Fundamentals of High Temperature Processes

Process analysis of non-contact continuous casting of materials using cold crucible

H.MAKINO et al.

An axi-symmetric process model for the cold crucible continuous casting is developed based on analyses of electromagnetic and temperature fields coupled with force balance around the free boundary of melt. The electromagnetic field around the system is predicted by means of a wire model using the vector potential method. A characteristic tempera ture field in the charge which is electro magnetically repelled by the crucible is given by a finite difference solution of the heat balance equation taking transitional phase change into consideration. The validity of the proposed theoretical model has been confirmed by experimental measurements of the electromagnetic field around the cold crucible and temperature field in the charge. Numerical predictions show that keeping a molten charge without contact of a surrounding crucible is possible when the position and shape of solidification front is properly controlled by a regulated water cooling of the surface in the lower part of the charge. A laboratory experiment has been conducted to support this predicted fact. Theoretical operational criteria as to casting speed, cooling position and its rate which allow a stable and non-contact melting of the charge are shown.

Steelmaking and Refining

Effect of stirring on oxidation rate of molten steel

K.SASAI et al.

As basic research to quantify the oxidation rate of molten steel in tundish, oxidation experiments were performed on nonkilled molten steel and aluminum-killed molten steel on laboratory scale, and the effect of stirring on the oxidation rate was studied. The following conclusions were derived. The oxidation rate of the nonkilled molten steel by air is not affected by stirring and is controlled by the diffusion of O_2 gas in the gasphase. Stirring changes the oxidation rate because of breaking the oxide film in the oxidation process of the aluminum-killed molten steel by air. The oxidation rate of the aluminum-killed molten steel in the still state is controlled by the diffusion of oxygen in the oxide film, while the oxidation rate of the aluminum-killed molten steel in the stirred state is controlled by the diffusion of O_2 gas in the gas phase.

Mathematical model for nitrogen desorption and decarburization reaction in vacuum degasser

T.KITAMURA et al.

A mathematical model for nitrogen desorption and decarburization reactions in vacuum degasser was developed. The rate controlling step is assumed to be the mass transfer of nitrogen, carbon and oxygen in molten steel and the chemical reaction of $\underline{N}+\underline{N}=N_2$ and $\underline{C}+\underline{O}=CO$. The bath surface and the surface both of the injected Ar gas bubble and CO gas bubble formed inside the bath are considered as the reaction sites. This model was verified by the agreement of the calculated results with the results of small scale experiments for nitrogen desorption and absorption reaction.

The following results were obtained by the analysis of a VOD process of commercial scale for degassing of stainless steel by this model. The ratio of reaction rate for nitrogen desorption and decarburization at each reaction site during operation was evaluated. The nitrogen desorption reaction occurs at the CO gas bubble formed inside steel (51 %), at bath surface (36 %) and injected Ar gas bubble (13 %). The decarburization reaction proceeds at bath surface (90 %), at CO gas bubble (8 %) and at injected gas bubble in (2 %).

Incorporation of sulfur in an optimized ladle steelmaking slag

F.PATSIOGIANNIS et al.

$CaO-Al_2O_3-SiO_2=50-42-8$ wt% eutectic slags, similar in composition to a secondary steelmaking slag, containing different amounts of CaS, were heated between 1 673-1 873K. DTA was performed. Samples were characterized by EMP and XRD. Four main phases were present: $CaO.Al_2O_3$, $2CaO.Al_2O_3.SiO_2$, $2CaO.SiO_2$ and $23CaO.14Al_2O_3.CaS$ or $22CaO.14Al_2O_3.2CaS$ products of the reaction of CaS with $12CaO.7Al_2O_3$ at 1 349(±21) K. The sulfur phases crystallized first and the rest of the melt followed the well known $CaO-Al_2O_3-SiO_2$ phase diagram. For comparison, typical iron-making and steelmaking slags ($CaO-Al_2O_3-SiO_2=48-12-40$ wt%) were also utilized to study the incorporation of sulfur in their structure. The resulting phases were all glasses with some non-stoichiometry.

Casting and Solidification

Surface quality improvement of continuously cast metals by imposing intermittent high frequency magnetic field and synchronizing the field with mold oscillation

T.LI et al.

In order to improve the surface quality of continuously cast steel, two new casting processes imposing are developed. One is the imposition of an intermittent high frequency magnetic field from the outside of a mold and the other is a synchronizing imposition of the intermittent high frequency magnetic field with mold oscillation. To distinguish the characteristics of the processes, the meniscus dynamic behavior was investigated in molten gallium as simulator of molten steel and the meniscus deformation was numerically analyzed. The surface quality was examined in the cast tin used as simulator of steel. The imposition of the high frequency magnetic field reduces the effect of mold oscillation on dynamic pressure in a flux channel between molten metal and a mold and suppresses the deformation on meniscus shape.

The intermittent high frequency magnetic field suppresses the surface wave motion generated by mold oscillation. When the timing of the magnetic field imposition is synchronized with the period including the lowest position in the stroke of mold oscillation, the better surface quality is obtained than that synchronized with the period including the highest position. The amount of electric current required to get the same surface quality decreases in the order of the imposition of continuous high frequency magnetic field, the imposition of intermittent high frequency magnetic field and the synchronizing imposition.

Relation between surface quality of cast strips and meniscus profile of molten pool in the twin roll strip casting process

T.MIZOGUCHI et al.

Experiments of laboratory scale twin roll casting to observe strip surface quality and to detect contact point between molten metal and roll by immersing a refractory bar into the molten metal pool have been done using stainless and carbon steels and copper alloy to elucidate the relation between surface quality and meniscus behavior of molten metal. Furthermore, dynamic meniscus profile near the roll surface and critical casting speed controlling surface wrinkles have been theoretically analyzed.

With increasing casting speed, the depth of surface wrinkles becomes shallow and the flat surface is obtained. The observed critical speed for the wrinkle-free surface is roughly 0.45 to 0.6 m/s for the cast metals. By the immersion of refractory bar over a depth, the solidification of columnar dendrite zone is delayed and the surface wrinkle is resultantly formed. With increasing casting speed, the depth of bar to result in surface wrinkles increases and the contact point between molten metal and roll moves downward.

It has been theoretically found that the descent of meniscus increases with increasing casting speed and surface tension of molten metal and with decreasing the density. The surface wrinkle does not appear when the descent of meniscus is deeper than a critical value, because vibration of the molten pool surface due to the teeming flow becomes less influential at the contact point. A theoretical equation of the critical speed for preventing surface wrinkles has been presented to show that it increases with increasing the critical descent of meniscus and the density and with decreasing the surface tension.

Instrumentation and Control System

A hybrid material design and evaluation system for steelmaking

S.S.SHIVATHAYA et al.

Development of material design system for steelmaking is a complex task, due to the interrelationship of many factors in steelmaking process. In addition to this, design specifications vary frequently and material design knowledge is held in largely intuitive undefined format. This paper discusses material design system which deals with the determination of the steelmaking aim chemistry utilising hybrid approach of knowledge bases along with mathematical modelling to deal with this complex task. Knowledge Elicitation (KEL) is the most important stage, but often the principal bottleneck, in the development of knowledge-based systems. A new methodology has been developed to efficiently elicit material design knowledge utilising a three character alphanumeric codification scheme, paper models and non-interview techniques.

The paper then presents the application of fuzzy logic to the material design system to rank the alternative steelmaking aim chemistries according to the degree which will satisfy the customer's requirements of chemistry and mechanical properties, with due consideration given to the economic aspects and the complexity involved in the production.

Finally, the paper describes the development of a codification scheme aided graphical user interface to enable quick and error free input of basic information about the steel plate required and customer special requirements. In addition to making the system more user friendly and visually appealing, the interface also adds flexibility and sophistication to the prototype knowledge-based system for designing steel plates.

Analysis and Characterization

Angle resolved XPS study of thin oxide layers formed on the surface of iron-chromium binary alloys exposed to air

S.SUZUKI et al.

Recent angle resolved X-ray photoelectron spectroscopy (AR-XPS) on the surface of iron-low chromium alloys due to air exposure at room temperature after sputter cleaning has suggested that an oxide layer of nanometer order of magnitude of thickness formed on the alloys, and a contaminated overlayer covered the oxide layer. In the present work, we have subsequently studied the surface of iron-chromium alloys containing chromium more than 50 mass%, in order to confirm the previous remarks for these thin oxide layers on a wider base. Estimation of the effective thickness of these layers by coupling with a model indicates that the thickness of the oxide layer on the surface decreases with increasing chromium concentration up to 50 mass%, and is kept almost unchanged with higher chromium. It is, however, noted that the intensity of metallic peaks in Cr 2p XPS spectra still increases with chromium concentration more than 50 mass%, and the position of O 1s XPS spectra shifts as the chromium concentration increases. These facts suggest that the characteristic features of the oxide layers are affected, more or less, by the bulk chromium composition.

Surface Science and Technology

Cold model experiment on fluid flow phenomena in hot dip plating bath

J.KUROBE et al.

Flow phenomena in a hot dip plating bath were investigated by using cold models with reduced scale of 1/5 and 1/10. The mean velocity components, root-mean-square value of turbulence components and Reynolds shear stress in the bath were measured using a hot-wire anemometer and a two-channel laser Doppler velocimeter (LDV). The flow in the bath had three dimensional components. Main flow induced by belt motion was directed from the entry region to the exit region, and this flow subsequently returned in the entry region along the side walls and the bottom wall. A part of the flow returning along the side walls entered the region enclosed with the belt. The flow in the region enclosed with the belt had also three dimensional components. The flow pattern in the whole bath was in good agreement with that suggested by mean velocity vectors measured with the LDV. Mean velocity components and the root-mean-square value of turbulence components were altogether low in the almost all part of the entry region except near the belt. As the value of Reynolds shear stress was very large in the vicinity of the belt in the exit region, the dross would be vigorously disturbed and dispersed there.

Microstructure

Effect of dislocation density in an unrecrystallized part of austenite on growth rate of recrystallizing grain

A.YOSHIE et al.

The growth rate of recrystallizing austenite grains of Si-Mn steels and Nb added steels after hot deformation was investigated by measurement of the fraction of recrystallized austenite and recrystallized austenite grain size. The fraction of recrystallized austenite (X_{cr}) at which the mechanism of recrystallization changed from nucleation and growth (NG) to site saturation(SS) was formulated as a function of Nb concentration and deformation conditions. According to the increase in deformation temperature and strain, X_{cr} increases while the increase in Nb in solution decreases X_{cr}.

The growth rate of recrystallizing austenite was also formulated as a function of strain energy (F_v) and Nb concentration. The growth rate decreases rapidly after deformation due to the decrease in F_v. The growth rate also decreases Nb addition.

Origin of the recrystallization texture formation in an interstitial free steel

Y.NAGATAKI et al.

A laboratory investigation has been carried out to reveal the mechanism of recrystallization texture formation in an interstitial free (IF) steel, based on the assumption that the reduced grain boundary constraint for a grain rotation during cold-rolling plays an important role on the mechanism. As a parameter of grain boundary constraint, the ratio of deformation strengths of grain boundary area and grain matrix were varied by changing the cold-rolling temperature (−100～200°C) and microalloying of boron into IF steel. The paper revealed that the reduced grain boundary constraint by scavenging the interstitial elements from grain boundaries not only enhanced a development of γ-fiber texture but also suppressed a formation of deformation bands inside the γ-fiber matrix during cold-rolling in IF-steel. In-situ like recrystallization from the strong {111} ⟨112⟩ γ-fiber texture, which is caused by a reduction of nucleation frequency of ⟨110⟩ // ND grains from deformation bands, is the origin of the strong {111} ⟨112⟩ γ-fiber recrystallization texture formation in IF steel.

Physical and Mechanical Properties

Dwell effects in isothermal and thermo-mechanical fatigue of advanced materials

T.GOSWAMI

Effects of dwell-times in the isothermal fatigue (IF) and thermal-mechanical fatigue (TMF) behaviors of six advanced high temperature materials are investigated in this paper; two of which belonged to types SS 304L and SS 304 stainless steels, two tantalum alloys; T-111 and ASTAR 811C, pure nickel Ni 201 and a nickel based, single crystal superalloy PWA 1480. The SS 304 and 304L steels were found to be sensitive under tensile dwells, however, effect of dwell-times was found to saturate with the increase in strain range (inelastic or total) for all materials examined. At lower strain ranges the effects of dwell-times were found to produce lower lives than at higher strains as in the case of AISI SS 304 and two tantalum based alloys T-111 and ASTAR 811C. Trends in various normalized life curves were found to be near sigmoidal for ASTAR 811C, in which a typical inflection point could be found at nearly 0.2 % inelastic strain range. Effects of dwell-times were more deleterious below that strain range and above

0.2 % inelastic strain range the effects of dwell-times were nearly the same. Mechanistic aspects under different test conditions were summarized.

Formulation of flow stress of Nb added steels by considering work-hardening and dynamic recovery

A. YOSHIE et al.

Flow stress of Si-Mn steel and Nb added steels measured under the usual hot deformation conditions for the rolling of steel plates was formulated by taking strain hardening and dynamic recovery into consideration. The functions derived include variables of deformation conditions such as deformation temperature, strain and strain rate and metallurgical factors such as austenite grain size and Nb concentration. The calculated stress-strain relations and the stress-dislocation density relations show close correlation with experimental data. The increase in flow stress by Nb addition is due to the additional effects of the increase in strain hardening rate and the decrease in dynamic recovery rate leading to a high level of dislocation density just after deformation.

Formulation of the decrease in dislocation density of deformed austenite due to static recovery and recrystallization

A. YOSHIE et al.

Decrease in dislocation density (ρ) in deformed austenite of Si-Mn steel and Nb added steels due to static recovery and recrystallization has been investigated. By comparing the flow stress measured at the second pass of a double compression test and the fraction of recrystallized austenite of the specimen quenched at a certain time after deformation, the change in ρ due to static recovery has been separated from the total change of ρ. The change in ρ due to static recovery has been formulated as functions of the concentration of Nb (Nb%), deformation conditions and time after deformation. The recovery process is mainly controlled by the climbing of dislocations in the case of higher deformation and holding temperature (DT) and lower Nb%, while it is mainly controlled by the annihilation of dislocations with opposite Burgers vectors in the case of lower DT and higher Nb%. Recovery is retarded by an increase in austenite grain size, a decrease in DT and an increase in Nb%.

Effects of strengthening mechanisms on fatigue properties of ferrite-pearlite hot-rolled sheet steel

M. KURITA et al.

The purpose of this study made to clarify the effects of strengthening mechanism on the fatigue properties of ferrite plus pearlite sheet steel. Ferrite plus pearlite sheet steels having the tensile strength of 400 to 600 MPa grade were prepared with being strengthened by solid solution, precipitation, increased dislocation density, grain-refinement or increased pearlite volume fraction. Furthermore, a ferrite plus bainite steel was prepared to investigate the effect of replacement of the second phase pearlite with harder phase, bainite. Load-controlled fatigue test and strain-controlled fatigue test were carried out to examine fatigue limits and obtain cyclic stress response curves, respectively.

Main results are as follows : (1) The ratio of an increase in fatigue limit to an increase in tensile strength ($\Delta\sigma_W/\Delta\sigma_B$) heavily depended on strengthening mechanism. The ratio was higher for both solid solution and precipitation strengthenings than bainite or grain-refinement strengthenings, while lower for dislocation and pearlite strengthenings. (2) Stress amplitude obtained from cyclic stress response curve related more closely to fatigue limit than to tensile strength. (3) The initial fatigue cracks were observed only in the ferrite matrix ; but not in the second phase. (4) It was concluded from these results that it is of vital importance to strengthen the ferrite matrix itself by solid solution or precipitation in order to obtain higher ratio of $\Delta\sigma_W/\Delta\sigma_B$.