（＊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

Reduction rate of Cr_2O_3 in a solid powder state and in $CaO–SiO_2–Al_2O_3–CaF_2$ slags by Fe–C–Si melts

T.NAKASUGA et al.

In order to understand effective conditions to recover chromium from stainless steel-making slags, the kinetic behavior of Cr_2O_3 reduction by iron–carbon melts were investigated at various conditions by using solid Cr_2O_3 powder and $Cr_2O_3–CaO–SiO_2–Al_2O_3–CaF_2$ slags. The effect of temperature on the reduction rate of solid Cr_2O_3 was fairly large and the apparent activation energy was about 180 kJ mol^{-1}. The overall reduction of solid Cr_2O_3 was considered to be controlled by a chemical reaction step. For reduction of Cr_2O_3 in slag, the addition of CaF_2 to slag and of silicon to iron melt promoted the reduction rate, but the reduction of Cr_2O_3 powder was retarded by the silicon addition. The kinetic behavior of reduction of Cr_2O_3 in slag could be well simulated by the kinetic reaction model proposed previously. As a result, it was found that the overall reduction rate of Cr_2O_3 in slag was controlled by the mass transport in the slag phase.

(cf. *ISIJ Int.*, **41** (2001), 937)

Desulfurization of molten iron with magnesium vapor produced *in-situ* by carbothermic reduction of magnesium oxide

J.YANG et al.

A new method of desulfurization of molten iron has been developed with magnesium vapor produced *in-situ* by carbothermic reduction of magnesium ox-ide. Pellets, the main composition of which was magnesium oxide and carbon, were charged into a graphite tube. The tube was immersed into the molten iron to produce magnesium vapor. This process has been studied experimentally and theoretically.

The rate of desulfurization depended mainly on the rate of reduction of magnesium oxide. Under the present experimental conditions, the desulfurization rate increased with increasing temperature and Ar carrier gas flow rate. The change in melt mass had little influence on the desulfurization efficiency of magnesium. The effect of pellet composition on the desulfurization has also been investigated.

A mathematical model of the desulfurization has been proposed. The calculated results are in good agreement with the experimental results. The rate-controlling step changes with the progress of desulfurization during bubble formation and ascent periods. At the beginning of the formation period, both of the mass transfer of sulfur in the melt and magnesium in the bubble should be considered as rate-controlling steps. At the end of the ascent period, the magnesium partial pressure in the bubble decreases close to the value in equilibrium with the sulfur concentration in the melt. The mass transfer of magnesium in the bubble becomes much slower than that of sulfur in the melt and becomes the rate-controlling step.

The desulfurization reaction mainly takes place on the bubble surface. The amount of desulfurization during the bubble formation period is larger than that during the bubble ascent period. Effects of pellet mass and initial sulfur concentration on desulfurization can be reasonably explained by the present mathematical model.

(cf. *ISIJ Int.*, **41** (2001), 945)

Smelting reduction mechanism of Fe–O–S melts using solid carbon

D.-H.KIM et al.

The reduction of iron oxide in Fe–O–S melts by solid carbon was investigated to determine the reduction rate of iron oxide and to elucidate the reduction mechanism. The solid iron product deposits at the carbon surface, and grows towards the melt. On immersion of a graphite rod into the melt, the reduction rate reaches a maximum value and continues to stay at the value for some length of time, and then exhibits a gradual fall, followed by a constant residual rate. The temperature dependence of the rate is well represented by the Arrhenius equation, and the activation energy is 190 kJ mol^{-1} for 53.4 wt% FeO. The maximum rate shows a first order dependence on the FeO concentration, and is directly proportional to the geometric interfacial area between the graphite and the melt. Agitation of the melt hardly affects the rate of reduction. Solid iron produced at the graphite surface is very low in carbon, showing a ferritic structure. It is concluded that the reduction is controlled by the chemical reaction at the interface. The electrochemical reactions $Fe^{2+}+2e^-=Fe(s)$ and $O^{2-}+C(s)=CO(g)+2e^-$ take place and are responsible for the major portion of the reduction reaction until the carbon surface has been fully covered by the product iron. The dissolution rate of carbon from the graphite rod into the product iron is much slower than either the diffusion rate of carbon in the iron or the reaction rate of iron oxide by carbon diffused in the iron. This results in the product iron being very low in carbon and ferritic in structure.

(cf. *ISIJ Int.*, **41** (2001), 955)

Desulfurization of molten iron with magnesium vapor produced *in-situ* by aluminothermic reduction of magnesium oxide

J.YANG et al.

Magnesium vapor produced *in-situ* by aluminothermic reduction of magnesium oxide was injected directly into the melt with argon carrier gas to desulfurize molten iron to an ultra-low sulfur concentration in a short time.

The desulfurization rate increased with increasing temperature in the range from 1 553 to 1 773 K. The desulfurization efficiency of pellet increased with decreasing pellet mass. The effects of initial sulfur concentration and carrier gas flow rate on the desulfurization were also investigated.

A mathematical model is developed to calculate the desulfurization rate and good agreement is obtained between calculated and experimental results. The calculated results show that when the initial sulfur concentration is not very high, the mass transfer rate of magnesium in the bubble is faster than that of sulfur in the melt. The amount of desulfurization during the bubble ascent period is 3.5–9.3 times larger than that during the bubble formation period. Effects of the pellet mass and the initial sulfur concentration on desulfurization can be well explained by the present mathematical model.

(cf. *ISIJ Int.*, **41** (2001), 965)

Casting and Solidification

Numerical analysis of fluid flow and heat transfer in the parallel type mold of a thin slab caster

H.-S.PARK et al.

The surface and internal defects in the continuously cast slab are closely related to the fluid flow conditions of the liquid steel in the continuous casting mold. Therefore, the control of the steel flow for example, by proper design of submerged entry nozzle and by optimum operating conditions, has become an important area for quality and productivity improvement. In this study, a three-dimensional numerical model for fluid flow and heat transfer analysis was employed and flow pattern and related phenomena in the parallel type thin slab mold were simulated together with a comparison with our previous study on the funnel type mold. The dependence of the flow on the shape of the SEN was illustrated for both straight and bifurcated nozzles. The bifurcated nozzle creates streamlines of two counter-rotating loops at each half of the mold similar to that of the funnel type mold with a bifurcated nozzle and produces a stabilized meniscus with a low surface velocity. The design of the nozzle port affects the velocity profile at the meniscus, heat transfer and accordingly the solidification process. An inclined bifurcated nozzle with a jet angle of 60° shows more stable velocity profile in the meniscus and more uniform distribution of solidified shell than the other port.

(cf. *ISIJ Int.*, **41** (2001), 974)

Influence of high frequency electromagnetic field on the initial solidification during electromagnetic continuous casting

Z.REN et al.

The initial solidification during electromagnetic continuous casting of metal has been investigated experimentally and numerically. The temperature profile in the metal was measured and the starting point of the initial solidification was detected. It was found that the magnetic field influenced the temperature profile greatly, and lowered the starting position of the initial solidification profoundly. Further, the induction heat in the metal was calculated according to the measured magnetic flux in the mold. The heat induced in the wall was converted from the temperature detected in the mold wall. In order to understand the influence of the magnetic field on the behavior of the interfacial heat exchange between the metal and the mold wall, a special experiment was carried out to measure the heat exchange coefficient on the interface.

Based on above measurement, a numerical model was built to describe the heat transfer and solidification of the metal. The influence of the magnetic field on the solidification was figured out. The role of the three main effects of the magnetic field, that is, in-

ducing heat in the metal, inducing heat in the mold wall, and decreasing the heat transfer rate on the interface between the metal and mold wall, was analyzed. It was shown that, the induced heat in the mold wall and the effect of decreasing the heat transfer on the interface between the mold and the metal may played a more important role in influencing the solidification.

(cf. *ISIJ Int.*, **41** (2001), 981)

Modeling of stable and metastable eutectic transformation of spheroidal graphite iron casting

H.ZHAO et al.

In this work, a mathematical model for stable and metastable transformation of SG cast iron, coupling with microsegregation of some elements and latent heat resulted from different phase formation, was presented. The quantitative experimental results of specimens obtained from a step-shape sample casting were compared with the simulation, and two results of nodular counts and sizes agreed quite well. For white eutectic growth in mottled SG iron, the frequent impingement of white eutectic with austenite–graphite bulks might suppress its growth remarkably and result in quite lower growth rate than that from the melt exclusively. Meanwhile, the relationship of morphology of carbides and solidification was discussed, and it was indicated that the growth of white eutectic and carbide morphology could also be predicted by solidification simulation. It was found that neglecting silicon microsegregation, if metastable transformation was advantageous to stable, the simulated carbide fraction was higher, and *vice versa*.

(cf. *ISIJ Int.*, **41** (2001), 986)

Modeling of globular and dendritic structure evolution in solidification of an Al–7mass%Si alloy

M.F.ZHU et al.

The evolution of globular and dendritic structures in solidification of an Al–7mass%Si alloy has been investigated by a modified cellular automaton model (MCA). Besides retaining the probabilistic aspects of the classical CA model for the heterogeneous nucleation and the preferential growth orientations of the nuclei, the present MCA model is coupled with the curvature, the solute partition between liquid and solid as well as diffusion in both phases. The effects of constitutional undercooling and curvature undercooling are incorporated on the equilibrium interface temperature. The relationship between the growth velocity of a dendrite tip and the local undercooling is calculated according to the KGT (Kurz-Giovanola-Trivedi) model. The finite volume method, coupled with the cellular automaton model, was used to calculate the solute field in the computational domain. The effects of pouring temperature, cooling rate, and inoculation on the growth morphology of the primary phase were studied. The simulation results were compared with those obtained experimentally. It can be concluded that the present simulation model can successfully predict the evolution of dendritic and globular structures in solidification of alloys

(cf. *ISIJ Int.*, **41** (2001), 992)

Development of a new simulation method of mold filling based on a body-fitted coordinate system

C.P. HONG et al.

A new numerical model has been developed for the simulation of mold filling in curved-shape mold cavities. In the present method, the SIMPLE scheme was adopted to solve the momentum transport and the VOF (Volume of Fluid) method to trace the free surface in mold filling processes. In order to improve the solution accuracy in modeling mold filling with curved-shape and thin-walled mold cavities, the body-fitted-coordinate (BFC) concept, known as the most effective method to predict a flow field in a curved-shape cavity, was adopted. The governing equations for fluid flow were transformed based on the BFC concept. The non-staggered mesh and the momentum interpolation method were used which are essential for the BFC method. In addition, the standard VOF method was modified for the treatment of free surface in the BFC system. The standard DAFA (donor and acceptor flux approximation) method was also revised as a suitable form to the BFC system. In order to verify the present SIMPLE-BFC-VOF method, several examples on mold filling problems having curved-shape mold cavities were simulated, and the results were compared with the experimental results and other simulation methods. It is concluded that the present method can be used as an effective simulation method for the simulation of mold filling in thin-walled and curved-shape mold cavities.

(cf. *ISIJ Int.*, **41** (2001), 999)

Welding and Joining

Crack repair of hot work tool steel by laser melt processing

Y.SUN et al.

Tool steel used in hot work such as die-casting is required to have the resistance to heat checking which results in fine shallow cracking on the part surface. Laser melt processing, which can produce a localized shallow melted zone, has been adapted to repair such kind of cracks. However, the melted zone has a detrimental effect on impact toughness because the laser heating may generate hard structures during the processing. In this paper, the effect of laser melt processing on repairing cracks was evaluated by means of the Charpy impact test and fractography. The test results suggested that when this laser melt processing can eliminate an extensive damaged volume through heat treatment after laser melt processing, the impact toughness is able to recover again to the initial state after heat treatment.

(cf. *ISIJ Int.*, **41** (2001), 1006)

Surface Treatment and Corrosion

Microstructure and oxidation behavior of low pressure plasma sprayed iron aluminides

N.MASAHASHI et al.

Microstructure and oxidation behavior of plasma sprayed iron aluminide have been investigated focusing on the spraying conditions of atmosphere and pressure. Iron aluminide powder for spraying was prepared by ball milling of turnings fabricated from an Fe–40at%Al ingot. Microstructure of laminated layers including cavities was observed in all samples and particles with a size of about 100 μm were observed only in the sample sprayed in 50 Torr Ar atmosphere. Chemical analysis revealed an amount of aluminium loss and oxygen pick-up in samples sprayed in air, while X-ray diffraction analysis exhibited only the iron aluminide spectra without the second phase. The intensity of superlattice spectra of aluminide was strong in the samples sprayed in Ar compared with in air. Change of mass gain in oxidation testing was small in the sample sprayed in 50 Torr Ar, which is equivalent to as-cast bulk sample, while large in other samples. SEM observation revealed the evolution of iron oxides in the samples sprayed in air, which was not observed in the sample sprayed in Ar. The mechanism for superior resistance to oxidation in the sample sprayed in 50 Torr Ar is attributed to infusible particles deposition, which inherited the intrinsic oxidation resistant property of iron aluminides.

(cf. *ISIJ Int.*, **41** (2001), 1010)

Transformations and Microstructures

Some theoretical aspects on designing nickel free high nitrogen austenitic stainless steels

G.BALACHANDRAN et al.

Nickel free high nitrogen austenitic stainless steel design calls for proper choice of alloying constituents that enhances nitrogen solubility and retention of the same after alloying. The nitrogen alloyed should be adequate enough to give a single phase austenitic matrix along with other alloying elemental constituents. The various studies that evaluated these aspects show certain inconsistencies. Certain empirical formulations have been evolved in this study by analyzing all various published data. The formulae obtained, enables choice of alloying elemental composition to get desired microstructure and strength in the solution annealed condition. The various inadequacies that exists in the data used for assessing nitrogen solubility calls for caution when they are applied to actual nitrogen steel production process conditions.

(cf. *ISIJ Int.*, **41** (2001), 1018)

The effect of plastic deformation of austenite on the kinetics of subsequent ferrite formation

D.N.HANLON et al.

A modeling approach to account for the effect of deformation on the austenite to ferrite transformation is described. In this approach the stored energy of deformation resulting from the formation of a dislocation substructure is considered to result in an elevation of the driving force for transformation. A scheme which accounts for the competition between softening and transformation processes is also described. Model data illustrating the effects of discrete dislocations and cell structures, with and without concurrent recovery are presented. Comparison of modeled and experimental transformation curves indicates that deformation affects the transformation

principally *via* a reduction in the undercooling required for nucleation rather than *via* an acceleration of the growth kinetics.

(cf. *ISIJ Int.*, **41** (2001), 1028)

The γ–α transformation kinetics of low carbon steels under ultra-fast cooling conditions

Y.vanLEEUWEN et al.

Current evolutions in the processing techniques of hot rolled steel sheet, like the development of an ultra fast cooling unit which cools the material after the final rolling step, stretch the domain of the material models used to control these processes. When employing a so-called ultra fast cooling unit an accurate description of the transformation kinetics is needed at cooling rates that are significantly higher than the range in which most austenite to ferrite transformation models have ever been tested. In this paper a physically based transformation model is applied to a set of dilatometer experiments involving four different commercial steel grades and cooling rates from 20 K/s to 600 K/s. The model describes the transformation by means of moving γ–α interfaces in a single austenite grain. Parameters that were varied in the modelling procedure are the degree of undercooling below the A3-temperature, ΔT, at which the transformation is assumed to start, and the intrinsic interface mobility pre-factor, M_0. By analysing the errors in the fit of the calculated transformation behaviour to the experimental data, ranges of optimum fit in the $\Delta T - M_0$ space were determined. In order to determine a unique combination of ΔT and M_0, a physically justified value of ΔT was determined using the classical nucleation theory. The resulting values of M_0 increase with increasing cooling rate and decrease with increasing carbon content.

(cf. *ISIJ Int.*, **41** (2001), 1037)

Recrystallization of lath martensite with bulge nucleation and growth mechanim

T.TSUCHIYAMA et al.

The recrystallization behavior of lath martensite during tempering was investigated in high-chromium martensitic steels by means of hardness testing, optical and transmission electron microscopy. The role of carbide particles on the recrystallization was also discussed in terms of the grain boundary pinning effect. The hardness of tempered specimens was plotted as a function of the tempering parameter, $T(\log t+20)$, for a low-carbon steel (Fe–9Cr–0.1C mass%) and an ultra-low carbon steel (Fe–9Cr–1Ni–0.006C mass%). The low-carbon steel exhibited gradual softening with recovery but did not undergo recrystallization. However, the ultra-low carbon steel suffered abrupt softening owing to the discontinuous recrystallization of lath martensite. Microstructural observations in the ultra-low carbon steel indicated that the recrystallization of lath martensite occurs with the 'bulge nucleation and growth (BNG) mechanism'. The possibility of recrystallization *via* this mechanism depends upon both the spacing of carbide particles on grain boundaries and the dislocation density of martensite. An energetic analysis on the formation of a recrystallized grain revealed the critical carbide spacing minimum required for the occurrence of recrystallization as a function of dislocation density. In the case of the low-carbon steel, carbide precipitates on grain boundaries with spacing smaller than the critical value, thus suppressing recrystallization.

(cf. *ISIJ Int.*, **41** (2001), 1047)

Recrystallization kinetics of low and ultra low carbon steels during high-rate annealing

M.FERRY et al.

Annealing experiments were carried out to study the effect of rapid heating rates on the recrystallization kinetics and grain size of steels with a range of carbon levels (0.003–0.05%C). The steels were cold-rolled to 70% reduction and subsequently annealed at heating rates from 50 to 1 000°C/s to peak temperatures (T_p) in the range 600 to 800°C and held at T_p for various times and cooled to ambient temperature at a rates up to 2 000°C/s. For the steels investigated, the rate of anisothermal recrystallization and the final grain size decreases with increasing heating rate. These results do not support previous work in which it was concluded that ultra-rapid softening (which was associated with an observed decrease in recrystallization temperature at high heating rate and a concomitant increase in grain size) occurs at heating rates in excess of 500°C/s. An annealing model, based on JMAK transformation kinetics, is presented, which predicts the kinetics of recrystallization for any combination of input parameters: heating rate, peak temperature, holding time and cooling rate. The model is shown to predict the strong effect of holding time and cooling rate on the rate of recrystallization at high heating rates.

(cf. *ISIJ Int.*, **41** (2001), 1053)

Mechanical Properties

The developments of cold-rolled TRIP-assisted multiphase steels. Low silicon TRIP-assisted multiphase steels

P.J.JACQUES et al.

TRIP-assisted multiphase steels are newly developed steels exhibiting an improved balance of strength and ductility very well adapted for the automotive industry. In order to allow the retention of austenite, the steels studied up to now contained high levels of silicon incompatible with the industrial practice. This study shows how the combination of both a composite strengthening effect and the TRIP effect can improve the mechanical properties of a cold-rolled 0.16wt%C–1.3wt%Mn steel containing only 0.4 wt% of silicon. A complete characterisation of the bainite transformation and of the resulting microstructures, tensile properties and mechanical stability of retained austenite has allowed the determination of the factors responsible for the enhanced balance of strength and ductility of this steel well adapted for automotive applications.

(cf. *ISIJ Int.*, **41** (2001), 1061)

The developments of cold-rolled TRIP-assisted multiphase steels. Al-alloyed TRIP-assisted multiphase steels

P.J.JACQUES et al.

The influence of heat-treating conditions on the retention of carbon-enriched austenite of TRIP-assisted multiphase steel grades containing different amounts of silicon and/or aluminium is investigated. The ensuing mechanical properties resulting from the TRIP effect are also scrutinised. The bainite transformation kinetics was followed by dilatometry whereas a detailed characterisation of the microstructures led to the construction of transformation maps giving the volume fractions of the different phases and the carbon content of austenite. The role of silicon and aluminium additions (i) on the retention of austenite by partial bainite transformation and (ii) on the mechanical properties is enlightened. A strong influence of the solid-solution strengthening effect of silicon is highlighted. Aluminium seems to be an effective alloying element for the retention of austenite in TRIP-aided steels even if lower strength levels can be attained. A mixed Al-Si TRIP-aided steel seems to be a very good compromise between the processing needs, the required mechanical properties and the industrial constraints.

(cf. *ISIJ Int.*, **41** (2001), 1068)