(＊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

Investigation, prediction and disarming of drain sink formation during unsteady-state bottom teeming

N.KOJOLA et al.

The behavior of an unsteady-state drain sink as function of outlet diameter, outlet length, supernatant phase viscosity, supernatant phase density and supernatant phase layer thickness was studied using physical modeling. Two new hydrodynamic models for the prediction of the drain sink formation height were derived and compared to models found in literature. Both could accurately predict the drain sink formation height in their respective domain as function of all variables mentioned above, except supernatant phase viscosity since its influence on drain sink formation height was negligible in the experimental systems. Finally, the influence of the vessel bottom shape on the increased yield of a steel plant teeming operation is discussed.

(cf. *ISIJ Int.*, **49** (2009), 1)

Evaporation behavior of zinc chloride in Ar–O_2–H_2O atmosphere

K.YAJIMA et al.

Evaporation behavior of $ZnCl_2$ melts and $ZnCl_2$–ZnO mixtures in Ar–O_2–H_2O atmosphere was observed at 873 K by measuring change of weight and chemical composition. When water vapor or oxygen was added, weight loss of $ZnCl_2$ decreased, and the effect of water vapor on repression of weight loss was much stronger than that of oxygen. Especially, weight loss stagnated after 20 min at 40% of weight loss in Ar–5%H_2O atmosphere. It is considered that the reaction product between zinc chloride and water vapor covered the surface of melt.

In the case of $ZnCl_2$–ZnO melt, weight loss reached and stagnated at about 60% of initial weight in Ar and Ar–O_2 atmospheres. This value is close to initial $ZnCl_2$ content. However, weight loss reached and stagnated at about 50% of initial weight in Ar–H_2O atmosphere, and the residue was converted to zinc oxide after 60 min experiments. From these results, formation of zinc oxide by the reaction between zinc chloride and water vapor in Ar–H_2O atmosphere was confirmed. It is concluded that zinc oxide formed by the reaction on surface of melt prevented the contact between zinc chloride and gas phase, and the evaporation of zinc chloride. This phenomenon caused the stagnation of weight loss with atmosphere containing water vapor.

(cf. *ISIJ Int.*, **49** (2009), 10)

Intensification of bubble disintegration and dispersion by mechanical stirring in gas injection refining

Y.LIU et al.

Water model experiments were performed for establishing highly efficient gas injection refining processes. Mechanical stirring was applied to disintegrate the injected bubbles and to disperse them widely in the bath. The bubble disintegration and dispersion were investigated by changing rotation mode (direction of rotation), rotation speed, blade size of the impeller and gas flow rate. Forward rotation of the impeller induced a stable tangential flow and could not disperse bubbles in the bath due to formation of a vortex around the impeller shaft. The tangential flow could be suppressed by forward–interrupt rotation, which could reduce the vortex formation to some degree. However, forward–interrupt rotation could not disperse the bubbles widely in the bath. Forward–reverse rotation could prevent the vortex formation completely and create a strong shear stress field, which intensified the bubble disintegration and dispersion in the bath. Higher impeller rotation speed and larger blade length in forward–reverse rotation could enhance the bubble disintegration and make the dispersed bubbles smaller. The bubble dispersion zone became wider with larger blade length. The bubble size tended to be larger at higher gas flow rates. However, its dependence on the gas flow rate became smaller at higher impeller rotation speed.

(cf. *ISIJ Int.*, **49** (2009), 17)

Steelmaking

Analysis of droplet generation in oxygen steelmaking

N.DOGAN et al.

Knowledge of droplet generation during oxygen blowing, which can be characterized by a blowing number (N_B), is crucial for better understanding of the fundamentals of the kinetics of oxygen steelmaking. A mathematical model has been developed considering the influence of surface tension on the blowing number (N_B) using plant data from the study of Holappa and Jalkanen. The model predicts the droplet formation as a function of carbon, sulphur and oxygen contents in the metal, the temperature profile of the metal bath and lance height. This study includes a sensitivity analysis to investigate the effect of the changes in the oxygen concentration throughout the process. It has been found that the rate of droplet generation increases with increasing jet momentum onto the metal bath and with decreasing surface tension of the liquid metal. The model also suggests that generally the variation in oxygen and sulphur contents in liquid bath has relatively little influence on droplet generation compared to the effect of blowing parameters. However, in the case of low carbon steels (<0.05 mass% C), the blowing number increases by more than 50% at the end of the blow due to lowering of surface tension.

(cf. *ISIJ Int.*, **49** (2009), 24)

Effect of fluid physical properties on the emulsification

J.SAVOLAINEN et al.

Slag entrainment during metallurgical processes is a common source of macro inclusions, existing in a final product. This is the main reason why emulsification of slag should be controlled during the steel making processes. The onset for emulsification during the metallurgical processes is a function of practice specific issues and properties of used melts. The objective of this research was to study the effect of fluid physical properties on the emulsification. The research was made with a water model, using oil simulating slag and water simulating metal. Critical fluid flow velocity needed for emulsification and diameter of entrained droplets were measured. Role of fluid physical properties, affecting critical fluid flow velocity and diameter of entrained droplet were studied with varying density difference, oil viscosity and interfacial tension. Thickness of oil layer was also varied. Use of dimensionless numbers were also studied as a criterion for droplet formation. The results of this research proved, that the increase in density difference, oil viscosity, interfacial tension and oil layer thickness increase the fluid flow velocity needed for emulsification. Entrained oil droplet diameter increased with increasing oil viscosity, interfacial tension and oil layer thickness. On the other hand, oil droplet diameter decreased with increasing density difference. Research proved also, that dimensionless numbers can be used as a criterion for emulsification but dimensionless numbers usually suffers from lack of necessary variables. Studied dimensionless numbers were also compared to the real ladle system.

(cf. *ISIJ Int.*, **49** (2009), 29)

Casting and Solidification

Characterization of dendrite morphology for evaluating interdendritic fluidity based on phase-field simulation

H.ISHIDA et al.

Evolution of dendrite morphology in Fe-base alloys was simulated by using the phase-field method and complexity of the dendrite morphology was evaluated by fractal dimensions and dimensionless perimeter of dendrites. It was shown that the both parameters of the fractal dimension and the dimensionless perimeter are effective to evaluate the complexity of dendrites. Factors controlling the dendrite morphology such as materials properties, composition and cooling rate were investigated by the simulation. Permeability of simulated dendrite array was estimated from the fractal dimension and the dimensionless perimeter, and obtained permeability corresponded to reported values of the permeability for metallic alloy systems.

(cf. *ISIJ Int.*, **49** (2009), 37)

Electromagnetic field distribution in two-section slitless mold for soft-contact electromagnetic continuous casting

B.JIN et al.

Numerical simulations and orthogonal experiments were used to study the effects of electromagnetic and structural parameters on magnetic distribution in a two-section slitless mold for the SC-EMCC process. The results showed that magnetic flux density decreased as the electrical frequency (f) and the thickness of the mold (d) increased, but it increased as the resistivity of the top half mold (ρ_R), the coil current intensi-ty (I), the length of the top

half mold and the location of the coil increased. By dimensionless analysis, the reltive equation among magnetic flux density and the parameters was given as $B/(\mu_0 I/d)=0.058\times(\rho_R\cdot I^2/\rho_v d^6 f^3)^{0.29}$. Also the level of the initial meniscus should be controlled between the center and the top of the coil to attain better soft-contact effects. The total distribution of the electromagnetic field in the whole system of the two-section slitless mold was obtained. The magnetic flux density on the vertical direction mainly acted on the location of the initial liquid level, and the magnetic flux density was uniform along the circumferential direction but degenerated along the radical direction.

(cf. *ISIJ Int.*, **49** (2009), 44)

Instrumentation, Control and System Engineering

An inherited tabu search algorithm for the truck and trailer vehicle scheduling problem in iron and steel industry

L.TANG et al.

The truck and trailer vehicle scheduling problem (TTVSP) involves vehicles and products allocation when the products are transported from warehouse to dock yard. The TTVSP with multiple types of vehicles which can be assigned to different tasks more than one time is considered and the vehicle can also transport the products that don't absolutely suit it. For this TTVSP, the continuity of task and truck are also under the consideration based on the practical requirement. This problem is formulated as a mixed integer programming model to minimize the total cost by considering some practical issues. In this paper, the problem how to transport the last operation in appointed task is also analyzed and the property about the scheduling of last operation is put forward to optimize algorithm. An inherited composite neighborhood tabu search algorithm is developed to find a near-optimal scheduling where an initial solution is obtained based on the know-how knowledge. The results of experiment show that the proposed method could resolve the problem more effectively than current manual method.

(cf. *ISIJ Int.*, **49** (2009), 51)

A new incremental learning modeling method based on multiple models for temperature prediction of molten steel in LF

H.TIAN et al.

Traditional temperature prediction models of molten steel have to face the dilemma problems about updating models. Aiming at these problems, a new incremental learning modeling method based on multiple models is proposed in this paper. Firstly, an intelligent model based on ELM is established by analyzing the conversation of energy during whole refining process of LF as generic sub intelligent model. Secondly, the errors of different generic sub intelligent models are calculated. The weights of sub intelligent models can be obtained by these errors. Then the temperature prediction model is presented by aggregating these sub intelligent models. Finally, when new production data accumulate enough, they will be used to train a new sub intelligent model and the sub model's weight will be obtained according to the errors of training. Then the new aggregated temperature prediction model is established based on all of the generic sub intelligent models that include the old ones and the new one. Till then, the updating of prediction model is completed. The new incremental learning method preserves the information of old sub models by this process, and no longer by saving the all original data. Therefore, it is efficient to save a mass of space and time. The new temperature prediction model with incremental learning is used in 300 t LF of Baoshan Iron & Steel Co. Ltd. The results demonstrate both updating ability and accuracy of new model are satisfied for production.

(cf. *ISIJ Int.*, **49** (2009), 58)

Integration of systems engineering-based paradigms for the scheduling and control of an experimental hot-rolling mill

M.A.GAMA et al.

This paper presents research work associated with the integration of systems engineering-based paradigms for implementing state-of-the-art mechanisms of scheduling and control on an experimental laboratory-scale hot-rolling mill located at Sheffield University (UK). A comprehensive hybrid model for metal processing was combined with a Genetic Algorithm (GA)-based optimisation method to calculate the optimal rolling schedule, hence realising the concept of *right-first-time* production of steel alloys. Furthermore, the mill used Model-based Predictive Control (MPC) to guarantee optimal control performance during its real-time operations. Results from hot-rolling experiments are presented to provide *a proof-of-concept* about the use of integrated model-based systems to solve complex metallurgical problems.

(cf. *ISIJ Int.*, **49** (2009), 64)

Chemical and Physical Analysis

Polycrystalline wüstite surface observed by STM and LEED

Y.MASAKI et al.

After annealing at 1 273 K in UHV chamber to remove adsorbed molecule, the surface crystal structure and the composition of polycrystalline $Fe_{1-x}O$ were analyzed at room temperature using STM, LEED and AES. The $Fe_{1-x}O$ sample was prepared by oxidizing an polycrystalline electrolytic iron strip. The $Fe_{1-x}O$ surface consists of facets, where many steps like zig-zag shape are arranged. The mesh-like structure, of which periodicity is about 0.8–1.3 nm, was observed on the terrace. The facets are (001) planes of $Fe_{1-x}O$, and the step direction is ⟨110⟩ by LEED measurement. The mesh-like structure is considered as the defect clusters derived from nonstoichiometry.

(cf. *ISIJ Int.*, **49** (2009), 74)

Forming Processing and Thermomechanical Treatment

Controlled warm working: Possible tool for optimizing stored energy advantage in deformed γ-fiber (ND//⟨111⟩)

R.KHATIRKAR et al.

In the present study, ultra low carbon steel samples were deformed in near plane-strain mode with different strains, strain rates and temperatures. Estimates of in-grain misorientation developments were obtained respectively for the γ-fiber (ND//⟨111⟩) and α-fiber (RD//⟨110⟩) oriented deformed grains. Though a general drop in in-grain misorientation was observed with increase in deformation temperature, the highest reduction of 70% showed a clear increase at the intermediate deformation temperatures. Under these condition(s), the misorientation increase in deformed γ-fiber grains was more substantial than in α-fiber grains. The phenomenon was related to the preferred appearance of grain interior strain localizations. The study brings out a clear possibility of optimizing the stored energy advantage in the deformed γ-fiber grains through controlled warm working.

(cf. *ISIJ Int.*, **49** (2009), 78)

Welding and Joining

Pulse pressuring diffusion bonding of Ti alloy/austenite stainless steel processed by surface self-nanocrystallization

J.HAN et al.

Nanostructured surface layers were synthesized on the end face of Ti–4Al–2V titanium alloy and 0Cr18Ni9Ti austenite stainless steel rods by means of high energy shot peening (HESP). Making treated end surfaces as bonding interfaces, Ti–4Al–2V and 0Cr18Ni9Ti rods were bonded by pulse pressuring diffusion bonding (PPDB) on Gleeble-1500D tester at 650–750°C. Joints were tested on tensile testing machine, the fractures and microstructures of joints were researched. Results showed that the maximum tension strength of 262.0 MPa was achieved, cleavage fracture took place while tension test of joints, and the grains in the vicinity of the diffusion layer are fined. But, brittle intermetallic compounds were absence on the bonding interface.

(cf. *ISIJ Int.*, **49** (2009), 86)

Surface Treatment and Corrosion

Mathematical modeling for corrosion environment estimation based on concrete resistivity measurement directly above reinforcement

Y.-C.LIM et al.

This study aims to formulate a resistivity model whereby the concrete resistivity expressing the environment of steel reinforcement can be directly estimated and evaluated based on measurement immediately above reinforcement as a method of evaluating corrosion deterioration in reinforced concrete structures. It also aims to provide a theoretical ground for the feasibility of durability evaluation by

electric non-destructive techniques with no need for chipping of cover concrete. This Resistivity Estimation Model (REM), which is a mathematical model using the mirror method, combines conventional four-electrode measurement of resistivity with geometric parameters including cover depth, bar diameter, and electrode intervals. This model was verified by estimation using this model at areas directly above reinforcement and resistivity measurement at areas unaffected by reinforcement in regard to the assessment of the concrete resistivity. Both results strongly correlated, proving the validity of this model. It is expected to be applicable to laboratory study and field diagnosis regarding reinforcement corrosion.

(cf. *ISIJ Int.*, **49** (2009), 92)

The effect of Si and Mn content on dynamic wetting of steel with liquid Zn

Y.TAKADA et al.

Non-wetting behavior of liquid Zn alloy sometimes occurs on high-tensile strength steels that usually contain Si and Mn. Many studies have been undertaken to improve the wettability of liquid Zn. In this work, we applied the sessile drop method to measure the change in contact angle and diameter of liquid Zn droplets wetted on steels containing Si and Mn with time. We could then quantitatively evaluate the wettability of those steels using liquid Zn. Si weakens the work of adhesion and spreading velocity of liquid Zn on steels. Mn, however, has a small effect on the contact angle and the work of adhesion but occasionally increases the spreading velocity even when Si content is high in steels.

(cf. *ISIJ Int.*, **49** (2009), 100)

Transformations and Microstructures

Change of rotated cube texture through multi-processing in 3% Si-steels

S.K.CHANG et al.

Rotated cube texture was obtained about 5% during the 1st heavy cold rolling 80% and the subsequent annealing increased it by 40% but thereafter both the 2nd light cold rolling 10% and the 2nd low temperature annealing at 700°C were not able to increase the rotated cube orientation. This result assures that a small amount of reduction grows hardly the rotated cube orientation and even subsequent annealing of such lightly cold rolled materials does not increase it properly either. The γ fiber of hard magnetizing orientation revealed a large volume fraction above 20% through the 1st cold rolling and subsequent annealing, but it decreased noticeably after the 2nd cold rolling and annealing, which also means that it does not change under such low cold reduction and low temperature annealing. The CSL boundaries of Σ3, Σ7, Σ9 and Σ15 appeared as the main Σ boundaries.

(cf. *ISIJ Int.*, **49** (2009), 105)

Precipitation hardening with cupper sulfide in Cu bearing extra low carbon steel sheet

S.I.KIM et al.

High strength cold-rolled bake hardenable steel sheets for automotive use have been developed. In the last decade, the major strengthening methods of extra low carbon (ELC) steel and interstitial free (IF) steel were the solid-solution strengthening with silicon, manganese and phosphorous and the precipitation strengthening with microalloying elements, such as niobium and titanium. When the steels are strengthened with the high amount of solid-solution elements such as silicon and manganese, it shows the low surface quality due to surface oxidation. In addition, phosphorous added ELC and IF steels become susceptible to the secondary work embrittlement because of the lack of grain boundary strength, which is the essential drawback of the steels.

In this paper, we propose the extra low carbon bake hardenable steel which is precipitation strengthened by means of the fiine distribution of Copper sufiide (C_2S) precipitates instead of solid-solution strengthening and precipitation strengthening using silicon, manganese, niobium and titanium. These Cu sulfiides are oriented to the body-centeredcubic α-Fe matrix in $(001)_{Cu_2S}//(001)_{\alpha\text{-Fe}}$ and $[001]_{Cu_2S}//[001]_{\alpha\text{-Fe}}$ relationships.

(cf. *ISIJ Int.*, **49** (2009), 109)

Topology of the deformation of a non-uniform grain structure

J.-Y.CHAE et al.

The study of changes in the amount of grain boundary surface (or edge) as a function of plastic strain is important in the design of metallic materials. The quantitative expression of these changes is usually made assuming idealised and uniform grain structures. In this work we develop a method for treating a distribution of grain sizes and shapes, and demonstrate that this modification in fact has little effect on the evolution of grain parameters during plastic deformation.

(cf. *ISIJ Int.*, **49** (2009), 115)

Mechanical Properties

Finite element analysis of the interfacial debonding of the galvannealed coating layer with high tensile strength steel substrates

S.IWAMOTO et al.

For energy saving, it is planned to use galvannealed high strength steels for the car body materials. However, the influences of the high strength steel substrate on the fracture behavior of the coating layer and interfacial debonding behavior have not been revealed yet. In the present work, numerical analysis using a finite element method was carried out. It was revealed that (i) the higher the tensile strength of the substrate, the shorter becomes the crack spacing of the coating layer and (ii) the less interfacial debonding takes place in high strength substrate steels due to the short crack spacing, as long as the coating layer- and interfacial bonding-strengths of high strength substrate samples are the same as those of low strength ones.

(cf. *ISIJ Int.*, **49** (2009), 119)

Evaluation of subsurface fatigue crack life in forged Ti–6Al–4V alloys at cryogenic temperatures

M.HAMADA et al.

Fatigue crack growth modeling was performed for Ti–6Al–4V forged materials failed by subsurface crack generation at cryogenic temperatures. The modeling that was based on linear fracture mechanics under the Mode I condition provided a good estimate of the stress intensity range of subsurface or surface and fatigue crack growth, enabling the estimation of the crack propagation life. The fatigue crack growth rate calculated using the Paris rule, $da/dN=C(\Delta K_I)^m$, almost corresponded to the one obtained from the analysis of the striation on the fracture surface. The calculated crack propagation life was less than a tenth of the number of cycles to failure over 10^6. As a result, the subsurface crack initiation (Stage I crack generation) process consumed a large number of cycles to failure—as many as that at a lower stress level.

(cf. *ISIJ Int.*, **49** (2009), 124)

The influence of austempering temperature on the wear resistance of ductile iron under two different tribosystems

S.LAINO et al.

This paper reports the results obtained in a research conducted to evaluate austempered ductile iron (ADI) as a wear resistant material for the production of machine parts processed at intermediate and high austempering temperatures (Ta). Severe abrasion in actual service performance trials and low stress abrasion laboratory tests (ASTM G-65) were carried out along with microstructural characterization by optical microscopy and X-ray diffraction. The results derived show that ADI yields excellent abrasion resistance under the operating conditions resulting from the field tests when Ta is raised. Nevertheless, ADI show an opposite trend under the low stress abrasion conditions imposed by the dry sand/rubber wheel abrasion apparatus (ASTM G-65). The presence of a metastable and ductile ausferrite phase (reacted and unreacted austenite+ferrite) in ADI microstructure appears to be the most relevant factor influencing the performance observed. In addition to a high deformation capability detected at the wear surfaces, an austenite to martensite transformation took place as determined by X-ray diffraction. These two factors combined make the ausferritic microstructure overcome hardness reduction when the austempering temperature is raised, improving or sustaining the resistance to severe abrasive wear but, at the same time, increasing impact toughness.

(cf. *ISIJ Int.*, **49** (2009), 132)

Analysis of group-buckling and -debonding behaviors of galvannealed coating layer on steel substrates under applied tensile strain

S.IWAMOTO et al.

The hot-dipped galvannealed steels are composed

of brittle coating layer with low failure strain and ductile substrate with far higher failure strain. When tensile stress is applied externally on the coated steels, the coating layer exhibits multiple cracking perpendicular to the tensile direction, and then interfacial debonding occurs, following the buckling of the coating layer in the sample width direction. In the buckling behavior, the series of cracked-coating layers arraying along the tensile direction exhibit group-buckling. In the present work, the group-buckling behavior was observed with the scanning electron microscope and analyzed with 3-dimensional finite element models. It was observed that the preceding buckling of the coating enhances the buckling of the neighboring coating. Such a behavior was well accounted for by the present analysis.

(cf. *ISIJ Int.*, **49** (2009), 139)