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Transformations and Microstructures

Ultra-fine Bainite Structure in Hypo-eutectoid Steels (Review)

M.SOLIMAN et al.

Ultra-fine, carbide-free bainitic structure of plate thickness between 34 and 116 nm has been obtained by low temperature austempering process of two hypo-eutectoid steels with 0.42 and 0.57% C. Decreasing the carbon content results in accelerating the bainite transformation reaction together with decreasing the retained austenite content, which is known to be detrimental to the mechanical properties. Furthermore, lowering the carbon content below the eutectoid composition allowed intercritical annealing of the material which resulted in a wider window for heat treatment parameters and consequently in a spread field for mechanical properties. Dilatometric measurements were used to design the suitable heat-treatment parameters including an estimation of the required time frames for the cessation of the bainitic reaction. The structure was characterized using light optical microscopy (LOM), scanning electron microscopy (SEM) and X-ray diffractometry. In order to investigate the effect of the microstructure parameters on the materials mechanical properties, compression tests had been conducted at room temperature.

(cf. *ISIJ Int.*, **47** (2007), 1703)

Fundamentals of High Temperature Processes

Kinetic Studies of Fluoride Evaporation from Slags

M.PERSSON et al.

In view of the environmental problems associated with the evaporation of fluoride from slags and fluxes, a systematic study of the fluoride emission from slags at temperatures, relevant to steelmaking and casting, has been initiated in the present work. The loss of fluoride from slag melts was monitored by Thermogravimetric Analysis (TGA). The present paper reports the fluoride evaporation in the three binary systems Al_2O_3–SiO_2, CaO–SiO_2 and MgO–SiO_2 with additions of CaF_2 (*ca.* 3.5, 5 and 9 wt%). The thermogravimetric experiments were carried out in argon atmosphere in the isothermal mode in the temperature range 1 673–1 873 K. The gas flow was kept above the starvation rate in order to avoid the gas phase mass transfer step. From the results, the Arrhenius activation energies for the evaporation reaction were evaluated. The activation energies were found to be dependent on temperature and slag chemistry for the various slags studied. In binary systems, the activation energy for fluoride evaporation was found to depend on the square of the activity of SiO_2 in the slag melt. This correlation obtained in the case of the binary systems could be validated in the case of the results obtained for the ternary system Al_2O_3–CaO–SiO_2 with 5 and 10 wt% of CaF_2. The present results are considered to be useful in estimating the fluoride emissions from industrial slags and mould fluxes.

(cf. *ISIJ Int.*, **47** (2007), 1711)

Solubility of MgO in New Ironmaking Process-typed Slags

S.-M.JUNG et al.

The solubilities of MgO obtained from the data obtained from equilibrium experiments between liquid CaO–SiO_2–Al_2O_3–Fe_tO–MnO slags and liquid silver and solid iron in the temperature range of 1 703 to 1 773 K in a CO/CO_2 gas mixture are analyzed in the current study. The solubilities of MgO decreased with increasing Fe_tO content and the slag basicity, (mass% CaO)/(mass% SiO_2) in the slag basicity less than 2.0 and they were compared with the change of the MgO solubility with increasing MnO concentration in the slags. The present data were temperature-extrapolated to those at 1 873 K and compared with the previously reported MgO solubilities in steelmaking slags. The application of the optical basicity resulted in correlation of MgO solubility with COREX process-typed slag compositions.

(cf. *ISIJ Int.*, **47** (2007), 1718)

Ironmaking

Numerical Investigation for the Effect of Shapes and Arrangement of Inerts on Coke Strength

K.UEOKA et al.

In this study, the effect of inert shapes and arrangements on coke strength is numerically investigated using a homogenization method. In the analysis, coke texture is assumed to be composed of active component and inert, with disregard to the existence of pores. The stress analyses for tensile test and the thermal stress analysis are carried out for three cases of inert shapes and arrangement. In Case 1, the round shape inerts with the same diameters are regularly arranged in the coke. In Case 2, complex irregular shape inerts are irregularly arranged in the coke by expanding randomly arranged round shape inerts and joining the overlapping of inerts. In Case 3, the inerts in Case 2 are converted into the other inerts with round shapes retaining the area of inerts and then randomly rearranged in the coke texture.

From the stress analyses of tensile test, the maximum stress in Case 1 shows the lowest for all the analytical cases. In addition, the analytical results for tensile test show that the load carrying capacity of inerts depends on the arrangement of inerts. As a result, the coke with regular arrangement of equal sized inerts is expected for the improvement of coke strength. From the thermal stress analyses, on the other hand, the analytical results shows that the maximum stress occurs in the region where inerts are close to each other. Therefore, it is important to prevent inerts from being close to each other in the coke texture in order to produce the coke with high strength.

(cf. *ISIJ Int.*, **47** (2007), 1723)

Nonlinear Prediction of the Hot Metal Silicon Content in the Blast Furnace

H.SAXÉN et al.

The processes in metallurgical industry are often extremely complex and measurements from their interior are scarce due to hostile conditions. Today's constraints on high productivity and minor impact on the environment still require that the processes be strictly controlled. Mathematical models can play a central role in achieving these goals. In cases where it is not possible, or economically feasible, to develop a mechanistic model of a process, an alternative is to use a data-driven approach, where a black-box model is built on historical process data. Feedforward neural networks have become popular nonlinear modeling tools for this purpose, but the selection of relevant inputs and appropriate network structure are still challenging tasks. The work presented in this paper tackles these problems in the development of a model of the blast furnace hot metal silicon content. A pruning algorithm is applied to find relevant inputs and their time lags, as well as an appropriate network connectivity, for solving the given time-series problem. In applying the model, an online learning of the upper-layer weights is proposed to adapt the model to changes in the input–output relations. The analysis shows results in good agreement with findings by other investigators and practical metallurgical knowledge.

(cf. *ISIJ Int.*, **47** (2007), 1732)

Prediction of Raceway Shape and Size

S.SARKAR et al.

Prediction of raceway *shape* and size has always been a challenging task. Based on the previous finding that raceway boundary is an iso-stress boundary, its *shape* and size has been predicted using a continuum approach. A relation has also been developed to get the stress at the raceway boundary at different blast velocity. Predicted raceway boundary is compared with the experimental raceway boundary/*shape* and size along with the comparison of theoretical and experimental pressure distribution. A reasonable agreement between the theoretical and experimental raceway *shape* and size is found. Extension of the work in real blast furnace case is also discussed.

(cf. *ISIJ Int.*, **47** (2007), 1738)

Modeling of Solid Particle Flow in Blast Furnace Considering Actual Operation by Large-scale Discrete Element Method

H.MIO et al.

The objective of this paper is to analyze the solid particle flow in a blast furnace having bell-type charging system by using large-scale Discrete Element Method (DEM). About 500 000 particles were calculated in this work. The particle discharging behavior of laboratory-scale blast furnace was compared to confirm the material properties used in the simulation work, and the simulated trajectories of tracer particle correlated with those of experimental very well. The melting behavior of iron ore and combustion of coke in the actual blast furnace were

modeled by shrinking particles. The simplified bell-type charging system in this simulation mimicked the actual blast furnace, the collapse of coke layer at the top was observed, and the time change of stock level was quite similar. The particle pulsating flow was observed at the upper area of blast furnace, and the descending velocity near side wall was much larger than that of center in this calculation. The melting position of ore was mapped and the most of iron ore were melting above the raceway. This area should be cohesive zone. This modeling is the first step of the analysis of blast furnace by using Discrete Element Method. Although only contact force was considered and simplified melting zone or raceway were introduced, this large-scale simulation has a high potential to analyze the solid flow in the blast furnace, and the abnormal phenomena or serious problem in blast furnace operation will be analyzed in the future by considering gas flow or heat transfer.

(cf. *ISIJ Int.*, **47** (2007), 1745)

Casting and Solidification

Prediction of Interfacial Heat Transfer Coefficients by Using a Modified Lump Capacitance Method for Aluminum Casting in a Green Sand Mold

H.-C.SUN et al.

This paper analyzes the heat flux and heat transfer coefficient at the mold/metal interface in the green sand mold casting of a cylindrical aluminum component. In the present casting experiment, thermocouples are used to measure the temperature at various points in the molten metal and the sand mold. Using the acquired temperature data, the heat flux and heat transfer coefficient at the sand-mold/metal interface are computed using a modified lump capacitance method, in which the latent heat term is calculated by considering the time-dependent variation of the solid/liquid interface location. For comparison purposes, the heat flux and heat transfer coefficient are also computed using Beck's inverse scheme. The results obtained from the two computational methods are found to be similar. The casting process is simulated by entering the values of the interfacial heat transfer coefficients computed by the two schemes into a commercial finite element analysis program (FIDAP). The cooling curve computed using the interfacial heat transfer coefficient determined by the modified lump capacitance method is found to be in good agreement with the experimental results. The predicted solidification time differs from that observed experimentally by just 2.8%. Furthermore, it is found that the Biot number is very small for the present aluminum casting. Therefore, the present results verify the feasibility of using the modified lump capacitance method to compute the interfacial heat flux and heat transfer coefficient in the green sand mold casting of small-sized components.

(cf. *ISIJ Int.*, **47** (2007), 1753)

Morphology and Segregation in Continuously Cast High Carbon Steel Billets

S.K.CHOUDHARY et al.

Morphology and centerline macrosegregation in continuously cast high carbon steel billet samples were investigated in order to establish the casting behavior of a six strand curved mold billet caster without electro-magnetic stirring. Several billet samples were collected from the continuous casting shop of Tata Steel, India and experimental observations were correlated with the operating parameters of the caster. Macrostructural examination revealed predominantly columnar structure associated with high degree of segregation and porosities in all billets cast above 21°C of tundish superheat. Centerline porosity was practically absent in the billet cast below 21°C. These billets showed prominent V-segregation and less prominent centerline segregation. Transition from U-segregation to V-segregation was observed around 21°C superheat. An attempt has been made to study the effectiveness of secondary cooling by measurements of the secondary dendrite arm spacing at various locations in billet samples. Finally, degree of segregation of constituent solute elements were correlated among themselves and applicability of one of the simple segregation models to the centerline macrosegregation has been tested.

(cf. *ISIJ Int.*, **47** (2007), 1759)

Forming Processing and Thermomechanical Treatment

Influence of Annealing Technology on Drawing Properties of Cold Sheets Rolled with CSP Hot Bands

G.XU et al.

The drawing properties of cold sheets rolled with CSP hot-bands (CSS) are not so good compared to cold sheets rolled with conventional hot bands (CSC). Therefore, influences of annealing technology on drawing properties of CSS have been studied in the paper. Research works included (1) drawing properties of cold sheets rolled with different CSP hot-bands, (2) drawing properties of CSS and CSS, and (3) influences of annealing technology on drawing properties of CSS. The results of annealing experiments, microstructural examinations and drawing property tests have shown that the drawing properties of CSS at higher finish deformation temperature (FDT) and lower coiling temperature (CT) are superior to those of CSS at lower FDT and higher CT. It was also found that the drawing properties of CSC are superior to those of CSS after heat treatment with same annealing technology. The annealing temperature for experimental steel grade (DC03) should be higher than 680°C.

(cf. *ISIJ Int.*, **47** (2007), 1767)

Welding and Joining

Porosity and Nitrogen Content of Weld Metal in Laser Welding of High Nitrogen Austenitic Stainless Steel

L.ZHAO et al.

Some problems such as nitrogen desorption and pores always occur in the weld metal during welding of high nitrogen steel. In order to study the nitrogen content and porosity of the weld metal of high nitrogen steel 1Cr22Mn16N, the steel was welded by CO_2 laser welding, and the influence of the shielding gas composition and heat input on the nitrogen content and porosity of the weld metal was investigated. The experimental results indicate that the weld nitrogen content increases slightly with the increase of the nitrogen content in shielding gas under the same laser welding conditions. The nitrogen content of the weld metal decreases with the increase of the heat input when pure argon is used as the shielding gas, whereas that of the weld metal is improved with the increase of the heat input when some nitrogen is added to the shielding gas. The higher the heat input, the less the porosity in the weld metal, and the more nitrogen in the shielding gas, the less the porosity becomes.

(cf. *ISIJ Int.*, **47** (2007), 1772)

Transformations and Microstructures

Microstructure of Martensite/Bainite Dual-phase Grey Cast Iron and Its Strengthening Mechanism

J.XING et al.

By a process of combinations of microalloying with Ni, Mo and other elements, cast chilled by metal-mold and special heat-treatment, A martensite/bainite (M/B) dual-phase grey cast iron was fabricated. Quenching into oil after austenization at 900°C for 2 h, the hardness of the sample was above HRC 48. The microstructures of all samples were characterized by optical metallography or X-ray diffraction. The final microstructure was composed of M/B dual-phase and retained austenite. There were some "white-bright zone" composed of few high-carbon martensite plates and retained austenite, full of Mn and Mo elements, concentrating on the boundaries of eutectic cells. The nucleation site and mechanism of bainite were studied by short oil-quenching for 5 s after austenization at 860°C for 2 h. The result showed bainite first nucleated at interface between flake graphite and austenite, and austenite along the direction of flake graphite sharp corner was also tend to transform into bainite. The second site easy for bainite nucleation was the boundary of austenite, also the boundary of "white-bright zone". Strengthening mechanism of M/B dual-phase to this grey cast iron was studied by using pressing-in method to press round head into the surface of corrosive M/B dual-phase grey cast iron. The initiation and extension of cracks were observed through SEM. The result showed that M/B dual-phase could effectively strengthen graphite–matrix interface and restrain cracks extension, tips of high-carbon martensites in "white-bright zone" were another site prone to initiate

cracks under pressure. For lake of phase–phase interfaces, the cracks would extend straightly until to the whole interface of "white-bright zone" and matrix.

(cf. *ISIJ Int.*, **47** (2007), 1776)

Nucleation of Acicular Ferrite on Sulfide Inclusion during Rapid Solidification of Low Carbon Steel

Z.LIU et al.

A fine-grained microstructure yields the optimum combination of strength and toughness of steel. Refinement of the ferrite microstructure by formation of fine intra-granular acicular ferrite nucleated on inclusion has been caused wide interesting in weld metallurgy and other metallurgy fields. It is also important to refine the as-cast microstructure during strip casting and thin slab casting process in which the possibility of refining microstructure by rolling technology decreases. In present paper, the possibility to nucleate intra-granular acicular ferrite by sulfide inclusion in steel without special alloy elements during rapid solidification process has been investigated by optical microscopy, Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM). The orientation of the acicular ferrite clusters are also investigated by Electron BackScattered Diffraction (EBSD) analysis. Oxide inclusion and sulfide inclusion are popular in the sample and only sulfide inclusions are observed effective to assistant acicular ferrite nucleation. The possible mechanisms of formation of acicular ferrite in present sample, those are manganese depleted zone and phosphorus rich zone around inclusion in matrix, are discussed in detail.

(cf. *ISIJ Int.*, **47** (2007), 1781)

Modeling of Microstructure Evolution during Hot Strip Rolling of Dual Phase Steels

D.LIU et al.

Microstructure models for hot strip rolling of CMnSi and CMnMo dual-phase steels have been proposed. The constitutive behaviour of austenite prior to the onset of dynamic recrystallization has been described by a physically based Kocks–Mecking model. The static recrystallization kinetics has been simulated by the Johnson–Mehl–Avrami–Kolmogorov (JMAK) theory. The recrystallized austenite grain size is described using an empirical equation considering the effect of strain, prior austenite grain size and deformation temperature. Ferrite transformation start is modeled with an approach that considers early growth of corner nucleated ferrite. The fraction of ferrite transformed from austenite during continuous and/or stepped cooling is described using the JMAK approach in combination with the additivity rule. The ferrite grain size is quantified as a function of the transformation start temperature. The critical conditions for the onset of bainite and martensite transformations in the remaining austenite have been empirically evaluated as a function of ferrite fraction transformed. The microstructure models for these metallurgical phenomena have been validated with experimental studies in the laboratory emphasizing industrially relevant hot strip rolling conditions and run-out table cooling strategies.

(cf. *ISIJ Int.*, **47** (2007), 1789)

Dynamic Recrystallization of Austenitic Stainless Steel under Multiple Peak Flow Behaviours

A.DEHGHAN-MANSHADI et al.

The hot working behaviour of a Fe–0.02C–8.2Ni–18.5Cr (mass%) austenitic stainless steel was studied at high temperatures and low strain rates. These conditions led to a multiple peak stress–strain curve, where the second peak had a much larger strain and stress than the first peak. The first peak showed evidence of some grain refinement, indicative of conventional dynamic recrystallization. However, after this there was significant grain coarsening, similar to abnormal grain growth, with the formation of substructure within the grains. The strain to the first peak in the multi peak tests was much lower strain than expected from extrapolation of the single peak data.

(cf. *ISIJ Int.*, **47** (2007), 1799)

Mechanical Properties

Localized Deformation due to Portevin-LeChatelier Effect in 18Mn–0.6C TWIP Austenitic Steel

L.CHEN et al.

The thermo-mechanical properties of low stacking fault energy austenitic Fe18Mn0.6C steel exhibiting twinning-induced plasticity were investigated during uniaxial tensile deformation using infrared thermography. Over a wide strain range, the plastic deformation was by the movement of very few well-defined localized deformation bands. The formation and propagation of Portevin–LeChatelier (PLC) bands lead to type A and type B serrated stress–strain curves, exhibiting a negative strain rate sensitivity. The PLC band properties were analyzed in detail: strain, strain rate and mobile dislocation density within the bands were determined. The microstructures of the un-deformed and deformed Fe18Mn0.6C TWIP steel were studied by transmission electron microscopy. The possible dynamic strain aging processes causing the localized deformation are reviewed.

(cf. *ISIJ Int.*, **47** (2007), 1804)

Social and Environmental Engineering

Reaction Mechanisms of Blast Furnace Slag in Liquid and Vapor Dominated Hydrothermal Systems

S.-J.TAE et al.

In order to develop an efficient process for the treatment of waste slag, the behavior of hydrothermal reaction of blast furnace slag has been investigated. For blast furnace slag, an experiment was conducted under various hydrothermal conditions with a liquid and vapor phase in the presence of saturated water steam pressure using an autoclave.

The results indicated that calcium silicate hydrate (C-S-H) and tobermorite ($Ca_5Si_6O_{16}(OH)_2 \cdot 4H_2O$) were the major phases formed in the treated samples. It was also confirmed that the hydrothermal reaction process was strongly affected by the hydrothermal conditions. In particular, the hydrothermal reaction proceeded more rapidly in vapor phase than in liquid one. Accordingly, the reaction mechanism of the hydrothermal treatment of blast furnace slag has been clarified.

(cf. *ISIJ Int.*, **47** (2007), 1813)

Behavior of Cobalt in Iron- and Steel-making Processes

S.KITAMURA et al.

During the decommissioning phase of a nuclear reactor, most of the steel-reinforced concrete shielding around the pressure vessel is considered as low-level radioactive waste. It is very desirable to reduce the radioactivity of the low-level radioactive waste to below the clearance level. Normally, the radioactivity of steel after irradiation is found to be proportional to the cobalt content. In this study, for the production of low-activation steel, the mixing source and the partition behavior of cobalt in the iron- and steel-making processes are investigated. The results are summarized as follows: (1) the cobalt content in hot metal was found to be approximately 20 ppm, and the main source was serpentine. The ratio of the cobalt content to the iron content in the ore varied from 1.5 to 6.5 ppm, depending on the brand. In the charge materials for the BOF process and typical refractories, the cobalt content was negligible except for some ferroalloys. (2) By thermodynamic calculations, it can be deduced that the activity coefficient of CoO is very small in the slag.

(cf. *ISIJ Int.*, **47** (2007), 1818)