（＊掲載記事題目及び掲載頁は変更になる場合があります。）

Casting and Solidification

Comparison of continuous strip casting with conventional technology (Review)

N.ZAPUSKALOV

Increased competition and the need to decrease steel product prices has combined with other factors such as growing salaries, increasing cost for electricity and raw materials to apply pressure to both mini and integrated mills. To compete in the future market and to maintain market share, both mills will need to use new efficient technologies capable of supplying steel strip products of high quality at low cost. Large investments in the development of strip casting process by the main world steel produces and plantmakers have already occurred due to its huge potential to substantially reduce the investment cost of steel strip production. Open literature on the continuous casting has been reviewed, with emphasis on strip casting of steel as new generation of continuous casting technology and has covered the following topics: current trends in production of steel strip; advantages of strip produced direct from the melt; strip casting process; strip quality; commercial strip casters and expenditure on research and development of the strip casting process.

(cf. *ISIJ Int.*, **43** (2003), 1115)

Fundamentals of High Temperature Processes

Numerical modelling of an anodic metal bath heated with an argon transferred arc

A.DOUCE et al.

A new 3-D model has been developed to describe the interaction between a transferred electric arc and a liquid metal bath, and has been used to simulate a pilot axisymmetrical transferred arc furnace operating in the EDF Research and Development laboratory.

This model enables calculations of the flow patterns, temperature distribution and electromagnetic fields in both the arc and the bath. The Navier–Stokes equation coupled with the electromagnetic relations are solved in each domain using a finite volume method. The source term in the radiative energy equation is modeled using the radiative transfer method in order to take into account the strong temperature variations in the electric arc. The transport and condensation of metal vapour in the arc domain are considered by solving a conservation equation for the vapour mass fraction. The arc flow calculation at the bath surface uses a one-dimensional sheath model taking account of the metal vapour, in order to ensure the coupling between the plasma and the bath by evaluating the boundary conditions at the arc/bath interface. The calculations were performed for an arc length of 0.25 m.

Realistic predictions are obtained for the electrical, dynamic and thermal behaviour of the plasma and liquid metal, and also for the arc voltage. The results indicate that the effects of the arc impact and Lorentz forces are not sufficient to induce effective mixing throughout the metal bath, leading to a marked thermal stratification in the liquid metal. In the bath, the liquid/solid interface has been determined by calculations.

(cf. *ISIJ Int.*, **43** (2003), 1128)

Ironmaking

Kinetic model for the uniform conversion of self reducing iron oxide and carbon briquettes

J.MOON et al.

A kinetic model has been developed to describe the uniform conversion of a self reducing mixture of iron oxide and carbon. The model takes into account the reaction kinetics of both the iron oxide reduction and carbon oxidation. The model is validated with experimental data. Rate constants are compared with those in the literature.

The combination of existing reaction analysis techniques coupled with the model developed has shown that for the experimental conditions used here, the Boudouard reaction controls the self reduction kinetics.

(cf. *ISIJ Int.*, **43** (2003), 1136)

The effect of the change of furnace profile with the increase in furnace volume on operation

T.INADA et al.

Based on the characteristics of the change of furnace profile with an increase in furnace volume, the effects of blast furnace profile on operation are investigated. The investigation is made by use of numerical simulation models that are integrated to evaluate the whole furnace state including hearth. First, the characteristics of the change of furnace profile with the increase in furnace volume are reviewed. Then, evaluation of the effects of furnace profile is made from the viewpoint of efficiency and stability of operation. The larger furnaces are advantageous to lowering a fuel rate, while stability against channeling at periphery is poor. In addition, as for furnace hearth life extension, the effect of furnace volume is discussed. As the furnace volume increases, the molten iron velocity at peripheral region of the hearth increases.

(cf. *ISIJ Int.*, **43** (2003), 1143)

A new estimation method of coke strength by numerical multiscale analysis

Y.ASAKUMA et al.

The homogenization method is proposed as new numerical approach to understand the fracture mechanism of the microscopic behavior in coke because the evaluations of the strength has been still difficult for the improvement of coke qualities in coke making process. The conditions for the stress concentration and relaxation effect are investigated by homogenization method. These results show that the distribution of micro cracks and pores in coke is important factor for the microscopic fracture. Also, the digital image technique is applied to the actual coke with the complicated microstructure and the improvement mechanism of coke strength by the carbon deposition is clarified by using homogenization method. The effect of carbon deposition on the coke strength is illustrated from the stress distribution while calculating the homogenized elastic modulus. Although the stress concentration between large pores is caused in the case of carbon deposited coke, the maximum stress becomes smaller than the tensile strength of coke because of large homogenized elastic modulus. As a result, the microscopic fracture does not easily occur for carbon deposited coke.

(cf. *ISIJ Int.*, **43** (2003), 1151)

Stabilizing burden trajectory into blast furnace top under high ore to coke ratio Operation

Y.MATSUI et al.

It becomes still more important to control the falling trajectory in order to stabilize burden distribution control under intensive coal injection in a blast furnace. The present report clarifies the effect of ore falling trajectory on coke collapse in a two-dimensional bell-less burden distribution test and the effect of burden particle size on the falling trajectory, which serves as a disturbance factor. There has been no analysis on the motion on a bell-less rotating chute and falling parabolic motion as a mass flow, and particle dynamics are applied, and it is presently difficult to predict changes of the falling trajectory as a mass flow. Therefore, a falling trajectory measuring technique was developed utilizing acceleration sensors that can continuously measure the falling trajectory of burdens, in particular, the main stream position and the falling width, and was actually applied to Kobe BF3 (3rd campaign) (inner volume: 1 845 m^3; blown in on April 5, 1983). It has been confirmed that this falling trajectory measuring technique has enabled the measurement of the falling trajectory which is subject to centrifugal force on the rotating chute, a discharge flow rate from a top hopper, and particle size segregation, and which varies in time series, and furthermore, the physical main stream position that is determined by the mass flow rate can be determined uniquely.

(cf. *ISIJ Int.*, **43** (2003), 1159)

Steelmaking

Mathematical modeling of a DC electric Arc—dimensionless representation of a DC arc

M.RAMÍREZ et al.

A mathematical model presented in previous publications is used to describe fluid flow, heat transfer and electromagnetic phenomena in the arc region of a Direct Current Electric Arc Furnace (DC-EAF). The effects of the arc current and the arc length on the arc characteristics and arc bath interactions are analyzed in a rather generalized way. This analysis leads to the conclusion that the arc behaves in such a way that when the arc shape (defined with the location of the 10 000 K isotherm) is plotted in the appropriate dimensionless form a unique arc expansion is achieved. This unique expansion (only restricted to arcs burned between graphite electrodes in air and outside the region where the arc jet impinges on the bath surface) gives the possibility to provide single dimensionless arc characteristics regardless the values of the arc current and arc length. These dimensionless correlations represent the main finding of this work and they allow means to estimate the important characteristics of the arc under different operational conditions without the need to run complex numerical calculation. The dimensionless characteristics of arc expressed in simple alge-

braic forms can be used for this purpose employing a pocket calculator.

(cf. *ISIJ Int.*, **43** (2003), 1167)

The determination of the minimum and operational gas flow rates for sidewall blowing in the AOD-converter

T.M.J.Fabritius et al.

Gas flow rates from the sidewall tuyeres in the AOD-converter can vary within large range during processing. Back-attack phenomenon, blocked tuyeres, uneven wear of refractory lining and oscillation of the bath set inconsistent demands for the optimum tuyere diameter, number of tuyeres and the angle between each tuyere. Oscillation of the liquid bath, mixing and the penetration of the gas jets with different sidewall blowing procedures were studied by a physical model. The aim of the present study was to determine the criteria for minimum and operational gas flow rate in the actual AOD based on the studied physical phenomena. According to the tests, minimum and operational gas flow rates through the different sized sidewall tuyeres can be defined by modified Froude number based on the appearance of the tuyere blockage (or back-attack) and oscillation. In sidewall blowing, the main reason for the oscillation of the bath is the symmetry of the plume on the vertical axis of the vessel caused by deep penetration of the gas jets. The nominal frequency of the oscillation of steel bath in the actual AOD was determined by dimensional analysis. The gas flow rate, which should be avoid is limited by appearance of oscillation of the bath. Penetration of the molten steel into the tuyeres determines the minimum gas flow rate from sidewall tuyeres. Smaller number of sidewall tuyeres and also a smaller diameter of tuyeres provide larger operational area as far as gas flow rate is considered.

(cf. *ISIJ Int.*, **43** (2003), 1177)

Modelling of temperature distribution in refractory ladle lining for steelmaking

O.Volkova et al.

As a first step towards optimisation of ladle treatment work, mathematical modelling of heat transfer in the ladle has been undertaken. A numerical model considering heat transfer is developed which can be used for prediction of the ladle lining temperature fields during steel casting sequences depending on wear rates and used lining materials. The model is based on Fourier differential equations. In the cases of dolomite brick, the calculational results are compared with temperature measurements from earlier publications for the periods of charged ladle, teeming, empty state and preheating whereby a good agreement is found.

(cf. *ISIJ Int.*, **43** (2003), 1185)

Improvement in the comprehension about the development of the non metallic inclusions in different stainless steel grades

C.Mapelli et al.

In this study the processing routes of three different stainless steel grades were followed; during the reducing period in the AOD plant samplings of steel and slag and measurements of temperature and oxygen activities were performed. The goal was to develop tools for the improvement in the comprehension about the development of the non metallic inclusions in stainless steels. The inclusions in the steel samples were analysed by means of a SEM and then the evaluation of the oxide activities and phases present within them was performed with Thermocalc©. A model developed by Janke and co-workers was implemented in order to compute the activity of elements in the liquid steel. This is based on Wagner's formalism but it is more accurate for the steel baths where solutes are not at infinite dilution. This is the reason why Janke's formalism is better than the Wagner's one in the study of stainless steels, as they are high-alloy steels. It was found that Janke's formalism lacks reliability, when it neglects some strong interactions between two elements (*e.g.* O and another element having high affinity to oxygen).The activities of oxides at the equilibrium with the liquid metal were calculated and compared to those obtained from the Thermocalc©-based analysis of inclusions. From this comparison some hypotheses were made about the nucleation and modification of SiO_2, Al_2O_3 and Cr_2O_3. By making some variations to the model for the calculations of the oxides activity at the equilibrium with the steel bath, it has been also assessed how the model results are influenced by the choice of some thermodynamic parameters such as the interactions coefficients and the equilibrium constants.

(cf. *ISIJ Int.*, **43** (2003), 1191)

Casting and Solidification

A numerical model of rapid solidification processing of Ni–Al alloy in planar flow casting

F.Ba et al.

A numerical model has been developed for simulating the rapid solidification processing (RSP) of Ni–Al alloy in order to predict the resultant phase composition semi-quantitatively during RSP. The present model couples the initial nucleation temperature evaluating method based on the time dependent nucleation theory, and solidified volume fraction calculation model based on the kinetics model of dendrite growth in undercooled melt. This model has been applied to predict the cooling curve and the volume fraction of solidified phases of Ni–Al alloy in planar flow casting. The numerical results agree with the experimental results semi-quantitatively.

(cf. *ISIJ Int.*, **43** (2003), 1200)

Development of a new simulation method of mold filling and solidification based on the SIMPLER algorithm

J.Mok et al.

A new combined method is to be introduced and applied to the mold filling and solidification process. In the present method, the SIMPLER algorithm was adopted to solve the momentum and energy equations. The VOF (Volume of Fluid) method was also adopted to track the free surfaces in the filling process and the Equivalent Specific Heat Method to solve the phase change heat transfer problem in the solidification process. The staggered grid system was used to prevent the false velocity field and the non-uniform control volumes were used to improve the efficiency of calculation. The standard DAFA (donor and acceptor flux approximation) method was adopted in the VOF method. In order to verify the new combined method, the numerical results were compared with the experimental results of mold filling and other simulation methods. It is concluded that the new method can be used as an effective simulation method for the simulation of mold filling and solidification in the casting processes.

(cf. *ISIJ Int.*, **43** (2003), 1206)

Forming Processing and Thermomechanical Treatment

Effect of Nb on recrystallization after hot deformation in austenitic Fe–Ni–C

A.Abdollah-zadeh et al.

In high-strength low-alloy steels, the deformation, restoration and precipitation effects which occur during finish rolling in the austenitic condition are difficult to study because of the transformation of austenite to ferrite and/or martensite on cooling. To overcome this difficulty a series of austenitic Fe–Ni–C alloy were prepared with and without niobium to allow a more detailed study of the phenomena occurring during finish rolling. The effect of niobium on the static recrystallization of austenite after single-pass hot compression has been studied for a strain range of 0.25–0.9 at temperatures in the range of 850–1 000°C.

The results obtained by optical microscopy and transmission electron microscopy indicated that the retardation of static recrystallization was caused by either niobium in solution and/or strain-induced precipitates. Static recrystallization in the niobium steel was retarded when niobium was in solution by several times compared with the niobium-free steel. However, much stronger retardation in the niobium steel was observed when strain-induced precipitates were formed. It was observed that the dislocations, subgrain boundaries, and grain boundaries are preferential sites for strain-induced NbC precipitation. Small precipitates (<3 nm) were responsible for the retardation of recrystallization by the pinning of subgrain boundaries and grain boundaries.

(cf. *ISIJ Int.*, **43** (2003), 1213)

Transformations and Microstructures

Effect of intercritical deformation on bainite formation in Al-containing TRIP steel

H.Luo et al.

The Influence of intercritical deformation, cooling rate and prior austenite grain size on bainite formation were investigated by dilatometry tests. Intercritical deformation (0–40%) performed in steels with a prior austenite grain size of 15–28 μm leads to formation of more ferrite during the cooling and less bainite during the subsequent isothermal stage, and even almost no bainite is formed after 40% strain. Fast cooling after deformation can suppress

ferrite transformation. Relaxation following deformation can significantly, but not completely, reduce such effect of deformation due to the occurrence of recovery and recrystallization, particularly for the finer prior austenite grain size. When the prior austenite grain size was changed from 26.8 to 16.8 μm, bainite formation was suppressed. The mechanism for influence of deformation on bainite formation was discussed on the basis that deformation could refine the austenitic microstructure. Further, it is suggested that there is a critical size of austenite grains or subunits after deformation for the formation of bainite.

(cf. *ISIJ Int.*, **43** (2003), 1219)

Modelling of phase transformation kinetics by correction of dilatometry results for a ferritic Nb-microalloyed steel

M.GÓMEZ et al.

Using the dilatometry technique, $\gamma \rightarrow \alpha$ transformation kinetics has been determined at different cooling rates in a steel with low carbon and low niobium contents (0.09 and 0.017 mass% respectively). First of all the real and the conventional transformation temperatures of the steel were determined. The real start temperature for proeutectoid ferrite formation (A'_{r3}) corresponds to the point where the dilatometric curve starts to diverge from the straight during cooling. The conventional start and finish temperatures for proeutectoid ferrite formation (A_{r3} and A_{r1}) are given by two points close to the minimum and the first maximum of the curve, respectively. The real start and finish eutectoid transformation temperatures —$(A'_{r1})_s$ and $(A'_{r1})_f$— correspond to the second point of inflection and a point close to the second relative maximum of the curve, respectively. Carbon enrichment of the remaining austenite, as the transformation to ferrite advances, is corrected taking into account the dependence on the carbon content of the atomic volume of austenite. On the other hand, the dilatometric data have also been corrected with regard to the different expansion coefficients of austenite and ferrite. In this way it has been seen that the lever-rule method applied to the dilatometric curve is useful for determining transformation temperatures, but not for determining transformation kinetics, since the amount of proeutectoid ferrite calculated with this method was up to 10% greater than the real amount measured with an image analyser. Finally a model based on Avrami's law has been developed for the real $\gamma \rightarrow \alpha$ transformation kinetics.

(cf. *ISIJ Int.*, **43** (2003), 1228)

Development of hard bainite

C.GARCIA-MATEO et al.

It is demonstrated that in a high-carbon steel where carbide precipitation is suppressed, bainite can be obtained by isothermal transformation at temperatures as low as 200°C. The time taken for nucleation at this temperature can be many days, but the transformation results in the growth of extremely thin platelets of bainite, so thin that the hardness of the resulting steel can be greater than 600 HV.

(cf. *ISIJ Int.*, **43** (2003), 1238)

Alloy design of Ni-based single crystal superalloys for the combination of strength and surface stability at elevated temperatures

M.MONIRUZZAMAN et al.

Following the findings regarding the surface stability of superalloys recently obtained by the authors, three Ni-based single crystal (SC) superalloys containing Re are designed with the aid of d-electrons concept. Creep-rupture, hot-corrosion and oxidation tests are conducted with the designed alloys in order to investigate experimentally their high temperature properties. The superalloy containing 5.4 mass% Re and 3.8 mass% Cr (A-1) shows an excellent combination of high temperature creep strength and hot corrosion resistance in comparison with a commercial second generation SC superalloy containing 3 mass% Re. The A-1 alloy exhibits better creep rupture strength than the 3 mass% Re alloy under all the test conditions of 1 313 K/137 MPa, 1 193 K/314 MPa, 248 MPa, 206 MPa and 1 123 K/441 MPa. Performance of the A-1 alloy is well comparable to the second generation alloy in the isothermal oxidation test but poor in the cyclic oxidation test. Another alloy (A-3) exhibits an excellent resistance to the cyclic oxidation test but its creep strength is not a level comparable to the second generation superalloy. Alloying balance is discussed for the excellent combination of high temperature creep rupture strength and good surface stability of superalloys.

(cf. *ISIJ Int.*, **43** (2003), 1244)

Effect of matrix substructures on precipitation of the lavesphase in Fe–Cr–Nb–Ni system

K.YAMAMOTO et al.

In order to make clear the effect of matrix substructures on the Laves phase precipitation in Fe–Cr–Nb–Ni system, age hardening behavior was examined during isothermal aging up to 1 000 h at 873 and 973 K and the precipitation morphology of the Laves phase was investigated by transmission electron microscopy (TEM). The microstructures of Fe–10Cr–1Nb and Fe–15Cr–1Nb (mol%) alloys with ferrite matrix contain high density of rod-shaped Laves phase which precipitates within the ferrite grains during aging. On the other hand, in the Fe–10Cr–1Nb–1Ni alloy with massive ferrite matrix, most of the Laves phase precipitates in subgrain boundaries. Additionally the deformed ferrite matrix has been prepared for examining the effect of dislocation density on morphology of the Laves phase. It is found that the difference of matrix substructures between the ferrite and deformed ferrite phases provides the different number and distribution of nucleation sites for precipitation of the Laves phase. Mechanical properties were evaluated by tensile tests conducted at room temperature, 873 and 973 K.

(cf. *ISIJ Int.*, **43** (2003), 1253)

Grain refinement and texture change in interstitial free steels after severe rolling and ultra-short annealing

A.C. da C.REIS et al.

A Ti-stabilized interstitial free steel was highly cold deformed to a reduction of 95% and subsequently submitted to extremely short annealing cycles with heating rates varying between 300°C/s and 4 500°C/s followed by water quench at various temperatures. The microstructural and textural development was studied through various consecutive stages: partially recrystallized, fully recrystallized and after $\alpha \rightarrow \gamma \rightarrow \alpha$ transformation. It was found that irrespective of the heating rate the recrystallization has completely terminated before the onset of the ferrite to austenite phase transformation. In the fully recrystallized condition, ultra-rapid heating gave rise to substantially refined structures with an average ferrite grain size of 6 μm. It was also observed that this grain refinement saturates with heating rates beyond 1 000°C/s.

The transformation structures obtained by ultra fast heating to temperatures in the full austenite region exhibited remarkably coarser grains than the ones observed after ferrite annealing. This coarsening effect was attributed to the effects of heterogeneous nucleation during phase transformation as C was initially present as TiC precipitates in the ferrite matrix.

With regard to the texture formation, the characteristic {111} deep drawing fibre of cold rolled IF steels was observed, irrespective of the heating rate, in an annealing treatment as short as 0.3 s. After the forward and reverse $\alpha \rightarrow \gamma$ transformation, the ensuing ferrite texture displayed a strong memory effect, as the {111} fibre was even more intense after the double transformation than before.

(cf. *ISIJ Int.*, **43** (2003), 1260)

Mechanical Properties

Evaluation of fatigue crack growth and fracture resistance of SA350 LF2 material

P.K.SINGH et al.

The aim of the present paper is to evaluate the tensile and fracture mechanics properties of the SA350 LF2 carbon steel material used as the Header material in the primary heat transport (PHT) system piping of the Indian pressurized heavy water reactors (PHWR). Tensile, fatigue crack growth rate and fracture toughness tests have been carried out on specimens machined from the Header of the actual PHT pipes. The effect of temperature on tensile properties has been discussed. The effect of temperature and notch orientation on fracture resistance behavior of the material and fatigue crack growth rate dependence on the notch orientation and stress ratio has also been discussed.

(cf. *ISIJ Int.*, **43** (2003), 1268)

High temperature tensile and abrasive wear characteristics of As-cast ductile irons

O.Celik et al.

In this study, tensile and abrasive wear performances of two different quality as-cast ductile irons have been examined at various temperatures between 25 and 600°C. Tensile tests were carried out with a strain rate of 3×10^{-4}/s. Wear tests were performed under a compression stress of 5.7 N/mm^2, by rubbing samples on 125 μm Al_2O_3 abrasive grains.

In the temperature range of 100–300°C, where serrated flow is observed during tensile testing, tensile strength values of both ductile irons were invariable. Above 400°C, further increase of temperature caused dramatic decrease in tensile strength. As a general trend, abrasive wear resistances of the both ductile irons increased with increasing tensile strength. Exceptionally, maximum resistance to abrasive wear is obtained from both ductile irons at 100°C, probably due to dynamic strain aging.

(cf. *ISIJ Int.*, **43** (2003), 1274)

お詫びと訂正

1）本誌 Vol.89, No.6　623 ページ「電磁振動による介在物合体のモデル実験」の著者名に誤りがございました。お詫びして下記の通り訂正いたします。

誤：亀山智樹

正：亀山智基

2）本誌 Vol.89, No.7　A22 ページ

ISIJ International Vol.43(2003), No.7 に掲載予定の下記の論文は、一部に引用したデータが非公開資料のため、今回は掲載を中止しました。

「Exergy analysis of charcoal charging of blast furnace」 *H.NOGAMI et al.*