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Steelmaking

The use of fundamental process models in studying ladle refining operations (Review)

P.G.JÖNSSON et al.

Existing fundamental models of ladle refining operations have been reviewed. No fundamental model that takes all the individual parts of ladle refining into account has been found in the open literature. Nor does a model exist which considers all refining in only one part of a refining step such as vacuum treatment. However, separate fundamental models for prediction regarding alloying, temperature, hydrogen, sulfur, reoxidation, and inclusion growth and removal do exist. In one case, a reoxidation model has also been combined with a sulfur-refining model. Predicted values from the separate models for alloying, temperature, sulfur and hydrogen have been found to agree well with corresponding measured data. The verification of the models for reoxidation and the growth and removal of inclusions is currently lacking and separate models for refining operations such as nitrogen or carbon removal need to be developed. Also, more complex models of parts of ladle refining such as vacuum treatment need to be developed, incorporating the sulfur, hydrogen, reoxidation and inclusion growth and removal models. The ultimate goal is, of course, one overall model that can predict desired parameter values for all steps of ladle refining. Even though such a model does not exist today, the usefulness of existing fundamental models is exemplified. This is to illustrate the potential of more complex and more realistic ladle models in process optimization.

(cf. *ISIJ Int.*, **41** (2001), 1289)

Fundamentals of High Temperature Processes

Distribution equilibria of Fe, Co and Ni between MgO-saturated FeO_x–MgO–SiO_2 slag and Ni alloy

G.LI et al.

As a fundamental study related to the recycle of Ni–Fe–Co alloy, the distribution equilibrium of Fe, Co and Ni between MgO saturated FeO_x–MgO–SiO_2 slag and nickel alloy was investigated at 1 773, 1 823 and 1 873 K with controlled oxygen partial pressure between 10^{-4} to 10^{2} Pa. The distribution ratios of Fe, Co and Ni at 1 773 K vary from 0.61 to 26, 0.040 to 4.2 and 0.0030 to 0.34 respectively with increasing oxygen partial pressure.

The distribution ratios of Fe, Co and Ni between MgO saturated FeO*x*–MgO–SiO_2 slag and nickel alloy suggest that most of nickel and cobalt can remain in the alloy phase with lower oxygen partial pressure, and iron can be eliminated adequately from nickel alloys with higher oxygen partial pressure. However, the solubility of nickel and cobalt oxide in the slag also increases with increasing the oxygen partial pressure. Lower oxygen partial pressure and higher temperature are favorable for decreasing the loss of nickel and cobalt into slag. An oxygen partial pressure at which the separation coefficients show minimum was observed.

The MgO solubility in the FeO_x–MgO–SiO_2 slag decreases when the NiO content exceeds about 25% at higher oxygen partial pressure.

The activity coefficients of NiO and CoO in slags were calculated and found that their values increased with increasing of the NiO and CoO contents in slag respectively.

(cf. *ISIJ Int.*, **41** (2001), 1303)

Phase equilibria of the MnO–SiO_2–CrO_x system at 1873K under controlled oxygen partial pressure

M.TANAHASHI et al.

In order to determine the phase diagram of the MnO–SiO_2–CrO_x system for $P_{O_2}=2\times10^{-6}$ Pa at 1873 K, one of the important information for the controlling of non-metallic inclusions (deoxidation products) formation during the stainless steel Si-deoxidation process, the following equilibrium experiments were conducted at 1 873 K under controlled oxygen partial pressure, P_{O_2}:

(I) Phase equilibria of the MnO–Cr_2O_3 binary system were measured as a function of P_{O_2} (2×10^{-6}–2×10^{2} Pa).

(II) Phase equilibria of the MnO–SiO_2–CrO_x ternary system were measured for $P_{O_2}=2\times10^{-6}$ Pa.

Finally, the change in composition of inclusions during this process with increasing silicon addition was examined by using the determined phase diagram of this ternary system.

(cf. *ISIJ Int.*, **41** (2001), 1309)

Ironmaking

Mechanisms of pig-iron making from magnetite ore pellets containing coal at low temperature

K.NAGATA et al.

A new pig-iron making process using magnetite ore pellets containing coal as reducing agent has been investigated. The pellets were heated rapidly in argon at furnace temperatures between 1 573 and 1 723 K and the temperature and partial pressure of oxygen in the pellets were recorded *in situ*. Molten iron containing 1.1–3.6 mass% carbon over the composition on the liquidus line of iron–carbon system was produced at the furnace temperatures higher than 1 598 K within 16 min. The whole process consists of four steps, *i.e.*, heating, reduction of iron ore, carburization and melting of pig iron. The solution-loss of carbon and the reduction of iron ore are coupled and concentrically take place from the surface to centre due to the heat transfer control because of the endothermic reaction of solution-loss. The reduced iron particles were carburised by CO gas, rapidly absorbed carbon from coal and become molten pig iron particles. The particles cohered to make large drops and the pellet suddenly collapsed to melt. The conditions determining the lowest temperature for producing pig iron are discussed.

(cf. *ISIJ Int.*, **41** (2001), 1316)

Improvement of gas flow through analyzing discharge behavior in the bunker used in blast furnace

S.-K.JUNG et al.

According to the analysis of solid flow behavior in center feed/parallel bunker through videotaping, the flow pattern was changed from plug flow at the initial stage to funnel flow after the middle stage irrespective of the bunker type. As there were some structural parts such as stone box in the bunker, which changes the direction of solid flow, it resulted in the shape change of burden layer, and brought about the particle size distribution in the bunker. Consequently, it was found that the flow pattern and the shape of burden layer in the bunker determined the particle size distribution in the radial direction of the blast furnace. By attaching a central chute around the stone box in the lower bunker, the shape of burden layer was modified to obtain the central gas flow in the blast furnace without removing the stone box. The mechanism of flow region formation at the initial discharge stage was analyzed by an approximate stress analysis based on the method of differential slice.

(cf. *ISIJ Int.*, **41** (2001), 1324)

Steelmaking

Mechanism of alumina adhesion to continuous caster nozzle with reoxidation of molten steel

K.SASAI et al.

Basic experiments were conducted on the adhesion of Al_2O_3 in molten steel when molten FeO is present in the molten steel. It was found that the adhesion and coalescence of Al_2O_3 particles are promoted when molten FeO is present in the molten steel, that FeO and $FeAl_2O_4$ are observed in the bond between the Al_2O_3 particles, and that this observed result agrees with the pattern of Al_2O_3 adhesion to the continuous caster nozzle when the molten steel is reoxidized. Based on these experimental results, a study was made of the mechanism whereby Al_2O_3 adheres to the continuous caster nozzle when the molten steel is reoxidized. When the oxygen concentration in the molten steel is locally raised by the reoxidation of the molten steel, the adhesion force of the Al_2O_3 particles due to the liquid bridge force of the molten FeO is far greater than the adhesion force of the Al_2O_3 particles due to the van der Waals force or the surface tension of the molten steel. The adhesion of Al_2O_3 to the nozzle interface is thus considered to proceed mainly with the molten FeO serving as binder. Since the molten FeO binder changes into a solid bridge of $FeAl_2O_4$ in a short time, the Al_2O_3 particles adhering to the nozzle interface are considered to integrate to form a network of Al_2O_3 particles faster than possible with solid-phase sintering.

(cf. *ISIJ Int.*, **41** (2001), 1331)

Casting and Solidification

A technique for the evaluation of instantaneous heat fluxes for the horizontal strip casting of aluminum alloys

P.G.Q.NETTO et al.

Transient heat transfer between solidifying light metals strips and a moving substrate has been investigated. For this purpose, an experimental apparatus was constructed, consisting of a cold moving substrate onto which molten metal from a containment

mold is deposited. The substrate was flame sprayed with various commercial coatings while its speed and the thicknesses of strip produced matched industrial values. The primary objective of this work was to study the effects of some important variables, such as roughness of substrate, type of coating, thickness of strip and initial superheat, on heat fluxes. Substrate speeds in the range of 0.4–1.2 m/s were employed and strips with thicknesses between 1 and 5 mm were produced. The heat fluxes were determined "inversely" by an inverse heat transfer technique, using temperature measurements from thermocouples embedded within the substrate. Peak heat fluxes between 0.6 and 3.0 MW/m^2 were found for the diverse experimental conditions investigated. The heat transfer coefficients were deduced using a one-dimensional, finite-difference model, based on the corresponding calculated heat fluxes. Values of h ranged from 700–5000 $W/m^2 \cdot K$. The various coatings used, and the different levels of substrate roughness, contributed to the wide range of h values reported. The heat transfer coefficient was found to increase with initial superheat, thickness of strip and smoother coatings. Correlations were derived between peak heat fluxes and the most significant variables. More importantly, the transient evolution of q and h after their peak values were assessed and good correlations could be derived. The findings of this work are believed to be useful for industrial processes, since they give a better picture of the influence of some important variables on the heat transfer involved for this particular type of metal-substrate contact. This is relevant, for example, to horizontal direct strip casting processes currently under investigation for the production of low carbon steel strips.

(cf. *ISIJ Int.*, **41** (2001), 1340)

Effect of thermomechanical processing on the hot ductility of a Nb–Ti microalloyed steel

S.AKHLAGHI et al.

Many attempts have been made to understand the problem of transverse cracking in continuous casting process. Much of this research has involved the study of hot ductility using 'conventional' isothermal hot ductility testing. In these tests, the specimens were isothermally tensile tested to fracture, at temperatures achieved by cooling from a solutionizing temperature, close to the solidus, or above the liquidus. These studies showed that hot ductility at the test temperature is highly depended on the thermal path followed by the specimens. The thermal histories experienced by strands during continuous casting were found to be quite complex and invariably involve rapid cooling and heating cycles. This may therefore lead to high thermal gradients, which, in turn, can generate strains in the surface of the solidifying strand. This then may alter the microstructural evolution of the strand surface and the corresponding hot ductility, a possibility that has not been addressed in any previous studies. Thus, the purpose of this study was to consider the effect of the thermomechanical history on the hot ductility of steel.

After *in-situ* melting and solidification, Nb–Ti microalloyed tensile specimens were subjected to a thermal history typical of a continuously cast billet. Different degrees of deformation were imposed on the specimens at selected stages of this thermal history, before tensile testing to fracture point at the time and temperature corresponding to the unbending stage of the billet casting. It was found that the hot ductility varied from 1 to 98%, depending on the stage in the thermal history at which deformation was executed. The microstructural evolution during the thermomechanical profile was followed to study the effect of thermomechanical history on the hot ductility.

(cf. *ISIJ Int.*, **41** (2001), 1350)

Chemical and Physical Analysis

Analysis of size distribution of inclusions in metal by using single-particle optical sensing method

A.V.KARASEV et al.

The spatial size distributions of oxide and/or nitride inclusions on a film filter after chemical or electrolytic extraction have been measured using single-particle optical sensing (SPOS) method in an Fe–10mass%Ni–0.2mass%M (M=Ti and Al) and an Fe–10mass%Ni–0.025mass%Al–0.1mass%Ti–0.02mass%N alloys. The size distributions obtained from the SPOS method are compared with those obtained from the three-dimensional observation of particles on a film filter using scanning electron microscope (SEM) with electron probe microanalysis. The volume fractions of particles calculated from the size distributions by the SPOS method and SEM observation have been compared with those calculated from chemical analysis. It is found that in the size distribution measurement the SPOS method is superior to the SEM observation, particularly, in the range of $d_V > 5\ \mu m$.

(cf. *ISIJ Int.*, **41** (2001), 1357)

Forming Processing and Thermomechanical Treatment

Development of pinch rolls to control strip wandering in strip processing lines

Y.KASEDA et al.

In strip processing lines, it is important to restrain strip wandering which obstructs operational reliability and makes productivity decline. To improve the stability of the strip conveyance at the existing facilities in addition to the new facilities, a compact guiding apparatus was able to be introduced easily and was valid. In this report, the structure of the unique bent roll covered with a rubber sleeve, which has a wandering restraint function, was examined and the effect was clarified using an experimental apparatus. A rubber sleeve that needs durability to endure expansion and contraction by rotation of the bent roll was also examined. Production machine size rolls were newly developed and evaluated as pinch rolls in processing lines. Under the general condition to set pinch forces identically on both sides of the roll, this roll always has the ability to restrain strip wandering. When putting deviation of pinch forces on both sides, the ability of the wandering correction was increased. It was proposed that the wandering correction system, which controls the pinch force using the output of width sensor, was useful in the processing line. It was also possible to use these pinch rolls as the wandering correction apparatus at the place where it is difficult to use a general guiding apparatus because there is no restriction of line tension.

(cf. *ISIJ Int.*, **41** (2001), 1366)

Interaction between recrystallization and precipitation during multipass rolling in a low carbon niobium microalloyed steel

R.ABAD et al.

The interaction between recrystallization and precipitation processes during multipass deformation has been analysed in terms of the non recrystallization temperature (Tnr). Multipass torsion tests performed at continuous cooling conditions have been used for thermomechanical simulation. The effect of the pass-strain and the initial austenite microstructure on the Tnr value have been investigated. Conventionally reheated austenite (Tsoak51 200–1 250°C) and as-cast austenite, the latter simulated in the laboratory by reheating at very high temperatures (Tsoak51 400°C), have been considered. It was observed that at low pass-strains the retardation on recrystallization was mainly due to solute drag effects, while increasing the strain, precipitation induced by deformation was allowed to occur during the interpass interval leading to a drastic reduction of the softening reached between passes at temperatures below the Tnr. The increment of the reheating temperature led to higher Tnr values, being this effect related to higher austenite supersaturation levels prior to deformation.

(cf. *ISIJ Int.*, **41** (2001), 1373)

Transformations and Microstructures

Modeling of phase transformation kinetics in the CGHAZ of C–Mn steel weld considering prior austenite grain size

C.-W.LEE et al.

A metallurgical model for the phase transformation kinetics in the coarsened grain heat affected zone (CGHAZ) on the basis of the Johnson–Mehl–Avrami equation is proposed. In this model, the effects of the prior austenite grain size on the transformation and the morphological changes of ferrite are considered. Isothermal dilatometer tests were performed to determine the effects of the prior austenite grain size on the austenite decomposition to ferrite and pearlite in plain carbon steel. By comparing the calculated volume fraction with measured data, the reliability of the developed model is discussed.

(cf. *ISIJ Int.*, **41** (2001), 1383)

Formation mechanism and annealing behavior of nanocrystalline ferrite in pure Fe fabricated by ball milling

J.YIN et al.

Nanocrystalline ferrite formation by ball milling in pure Fe (0.004 mass% C) has been studied through morphology observation and microhardness measurements. It was found that nano-ferrite first

formed at the outer surface area in the powders at the early stage of ball milling, which was attributed to the deformation localization. The boundaries between the nano-ferrite and work-hardened regions are quite clear under SEM and the hardness of nano-ferrite region is more than 3 GPa higher than that of the work-hardened region. Further milling led to the particle refinement and formation of nano-ferrite of the whole particles. It has been suggested that the nanocrystalline ferrite formed through a transition from dislocation cell wall created by work hardening during ball milling to grain boundary, which is regarded to contribute to the hardness gap between the work hardened structure and the nanocrystalline ferrite. A relatively high stability against temperature was observed in the nano-ferrite formed by ball milling. The irregular grain boundaries of nano-ferrite annealed at high temperature was attributed to that the grain growth of nanocrystalline ferrite takes place by coalescence of neighboring grains.

(cf. *ISIJ Int.*, **41** (2001), 1389)

Mechanical Properties

Effects of heat-treatment process of a novel bainite/martensite dual-phase high strength steel on its susceptibility to hydrogen embrittlement

K.-D.CHANG et al.

The susceptibility to hydrogen embrittlement of a bainite/martensite dual-phase high strength steel with different morphologies obtained by the conventional or thermomechanical heat-treatment has been investigated by means of electrolytic hydrogen charging in this paper. The results show that the finer the microstructure, the lower the sensitivity of steel to hydrogen embrittlement is. The fractographic analysis suggests that the fracture mode of the hydrogen-charged specimens is a mixture of quasi-cleavage and dimple for both treating processes. The quasicleavage facet of the thermomechanical treated specimens is smaller than that of the conventional heated ones. The observation of the fracture profile specimen shows that the crack propagates preferentially along bainite/martensite laths boundary, suggesting that the fracture mode is predominantly lath boundary separation. In addition, the fractographic analysis indicates that the rhombic Ti(N,C) inclusion is the predominant type of inclusions on the fracture surface of the hydrogen-charged specimens of thermomechanical heat-treatment. The separation between Ti(N,C) inclusions and matrixes is a brittle fracture with small facets, which indicates that inclusions such as Ti(N,C) are harmful to hydrogen embrittlement.

(cf. *ISIJ Int.*, **41** (2001), 1397)

New type of IF high strength steel with superior anti-secondary work embrittlement

F.KITANO et al.

High strength cold-rolled steel sheets (HSS) with sufficient formability have been developed for the IF steel-bases in the last decade, in which the major strengthening method was solid-solution hardening with silicon, manganese and phosphorous. When the IF steel is strengthened with the high amount of solid-solution elements, it becomes susceptible to the secondary work embrittlement because of the lack of grain boundary strength, which is the essential drawback of interstitial free steel. Although the grain refinement is an effective method to improve the toughness of steel, this method has not been taken into consideration in view of press-formability because it leads the steel to higher yield ratio, lower n-value and lower r-value.

A new type of IF-HSS was strengthened by hybridizing the grain refinement and the supplemental solid-solution hardening. The grain refinement was achieved by means of the fine distribution of carbide under the appropriate combination of the relatively higher carbon content near 60 ppm with a suitable carbide-forming element. While this steel has the fine grain structure, yield strength hardly increases due to the formation of unique microstructure containing PFZ, and the γ fiber texture sufficiently develops. As the result, a new type of grain-refined IF-HSS has been successfully developed to reach a higher r-value and a superior secondary work embrittlement as compared with the conventional IF-HSS.

(cf. *ISIJ Int.*, **41** (2001), 1402)