Fundamentals of High Temperature Processes

Mixing time in cylindrical bath agitated by plunging jet

K.ABE et al.

A plunging jet is a powerful tool for the agitation of a bath as well as the entrapment of fine powder into the bath. As a fundamental model study of the development of novel refining processes using a plunging jet, the mixing time in a cylindrical water bath agitated by the jet was measured with an electric conductivity meter. The measured values of the mixing time depended significantly on the aspect ratio of the bath. Two empirical equations of the mixing time were proposed for two aspect ratio regimes; regime 1 (aspect ratio≅0.3～1.0) and regime 2 (aspect ratio≅1.0～2.0). Uniform mixing was established in regime 1 just after the completion of plunging. The mixing time in regime 2 became much longer than that in regime 1. The relationship between the mixing time and the rate of dissipation of energy density was also discussed. In regime 1, a plunging jet had higher mixing ability than gas injection.

(cf. *ISIJ Int.*, **42** (2002), 581)

Evaluation of surface tension and adsorption for liquid Fe–S alloys

J.LEE et al.

Surface tension of liquid iron is strongly influenced by the adsorption of sulfur. In this study, surface tensions of liquid Fe–S alloys at 1 823 K were measured by the sessile drop technique in a purified argon atmosphere. Experimental results were compared with the model based on Butler's equations considering the effect of size and interactions of the adsorbed elements assuming that the system was composed of Fe–"FeS" binary. The model could evaluate the surface tension and the adsorption of sulfur more reasonably rather than a simple ideal adsorption model. In the calculations, excess free energy expanded by Margules' series over the entire composition range of Fe–FeS system was used.

(cf. *ISIJ Int.*, **42** (2002), 588)

Effects of operating parameters on desulfurization of molten iron with magnesium vapor produced *In-situ* by aluminothermic reduction of magnesium oxide

J.YANG et al.

The effects of operating parameters on desulfurization of molten iron with magnesium vapor produced *in-situ* by the aluminothermic reduction of magnesium oxide have been studied. To promote the reduction of magnesium oxide and to make use of the heat of the molten iron, a refractory tube charged with the pellets that were made of the mixture of magnesia and aluminum powders, was immersed into the melt. The produced magnesium vapor was injected directly into the melt with Ar or N_2 carrier gas to react with sulfur in it.

Compared with using Ar, using of N_2 as the carrier gas resulted in lower desulfurization efficiency due to a part of aluminum reacting with N_2 to form AlN. Increasing the pellet forming pressure promoted the reduction of magnesium oxide, and hence improved the desulfurization efficiency. The use of a porous Al_2O_3 or MgO tube decreased the desulfurization rate as compared with that of a dense graphite tube. In the case of the porous Al_2O_3 tube, the magnesium vapor reacted and/or was adsorbed with the porous Al_2O_3 tube in the initial stage of the experiment. The reverse reaction and/or the desorption took place to produce magnesium vapor in the later stage of the experiment. In the case of the porous MgO tube, the magnesium vapor was adsorbed and desorbed by the tube during the experiment. When the dense Al_2O_3 tube was used, a horizontal nozzle was installed to improve the desulfurization efficiency. It is possible to enhance the desulfurization efficiency of pellet by dividing pellet charging into two portions. As the oxygen partial pressure in the atmosphere was increased, the desulfurization efficiency became low and the resulfurization reaction became more noticeable in the later stage of the experiment.

(cf. *ISIJ Int.*, **42** (2002), 595)

Effect of niobium on nitrogen solubility in high chromium steel

S.-B.LEE et al.

The interaction parameters of alloying elements on nitrogen in liquid Fe–Cr alloys containing niobium have been determined. The equilibrium nitrogen solubility in the liquid iron alloy was measured by metal–gas equilibrium technique under 0.04 to 1.0 atm of nitrogen atmosphere at 1 823 to 1 923K. Nitrogen solubility in Fe–Cr–Nb melts obeyed Sieverts' law for all compositions studied in present study.

The results obtained are summarized as follows;

(1) The solubility of nitrogen markedly increased with increasing chromium and niobium. The interaction parameters in liquid iron alloys containing 10–18% of Cr and 0.2–2% of Nb are obtained.

(2) The solubility of nitrogen was lower at a higher temperature in Fe–Cr melts in this study.

(3) Test results indicated that it is not likely to form niobium nitride in Fe–Cr–Nb–N alloys and it was confirmed by EDS.

(cf. *ISIJ Int.*, **42** (2002), 603)

Reduction behavior of chromium oxide in molten slag using aluminum, ferrosilicon and graphite

E.SHIBATA et al.

To reduce chromium in stainless steel slag and simultaneously recover chromium as a ferroalloy for the steel making industry, the direct smelting reduction of chromium oxide in molten slag was investigated by small furnace experiments. Thermodynamic equilibrium calculations were also carried out to suggest the limit of reduction of CrO_X in the slags. Aluminum, ferrosilicon and graphite were used as reductants under conditions of 1 723–1 823 K and various slag compositions. In the experiments, the formation of high Al_2O_3 solid phase in the upper and middle parts of slag prevented uniform reduction when aluminum was added as a reductant, although FeO and CrO_X were reduced drastically to a low content compared with the cases of ferrosilicon and graphite except for the lower part of slag melt. The low content of CrO_X by aluminum was about 0.01 mass% which was about one order higher than calculated thermodynamic equilibrium one. The reductions of FeO and CrO_X by aluminum were promoted to the lower part of slag with the increase in temperature and CaO/SiO_2 ratio because of the increase in fluidity of slag. A liquid metal containing chromium was formed and precipitated on the bottom of slag during the reduction. The formation behavior of metal drop was observed directly by an X-ray fluoroscopy technique.

(cf. *ISIJ Int.*, **42** (2002), 609)

Steelmaking

Physical and mathematical modelling of thermal stratification phenomena in steel ladles

Y.PAN et al.

A 1/4-scale hot-water model of industrial 107-tonne steel ladles was established in the laboratory. With this physical model, thermal stratification phenomena due to natural convection in steel ladles during the holding period before casting were investigated. By controlling the cooling intensity of the water model to correspond to the heat loss rate of steel ladles, which is governed by dimensionless numbers Fr and $\beta\Delta T$, temperature distributions in the water model can simulate those in the steel ladles. Consequently, the temperature profile in the hot-water bath in the model can be used to deduce the thermal stratification phenomena in liquid steel bath in the ladles. In addition, mathematical simulations on fluid flow and heat transfer both in the water model and in the prototype steel ladle were performed using a computational fluid dynamics (CFD) numerical method. The CFD model was validated against temperatures measured in the water model. Comparisons between mathematically simulated temperature profiles in the prototype steel ladle and those physically simulated by scaling-up the measured temperature profiles in the water model showed a good agreement. Therefore, it can be concluded that, as long as accurate heat loss information is known, it is feasible to use a 1/4-scale water model to non-isothermally simulate fluid flow and heat transfer in steel ladles during the holding period before casting.

(cf. *ISIJ Int.*, **42** (2002), 614)

Instrumentation, Control and System Engineering

Mill-balance control technique for tandem cold mill

A.MURAKAMI et al.

This paper describes a mill balance control (MBC) for a tandem cold mill (TCM) with an automatic gage control system (AGC).

The stand exit gages are controlled by the AGC, but the motor currents and the rolling forces of stands cannot be controlled.

When the setup control is not proper or when the incoming strip has variations in gage and hardness, the distribution pattern of the motor currents and the rolling forces (mill balance) sometimes becomes inappropriate. When a motor current exceeds its rated value, usually all roll speeds are reduced manually, and the productivity decreases. When a rolling force varies to a great extent, strip shape defects may occur.

The MBC operates the stand exit gages except for the finish gage and the interstand tensions, and it controls the distribution pattern of the motor currents and the rolling forces while guaranteeing the finish gage accuracy.

The MBC controller is designed based on the ILQ design method and is applied to an actual process.

Experimental results show that desired mill balance is achieved and the finish gage accuracy is maintained.

(cf. *ISIJ Int.*, **42** (2002), 624)

Forming Processing and Thermomechanical Treatment

Prediction of three dimensional strip temperatures through the entire finishing mill in hot strip rolling by finite element method

C.G.SUN et al.

A finite element-based approach is presented for the prediction of the thermal behavior of the strip occurring in the finishing mill during hot strip rolling. The approach, which is fully coupled and three dimensional, is described in detail. The validity of the proposed approach is examined through comparison with measurements. Then the capability of the approach to predict the detailed aspects of the thermal behavior is demonstrated through an application to revealing the effect of an edge heater.

(cf. *ISIJ Int.*, **42** (2002), 629)

The evolution of microstructure during thin slab direct rolling processing in vanadium microalloyed steels

Y.LI et al.

The evolution of microstructure during a simulation of the thin slab direct rolling process has been studied on two low carbon steels, microalloyed with V–N and V–Ti–N. The steels were examined using optical microscopy, analytical transmission electron microscopy (TEM) and energy dispersive X-ray (EDAX).

After the 4th rolling pass, in a five pass schedule, the initial coarse austenite grain size (≈1 mm) was reduced to about 50 μm in Steel V–N and 22 μm in Steel V–Ti–N. The average ferrite grain size in the final strip was slightly smaller in Steel V–Ti–N (4.8–6.6 μm) than in Steel V–N (5.3–7.2 μm). For Steel V–N, VN was only observed after 1 050°C equalization, but it was not found after 1 200°C and 1 100°C equalisation. For Steel V–Ti–N, V–Ti(N) particles formed during casting and during equalization for all the equalization temperatures (1 200°C, 1 100°C and 1 050°C). AlN particles precipitated in Steel V–N only during 1 050°C equalization and were often associated with MnS or MnS and VN. No AlN was detected in Steel V–Ti–N. Fine V containing precipitates (<10 nm) were observed in the final strip for both of the steels, but the frequency of the fine particles was lower in Steel V–Ti–N than in Steel V–N. The fine precipitates in the final strip make a major contribution to dispersion strengthening. High strength (LYS≈460–560 MPa) with good toughness and good ductility were achieved in the steels, which are competitive to similar products made by conventional controlled rolling. However, the addition of Ti to the V–N steel decreased the yield strength due to formation of V–Ti(N) particles in austenite, which reduced the amounts of V and N available for subsequent V rich fine particle precipitation in ferrite. @005-abst text-cf.ISIJ:(cf. *ISIJ Int.*, **42** (2002), 636)

Welding and Joining

Effect of Zr and Ta inserts on bonding strength and interfacial microstructures of Ti/steel clads

Y.MORIZONO et al.

Bonding strength and interfacial microstructures of Ti/steel clads using Zr and Ta inserts have been investigated from the viewpoint of diffusion barrier effect of carbide layer formed at the interface. Diffusion bonding was performed at 1 073 to 1 273 K for 3.6 and 14.4 ks in a vacuum. TiC layer, as a diffusion barrier, is observed at the interface in the Ti/low carbon steel (structural steel, SS400) clad bonded at 1 073 K and 1 173 K without Zr and Ta inserts. However, the clad bonded at 1 273 K has no TiC barrier layer, and thus microstructural change resulting from the diffusion of Fe and Ti atoms into each parent material is observed. Although Zr insert is used in order to produce the carbide layer showing diffusion barrier effect at 1 273 K, such a layer cannot be obtained because of eutectic reaction between the steel and the insert. On the other hand, Ta insert leads to the formation of reaction layer consisting of TaC and Ta_2C in the clad bonded at 1 273 K. This clad shows the highest bonding strength in the present study. Therefore, Ta insert makes it possible to retain diffusion barrier effect of carbide layer at the temperature of 1 273 K and improves the bonding strength of the Ti/SS400 steel clad as well. The advantages of Zr and Ta inserts for Ti/high carbon steel and Ti/stainless steel clads are also discussed.

(cf. *ISIJ Int.*, **42** (2002), 645)

Surface Treatment and Corrosion

Characterization of oxide coatings deposited on pure titanium by alternating-current microarc discharge in electrolyte

W.XUE et al.

Microarc oxidation is an advanced coating process to deposit thick, hard ceramic oxide coatings on metal surfaces. In this paper, a ceramic oxide coating of 30 μm was prepared on TA2 pure titanium by alternating-current microarc oxidation in aluminate solution. Its morphology, composition and structure were characterized by scanning electron microscopy, X-ray diffractometry, Raman spectroscopy. The Al, Ti, O concentration profiles across the coating were determined by energy dispersive spectroscope. The outer layer of the coating is composed of a large amount of $TiAl_2O_5$ and a little rutile type TiO_2 compounds. But the rutile content in the inner layer is much higher than in the outer layer while the $TiAl_2O_5$ content decreases obviously in the inner layer. All of these oxides derive from a rapid solidification of the melt in microarc discharge zone. The Al atoms from the aqueous solution have diffused to the coating/titanium substrate interface, but are enriched in the outer layer. However, the oxygen and aluminum atoms have not diffused into the unoxidized titanium substrate, even near the coating/substrate interface. This facilitates maintaining mechanical properties of pure titanium substrate after microarc oxidation treatment on titanium surface.

(cf. *ISIJ Int.*, **42** (2002), 651)

Mechanical Properties

Evolution of fracture behaviour in progressively drawn pearlitic steel

J.TORIBIO

In this paper the fracture behaviour of progressively drawn pearlitic steels is studied. To this end, samples from different stages of an industrial manufacturing process were analyzed to elucidate the consequences of steelmaking by cold drawing on the fracture toughness and the microscopic fracture modes. The real manufacture chain was stopped in the course of the process, and samples of five intermediate stages were extracted, apart from the original material or base product (hot rolled bar: not cold drawn at all) and the final commercial product (prestressing steel wire: heavily cold drawn). Results demonstrated that progressive cold drawing affects clearly the fracture performance of the materials, so that the most heavily drawn steels exhibit anisotropic fracture behaviour with crack deflection, *i.e.*, a change in crack propagation direction which deviates from the original mode I propagation and approaches the wire axis or cold drawing direction, thereby producing a mixed mode stress state. At the microscopical level, clear changes are observed in the micrographs with appearances from cleavage-like in the slightly drawn steels to predominant micro-void coalescence in the heavily drawn steels. From the macroscopic fracture mechanics viewpoint, the manufacture process by cold drawing is beneficial, since the fracture toughness is progressively increased by steelmaking. These important results demonstrate that both the traditional mechanical properties (*e.g.* the yield strength) and the fracture mechanics properties (*e.g.* the fracture toughness) are improved by cold drawing.

(cf. *ISIJ Int.*, **42** (2002), 656)

Social and Environmental Engineering

Evaluation of CO_2-capturing power generation systems utilizing waste heat from ironworks

P.S.PAK

Two kinds of CO_2-capturing power generation

systems with and without regenerator are proposed which utilize saturated steam produced by making use of waste heat from ironworks, and their thermodynamic and economical characteristics were investigated. As an example of saturated steam, temperature and quantity was assumed to be 200°C and 10 t/h, respectively, by considering use of waste heat from a kiln at a pellet factory in an ironworks. Fundamental characteristics of the two proposed systems are estimated through computer simulation, such as power generation efficiency, energy saving characteristics, amount of CO_2 reduction, and economics. It was shown that the best system is attained for the proposed system without the regenerator when its turbine inlet temperature is set at 350°C. At this condition, the system was estimated to be economically feasible and to have following characteristics: repowering power generation efficiency 97.7%, annual amount of saved energy 83.3 TJ, annual amount of CO_2 reduction 1 738 t-C, unit cost of generated power 6.42 yen/kWh, annual gross profit 25.4 million yen, and depreciation year 5.70. The proposed system could be adopted in many other waste heat emitting factories owing to its large CO_2 reduction characteristics and its economical profitability.

(cf. *ISIJ Int.*, **42** (2002), 663)