Fundamentals of High Temperature Processes

Evaporation of Cu and Sn from induction-stirred iron-based melts treated at reduced pressure

L.Savov et al.

The evaporation of Cu and Sn from iron-based melts at reduced pressure has been investigated. The experimental work was carried out in a laboratory-scale vacuum induction melting (VIM) furnace. The effects of (1) chamber pressures of 1 to 100 Pa, (2) melt temperatures of 1 673 to 1 873 K, (3) different melt compositions and (4) two different stirring intensities of the metal bath on the evaporation rate of Cu and Sn, respectively, were studied. It was found that the evaporation of Cu represents a reaction of first order with respect to Cu content of the melt. The evaporation of Sn is represented by a first order rate law, too. Under the same experimental conditions, the evaporation rate of Cu exceeds that of Sn. The rate controlling steps of evaporation are discussed. The optimal conditions of vacuum refining iron melts with respect to Cu and Sn were determined. Recommendations for the design of new vacuum treatment equipment are also given.

(cf. *ISIJ Int.*, **40** (2000), 95)

High volume reduction and group separation of simulated fission products by cold crucible

T.Tanaka et al.

An advanced technology of SHTM (Super High Temperature Treatment Method) using an induction cold crucible for the treatment of fission products generated after the reprocessing of spent fuel is proposed as the future stage of the current vitrification. Without adding any glass materials, 2 000 g of simulated fission products consisting of 23 elements, including lanthanides oxides simulating highly active nuclides and corrosion products, together with the minimum amount of reducing agent were inductively heated up to 2 000°C, followed by melting and solidification in a convergent type cold wall crucible. Internal diameter of the crucible, applied electric power and the frequency was 100 mm, less than 100 kW and 25 kHz, respectively. As a result, highly volume-reduced materials, approximately 1/20 of the current vitrification, was obtained. Platinum metal group, such as palladium and ruthenium, got together in the center and bottom of the crucible, surrounded with the titanium oxides immobilizing lanthanides elements. Validity of the process concept was confirmed experimentally.

A cylindrical mathematical model with three phases coupled with electromagnetic field, heat conduction and mass balance has been developed to get better understanding of SHTM. The model predicts the presence of critical value of magnetic flux density and the initial dimension of the pre-treated fission products that triggers the whole melting of the fission products in the crucible surrounded with the cold wall. Reaction free layer of fission products plays an important role for the melting. There exits an optimal intensity of the magnetic flux density sustaining high temperature of the material near the cold wall.

(cf. *ISIJ Int.*, **40** (2000), 105)

Ironmaking

Burden distribution analysis by digital image processing in a scale model of a blast furnace shaft

J.Jimenez et al.

During the realigning of Aceralia's blast furnace B in Gijon, a 1/10 scale half-section, three-dimensional cold model of the BF shaft was built to test charging patterns and the effect of gas flow in burden distribution. The front side of this half model is closed by a methacrylate sheet that allows images of the burden distribution inside the model to be obtained, during and after the charging process. Image processing techniques were applied to obtain useful information from burden profile images. A complete study of a charging pattern is presented in this paper.

The model has allowed study of some local effects of gas flow in burden distribution, such as changes in the final coke layer during ore charging, and the formation of a narrow window in the centre of the model that connects the successive coke layers.

(cf. *ISIJ Int.*, **40** (2000), 114)

Steelmaking

Effect of slag composition on the kinetics of formation of Al_2O_3–MgO inclusions in aluminum killed ferritic stainless steel

G.Okuyama et al.

Kinetics of both slag/metal reactions and metal/inclusion reactions were investigated experimentally using 20 kg vacuum induction furnace in order to clarify the mechanism of the formation of $MgAl_2O_4$ spinel inclusions in aluminum killed ferritic stainless steel (SUS430).

The results obtained are summarized as follows :

1) By reducing CaO/SiO_2 and CaO/Al_2O_3 ratio of top slag, MgO contents in Al_2O_3 based inclusions decreased.

2) The two film theory was employed to analyze the rate determining step of slag/metal reaction (reduction of MgO in top slag). By this model, it was found that the rate determining step of the reaction was the mass transfer of Mg through the film in molten steel. The increase rate of Mg in molten steel is determined by the activities of soluble oxygen and MgO at the slag/metal interface, and hence by slag composition.

3) The unreacted core model was employed to analyze the rate determining step of metal/inclusions reaction.

The analysis showed that the rate determining step of the reaction in the case of 20 kg vacuum induction furnace was the diffusion of Mg in molten steel.

(cf. *ISIJ Int.*, **40** (2000), 121)

Casting and Solidification

Analysis of solidification cracking using the specific crack susceptibility

Y.M.Won et al.

Using a 2-dimensional finite element, the effects of carbon content, slab width, narrow face taper and casting speed on solidification cracking during continuous casting of slabs were analyzed. The possibility of solidification cracking during continuous casting of slabs was predicted using the "Specific Crack Susceptibility", $^{S}S_C$. The new proposed parameter, $^{S}S_C$, can represent the averaged possibility of solidification cracking of the strand during continuous casting in the mold. The surface crack formed near corner region of strand at the initial stage of solidification, and the internal crack was found in the internal regions of wide center, corner and off-corner at the middle and final stage of solidification. The carbon range sensitive to solidification cracking is between 0.1 wt% C and 0.14 wt% C steels. At the slab widths of 1 900 mm and 2 150 mm, the possibility of solidification cracking increased in the regions of wide center, corner and off-corner in comparison with the slab width of 1 600 mm. With increasing narrow face taper, the possibility of solidification cracking decreased along the region of wide face due to the mechanical compression imposed by the narrow face taper. With increasing casting speed, the possibility of solidification cracking increased in the regions of wide center, corner and off-corner, because the shell thickness is largely decreased due to decrease of dwelling time of strand within the mold. These predictions at various casting conditions were in good agreement with the experimental observations in industry.

(cf. *ISIJ Int.*, **40** (2000), 129)

Mathematical modeling of thermally induced stresses in two-roll melt drag thin strip casting of steel

M.Gupta et al.

In thin strip casting of steel, a major problem is the formation of cracks due to thermally induced stresses in the solidifying material. To compute these stresses and the susceptibility of the material to crack due to these stresses, a two-dimensional finite element based thermo-mechanical model has been developed. The temperature field obtained by the fluid flow and heat transfer model is imposed as a thermal load to the system. A visco-plastic constitutive relation has been used to describe the behavior of solidifying steel. A temperature dependent ultimate strength is used to define the cracking index, which indicates the susceptibility of the material to crack. Stress calculations are performed using a commercial software ANSYS.

(cf. *ISIJ Int.*, **40** (2000), 137)

Mathematical modeling of fluid flow, heat transfer, and solidification in two-roll melt drag thin strip casting of steel

M.Gupta et al.

A two-dimensional finite element model has been developed to simulate fluid flow, heat transfer, and solidification in two-roll melt drag thin strip casting of steel. The two equation k–ε model is used to incorporate the turbulence in fluid flow. The effect of solidification of liquid metal on the viscosity of melt is also considered. The release of latent heat of fusion at the solid–liquid interface was not considered explicitly, but the specific heat was increased appropriately to account for the released latent heat. The roller velocity, melt-roll heat transfer coefficient and melt superheat are identified as important process variables, and their effect on the thickness of cast strip is predicted.

(cf. *ISIJ Int.*, **40** (2000), 144)

Numerical simulation of the critical velocity for particle pushing/engulfment transition in Fe–C alloys using a phase-field model

M.ODE et al.

The particle/interface problem is numerically analyzed using a phase-field model in thin interface limit. A new double-well potential function in free energy density of the alloy is defined using a dilute solution approximation. With the function, a negative value of double-well potential height is usable and the mesh size restriction is largely relaxed. A pushing force for alloy systems is also introduced so as to relate to the interface energy change caused by the deformation of interface shape. With the pushing and drag forces calculated from the interface shape, the acceleration and velocity of the particle are estimated and the particle movement relative to the interface is analyzed. Using the model, the particle pushing and engulfment behaviors are successfully reproduced for the system of Fe–C alloys and an alumina particle. The critical velocities for the pushing/engulfment transition are determined for the particles with different diameters. The effect of initial carbon content on critical velocity is also examined and discussed in terms of the pushing force.

(cf. *ISIJ Int.*, **40** (2000), 153)

Reactive casting of Ni–Al–Fe ternary intermetallic alloys

K.MATSUURA et al.

NiAl-base intermetallic alloys containing iron up to 25 at% are produced by reactive casting, which involves an exothermic reaction between elemental liquids and enables one to cast high-melting-point intermetallic alloys without the need of external heating. In this study, aluminum liquid at 1 023 K and a molten nickel-iron alloy at 1 773 K are mixed to produce a molten Ni–Al–Fe ternary intermetallic alloy with a temperature of over 2 300 K, which is approximately 400 K higher than the melting point of the alloy produced. The concentrations of the constituent elements are approximately homogeneous in the ingot of 30 mm in diameter and 130 mm in height. The grain size of the ingot decreases, as the iron content increases. The increase in iron content improves the hardness, bending strength and wear resistance of the alloy. Young's modulus of the alloy decreases with the increase in temperature and iron content.

(cf. *ISIJ Int.*, **40** (2000), 161)

Fabrication of NiAl/steel cladding by reactive casting

K.MATSUURA et al.

A novel joining process based on reactive casting is proposed. By pouring molten aluminum and nickel onto a steel block, molten nickel monoaluminide, NiAl, is exothermically synthesized, and is joined to the steel block when it solidifies on the steel block. Heat generated by an exothermic reaction, Ni+Al→NiAl+ΔH_{p298}, is transferred from the synthesized NiAl to the steel block, and the surface layer of the steel block is melted. The depth of the melted steel increases with both the preheating temperature of the steel block and the thickness of the synthesized NiAl. Iron from the melted steel dissolves in the molten NiAl, and an NiAl-base intermetallic compound, (Ni, Fe)Al, is produced. Cracks or other intermetallic phases such as $NiAl_3$ or FeAl are not formed at all at the joint interface between the (Ni, Fe)Al and the steel block. The synthesized (Ni, Fe)Al has an excellent resistance to corrosion and oxidation.

(cf. *ISIJ Int.*, **40** (2000), 167)

Surface Treatment and Corrosion

Effect of microstructure on fracture mechanisms in galvannealed coatings

A.T.ALPAS et al.

Fracture mechanisms in galvannealed coatings have been studied by performing draw bead tests on galvannealed Ti stabilized interstitial free and Aluminum killed low carbon steel sheets and by investigating coating microstructures by scanning electron microscopy. Galvannealing treatments, on samples galvanized using an industrial hot-dip galvanizing process, were conducted at 450, 500 and 550°C for several time periods between 1 and 360 s in a laboratory induction furnace.

In the coatings with low Fe content (up to 5 g/m^2), the amount of powdering during the draw bead test was minimal. Growth of cracks nucleated within the δ_1 phase was arrested at the steel-coating interfaces where only a limited amount of decohesion occurred. A steep increase in the amount of powdering was observed in coatings with Fe contents between 6–9 g/m^2. In these coatings, cracks originating from the δ_1 phase reached Γ–Γ_1–δ_1 phase boundaries, which provided preferential crack growth paths and thus facilitated fracture within the coating. A fracture mechanics model was proposed to account for the powdering resistance of galvannealed coatings.

(cf. *ISIJ Int.*, **40** (2000), 172)

Transformations and Microstructures

Thermodynamic calculations of phase equilibria in the Fe–Cr–S system

K.OIKAWA et al.

Phase equilibria in the Fe–Cr–S system were analyzed on the basis of the thermodynamic evaluation of the Fe–FeS, Fe–Cr, Cr–CrS and Fe–FeS–CrS–Cr systems. The Gibbs energy of individual phase was approximated by the two sub-lattice model for describing the thermodynamic properties. Most of the experimental information was well described by the present set of thermodynamic parameters. In particular, the calculated liquidus surface in the Fe-rich portion and the solubilities of S in the fcc and the bcc phases were shown to be in excellent agreement with experimental results. Discrepancies observed in some experimental phase diagrams were explained on the basis of the calculated results.

(cf. *ISIJ Int.*, **40** (2000), 182)

The segregation behavior of phosphorus in Ti and Ti+Nb stabilized interstitial-free steels

J.S.REGE et al.

The phenomenon of cold work embrittlement (CWE) in the P-added high strength interstitial-free steels has been associated with the segregation of P to the ferrite grain boundaries. This segregation by P is believed to decrease the cohesive strength of the grain boundaries by weakening their bonding. Hence, the resistance of the steel to brittle fracture, *i.e.*, intergranular fracture, is greatly decreased. The goal of the present study was to investigate the segregation behavior of P during the different stages of processing (prior to and after coiling, and after cold rolling and annealing) in Ti and Ti+Nb stabilized interstitial-free steels. It was found that a considerable amount of segregation of P to the ferrite grain boundaries occurred during the coiling process in Ti-stabilized interstitial-free steels. However, with the addition of Nb in the Ti+Nb-stabilized interstitial-free steels, the segregation of P was decreased in the as-coiled condition. The P content on the ferrite grain boundaries in the final cold rolled and annealed condition was found to depend on two factors; (1) the segregation of P in the as-coiled condition, and (2) availability of Ti to form phosphides during the annealing process. It was confirmed in this study that the addition of P decreases the CWE resistance of the steel. Furthermore, it appears that the CWE resistance of the Ti+Nb-stabilized interstitial-free steels is improved by the presence of solute Nb on the ferrite grain boundaries.

(cf. *ISIJ Int.*, **40** (2000), 191)

Dynamic $\gamma\rightarrow\alpha$ transformation during hot deformation in Iron–Nickel–Carbon alloys

H.YADA et al.

Fe–6mass%Ni–(0.0008~0.29)mass%C alloys were hot-deformed in torsion at 600–720°C (above the cooling transformation start temperatures A_{r3}) after austenitization. An *in-situ* X-ray diffraction study revealed that $\gamma\rightarrow\alpha$ transformation occurred during deformation in a wide range of condition, even above A_3^p (paraequilibrium $\gamma\rightarrow\alpha$ transformation temperature). Corresponding to this transformation, apparent decrease in deformation stress from that expected for austenite was observed. Microstructural study of the specimens quenched after the deformation showed that a large amount of fine-grained ferrite was formed due to the deformation. The analysis of deformation stress and chemical driving-force of the transformation indicated that the transformation occurred in order to reduce the total energy of deformed material since the deformation of energy of α was revealed to be considerably smaller than that of γ and the amount of deformation energy saved by the transformation was shown to be much greater than the chemical energy consumed by the transformation at the tested temperatures.

(cf. *ISIJ Int.*, **40** (2000), 200)

Mechanical Properties

Stress rupture ductility diagram—a diagnostic tool

S. Chaudhuri et al.

The present work suggests a methodology for construction of stress rupture ductility diagram using the concept of geometrical factor k that determines the nature of creep rupture. Large volumes of stress rupture ductility data of a range of engineering materials generated experimentally in the laboratory and reported in the literature have been used to study the nature of creep rupture by superimposition of these data on the above diagram.

The rupture ductility of Ni-base superalloy, when superimposed on such diagram, indicates that the failure in this alloy could be due to limited amount of localised deformation or cavitation. In case of Zr–Nb alloy, the rupture ductility data lie in the necking regime extending from $k=0.9$ to 0.4. In contrast, the data on Cr–Mo steel show a wider variation extending from the regime of cavitation to extensive necking.

Reliable prediction of rupture ductility is possible within a narrow range of k in which the nature of creep rupture remains the same.

(cf. *ISIJ Int.*, **40** (2000), 207)