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Fundamentals of High Temperature Processes

Karman vortex probe for the detection of molten metal surface flow in low velocity range

M.IGUCHI et al.

A previously developed Karman vortex probe is equipped with a circular cylinder for the generation and detection of Karman's vortex streets. This probe is known to be useful for the measurement of the meniscus velocity of molten steel flow in the real continuous casting mold. The detectable velocity ranges from approximately 10 to 70 cm/s. Efforts were devoted in this study to develop a Karman vortex probe capable of measuring a meniscus velocity lower than 10 cm/s. Three kinds of non-circular cylinders were selected to detect the shedding frequency of Karman's vortex streets in this low velocity range. A triangular cylinder was found to meet this requirement provided that the direction of flow approaching the cylinder is known *a priori*. Accurate measurement was possible for a minimum approaching velocity of 5 cm/s.

(cf. *ISIJ Int.*, **42** (2002), 939)

Steelmaking

Splashing and spitting behaviour in the combined blown steelmaking converter

M.J.LUOMALA et al.

The amount of iron droplets ejected in the BOF affects on metallic yield, refactory wear and the progress of decarburisation. The purpose of this study was to investigate the effect of lance height, lance nozzle angle, lance position, top gas flow rate, bottom blowing and foamy slag on splashing and spitting. A new cold model method for investigating the effects of above-mentioned parameters on the location and quantity of liquid splashed on the walls of the model was utilised. According to the model tests, reduction of the nozzle angle increased the total amount of splashing and spitting considerably. Consequently, reduced productivity due to an increase in metal losses, skulling of the cone and converter mouth and further increased time for skull removal is expected. Introduction of bottom blowing increased splashing significantly on lower parts of the vessel. Lance position has an effect on total amount of splashing when bottom blowing is used. The presence of even minor foam layer on water surface reduced the amount of total splashing significantly.

(cf. *ISIJ Int.*, **42** (2002), 944)

Casting and Solidification

Mathematical model of sulfide precipitation on oxides during solidification of Fe–Si alloy

Z.LIU et al.

A mathematical model of sulfide precipitation on oxides during solidification is established based on the coupled model of microsegregation and inclusion precipitation, which is also established by the present authors.[1] In this paper, sulfide capacity and optical basicity are introduced to calculate the distribution of sulfur between liquid oxides and molten steel during solidification, and the effect of composition of oxides on the precipitation of sulfide is also discussed. The calculated results agree well with the experiment results and data reported.

(cf. *ISIJ Int.*, **42** (2002), 950)

A coupled mathematical model of microsegregation and inclusion precipitation during solidification of silicon steel

Z.LIU et al.

A coupled mathematical model of microsegregation and inclusion precipitation during solidification is established. The model can be used to calculate the kind of precipitated inclusion, the amount of inclusion precipitation and the growth of inclusion during solidification. The calculation by this model shows that the segregation degree of solute elements is suppressed greatly due to the precipitation of inclusions during solidification. A non-coupled model will overestimate the segregation degree and the amount of inclusion precipitation and even give a wrong prediction for the kind of the inclusions. In this paper, the effects of cooling rate on the precipitation and growth of oxides are also discussed.

(cf. *ISIJ Int.*, **42** (2002), 958)

High temperature deformation behavior of peritectic carbon steel during solidification

H.MIZUKAMI et al.

Phase dependence of tensile strength of Fe–C binary steel and peritectic carbon steel during and after solidification has been studied by a technique for high temperature tensile testing. The experimental technique enabled a sample to melt and solidify without a crucible, and the measurement of a minute load in a solidification temperature range became possible. A numerical model for the analysis of phase transformation during and after solidification was developed with the assumption that local equilibrium holds at liquid/solid interface or δ/γ phase interface.

The zero strength temperature was in agreement with zero ductility temperature, and both of these temperatures appeared at the fraction solid of 0.8. Both the tensile strength and elongation of Fe–C binary steel were dependent on the phase state but not on carbon contents. The strain which seems to cause cracks in continuously cast steel slabs for the peritectic carbon steel is predicted to be generated during solidification.

(cf. *ISIJ Int.*, **42** (2002), 964)

Mathematical analysis and numerical simulation of high frequency electromagnetic field in soft contact continuous casting mold

X.NA et al.

The electromagnetic parameters in soft contact continuous casting billet mold were analyzed in this paper by mathematical analytic method and numerical simulation; the optimized frequency range was fixed on 20 000–40 000 Hz. The distribution of magnetic flux density and electromagnetic body force in split mold was obtained; the research results achieved respectively by mathematical analytic method and numerical simulation agree with each other. With increase of frequency of electromagnetic field, the electromagnetic body forces acted on the surface of strand increase, and attenuate rapidly towards the center of strand. When the meniscus was located at the middle of coil height, the electromagnetic body force acted on it is biggest, and then decreased along the casting direction to almost zero at the location of charge bottom. On the transverse direction perpendicular to the casting direction, the asymmetrical distribution of magnetic field at the surface of strand permeated through the slit of mold was enhanced slightly with the increase of frequency. The magnetic flux density at the slit area is about 10% higher than that at other area at 40 000 Hz, and the distribution of magnetic body force is almost even on this direction.

(cf. *ISIJ Int.*, **42** (2002), 974)

Forming Processing and Thermomechanical Treatment

Development of cold rolling mill rolls of high speed steel type by using continuous pouring process for cladding

M.HASHIMOTO et al.

The quality of work rolls that come into direct contact with the steel product has a direct effect on product quality and mill operation. A forged steel with a chromium content of 5 mass% has been conventionally used to meet the requirement of metallurgical structure homogeneity and high hardness for work rolls in cold rolling. Rolls having improved performance are strongly demanded. The authors develop the rolls of high speed steel type by using a continuous pouring process for cladding (CPC process). The characteristics and benefits of the new rolls are summarized as follows. (1) Precipitated hard carbides are utilized to attain a fine cast structure. (2) Low-frequency progressive induction hardening and high-temperature tempering are employed to provide a high hardness of HV 800 or more, a stable structure at elevated temperatures and low residual stress. As a result, the new rolls are improved in dent resistance and crack resistance. (3) When used in rolling operation, the new rolls retain a stable friction coefficient in the roll bite and allow continuous rolling of a large tonnage since their surface roughness decrease is small. (4) The wear of the new rolls is extremely small. A schedule-free rolling operation can be done when the work rolls are lubricated with rolling oil. In this way, high speed steel rolls manufactured by the CPC process exhibit high wear resistance, surface roughness retentivity and crack resistance.

(cf. *ISIJ Int.*, **42** (2002), 982)

Development of a finite element analysis program for roller leveling and application for removing blanking bow defects of thin steel sheet

K.PARK et al.

For the analysis of roller leveling process and application for controlling blanking bow defects in a thin steel sheet, a finite element analysis program

modeling large deformation of shell has been developed. This program for elastic-plastic large deformation analysis of sheet includes spring-back analysis as well as contact treatment between sheet and rolls of roller leveler. This is verified by the simple leveling experiment with 5 rolls at laboratory. The residual curvatures of strip predicted by finite element analysis are within 20% error range of the experiment. An optimum entrance intermesh condition, that is able to remove the blanking bow or deviation of curvature of a sheet, are found by finite element analysis for initially curved three strips by applying virtually divided strip model. The curvature difference of strips after leveling is decreased as increasing the entrance intermesh of roller leveler, and the optimum intermesh value is affected by the roll diameter and arrangement. The predicted optimum intermesh values are consistent with the experimental results. The residual stress distributions after leveling is predicted numerically by the curvature of strip obtained from the finite element analysis. It is found that the change in the residual stress distributions due to leveling is also markedly affected by the intermesh condition.

(cf. *ISIJ Int.*, **42** (2002), 990)

Novel method to spread the width of strip

Y.SAITO et al.

The authors propose a new method for continuous spreading of long materials based on cross rolling method in this paper. The scheme of the new method is simple and it may be industrialized with in high yield efficiency and productivity. Its equipment consists of a flat platen and a roll. The idle roll may be mounted on linear bearings, and reversingly travels over the material width along the transverse direction. The roll axis is slightly tilted to few degrees against the horizontal plane, so the roll gap decreases towards downstream. The material is fed consecutively by some constant length. The thickness of material is reduced in the gap between the platen and the travelling roll. The material is widened gradually downstream. The rapid repetition of these operations realizes virtually continuous spreading of long materials. With the plasticine clay as a model material, the effectiveness of this method is investigated. In the case of the 20% reduction of 2.5 mm thick and 60 mm wide plasticine strip, the achievable lateral spread is approximately 20%. Although the lateral spread increases with the reduction, the edge waves occur when the reduction is greater than 20%.

(cf. *ISIJ Int.*, **42** (2002), 1000)

Welding and Joining

Effect of anode heat transfer on melted penetration in welding process by free-burning argon arc

M.TANAKA et al.

In order to make clear the physical relation among the arc plasma, the anode heat transfer and the results of materials processing by thermal plasma, namely, free-burning arc, the materials processing was focused on the welding for simplification of discussion. The experimental results of temperature measurements of arc plasma, the distributions of current density and heat input density on the anode, and the weld penetration were presented. It was shown that the electron temperature above the anode and current and heat input density on the anode was dominated by the position of the tungsten cathode. Furthermore, it was also shown that electron temperature of arc plasma was dominated by the cathode shape. These results were related with the results of the welded penetration. As a result, it was concluded that the electron temperature above the anode and current density distribution on the anode decided the heat input density distribution on the anode and then the heat input density on the anode remarkably dominated the size of the weld penetration in the welding process by the free-burning argon arc. Furthermore, it was suggested that the cathode played the important role in the determination of the weld penetration.

(cf. *ISIJ Int.*, **42** (2002), 1005)

Transformations and Microstructures

A model of isothermal and non isothermal transformation kinetics of bainite in 0.5% C steels

D.QUIDORT et al.

The present article proposes a kinetic model for the overall transformation of austenite into bainite including both nucleation and growth of the new phase. Nucleation of bainitic ferrite laths is considered in the general framework of the classical nucleation theory. Analysis of experimental data in a low alloyed 0.5% C steel suggests that austenite grain boundary diffusion of carbon is the limiting step in the formation of ferrite nuclei. Growth of bainitic laths is controlled by volume diffusion of carbon in austenite. Nucleation and growth equations are included in a Kolmogorov–Johnson–Mehl–Avrami analysis to provide a simple relationship for the bainite fraction as a function of time and temperature which contains only two semi-empirical parameters. This model is fitted to isothermal kinetics and extrapolated to continuous cooling conditions without changing the two parameters. Comparison between predictions and experimental kinetics in two different 0.5% C steels gives a very good agreement.

(cf. *ISIJ Int.*, **42** (2002), 1010)

Prospect of nickel-based superalloys with low Cr and high Re contents

M.MONIRUZZAMAN et al.

There is a clear trend of lowering Cr and increasing Re content in the evolution from the 1st- to the 2nd- and to the 3rd-generation Ni-based single crystal (SC) superalloys. Following this trend, two groups of superalloys were made with the aid of the *d*-electrons concept. One is the A-group which is characterized by the lower Cr and the higher Re contents in the alloys than in the 3rd-generation SC alloys. A homogeneous microstructure was obtained in these A-group superalloys containing 0, 1 and 2 mass% Cr, while their Re and Co contents were set at about 8.5 mass% and 13.5 mass% respectively. The other is the B-group which is characterized by the lower Re content than the A-group. Three alloys in the B-group containing 2.5, 4.2 and 12.1 mass% Cr were studied for the comparison with the A-group. According to a hot corrosion test, weight gain occurred in a Cr-free alloy instead of observing weight loss in Cr containing alloys. Hot corrosion resistance of 2 mass% Cr alloy was quite good as long as the alloy contains about 8.5 mass% Re. The oxidation resistance was improved remarkably in 1 mass% Cr alloy than in the Cr-free alloy. It was found that the addition of at least 2 mass% Cr into superalloys is necessary in order to keep good surface stability at high temperatures. Also, it was seen that Re is a harmful element for oxidation resistance.

(cf. *ISIJ Int.*, **42** (2002), 1018)

Serration of grain boundary in Ni-30Fe alloy due to high temperature deformation

D.-W.SUH et al.

Grain boundary serration that evolved during high temperature deformation was investigated under various deformation conditions in a Ni–30Fe alloy. The maximum amplitudes of the serration at compressive strains of 0.13 and 0.34 were about 7 μm and 9 μm, respectively, at 1 123 K. The amplitude decreased at lower deformation temperature and no serration was observed at 823 K. The amplitude of the serration increased linearly with an increase of strain in the first stage and became saturated above the strain of 0.2. TEM analysis showed that the grain boundary serration was closely related to the evolution of the sub-boundaries. The correlation between the development of the grain boundary serration and the size of the recovered equiaxed grain is discussed.

(cf. *ISIJ Int.*, **42** (2002), 1026)

Kinetics and crystallography of intragranular pearlite transformation nucleated at (MnS+VC) complex precipitates in hypereutectoid Fe–Mn–C alloys

Z.GUO et al.

Kinetics and crystallography of intragranular pearlite nucleated at the surface of (MnS+VC) complex precipitate was studied in hypereutectoid Fe–Mn–C steels. The incoherent MnS embedded into the austenite does not act as a strong nucleation site of pearlite unless the transformation time is prolonged. The intragranular pearlite transformation is promoted effectively by the addition of vanadium (V). EPMA analysis showed that the intragranular pearlite nucleates on the (MnS+VC) complex precipitate in the V-added alloy. As the transformation temperature decreases, the intragranular pearlite formation occurs more frequently. A single intragranular pearlite is composed of several colonies, indicating that multiple pearlite colonies nucleate on (MnS+VC) complex precipitates for intragranular pearlite transformation. There is no specific orientation relationship (OR) between ferrite in intragranular pearlite and austenite matrix while there is a specific OR (Pitsch-Petch OR) between pearlitic ferrite and cementite in the intragranular pearlite.

(cf. *ISIJ Int.*, **42** (2002), 1033)

Mechanical Properties

Fatigue properties of plasma carburized low carbon Cr–Mo steel

D.M.SHIN et al.

Low carbon Cr–Mo steel (0.176C, 0.119Si, 1.014Cr, 0.387Mo) has been plasma carburized and its fatigue properties have been investigated. The effective case depth in plasma carburized steel at a lower temperature for a shorter time increased up to 50% in comparison to that of gas carburizing. In case of boost-diffuse carburizing, which cycles the carburization and diffusion period, the number of cycle times had more effect than carburizing time on the surface carbon content. High cycle fatigue properties of plasma carburized steel were assessed by comparing with those of gas carburized steel in reference to microstructure, effective case depth, amount of retained austenite and compressive residual stress near the surface. The fatigue limit of the plasma carburized steel was higher than that of gas carburized steel in the same effective case depth because the former had a higher compressive residual stress and had no internal oxidation layer. Transgranular fracture was in plasma carburized steel due to the fact that it had no grain boundary internal oxidation layer that initiated the crack.

(cf. *ISIJ Int.*, **42** (2002), 1042)

Fracture process zone in notched samples of cold drawn pearlitic steels

J.TORIBIO et al.

This paper deals with the influence of the manufacturing process on the microscopic fracture behaviour of axisymmetric notched specimens of pearlitic steels with different degrees of cold drawing. To this end, samples from different steps of the manufacturing chain were obtained, from the initial hot rolled material (not cold draw at all) to the final prestressing steel (heavily cold drawn). A detailed fractographic analysis was performed by using scanning electron microscopy and image analysis techniques, in order to define and measure the fracture process zone in each case (final aim of this paper). Results show that the microscopic fracture modes range from ductile micro-void coalescence to brittle cleavage, depending on the stress triaxiality generated in the vicinity of the notch tip. A special fibrous region was detected, which allows a definition of the fracture process zone as the central region of the fractured area in bluntly notched samples and the external ring (*i.e.*, the notch tip) in sharply notched specimens.

(cf. *ISIJ Int.*, **42** (2002), 1049)