISIJ Int.*, **47** (2007), 1090)

Ironmaking

The reduction of wustite with high oxygen enrichment and high injection of hydrogenous fuel

J.LI et al.

In order to reduce CO_2 emission and energy consumption in a blast furnace, it is necessary to investigate the effects of some factors on direct reduction from wustite (FeO) to iron(Fe) with high oxygen enrichment and high injection of hydrogenous fuel, such as the composition and temperature of reducing gas mixture and the water–gas shift reaction. The current experiments reveal: (1) Reducing power of gas mixture with low oxygen enrichment and high PCI injection is limited, the reduction degree of wustite is 53.6% after 90 min at 1 000°C; While with high oxygen in blast (40%) and high natural gas injection (about 15% H_2 in hearth gas), the reduction degree reaches 100% after 64.81 min. In the case of reduction with pure oxygen and higher hydrogen, the reduction speed promotes further. At 900°C, 100% reduction needs 64 min. (2) The utilization efficiency of hydrogen drops when H_2 content is over 50% in the gas mixture without N_2. The optimum value of H_2 content for pure oxygen blast furnace is between 15–30% from the point of view of wustite reduction. (3) The water–gas shift reaction counteracts wustite reduction in the case of gas mixture with high content of CO_2 and H_2 at elevated temperature.

(cf. *ISIJ Int.*, **47** (2007), 1097)

Identification of multi-fractal characteristics of silicon content in blast furnace hot metal

S.LUO et al.

An improved approach was proposed to identify the multi-fractal characteristics of silicon content in hot metal from No. 7 BF at Handan Steel, No. 1 BF at Laiwu Steel and No. 6 BF at Linfen Iron and Steel Group Co. Comprehensive and quantitative details of the partial fluctuant singularity and fluctuant singularity at different levels are displayed through the computation of generalized Hurst index, scaling function and multi-fractal spectrum. The results confirm the existence of multi-fractal characteristics in the investigated time series. To describe such fluctuation in a single Hurst index or box dimension is insufficient. It is concluded that the theory and methods based on normal distribution, sequence unrelated and single fractal needs addition and amendments.

(cf. *ISIJ Int.*, **47** (2007), 1102)

Casting and Solidification

Mould heat transfer in the continuous casting of round billet

L.GUO et al.

Mould heat transfer behaviors during the continuous casting of round billets are elucidated in this paper. Round copper moulds were instrumented with 72 thermocouples and mould temperature together with heat flux were monitored simultaneously with mould powder lubrication during continuous casting of a diameter 178 mm round billets. The profiles of the temperature and heat flux were analyzed based on the longitudinal and circumferential monitoring data under different installation status of moulds. The influences of steel carbon content, casting speed, and mould oscillation frequency on heat transfer have been discussed especially at position 70–110 mm below the meniscus where the heat transfer was the highest and most sensitive to operational parameters. Eventually, the correlation coefficient, defined as the correlation of local heat flux and temperature (CCHT) in the hot face of mould around the mould circumference at the same mould height, has proved to be a good characteristic parameter for analyzing the influence of scale on abnormal heat transfer in quantity.

(cf. *ISIJ Int.*, **47** (2007), 1108)

Development of fluoride-free mold powders for peritectic steel slab casting

G.WEN et al.

In this paper, titanium-bearing blast furnace slags ($CaO–SiO_2–TiO_2$) produced at Panzhihua Iron and Steel Company (P. R. China) is used as the base material to develop fluoride-free (F-free) mold powders to improve the heat transfer between the mold and the strand. Effects of the binary basicity (CaO/SiO_2), TiO_2, Na_2O, Li_2O, MgO, MnO and B_2O_3 on the melting temperature, viscosity and heat flux of F-free mold powders are investigated. The laboratory results indicate that 1) the melting temperature and the viscosity of the F-free powder decrease, as expected, with increasing the content of Li_2O, B_2O_3 and Na_2O respectively, but the lowest viscosity is achieved with 6.0 mass% TiO_2; 2) the heat flux of the F-free slag film with 1.0–6.0 mass% TiO_2 is close to that of a conventional mold slag film with 2.0–10.0 mass% F; 3) the effect of basicity of the F-free powder on the heat flux is the same as the powder bearing fluoride; 4) the heat flux changes significantly with more than 8.0 mass% Na_2O and about 4.0 mass% MnO, whereas the effects of Li_2O and B_2O_3 in the F-free powder on heat flux are not significant. The suitable range of main components of the F-free powder with TiO_2 is proposed for casting peritectic-grade-steel slabs. The industrial trials of peritectic steel casting, using the proposed F-free flux, reveals a good surface quality of the slab. and well-controlled heat transfer at the continuous casting mold by the F-free powder with the precipitated crystalline phase being perovskite ($CaTiO_3$) instead of cuspidine in the conventional mold slags that contain fluoride.

(cf. *ISIJ Int.*, **47** (2007), 1117)

Instrumentation, Control and System Engineering

Prediction of hot flow stress of CrMoV steel using artificial neural network (ANN)

A.BAPARI et al.

Hot flow stress of CrMoV steel was extracted using hot compression test. Test was carried out in strain range of 0.1–0.9, with strain rate of 0.1–5 s^{-1} and the temperature of 900–1 200°C. Flow stress was predicted by using conventional regression method, *i.e.*, Zenner–Holloman parameter with hyperbolic function. The results showed low accuracy of prediction with a high relative error. Several two hidden layers Artificial Neural Networks (ANN) architectures with back propagation algorithm and momentum learning process were applied using Matlab software. They used strain, strain rate and temperature as input and flow stress as output. It was found that an optimum architecture of 3–9–10–1 shows proper prediction with respect to the conventional regression method, *i.e.*, the relative error reached −0.13% in place of 11.52%. This ANN method is also capable of generating high precision output for unseen deformation conditions if proper initial weights and biases are used.

(cf. *ISIJ Int.*, **47** (2007), 1126)

Chemical and Physical Analysis

Modeling of hydrogen thermal desorption profile of pure iron and eutectoid steel

K.EBIHARA et al.

We have developed a numerical model to simulate the hydrogen desorption profiles for pure iron and eutectoid steel, which is obtained in thermal desorption analysis (TDA). Our model incorporates the equation of McNabb and Foster without the hydrogen diffusion term combined with the Oriani's local equilibrium theory. It is found that the present numerical model successfully simulates the hydrogen desorption profile both for pure iron and for eutectoid steel. We further verify the model by discussing the trapping site concentration and the effect of hydrogen diffusion.

(cf. *ISIJ Int.*, **47** (2007), 1131)

Quantitative chemical analysis of fluorine in the slags produced in stainless argon–oxygen decarburization process by X-ray fluorescence spectrometry

S.-M.JUNG

A quantitative analysis method of fluorine in the slags produced in the stainless argon–oxygen decarburization (STS AOD) process by X-ray spectrometry was proposed employing fusion pretreatment technique. The research concerned the separate quantification of calcium fluoride and calcium oxide contained in stainless AOD slags. X-ray diffraction measurement was performed to identify the stable phase of fluorine compound, which is primarily present in the slags. Homogeneous glass discs were prepared under the following conditions: lithium borate mix as flux with sample dilution (1 : 15), with the addition of one tablet of ammonium iodide as releasing agent at 1 323 K for 20 min. XRD patterns and semi-quantitative results for the STS AOD slags provided synthetic standards based on the approximate compositional range of STS AOD slags by combining highly pure compounds and oxides. These standards were employed to establish the XRF calibration curves for F, Ca_tO, SiO_2, MgO, Al_2O_3 and Cr_2O_3. The calibration curves were used in the quantitative analysis of a synthetic standard and an pure calcium fluoride with satisfactory precision and accuracy, considering the matrix effects and line overlap corrections. The suggested method might be a useful solution to the problem with the quantitative analyses of calcium fluoride in stainless AOD slags by XRF spectrometry.

(cf. *ISIJ Int.*, **47** (2007), 1141)

Forming Processing and Thermomechanical Treatment

Prediction of residual stresses in a plate subject to accelerated cooling. —A 3-D finite element model and an approximate model—

J.-M.KOO et al.

In this paper, we present finite element (FE) models for the analysis of heat transfer and for the analysis of 3-D elastic–viscoplastic deformation of steel at elevated temperatures. Then, it is shown that, in conjunction with the models for the prediction of phase fraction, and thermal and mechanical properties, an integrated FE model can be obtained which is capable of predicting the detailed aspects of the thermal and mechanical behavior of the plate subject to accelerated cooling in a plate mill. Also, we present an approximate model for on-line prediction. The prediction accuracy of the approximate model is examined through comparison with the predictions from the integrated FE model. Then, using the model, the effect of some selected process variables on the residual stress distributions is investigated.

(cf. *ISIJ Int.*, **47** (2007), 1149)

Metallurgical conditions required for superior hot-workability of 13% chromium steels in a seamless rolling process

A.KAWAKAMI et al.

Hot-workability of 13% Cr steels was investigated in terms of microstructure by model elongator rolling tests and by tensile tests to develop modified types of 13% Cr steel seamless OCTGs (Oil Country Tubular Goods). Hot-workability deteriorated in both tests by the formation of δ-ferrite in austenite (γ) matrix; however, the deterioration occurred at lower temperatures in tensile tests than in model elongator tests. Materials are deformed more heavily in the latter than in the former, which is considered to be the cause of the difference. The result suggests that lower temperatures than the actual rolling temperature should be selected for the tensile tests in order to evaluate hot-workability of materials for seamless pipes. δ phase fraction during hot-working was almost equal to that estimated from the experimental phase diagram at a deformation temperature for plain C–13%Cr steels and at a primary heating temperature for Ni containing low C–13%Cr steels. This phenomenon is explained by a difference in the diffusion coefficient of C and that of Ni. Furthermore, it was clarified that isolated distribution and polygonal shape of δ prevented void-propagation during hot-working and was not harmful to hot-workability in plain C–13%Cr steels.

(cf. *ISIJ Int.*, **47** (2007), 1159)

Transformations and Microstructures

Vanadium precipitation during intercritical annealing in cold rolled TRIP steels

F.PERRARD et al.

Flat carbon steel manufacturers are currently developing new TRansformation Induced Plasticity (TRIP) steels as a response to strong demands for vehicle lightening and security reinforcement from the automobile sector. Compared to conventional high strength steels these advanced grades exhibit a very favourable compromise between strength and ductility and can therefore be produced in thinner, lighter gauge strips with equivalent functional properties. The excellent mechanical properties of TRIP steels are attributed to the high strain hardening coefficient generated by the progressive transformation of metastable retained austenite to martensite during plastic deformation. Further improvements in mechanical properties can be obtained by microalloying, especially with vanadium and nitrogen additions. In this paper we discuss the rather complex evolution of vanadium carbonitride V(C, N) precipitation during continuous annealing of cold rolled strip. Transmission electron microscopy (TEM) and selective chemical dissolution are used to characterise the precipitation state during interrupted intercritical annealing cycles. The experimental results are compared with calculations made using a recent kinetic precipitation model. We show that reasonable agreement can be achieved using a simple uncoupled model, however a complete description of the precipitation sequence during continuous annealing will require fully coupled kinetic models describing the interactions between cementite dissolution, the ferrite to austenite transformation and V(C, N) precipitation.

(cf. *ISIJ Int.*, **47** (2007), 1168)

Heterogeneous austenite grain growth in ASTM A213–T91 steel

N.ZAVALETA et al.

Heterogeneous grain growth during austenitization in ASTM A213–T91 steel has been studied using a Gleeble 3500 thermomechanical simulator. Starting from a uniform, fine austenite grain size distribution after 1 min austenite holding time, a heterogeneous austenite grain size distribution was observed after 15 min austenite holding time at 1 060°C and 1 080°C. The state of precipitation of second phase particles was studied in detail as a function of austenitization time. The particle size distribution changed towards a bimodal feature as a function of time whereas the count frequency of the coarse precipitates increased and the count frequen-

cy of fine precipitates diminished with time. V-rich precipitates were dissolved during austenitization and only Nb-rich particles remained after 15 min austenitizing time. The experimental observations on the evolution of the austenite grain size distribution are rationalized on the basis of the Gladman's approach to abnormal grain growth.

(cf. *ISIJ Int.*, **47** (2007), 1178)

Ferrite nucleation kinetics inside austenite grain

J.LIU et al.

The kinetics of ferrite nucleation inside an austenite grain under strong super cooling conditions are proposed by considering dislocation lines as nucleation sites based on cluster dynamics. The elastic energies within spherical space, cylindrical space and ellipsoidal space on a dislocation line have been studied, and are recognized to be approximately proportional to the cluster radius. By applying the conventional nucleation and grain growth theory on the dislocation line, the free energy change induced by a new ferrite nuclear generation on the dislocation line has been evaluated, and the ferrite nucleation rate has been formulated by considering the deformation elastic energy. According to the proposed inner-grain nucleation theory, the ferrite nucleation phenomenon inside austenite grain can be evaluated mathematically with strong super cooling conditions.

(cf. *ISIJ Int.*, **47** (2007), 1188)

Mechanical Properties

Designing high strength multi-phase steel for improved strength–ductility balance using neural networks and multi-objective genetic algorithms

S.DATTA et al.

The properties of steels depend in a complex way on their composition and heat treatment and neural networks have therefore recently been widely used for capturing these relationships. Two different methods of reducing the network connectivity, *viz* a pruning algorithm and a multi-objective predator prey genetic algorithm, have been used for neural network modeling of the mechanical properties of high strength steels, so that relevant connections within the networks are revealed. This provides important understanding on the variables and their relationship with mechanical properties. In the pruning algorithm the lower layer of the network is gradually reduced by removing less significant connections. In the predator prey algorithm, a genetic algorithm based multi-objective optimization technique is used to train the neural network and a Pareto front is developed by minimizing the training error along with the network size. The results of both techniques reveal that they can extract more knowledge from the data, which is difficult to obtain from conventional neural models. The relative relevance of the composition and processing parameters detected could be used for designing steel with tailored property balance. The results developed by the two techniques are also found to be comparable.

(cf. *ISIJ Int.*, **47** (2007), 1195)

Effect of coiling temperature on formability and mechanical properties of mild low carbon and HSLA steels processed by thin slab casting and direct rolling

R.RIVA et al.

Production of hot rolled HSLA steel strip is nowadays a well known practice; however information about the possibility to set their mechanical and formability performances through the control of the coiling temperature is quite rare, although the knowledge of this aspect can really improve the efficiency of the production process avoiding the application of other successive thermal treatment to condition the steel. In the present investigation a Nb-alloyed grade, a Nb–V grade and a V-grade have been rolled and coiled at different temperature and their mechanical, formability properties and attitude to the strain aging has been measured as a function of two different coiling temperatures. The results obtained on a mild low carbon steels which have undergone the same technological route have been used as a term of comparison. In the mild steel and in the Nb-alloyed ones the lowering of the coiling temperature improves the strength properties and the attitude to the strain aging, while decreases the formability of the steels while in the V-grade the coiling temperature performs a lower influence on these properties. This situation is confirmed also by the textural measurements and is probably related to the different removing rate of the interstitial elements, *i.e.* C and N. Actually, in the vanadium grades the precipitation temperature of the compounds formed by the vanadium and interstitial elements takes place about at the same thermal range of the coiling temperature producing a significant slowing of the kinetics of the nucleation and growth of those phases. This statement (concerning the fundamental role played by the concentration of the interstitial elements kept in solution in the metal matrix) seems to be supported by the strain aging measurements, which show a clear strain aging of the V-grade only after the artificial heating up which promotes their precipitation of the compounds formed by the interstitial elements.

(cf. *ISIJ Int.*, **47** (2007), 1204)

Influence of annealing at 1 100°C and 475°C on the mechanical properties at room temperature of an iron base ODS alloy

J.CHAO et al.

In the last few years the Fe-base oxide dispersion strengthened (ODS) PM 2000 alloy has been shown to be a biomaterial for its outstanding combination of mechanical properties and corrosion resistance. In this work, we are describing the effect of high temperature annealing at 1 100°C (pre-oxidation) and low temperature annealing at 475°C on the main mechanical properties at room temperature, with particular emphasis on tensile and fatigue properties, which are suitable for achieving the required biofunctionality of load bearing implants. It has been shown that annealing at 475°C is responsible for an increase in the YS and UTS with the subsequent decrease in ductility. However, despite of the loss of ductility, the material shows ductile behaviour as is observed in the necked zone of tensile specimens, which contrasts with the so-called "475°C embrittlement" observed for another ferritic alloys. Moreover, aged material at 475°C exhibits a better fatigue limit than that non aged pre-oxidised material.

(cf. *ISIJ Int.*, **47** (2007), 1214)

Modeling of the mechanical behavior of nanostructured HSLA steels

K.MUSZKA et al.

In the present paper the basic strengthening mechanisms operating in microstructures are discussed with respect to their application in submicron/nano materials. This analysis focuses on these strengthening mechanisms in bcc microstructures, where the effect of grain boundaries is very strong. An experimental study of the influence of the thermomechanical history on the microstructure and dislocation substructure was performed using two different grades of HSLA steels. As a result, a modified version of the Khan–Huang–Liang flow stress model (KHL) was developed and is discussed in the light of results from the present study. Comparison with experimental results showed significant diversity in the refinement and mechanical responses of each steel, due to different activity of strengthening mechanisms and microalloying elements in the microstructure evolution process. The effect of mechanical and microstructural inhomogeneity in severe plastic deformation (SPD) on the deformation induced grain refinement and mechanical properties was also considered.

(cf. *ISIJ Int.*, **47** (2007), 1221)

Damage evaluation of a welded joint in a long-term service-exposed boiler by using a small punch creep test

S.KOMAZAKI et al.

A small punch (SP) creep test was applied to the welded joint of a boiler header (1.0Cr–0.3Mo steel), which had been actually used for around 250 000 h, to evaluate the changes in creep properties. A miniaturized plate-type specimen of 10×10×0.5 mm was taken from the base metal, weld metal and the heat affected zone (HAZ), respectively, for the SP creep test and microstructure observation. Experimental results revealed that the creep rupture strength of each portion had decreased by long-term service exposure, especially in the high stress (load) conditions. The creep rupture time of the HAZ was shorter than that of the base and weld metals in the low stress (load) levels, suggesting the possibility of Type IV creep damage. TEM observation also revealed that film-like $(Mo, Fe)_6C$ carbides precipitated along the grain boundaries in the HAZ, as well as the coarsening of the $M_{23}C_6$ carbides. These microstructural changes were likely to cause the above-mentioned reduction in the creep rupture strength at the HAZ.

(cf. *ISIJ Int.*, **47** (2007), 1228)