Fundamentals of High Temperature Processes

Applications of numerical simulation to continuous casting technology (Review)

J.-K. YOON

The continuous casting process in steel production is a highly efficient and productive process. Since this process was first applied to steel foundations, rapid progress has been made. Recently, trends in continuous casting have been focused on near net shape casting, high speed casting and the adoption of electromagnetic processes. These systems involve many coupled phenomena such as fluid flow, heat and mass transfer, solidification and electromagnetic phenomena. Because of the interplay between the underlying phenomena, it is very difficult to understand these systems systematically. Consequently there are many unresolved technical problems. In order to analyze fluid flow, heat and mass transfer and solidification simultaneously, the finite volume method (FVM) with body fitted coordinate (BFC) is first used. The finite element method (FEM) code is applied to the analysis of the deformation of solid shell and mold, and electromagnetic fields. Some groups are trying to couple microsegregation with macrosegregation, and develop algorithms that can be applied to multicomponent solidification. In addition, a combined analysis of all the above-mentioned phenomena is being developed. In the future, caster design and on-line control of continuous casing processes based on numerical simulation will be even more important.

(cf. *ISIJ Int.*, **48** (2008), 879)

Formation of $MgO \cdot Al_2O_3$ inclusions in high strength alloyed structural steel refined by $CaO–SiO_2–Al_2O_3–MgO$ slag

M.JIANG et al.

Present paper focused on the formation of $MgO \cdot Al_2O_3$ inclusions in high strength 42CrMo alloyed structural steel refined by $CaO–SiO_2–Al_2O_3–MgO$ slag. Soluble aluminum contents in molten steel were less than 0.0100% when steel/slag equilibrium was established.

It is found by pre-equilibrium experiments that 90 min are sufficient for the attainment of equilibrium of slag–metal at 1 873 K. Spinel inclusions dispersed widely in the steel, with sizes between 2 μm and 4 μm. Magnesium content in molten steel influences the morphology of spinel inclusions greatly. With the rise of magnesium content in steel, globular spinel inclusions were modified into angular ones. However, trace amount of Ca in inclusions is effective to change the spinels from angular shape to globular shape. Solubility of MgO in slag was also discussed. It is shown that MgO in slags are saturated and activities of MgO can be considered as unity. Observed $\log(X_{MgO}/X_{Al_2O_3})$ of inclusions increases with the growth of observed $\log[a_{[Mg]}/(a^2_{[Al]} \cdot a^2_{[O]})]$ of molten steel as well as the rise of observed $\log(a_{MgO}/a_{Al_2O_3})$ in slag, both exhibiting good linear relation.

$MgO–MgO \cdot Al_2O_3–Al_2O_3$ stability phase diagram was obtained. It is found that aluminum and magnesium contents in molten steel mainly position in the $MgO \cdot Al_2O_3$ formation zone, which is essentially pre-requisite for the formation $MgO \cdot Al_2O_3$ in steel. Silica in slag is helpful to stabilize $MgO \cdot Al_2O_3$ phase, because it would react with calcium and aluminum in molten steel. In the scope of soluble aluminum contents, magnesium content influences the transformation among $MgO–MgO \cdot Al_2O_3–Al_2O_3$ ternary phases greatly, which is the reason for the formation of rectangular MgO inclusions.

(cf. *ISIJ Int.*, **48** (2008), 885)

A CFD-based nucleation-growth-removal model for inclusion behavior in a Gas-agitated ladle during molten steel deoxidation

Y.-J.KWON et al.

A coupled numerical model based on computational fluid dynamics (CFD), termed a CFD-based nucleation-growth-removal model, has been proposed to investigate the nucleation, growth and removal of inclusions in a bottom-blown gas-stirred ladle during molten steel deoxidation.

In order to account for the turbulent circulating flow induced by gas bubbling through the bottom, the κ–ε turbulence model was employed to evaluate time-averaged Reynolds stress while the fluctuation of the free surface of the melt was traced by means of the VOF technique. This model enables to couple transient flow fields, and temperature fields with concentration fields of elements and inclusions in melt so that it can meet the requirements of evolution of time- and space-dependent particle size distributions (PSD) without any given initial PSD of inclusions but directly from chemical reaction.

The model was applied to the simulation of the molten steel deoxidation process in Fe–Al–O system in an argon gas-stirred ladle. The model successfully predicted important phenomena including turbulent recirculation flow patterns, streamline structure of steel melt, turbulence energy variation and its dissipation rate, transient temperature fields and particle size distributions of alumina inclusion. Comparison with some industrial data showed that the predicted PSDs were reasonable in time-dependent variation of inclusion size distribution.

(cf. *ISIJ Int.*, **48** (2008), 891)

Copper distribution in Fe–Cu and Fe–C–Cu alloys under imposition of an intense magnetic field

Y.YUAN et al.

Solidification experiments of Fe–0.44%Cu and Fe–3.95%C–0.40%Cu alloys were conducted to investigate the effects of an intense magnetic field on copper distribution in their solidified structures. Experiments with melting and solidifying the samples were carried out in a superconducting magnet. Around the center of the vertical cross-section of the solidified sample, multiple line analysis of copper concentration was conducted with the help of FE-SEM/EDS. The following results have been found. The copper distribution in Fe–0.44%Cu alloy is independent of the imposition of the magnetic field during the solidification. On the other hand, the solidifying process under a 10 T magnetic field tends to make a uniform micro distribution of copper in Fe–3.95%C–0.40%Cu alloy in comparison with the sample solidified without the magnetic field.

(cf. *ISIJ Int.*, **48** (2008), 901)

Manganese furnace dust: Drying and reduction of zinc oxide by tar

T.HAMANO et al.

Manganese furnace dust collected in smelting of manganese alloys is in the form of a slurry containing oxides of manganese, iron, zinc and other metals, and tar. Drying of manganese furnace dust and removing zinc from the dust are essential steps to recycle the dust to the smelting furnaces. This paper presents results of drying tests of manganese dust under different conditions and zinc removal from dried dust in sintering experiments. On the basis of drying tests, an empirical relationship correlating the moisture content and drying time with temperature and sample thickness was derived. The effects of sintering time, temperature, moisture content and thickness of a sample on zinc removal in sintering experiments have been established.

(cf. *ISIJ Int.*, **48** (2008), 906)

Phosphorus gasification from sewage sludge during carbothermic reduction

E.MATINDE et al.

The gasification process of phosphorus from municipal sewage sludge during carbothermic reduction process was investigated using a quadrupole mass spectrometer gas analysis and thermo-gravimetric analysis. Two types of sludge, with high and low Fe_2O_3 content, were used to evaluate the possible effect of Fe_2O_3 on the gasification behavior of phosphorus from sewage sludge during incineration processes. The gas species vaporized during the carbothermic reaction were measured by the quadrupole mass spectrometer with comparison to the ion currents for the respective molecular gas species. From the gas analysis, it was observed that PO and PO_2 gas species were dominantly vaporized around 1 073 K. Metallic phase phosphorus gas of P_2 vaporized in the 1 273–1 700 K temperature range. The evolution of another metallic phase phosphorus gas of P_4 was found to be negligibly small. Fe_2O_3 in the sludge has an important role in the phosphorus emission from the sludge during carbothermic reduction reaction, since metallic phosphorous gases react with the reduced iron and form Fe–P alloy.

(cf. *ISIJ Int.*, **48** (2008), 912)

Ironmaking

Reduction and degradation behaviour of sinter under simulated vertical probe trial condition

R.JAFFARULLAH et al.

Ferrous burden encounters several low temperature isotherms during descent in the blast furnace. Low temperature degradation of ferrous burden becomes critical particularly in the temperature region of 450–650°C. The low temperature degradation, mainly of sinter, results in generation of fines, which affect gas permeability in the stack region. A severe reduc-

tion degradation of sinter hampers permeability causing imbalance in reduction degree in the radial and circumferential direction and disturbs the furnace heat level-all detrimental to stability of furnace operation.

Experimental studies were carried out with the following conditions: Temperature: 550, 650, 900 and 1 000°C; soaking time: 30, 60 and 90 min, and Gas composition corresponding to Softening-melting test condition (CO - 40% and N_2 - 60%) and Vertical Probe trial condition (η_{CO} - 40% and η_{CO} - 30%). Degradation takes place both at low temperature (550 and 650°C) and high temperature (900 and 1 000°C) reduction of sinter simulated under Vertical Probe trial condition. Reducibility was appreciably lower for all tests carried out under simulated Vertical Probe trial condition compared with the results obtained using Softening-melting test condition.

Results clearly showed that for minimizing sinter degradation and improving reduction degree in the blast furnace, low temperature holding zone has to be avoided and high temperature holding zone has to be minimized. This can be achieved by increasing sinter reduction degree by adjusting sinter chemistry and burden distribution in blast furnace.

(cf. *ISIJ Int.*, **48** (2008), 918)

Steelmaking

Effect of alkali oxides on crystallization in CaO–SiO_2–CaF_2 glasses

T.WATANABE et al.

In the initial solidification stage in continuous steel casting, controlled crystallinity of the slag film is essential for regulating the horizontal heat flux from the strand to the mold. The effects of alkali oxides on the formation of cuspidine ($3CaO \cdot 2SiO_2 \cdot CaF_2$), which is the primary crystalline phase in the flux film in CaO–SiO_2–CaF_2–M_2O glasses (M=Li, Na, K), were investigated in both isothermal and heating conditions. Addition of alkali oxides enhances crystallization of cuspidine by lowering the glass transition temperature and lowering the apparent activation energy of crystal growth. However, single excess addition of alkaline oxide (M_2O) hinders the formation of cuspidine as CaF_2 is substituted by M_2O.

(cf. *ISIJ Int.*, **48** (2008), 925)

Casting and Solidification

Micro-structure refinement in low carbon high manganese steels through Ti-deoxidation-inclusion precipitation and solidification structure

N.KIKUCHI et al.

The substitution of Al by Ti as a de-oxidizing agent in a carbon (0.07 wt%) and Mn (0.9 wt%) containing steel was studied for two purposes. The first one was to establish whether inclusion precipitation during solidification (secondary de-oxidation) can be promoted. The second purpose was to investigate the influence of secondary inclusions on the subsequent evolution of the steel solidification-structure, varying initial oxygen and titanium contents along with cooling rate during solidification.

In the Ti-killed steel samples, the oxide inclusions were identified as MnO–TiO_2 (0.5–5 μm) and MnS (1–3 μm) in the samples with the higher initial oxygen contents (Total Oxygen (T.O)=50–80 ppm) while Ti–Al–(Mg)–O (0.3–1 μm) in the samples with the lower oxygen contents (T.O=7–10 ppm). Comparing with thermodynamic calculations, the latter inclusions are considered to be the result of solely secondary de-oxidation precipitated in the inter-dendrite regions. For the high initial oxygen content, the inclusions were found as a result of both primary and secondary de-oxidation. The influence of cooling rate during solidification was investigated by controlling the cooling rate between 3–10 K/s by using different molds in a vacuum induction furnace. In addition, cooling rates were controlled at 1.1, 14 and 84 K/s by re-melting the samples in a gold-image furnace attached to a Confocal Scanning Laser Microscope (CSLM). An increase in the cooling rate resulted in an increase in the inclusion density in the Ti-killed samples while such an effect was not observed in the Al-killed sample. The secondary particle sizes for the Ti-killed sample predicted by a solute segregation model during solidification agreed well with the observed average particle sizes.

In the Ti-killed samples, the solidification structure was finer with increasing density of inclusions below 1 μm, whereas such an effect was not observed in the Al-killed samples.

(cf. *ISIJ Int.*, **48** (2008), 934)

Simulation model for solidification process in planar flow casting using the multi-zone method

N.ITO

A numerical solution model based on the multi-zone method for a full transport equation system in planar flow casting was developed. The multi-zone consists of the solid, the liquid and the cooling roll zone. In the numerical solution model, the local solidification rate for the solidification front of the liquid zone (the puddle) is expressed as two components; *i.e.* the component of vertical velocity to the surface of the cooling roll zone and the component of partial ribbon thickness difference in the downstream direction. Additionally, a practical mesh deforming method in the liquid zone was proposed. In the mesh deforming method, the actual shape of the solidification front is considered when the free surfaces position of the puddle is explored; this shape could be more complex than that under the power series assumption as in conventional models. The prediction accuracy improved with the present model in the puddle shape and the ribbon thickness. A characteristic rise in solidification rate near the downstream end of the puddle was observed as a first in the simulation.

(cf. *ISIJ Int.*, **48** (2008), 944)

Interface migration behavior of the $\delta \rightarrow \gamma$ interface in low carbon high manganese steel samples de-oxidized with Ti or Al

N.KIKUCHI et al.

The effect of inclusions, generated during de-oxidation and solidification, of low carbon (0.07 wt%) and high manganese (0.9 wt%) steels, on the rates of migrations of the boundaries between delta-ferrite/gamma-austenite interfaces, during austenite formation was investigated. The presence of two types of de-oxidation products were investigated, namely Al_2O_3 (1–3 μm) in Al-killed steel samples, and Ti–Al–(Mg)–O (0.3–1 μm) in Ti-killed steel samples. The samples were prepared in a vacuum-induction furnace and a Confocal Scanning Laser Microscope was used to image in real time the interface movement on the surface of the samples.

Austenite was found to precipitate at the triple-points of the delta-ferrite grain boundaries during cooling from 1 500 to 1 460 and 1 450°C and the growth appeared to be diffusion controlled. The migration rates of delta/gamma interfacial boundaries were higher in the Al-killed steel samples than in the Ti-killed steel samples and this is attributed to the finer oxide particle population in the latter. When the samples were cooled to 1 440°C and below sword-like precipitation was observed in all samples that grew at a higher rate than what was observed at higher temperatures and the growth appeared to have linear time dependence, and thus the process appears to not be governed by long range diffusion.

(cf. *ISIJ Int.*, **48** (2008), 954)

Instrumentation, Control and System Engineering

Artificial neural network modeling of high pressure descaling operation in hot strip rolling of steels

A.KERMANPUR et al.

High pressure (HP) hydraulic descaling is usually used in hot strip mills to remove oxide scales from steel strip formed after the reheat furnace and during hot rolling. In the present work, an artificial neural network (ANN) model was developed to improve efficiency of the HP hydraulic descaling operation using flat spray nozzles. The model was trained based on the industrial data from the hot strip rolling mills of Mobarakeh Steel Complex. The spray angle, inclination angle, spray pressure, vertical spray height and water flow rate were all considered as the main input parameters of the HP descaling operation.

The ANN model developed is able to predict spray impact, spray width and spray depth for any given spray nozzle system. The model can also analytically compute the spray overlap for a given spray nozzle arrangement. A sensitivity analysis was carried out using the ANN model. It was shown that, among all process parameters, the spray angle followed by the inclination angle are the most important parameters affecting the spray impact. The model developed can be used as a proper tool to improve the efficiency of the descaling system in terms of achieving the highest spray impact and an optimum spray overlap for any process condition.

(cf. *ISIJ Int.*, **48** (2008), 963)

Forming Processing and Thermomechanical Treatment

Numerical simulation of temperature and thermal stress fields in cast-hot-working-die steel under high density electropulsing

H.Q.LIN et al.

The temperature field and thermal stress field of cast-hot-working-die (CHWD) steel under high density electropulsing were investigated by finite element analysis method. The simulation analysis showed that, during the electropulsing discharging process, the existence of specimen notch resulted in the concentration effect of electric current, namely that the increase of current density in local position. The electric current with high density induced the concentration release of Joule heat and the formation of heat affected zone (HAZ) ahead of specimen notch tip. Because the expanding of HAZ with high temperature was restricted by the neighboring matrix with low temperature, the thermal compressive stress formed in the former during electropulsing discharging. The metallurgy process, under the condition of high temperature and pressure and accompanying thermal compressive stress, was regarded as being beneficial for enhancing mechanical properties and thermal fatigue resistance of CHWD steel and prolonging service lifetime of die in extremely high temperature condition.

(cf. *ISIJ Int.*, **48** (2008), 971)

Effect of severe cold rolling and annealing on the development of texture, microstructure and grain boundary character distribution in an interstitial free (IF) steel

R.SAHA et al.

A systematic study on the evolution of microstructure, texture and grain boundary character distribution has been carried out for an industrially produced interstitial free (IF) steel after cold rolling by 90 and 98% and also after recrystallization anneal. The deformation microstructure shows refinement of the cell structure along with frequent formation of strain free nano-sized to sub-micron grains after severe cold rolling. Increase in the amount of cold rolling leads to a rise in the density of high angle grain boundaries and a corresponding sharpening of the deformation texture. Annealing of the severely cold rolled material also leads to the formation of submicron to ultra-fine grains. Higher amount of cold rolling sharpens the γ fibre intensity. Selective growth during annealing may take place in the more heavily cold rolled (98%) material. The texture, microstructure and grain boundary character distribution appear to be intimately related.

(cf. *ISIJ Int.*, **48** (2008), 976)

Effect of tempering on microstructure and mechanical properties in a multiphase ZrCuAlNiO alloy

F.QIU et al.

The changes in microstructure and mechanical properties of ZrCuAlNiO alloy after tempering were investigated. The morphology of the martensite changes, and both the interfaces of martensite variants and substructural boundaries fade after the tempering treatment. The Zr_2Al phase precipitates in Zr_2(Cu, Al, Ni) grains at temperatures higher than 747 K, and its size increases with the tempering temperature, while Zr_2Ni phase precipitates in martensite zone at temperatures higher than 1 053 K. The mechanical property was improved by the presence of the precipitates after tempering. The correlation between microstructure and property in this alloy was discussed.

(cf. *ISIJ Int.*, **48** (2008), 984)

Surface Treatment and Corrosion

Influence of zinc ions on initial stage of localized corrosion of Zn and Zn–Al alloy coated steels with photon rupture method

M.SAKAIRI et al.

The effect of pre-dissolved Zn ions in the solutions on the initial stage of localized corrosion after oxide films of Zn and Zn–Al alloy coated steels were removed by a photon rupture method, focused pulsed Nd-YAG laser beam irradiation, was investigated electrochemically. Zn ions can be inhibited dissolution of the Zn coated layer by precipitation of zinc hydroxide, which is formed by hydrolysis reaction of dissolved Zn ions in neutral buffer solutions. However, Zn ions do not affect the dissolution of a Zn–Al alloy coated layer. The absence of inhibition of the Zn–Al layer dissolution can be explained by pH change to lower values at the irradiated area by the hydrolysis reaction of the dissolved Al ions. The effect of Zn ions on corrosion inhibition of the coated layer by the photon rupture method established here was in good agreement with polarization experiments.

(cf. *ISIJ Int.*, **48** (2008), 988)

Transformations and Microstructures

Microstructural evolution and kinetics for post-dynamic transformation in a plain low carbon steel

X.SUN et al.

The post-dynamic transformation (post-DT), which could occur during isothermal holding after hot deformation, was investigated by using both dilatometry method and optical microstructural observation in a plain low carbon steel. The results indicates that the kinetics of post-DT at deformation temperature between Ae_3 and Ar_3 can be well described by the Avrami equation: $X=1-\exp(-kt^n)$, but the n value is lower than that of the corresponding static transformation due to the early impingement of formed ferrite grains. Furthermore, the ferrite-to-austenite retransformation was measured by dilatometry during the isothermal holding after hot deformation above Ae_3 temperature, which suggests that dynamic transformation can indeed occur even above Ae_3.

(cf. *ISIJ Int.*, **48** (2008), 994)

Effects of liquid Bi particles on grain growth of Fe–1.9vol%Bi alloy

T.HAGISAWA et al.

The recrystallization and grain growth characteristics of pre-deformed Fe–1.9vol%Bi alloy specimens in the two-phase region of αFe and liquid Bi were investigated by microstructural observation. Precipitate-free zones (PFZs) were mainly formed in the vicinity outside of the curved grain boundaries. Furthermore, large Bi particles were also observed on the grain boundaries of the matrix along the PFZs. These results suggest that the intragranular liquid Bi particles were trapped and dragged by grain boundaries. The grain growth of the matrix phase was extremely retarded by the effect of this dragging.

(cf. *ISIJ Int.*, **48** (2008), 1001)

Dynamic recrystallization behavior in a low-carbon martensite steel by warm compression

J.LI et al.

The dynamic recrystallization behavior during warm compression for a low carbon martensite steel was investigated to make clear the effects of initial martensite block size, compression strain and pre-tempering before compression. It is found that the average size of recrystallized ferrite grains is influenced neither by the initial martensite block size (austenitizing temperature) nor by the amount of compression strain. The pre-tempering before compression shows two competitive effects: cementite particles precipitated during pre-tempering at 600°C promotes the occurrence of dynamic recrystallization while the decrease in dislocation density during pre-tempering at a higher temperature delays the dynamic recrystallization. Dispersed cementite particles suppress ferrite grain growth. Hence, there is an optimum tempering condition before warm-compression in order to obtain fine grained microstructure.

(cf. *ISIJ Int.*, **48** (2008), 1008)

Mechanical Properties

Temperature dependence of pseudoelasticity and shape memory effect in Fe_3Ga single crystals with $D0_3$ structure

H.Y.YASUDA et al.

Pseudoelastic behavior and shape memory effect in $D0_3$-ordered Fe–24.4at%Ga single crystals deformed at different temperatures were investigated focusing on the microstructure and dislocation configuration. High strain recovery ratios more than 80% could be obtained at temperatures between −100 and 100°C. In particular, perfect pseudoelasticity appeared in the crystals deformed at room temperature. During unloading, antiphase boundaries (APB) left behind 1/4⟨111⟩ superpartial dislocations pulled back the superpartials resulting in the pseudoelasticity. In addition, Fe_3Ga single crystals compressed at −150°C demonstrated shape memory effect during heating to room temperature. On the other hand, the recovery ratio decreased with increasing deformation temperature up to 300°C and remained constant at about 10%. The $L1_2$ phase precipitating during deformation, dislocation configuration associated with 1/4⟨111⟩ superpartials connected by two kinds of APB and relaxation of the APB were found to strongly influence the pseudoelasticity and shape memory effect in Fe_3Ga single crystals.

(cf. *ISIJ Int.*, **48** (2008), 1014)

Flow stress analysis using the Kocks–Mecking model for ferrite–cementite steels with various ferrite grain sizes

N.TSUCHIDA et al.

True stress (σ)–true strain (ε) curves were calculated by using the Kocks–Mecking (KM) model for the ferrite–cementite steels with various ferrite grain sizes between 0.47 and 13.6 μm. In the KM model, the effect of ferrite grain size on flow stress is described by the athermal stress component that follows the Hall–Petch equation. The effects of temperature and strain rate on flow stress, which are correlated with the thermal stress component, are independent of the ferrite grain size. The calculated σ–ε curves by using the KM model agree with the measured ones at various temperatures and strain rates including the high-speed tensile test with a strain rate of $10^3\ s^{-1}$. From the calculations based on a micromechanic model, it is found that the volume fraction of second phase affects the grain size dependence in multi-phase steels. The m-value showing strain rate sensitivity for the external stress was decreased with a decrease in grain size and that for the thermal stress was independent of grain size.

(cf. *ISIJ Int.*, **48** (2008), 1020)

New Materials and Processes

Reaction synthesis of nano-scale ZrC particulates by self-propagating high-temperature synthesis from Al–Zr–C powder mixtures

M.SONG et al.

Nano-scale ZrC particles were synthesized by self-propagating high-temperature synthesis (SHS) reaction from 30–40 mass% Al–Zr–C powder mixtures. The size of ZrC particles evidently reduced from ~160 nm with a nearly spherical shape in 30 mass% Al to ~60 nm with a tetragonal morphology in 40 mass% Al. The reaction mechanism to form ZrC was discussed by DTA and X-ray diffraction analysis. The results revealed that $ZrAl_3$ metastable phase was initially formed by Al–Zr reaction, and then the formation of nano-scale ZrC grain was controlled by the dissolution of C into a Zr–Al melt and the precipitation from the melt. Al in the compact serves not only as a diluent inhibiting the ZrC particle from coarsening, but also as an intermediate reactant participating in the reaction process.

(cf. *ISIJ Int.*, **48** (2008), 1026)