

cated that the reduction progressed topochemically in this experimental condition. In the reduction rate analysis, it was found out that the reduction rate by CH<sub>4</sub> was higher than that by H<sub>2</sub> or CO. From the carbon concentration analysis, it was found that the phase of the metallic shell during reduction was not only solid state but also liquid state. From the above-mentioned kinetic analysis, it was concluded that the reduction rate determining-step by CH<sub>4</sub> was chemical reaction on Fe-FeO interface and the reduction of wüstite was preceded by the carbon dissolved into metallic shell from CH<sub>4</sub> gas.

(cf. *ISIJ Int.*, 47 (2007), 386)

## Steelmaking

### The role of mullite-based refractory chemical interactions on the formation of exogenous non-metallic inclusions in vacuum treated 0.3% C steel

G.CORNACCHIA *et al.*

Exogenous non metallic inclusions can be introduced into steel from many external sources. Typical examples are the particles of refractory material which detach from their parent material during ladle treatment, teeming and casting operations, remaining entrained in the steel. In the present work, the interactions between Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> refractories and steel during casting of ingots has been deeply investigated, permitting to explain the occurrence of ghelenite- and grossite-types inclusions into special grade steels. The experimental analyses were carried out on non-metallic inclusions and ex-service refractory materials by means of Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS) and X-Ray Microdiffraction ( $\mu$ XRD). The results were confirmed by thermodynamical considerations.

(cf. *ISIJ Int.*, 47 (2007), 392)

### Influence of P<sub>2</sub>O<sub>5</sub> on crystallization of V-concentrating phase in V-bearing steelmaking slag

X.WU *et al.*

Synthetic V-bearing steelmaking slag modified by Al<sub>2</sub>O<sub>3</sub>, containing three different amounts of P<sub>2</sub>O<sub>5</sub>, were heated to 1530°C and then slow cooling to 1300°C for several durations. The effect of P<sub>2</sub>O<sub>5</sub> on the solidified slags, especially on the crystallization behaviour of V-concentrating phase were characterized by XRD, SEM and EPMA. The results show that V is concentrated and formed into Ca<sub>3</sub>(VO<sub>4</sub>)<sub>2</sub> in P<sub>2</sub>O<sub>5</sub>-free slag and for the samples with 1.0 wt% and 2.4 wt% P<sub>2</sub>O<sub>5</sub>, V is precipitated into a solid solution Ca<sub>3</sub>[(P,V)O<sub>4</sub>]<sub>2</sub>, Ca<sub>3</sub>(VO<sub>4</sub>)<sub>2</sub> and Ca<sub>3</sub>[(P,V)O<sub>4</sub>]<sub>2</sub> are both the V-concentrating phases in the modified slag. Quantitative description of the morphologic texture of grains of the V-concentrating phases was based on computer-aided image analysis. For all samples, the fitted lognormal distribution is in good agreement with the distribution in the whole grain size range. It is concluded that P<sub>2</sub>O<sub>5</sub> accelerates the growth of V-concentrating phase and influence the morphology of V-concentrating phase and growth mechanism is surface-controlled. There exists a proper content range of P<sub>2</sub>O<sub>5</sub> between 1–2.4% for better growth of V-concentrating phase.

(cf. *ISIJ Int.*, 47 (2007), 402)

### Mass transfer characteristics between molten steel and particles under conditions of RH-PB(IJ) refining process

J.-H.WEI *et al.*

The mass transfer characteristics between liquid steel and powder particles in RH-PB(IJ) refining process have been investigated on a water model of 1/4 linear scale for a 150t multifunction RH degasser. Sodium chloride powder with analytical purity has been utilized as the flux for injection. The mass transfer coefficient (*k*) of solute (NaCl) in the liquid has been determined under the conditions of the RH-PB(IJ) process. The effects of the main technological and structural parameters on the characteristics have been examined. It may be concluded from the results that, under the conditions of the present work, the mass transfer coefficient in the liquid increases with increasing the lifting gas flow rate, with increasing the inner diameter of the up-snorkel, with increasing the circulation rate of the liquid, and with increasing the particle size of powdered flux, and decreases with an increase in the inner diameter of the downsnorkel. Its value is in the range of (3.392 × 10<sup>-5</sup>–2.661 × 10<sup>-4</sup>) m/s. The corresponding dimensionless relationships for the mass transfer coefficient in the range were obtained. Taking the relative velocity of the particles to the liquid into account, the mass transfer in the liquid may be characterized by

$$Sh = 2 + 0.0285(Re_c)^{3.4} Sc^{1/3}$$

Considering the energy dissipation caused by the fluctuation in the velocity of the liquid in turbulent flow, the following dimensionless relationship has been reached:

$$Sh = 2 + 0.0285(\epsilon_p d_p^4 / \nu^3)^{1/4} Sc^{1/3}$$

When the mass transfer is regarded as that between rigid bubbles and molten steel, it may be characterized by:

$$Sh = 2 + 0.00731[Re_s^{0.48} Sc^{0.339} (g^{1/3} d_p / D)^{2.3} \nu^{0.072}]^{1.455}$$

In comparison with the mass transfers coefficient in the molten steel between the powder particles and the liquid in RH-PTB process, that in the conditions of RH-PB(IJ) refining is smaller, being about 1/4–1/3 of the former, but the both have a similar feature and pattern.

(cf. *ISIJ Int.*, 47 (2007), 408)

### Simultaneous desulfurization and deoxidation of molten steel with *in situ* produced magnesium vapor

J.YANG *et al.*

A new simultaneous desulfurization and deoxidation process of molten steel with magnesium vapor produced *in situ* by aluminothermic reduction of magnesium oxide is proposed. The pellets composed of MgO and Al are charged into an immersion tube and the magnesium vapor produced *in situ* by aluminothermic reduction of magnesium oxide is injected directly into molten steel to react with the dissolved sulfur and oxygen in it. Effects of various operating parameters on desulfurization and deoxidation are discussed.

In the case of the high initial oxygen concentration, deoxidation of molten steel proceeds preferentially, and desulfurization does not take place. When the oxygen concentration in the melt is low enough, desulfurization of molten steel with magnesium vapor can proceed.

A higher initial sulfur concentration increases the desulfurization ratio of molten steel. The sulfur concentration in the melt tends to be in equilibrium with the magnesium partial pressure in the Mg-Ar bubble rather than the dissolved magnesium concentration in the melt. Increasing pellet mass promoted desulfurization of molten steel. The maximum desulfurization ratio of molten steel can be obtained at a relatively low argon carrier gas flow rate. In both cases of the porous magnesia and the dense alumina immersion tubes with injecting holes, addition of lime onto the melt surface increases the desulfurization ratio. The desulfurization using the dense alumina tube is accompanied by resulfurization more significantly at the later stage than that using the porous magnesia tube.

(cf. *ISIJ Int.*, 47 (2007), 418)

## Casting and Solidification

### Instability of fluid flow and level fluctuation in continuous thin slab casting mould

B.SHEN *et al.*

A full scale water modeling experiment has been conducted to address the relationship between the instability of fluid flow and level fluctuation in the continuous thin slab casting mould with the particle image visualization. The results show that the internal fluid flow and level fluctuation are unsteady and periodical. The probabilities of fluctuated meniscus and moving circumfluence center position seem Position distributions with the highest frequency near the average position. The circumfluence and meniscus profile are asymmetrical, and the phase difference of wave height and circumfluence center in the two sides of mould centerline is half period. The average meniscus profile, the highest and lowest meniscus positions are generally symmetry about the mould centerline, and the circumfluence center swings with a similar trace. The wave height mainly depends on the circumfluence center position along the mould height. The wave height has an inverse relation with the circumfluence center depth, and the wave height decreases with descending circumfluence.

(cf. *ISIJ Int.*, 47 (2007), 427)

### Three dimensional turbulent fluid flow and heat transfer mathematical model for the analysis of a continuous slab caster

M.R.R.I.SHAMSI *et al.*

Continuous casting of slab caster of Tata Steel has been simulated using a three dimensional mathematical model based on considerations of fluid flow, heat transfer and solidification for better understanding of the process. Liquid metal comes in the mould by bifurcated nozzle. The principal model equations are momentum and heat balances. In various zones, different standard boundary conditions have been used. In the mould region, Savage and Prichard expression

for heat flux has been used. In the spray cooling zone, heat transfer coefficient for surface cooling of the slab has been calculated by knowing the water flow rate and nozzle configuration of plant. The turbulence in the molten metal has been modelled by the Realizable  $k-\epsilon$  model. CFD software (Fluent) has been used for the solution of equations to predict the velocities in the molten pool of the slab, temperature of the entire volume of the slab, heat transfer coefficient in the mould region, heat flux in the spray and radiation region and shell thickness. The variables studied are different casting speed.

(cf. *ISIJ Int.*, 47 (2007), 433)

### Instrumentation, Control and System Engineering

#### A new ILS algorithm for cast planning problem in steel industry

L.TANG *et al.*

Cast planning is a practical problem frequently encountered in steel industry. Its task is to group charges into batches (casts) with respect to the similarities of steel-grade and dimensions between charges, taking account of the practical technique constraints on life-span of tundish. Effective cast planning can reduce the changeover cost of charges and enhance the productivity of continuous casters. The objective under our consideration is to minimize the total dissimilarity costs between the changes in the same casts, to minimize the number of casts and the number of unselected charges. A quadratic integer programming model with multiple objectives for this problem is formulated. It is NP-complete, and so an iterated local search (ILS) algorithm is developed for the problem. In this algorithm, cyclic transfer neighborhood is adopted, in which several charges are transferred among casts simultaneously as a manner of cycle. A new kick strategy is developed with the idea of assigning charges to different casts according to the dissimilarity costs between them and the casts' central charges identified by the current solution. Computational results using real data from an advanced iron & steel company in China indicate that the ILS algorithm provides optimal solutions for small instances, and better near-optimal solutions for larger instances compared with a linear solver, Lingo 8.0, used to solve the equivalent linear integer programming obtained by transforming the original model. Totally, 92.3% of the instances are solved to global optima by the ILS algorithm while it is possible that the other 9.7% instances also are solved to optimal, which indicates the efficiency of the algorithm. At the same time, the algorithm also provides better solutions than the ones obtained by the current system used in the company.

(cf. *ISIJ Int.*, 47 (2007), 443)

### Chemical and Physical Analysis

#### Analysis of iron oxyhydroxides and oxides converted from green rust in aqueous solution

K.INOUE *et al.*

In order to clarify the influence of reaction condi-

tions on the formation of iron oxyhydroxides and oxides obtained from hydroxysulfate green rust (GR), the X-ray diffraction method was used for analyzing the solid particles formed during conversion. GR was synthesized from solutions of ferric sulfate, ferrous sulfate, and sodium hydroxide. The suspension containing GR was oxidized by passing oxygen gas. X-ray absorption spectroscopy and transmission electron microscopy were used for analyzing the chemical state and structure of the solid particles separated from the suspension, respectively. The results revealed that GR was converted primarily to  $\alpha$ -FeOOH, and  $\gamma$ -FeOOH and  $\text{Fe}_3\text{O}_4$  were found to be partially formed during the conversion depending on the temperature and oxygen flow rate. Furthermore, the addition of manganese was shown to enhance the formation of  $\text{Fe}_3\text{O}_4$ . These results indicate that the formation of different structures of iron oxyhydroxides and oxides in an aqueous solution is sensitive to the reaction conditions.

(cf. *ISIJ Int.*, 47 (2007), 453)

### Surface Treatment and Corrosion

#### Crack spacing distribution in coating layer of galvanized steel under applied tensile strain

S.OCHIAI *et al.*

The crack spacing distribution of the Fe-Zn intermetallic coating layer of tensile-strained galvanized IF (Interstitial Free) and SPCC (Steel Plate Cold Commercial, Japanese Industrial Standard) steels under tensile applied strain at room temperature was studied. The experimental and analytical results revealed that the crack spacing decreases with increasing applied strain due to the increase in stress transfer efficiency and the cumulative probability-crack spacing curves at any applied strain of both samples lie in a unique curve when the crack spacing is normalized with respect to the average value at each applied tensile strain. Then, by combining these features, a comprehensive description method of the crack spacing distribution was proposed, in which the influences of the thickness of the coating layer, substrate material and applied strain are incorporated. With the proposed method, the measured change of the probability density-crack spacing curve with increasing applied strain was described well for both samples. Also with this method, the variation of the probability density-crack spacing relation as a function of applied strain was predicted for different thickness of the coating layer and substrate material. Based on these results, the influences of multiple cracking that takes place in advance of spalling of the coating layer on the non-uniform spalling and the influences of thickness of the coating layer and substrate material on the spalling behavior were discussed.

(cf. *ISIJ Int.*, 47 (2007), 458)

### Transformations and Microstructures

#### Magnetic anisotropies and textures in high-alloyed non-oriented electrical steels

S.K.CHANG

Effects of alloy addition on magnetic anisotropies

in non-grain oriented electrical steels were investigated. Tin and antimony improved magnetic induction and iron loss but increased anisotropy of magnetic induction and lessened anisotropy of iron loss. Texture effect was evaluated as texture factor expressing as a rate of sum of volume fractions of cube and Goss textures to volume fraction of  $\gamma$  fiber texture. Magnetic anisotropy of iron loss is inversely proportional to texture factor and magnetic induction were turned out proportional to texture factor.

(cf. *ISIJ Int.*, 47 (2007), 466)

#### Determination of the conditions of the chromium nitride formation in a ULC steel of Fe-Cr-N type with 0.7% Cr

V.MASSARDIER *et al.*

The nitrogen content in solution in the extra-mild steel sheets used in automotive or packaging industry after the different steps of their processing plays an important role both on the formability of the sheets and on their ability for strain ageing. This is why, the aim of the present work is to determine the conditions of the chromium nitride formation in a cold-rolled ULC steel with 0.7% Cr. In order to simulate the precipitation which may occur during the coiling or during the recrystallization annealing of the sheets, the investigated steel was submitted to different thermal treatments at temperatures ranging from 600 to 850°C. Then, the nitrogen content remaining in solution was evaluated after having defined a specific procedure based on thermoelectric power (TEP) measurements and using the segregation of the nitrogen atoms in solution to the dislocations introduced in the steel by cold-rolling. It was shown that the maximum precipitation speed is obtained at 650°C and that the precipitation is considerably delayed when the steel was recrystallized before the treatment.

(cf. *ISIJ Int.*, 47 (2007), 472)

#### Solution nitriding treatment of Fe-Cr alloys under pressurized nitrogen gas

H.MITSUI *et al.*

Performing the solution nitriding treatment under pressurized nitrogen gas atmosphere, the microstructure change and the relationship between the nitrogen gas pressure and the solute nitrogen content in Fe-Cr alloys were investigated. The microstructure of the ferritic Fe-Cr alloys changed to an austenitic structure by the pressurized solution nitriding treatment at 1473 and 1573 K. However, in the case that their martensite temperature did not decrease sufficiently lower than room temperature, martensitic transformation occurred during the cooling process. Examination of the interaction on nitrogen activity with the thermodynamic method confirmed that the deviation between the experimental and theoretical solute nitrogen contents in Fe-Cr alloys widened greatly in the high nitrogen region over 3 at% N because of the strong N-N interaction in austenite. The interaction parameter  $e_N^{[N]}$  between N atoms in austenite iron at 1473 K was obtained as 0.120. The temperature dependence of  $e_N^{[N]}$  is expressed as follows:

$$\epsilon_N^{[N]} = \frac{217}{T} - 0.0273$$

(cf. *ISIJ Int.*, 47 (2007), 479)

## Mechanical Properties

### Effect of aluminum content on the mechanical properties of dual stabilized Ti-Nb interstitial free high strength steel (IF-HSS)

*H.KANG et al.*

The effect of aluminum content during the annealing of interstitial free high strength steel (IF-HSS) containing Mn, P, Ti and Nb was investigated. The resulting mechanical properties were evaluated and recorded. The results showed that a super formable high strength IF steel with an *r*-value equal to or higher than 2.3 can be obtained by Al additions. One of the interesting observations of this investigation was the change of precipitation behavior with aluminum content. Aluminum has the effect of improving the formability, especially the drawability, of the IF-HSS when more than 0.10 wt% Al is added. Texture analysis showed that the  $\langle 111 \rangle$ /ND fiber ( $\gamma$ -fiber) was intensified, and  $\langle 110 \rangle$ /RD ( $\alpha$ -fiber) was weakened, with an increase of aluminum content. These benefits appear to result from the change of precipitation behavior with the increase of aluminum content. It was confirmed thorough the SANS analysis that the size of the precipitates in the sample with higher aluminum content was larger and their number was much fewer than in the sample with lower aluminum content. It appears that the high aluminum in IF-HSS containing Mn, P, Ti and Nb strengthened the scavenging effect of Ti or Nb and thus purifies the iron matrix.

(cf. *ISIJ Int.*, 47 (2007), 486)

### Evaluation of ductile forming limit stress in sheet forming processes and measurement of actual stress at fracture

*T.IGUCHI*

A stress-based ductile forming limit theory ap-

plicable to nonlinear strain paths is investigated with a 11% Cr steel which displays a highly anisotropic behavior in plastic deformation. The forming limit stress is evaluated by a theoretical method based on the M-K theory, and is also measured directly in some cases with nonlinear loading paths. The evaluated and measured stresses are compared with an experimentally-obtained forming limit stress diagram, where the stresses are converted from strains by Stoughton's method. The theoretically-evaluated limit stress corresponds not to the measured stress at the onset of fracture but to the stress at the onset of localized necking. The evaluated forming limit stress and experimentally-obtained localized necking stress demonstrate no dependency on strain paths, thus verifying the applicability of the theory to this particular material. The experimentally-obtained forming limit stress diagram was corrected using the above results, which has improved the discrepancies between the experimentally- and numerically-obtained forming limit stress.

(cf. *ISIJ Int.*, 47 (2007), 493)

### Ductile forming limit stress in sheet forming processes with nonlinear strain path involving out-of-plane forming

*T.IGUCHI*

The ductile fracture limit in nonlinear strain paths which include out-of-plane forming such as rolling was investigated for a 11% Cr steel sheet. For strain paths with only a plane stress state, e.g., in-plane strain, the forming limit stress diagram (FLSD) has been proven to be effective, even if the paths are nonlinear. In this research, a method of extending the FLSD theory to strain paths which include out-of-plane strain is investigated experimentally and theoretically. An experimental procedure is used to measure directly the stresses at the onset of diffused and localized necking and at the onset of separation with rolling-stretching loading paths. Theoretically, an assumption is introduced to consider out-of-plane strain in the M-K theory. The experimental and theoretical results of the forming limit stress show good agreement. When large rolling strain is in-

duced in first-stage loading paths, this research demonstrated that there are cases where the FLSD theory is not effective for predicting the ductile forming limit. Those cases are characterized by a stress state of the re-yielding point in the final loading stage. If the point is outside the FLSD curve, the forming limit stress is not on the FLSD curve but located near the subsequent yield surface. Thus, a modified FLSD curve can be defined by the lines connecting the outer line of the conventional FLSD curve and the subsequent yield surface of the loading path under consideration. With this extension, it is possible to demonstrate the applicability of the FLSD method to processes which include out-of-plane loading paths such as rolling.

(cf. *ISIJ Int.*, 47 (2007), 502)

## Social and Environmental Engineering

### Substance flow analysis of molybdenum associated with iron and steel flow in Japanese economy

*K.NAKAJIMA et al.*

Substance flow analysis of molybdenum associated with iron and steel flow has been conducted in this study. The demand of molybdenum in iron and steel section reaches approximately 85% of total molybdenum consumption in Japan. Total demand of special steel products in final commodity is  $18.4 \times 10^6$  t (for domestic:  $12.4 \times 10^6$  t), and that contains  $14.3 \times 10^3$  Mo-t (for domestic:  $9.6 \times 10^3$  Mo-t) of molybdenum in 2004 fy. In addition, crude steel for special steel ( $23.8 \times 10^6$  t) contains  $18.5 \times 10^3$  Mo-t of molybdenum. Approximately 70% ( $12.3 \times 10^3$  Mo-t) of molybdenum in the crude steel flows into domestic market, and about 45% of that is used for motor vehicles production. Improvement of dismantling technology and standardizing of special steel scrap will help to promote rare metal recycling.

(cf. *ISIJ Int.*, 47 (2007), 510)