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Fundamentals of High Temperature Processes

Calculation of thermophysical properties of ni-based superalloys

K.C.Mills et al.

Reliable thermophysical data of Ni-based superalloys are needed for the mathematical modelling of solidification in casting applications. This paper derives equations and procedures to calculate the following properties of these alloys from chemical composition of the alloy: the γ' phase content, liquidus and solidus temperatures, density and thermal expansion coefficient, heat capacity and enthalpy, electrical resistivity, thermal diffusivity and conductivity, viscosity, surface tension and contact angle. Estimates are also for the diffusion coefficient and emissivity. This work has revealed an urgent need for reliable property measurements on liquid Ni-based alloys for the following: heat capacity, electrical resistivity, thermal diffusivity and conductivity, emissivity and diffusion coefficients.

(cf. *ISIJ Int.*, **46** (2006), 623)

Liquid immiscibility in Fe–Cu–B–C system

K.Taguchi et al.

The metal in the shredder dust, which is produced from scrapped automobiles and home electric appliances by shredding and sorting, is mainly composed of iron and copper. It is more desirable to reuse as ferrous and cupreous resources by separating iron and copper. In the present work, the phase separation of iron and copper in the Fe–Cu–B and Fe–Cu–B–C systems is investigated at 1 523 K and 1 425 K. In the Fe–Cu–B system, the copper content of Fe-rich phase and the iron content of Cu-rich phase at 1 523 K are 4.60 mass% and 5.30 mass%, respectively, in the case of $[\text{mass\%B}]_{(\text{in Fe})}=2.90$. The contents are about 1 to 2 mass% lower than those at 1 873 K. In the Fe–Cu–B–3mass%C system, the copper content of the Fe-rich phase and the iron content of the Cu-rich phase are lower than those in the Fe–Cu–B system. The carbon addition widens the miscibility gap of iron and copper and is more effective for the separation. By the boron and/or carbon additions, it is almost possible to recover more than 80% of copper from Fe–20mass%Cu alloy.

(cf. *ISIJ Int.*, **46** (2006), 633)

Effect of additives on viscosity of LATS refining ladle slag

H.Wang et al.

To reduce or eliminate slag sticking onto the ladle immersion cover during the refining process of Ladle Alloying Treatment Station (LATS), the variation of the ladle slag viscosity before and after LATS refining process was investigated. The additives including $CaO–CaF_2$ (CaO/CaF_2 mass ratio is 1 : 1), $CaO–B_2O_3$ (CaO/B_2O_3 mass ratio is 1 : 1) and Li_2O were employed to decrease the viscosity of LATS refining ladle slag. The mechanism of additives decreasing slag viscosity was analyzed. The rotary cylinder method was adopted in the viscosity measurements. The results showed that the viscosity of LATS refining ladle slag was very high and could be further increased after LATS refining process, which was one of main reasons for slag sticking onto immersion cover. All the three kinds of additives employed in this research could decrease the viscosity of LATS refining ladle slag remarkably. At 1 500°C, the viscosity of ladle slag without any additives is about 6.5 Pa·s. But by adding 10 mass% $CaO–CaF_2$ or 10 mass% $CaO–B_2O_3$ or 4 mass% Li_2O, the slag viscosity at 1 500°C could be decreased lower than 2 Pa·s.

(cf. *ISIJ Int.*, **46** (2006), 637)

Formation of cementite from titanomagnetite ore

R.J.Longbottom et al.

This paper examines the formation of cementite in reduction of titanomagnetite ore by methane-containing gas. The reduction of titanomagnetite ore (New Zealand ironsand) by hydrogen–methane–argon gas mixtures was investigated from 600 to 1 100°C. Iron oxides were reduced by hydrogen to metallic iron, which was carburised by methane to form cementite. The reduction rate increased with increasing hydrogen content in the reducing gas, while the methane content had no effect on the reduction process. Preoxidation of the titanomagnetite accelerated its reduction. Reduced iron in titanomagnetite was converted to cementite more slowly than in hematite.

(cf. *ISIJ Int.*, **46** (2006), 641)

Wettability effect on a single bubble rising in stagnant water contained in a vertical circular pipe

K.Fukushi et al.

Observation has been made on the behavior of a single bubble rising in stagnant water contained in a vertical circular pipe. The inner wall of the pipe is coated with fluororesin to change its wettability. The rising velocity of a single bubble in a wetted pipe is favorably predicted by a previously proposed empirical equation. A prediction method has been proposed for the rising velocity of a single bubble rising in a poorly wetted pipe. The wettability effect disappears when the inner wall of the pipe exceeds a critical Reynolds number.

(cf. *ISIJ Int.*, **46** (2006), 647)

Ironmaking

Influence of temperature on carbon dissolution of cokes in molten iron

S.T.Cham et al.

Coke within the blast furnace not only supports the furnace bed and allows gas flow, it also carburises liquid iron. Although carburisation rates of iron by coke vary considerably between cokes, the factors controlling it have not been clearly identified. In this study the rate of carbon dissolution from two cokes prepared from Australian coals, and synthetic graphite, into liquid iron has been measured in the temperature range 1 723–1 823 K. The apparent activation energy, E_a, obtained for synthetic graphite ($E_a=54\ \text{kJ mol}^{-1}$) is in agreement with literature values. The observed E_a values for Cokes 1 and 3 ($479\ \text{kJ mol}^{-1}$ and $313\ \text{kJ mol}^{-1}$ respectively) are an order of magnitude larger than those of synthetic graphite. This difference in activation energies is attributed to mineral matter in the coke limiting the interfacial contact area between the carbon source and liquid iron. The interfacial contact area is a function of mineral matter yield and composition, which in turn is a function of temperature. Therefore, as temperature decreases the slag/ash layer produced at the carbon/iron interface can increase in area and viscosity and thus hinder carbon dissolution and increase the apparent activation energy of dissolution.

(cf. *ISIJ Int.*, **46** (2006), 652)

Casting and Solidification

Simulation of microstructure and behavior of interfacial mold slag layers in continuous casting of steel

Y.Meng et al.

A computational model of heat transfer, solidification and interface behavior during the continuous casting of steel is applied to interpret the crystallization behavior of slag layers in the interfacial gap between the mold and the steel shell. A mechanism for the formation of this crystalline layer is proposed that combines the effects of a shift in the viscosity curve, a decrease in the liquid slag conductivity due to partial crystallization, and an increase in the solid slag layer roughness corresponding to a decrease in solid layer surface temperature with distance down the mold. When the shear stress exceeds the slag shear strength before the axial stress accumulates to the fracture strength, the slag could shear longitudinally inside the layers. The predictions are consistent with measurements conducted in the real process and with the microstructure of analyzed slag samples.

(cf. *ISIJ Int.*, **46** (2006), 660)

Large inclusions in plain-carbon steel ingots cast by bottom teeming

L.Zhang et al.

Inclusions in industrial-cast bottom-teemed ingots of plain carbon steel are investigated using ultrasonic detection, optical microscope observation, and SEM analysis. The composition, size distribution, entrapment locations, and sources of ingot inclusions were revealed by examining all the macro-inclusions (larger than 20 μm) that were observed in 35 000 mm^2 of sample surface area. Based on 78 non-sulfide inclusions observed, around 3.23×10^7 macro-inclusions per m^3 steel exist in the ingot, with a size distribution increasing with decreasing size. Inclusions are distributed uniformly within a given horizontal section through the ingot, but with more found towards the bottom. The largest inclusions exceed 7 mm and originate from mold flux in the ingot. The largest inclusion source appears to be reoxidation, as evidenced by 59% of the ingot inclusions composed of pure alumina clusters and lumps. Eroded refractories from the ladle well block and ladle inner nozzle bricks accounted for 31% of the ingot inclusions.

(cf. *ISIJ Int.*, **46** (2006), 670)

Amplitude-modulated magnetic field coupled with mold oscillation in electromagnetic continuous casting

Z.LEI et al.

Molten metal meniscus profile and mold flux channel width were measured under high frequency magnetic field by model experiments, then the dynamic pressure in mold flux channel were calculated during one mold oscillation period. It is found that the high frequency magnetic field can decrease the dynamic pressure greatly, which may be one mechanism of improving the billets surface quality by the soft-contact mold electromagnetic continuous casting. Based on this study, a novel technology named Amplitude-Modulated Magnetic Field (AMMF) coupled with mold oscillation in electromagnetic continuous casting was proposed in order to balance the dynamic pressure caused by mold oscillation with a varied electromagnetic force inducted by AMMF. Based on the calculation of mold flux channel dynamic pressure, a model to optimize design of AMMF was proposed. Then continuous casting experiments under AMMF coupled with mold oscillation were carried out. It is shown that AMMF is effective in reducing the friction force during continuous casting and improving the billets surface quality.

(cf. *ISIJ Int.*, **46** (2006), 680)

Instrumentation, Control and System Engineering

Fuzzy control of micum strength for iron ore sinter

R.BAREA et al.

The proper performance of sinter plants is vital for efficient and uniformly blast furnace operations. For smooth sinter plants operation, changes to the operating conditions should be few and precise. This paper explains advisory platforms that supply control strategies and sinter quality estimations to the plant operators, developing mathematical model, which are able to advise them about the necessary decisions to improve sinter quality. These models, based on Fuzzy Logic sets, have been developed to supply control strategies and sinter quality estimations to the plant operators at a Spanish factory.

(cf. *ISIJ Int.*, **46** (2006), 687)

Forming Processing and Thermomechanical Treatment

Superplastic deformation behavior in Mg–Al alloy, AZ91, grain refined by isothermal-rolling

S.FUDETANI et al.

The isothermal rolling mill, which allows a large preform for materials having poor workability, has been developed. AZ91 alloy sheets made from Mg–9Al–1Zn tempered to a fine grain size by recrystallization have been prepared and tensioned at elevated temperatures. The maximum total elongation reached 170% and the *m*-value was found to be 0.5 in range of $1.0\times10^{-4}s^{-1}$ to $2.5\times10^{-4}s^{-1}$ except at the testing temperature of 573 K.

The activation energy required for high temperature deformation has been calculated to be about $124\,kJ\cdot mol^{-1}$, which is almost equal to the self-diffusion energy of Mg for volume diffusion. Therefore, the superplastic deformation of the recrystallized AZ91 has been accompanied by a volume diffusion.

(cf. *ISIJ Int.*, **46** (2006), 694)

Welding and Joining

Development of a chromium-free consumable for austenitic stainless steels: effect of dilution and the behavior of bead-on-plate welds

Y.H.KIM et al.

A Ni–10Cu–1Pd alloy was studied as a potential Cr-free consumable for welding austenitic stainless steels. The corrosion behavior of as-cast buttons with this base composition and alloys diluted by Type 304L stainless steel at levels of 4 to 84% were investigated in Cl^- solutions. Actual welds, made using a bead-on-plate welding technique, were evaluated using electrochemical testing and in long term crevice corrosion exposure testing. Ni–10Cu–1Pd alloy across the entire dilution range exhibited higher repassivation potential than Type 304L stainless steel in 0.1 M NaCl solution. The repassivation potential was also higher for 0, 25, and 50% dilution levels in aerated solutions with Cl^- concentrations of 105–35 000 ppm. The breakdown behavior of the bead-on-plate welds was similar to that of conventional welds made with Type 308L filler metal. After 31 d exposure of samples with crevice-formers in 500 and 1 000 ppm Cl^- solutions, the bead-on-plate weld showed one shallow attack in 1 000 ppm Cl^-, but the 308L weld was attacked both in 500 and 1 000 ppm Cl^- with many deep pits.

(cf. *ISIJ Int.*, **46** (2006), 698)

Computational simulation of arc melting process with complex interactions

H.NISHIYAMA et al.

The real-time computational simulation of arc melting process with considering complex interactions and solid–liquid mushy zone in molten anode has been successfully conducted to provide the fundamental data for highly economical performance of arc melting process. The configuration of molten anode predicted by realistic numerical model shows the quantitative agreement with the experimental data. The effects of sulfur content concentration in molten metal, arc current and cathode vertex angle on the welding structure is discussed in detail. Finally, the heat exchange efficiency and molten cross-sectional area are evaluated under different arc currents and cathode vertex angles for optimum welding process with high efficiency.

(cf. *ISIJ Int.*, **46** (2006), 705)

Transformations and Microstructures

A new physical model for the kinetics of the bainite transformation

D.GAUDE-FUGAROLAS et al.

A model describing the bainite reaction is presented that takes intoaccount the effect of very small austenite grain size. This model considers the displacive approach and uses thermodynamic criteria for the description of the nucleation and growth of bainite sub-units forming either at grain boundaries or autocatalytically on previous sub-units. The evolution of the austenite composition with the partitioning and redistribution of carbon is estimated as the transformation proceeds. The size of the sub-units is calculated for each composition and temperature.

The transformation kinetics, as well as the incomplete reaction phenomenon, are correctly predicted. Furthermore, the influence of the austenite grain size on the bainite transformation rate is addressed in the case of austenite grains smaller than the length of an unconstrained bainite sub-unit. In this case, the observed enhanced nucleation rate is semi-empirically related to the austenite yield strength. This semi-empirical relationship is corroborated with kinetics data from different alloys.

(cf. *ISIJ Int.*, **46** (2006), 712)

Effect of particle size distribution on austenite grain growth in Fe–0.05mass%C alloy deoxidized with Mn–Si, Ti, Mg, Zr and Ce

A.V.KARASEV et al.

The austenite grain growth in an Fe–0.05mass%C alloy deoxidized with Mn–Si, Ti, Mg, Zr and Ce has been studied as a function of holding time at 1 200°C and inclusion characteristics such as particle diameter, d_V, number and surface area, A_V^P, of particles per unit volume and volume fraction of particles. The mean limiting diameters of grains obtained by the Zener, Doherty *et al.* and Nishizawa *et al.* relations are compared with those observed experimentally and calculated by the relationship between surface area of particles, A_V^P, and grains, A_V^G, per unit volume. The contribution of small size particles with $d_V<0.5\,\mu m$ to limiting grain size is estimated for the particles with uniform size, log-normal size distribution and observed size distribution.

(cf. *ISIJ Int.*, **46** (2006), 718)

Particle erosion of SUS403 tempered martensitic stainless steel

D.C.WEN et al.

The particle erosion behavior of SUS403 martensitic stainless steel tempered with five different temperatures range from 200 to 600°C were studied as a function of impact angle and hardness. The results indicate that the dominated mechanisms for material removal are cutting and extrusion at low and high impact angles, respectively. A transition of mechanism mixed by cutting and extrusion occurs at medium impact angle. Grain boundary cracking is often found for all impact angles that seem to be one of the major erosion mechanisms for two-phase materials mixed with martensite and ferrite. The erosion rate of all the experimental materials increases first, and then decreases with increase in impact angle. Thus, the maximum erosion rate occurs at the angle between 30° and 45°. At 15° and 30° of impingement, the erosion rate is virtually independent of hardness. While impact angles exceed than 30°,

erosion rate increases with increasing hardness.

(cf. *ISIJ Int.*, **46** (2006), 728)

The mechanical behaviour and microstructures of interstitial free steel strained in monotonic or cyclic torsion at 1 223 K

I.P.PINHEIRO et al.

The work hardening behavior of metals under cold cyclic or multiaxial deformation involves lower hardening rates than those caused by monotonic strain to the same total magnitude. The hardening is lower as the strain per cycle decreases. Similar studies under hot working conditions, for a limited number of cycles, also lead to lower hardening, as well as to changes in the shape of the flow curves and to delays in the initiation of Dynamic Recrystallization (DRX) and in the post-processing static softening kinetics. These results point to a decrease in stored energy caused by cyclic straining. A higher number of hot deformation cycles leads to lower steady state stresses (σ^r_{ss}) than those corresponding to monotonic deformation (σ_{ss}). Besides, DRX can be suppressed and replaced by Dynamic Recovery (DRV), and the successive cycles have been associated with the repeated build-up and disintegration of dislocation structures. The present research discusses the hot deformation of an IF steel in the austenitic temperature range, for monotonic torsion or a large number of reversed torsions with various strain amplitudes ($\Delta\varepsilon$). It was confirmed that σ^r_{ss} depends on the relative amplitude of the strain cycles ($\Delta\varepsilon/\varepsilon_p$, where ε_p is the strain at the peak stress in the monotonic torsion of the material), and that lower values of $\Delta\varepsilon/\varepsilon_p$ eliminate DRX, which is replaced by DRV. The ferritic grain size after deformation into the cyclic steady state stress depends on the value of σ^r_{ss}, similarly to results in the literature for monotonic torsion of IF steels.

(cf. *ISIJ Int.*, **46** (2006), 734)

Morphology control of copper sulfide in strip casting of low carbon steel

Z.LIU et al.

Copper and sulfur are the typical residual elements and impurities in steel. Previously, we reported the precipitation of very fine particles of Cu_2S in copper and sulfur containing steel by strip casting process. In the present paper, the morphologies of copper sulfides in strip casting low carbon steels were distinguishably investigated by Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM).

Four kinds of copper sulfide with different morphology were observed, namely duplex inclusion of oxide and sulfide (OS), plate-like copper sulfide (PS), shell-like copper sulfide surrounding the inclusions (SS), and nano-scale copper sulfide (NS), and their formation mechanisms were discussed.

The OS is considered to firstly form as molten manganese silicate in molten steel, and grow up with the formation of sulfide inside of the silicate after the solidification of steel. The PS is considered to precipitate from the γ-Fe phase with plate-like shape due to semicoherency with the γ-Fe matrix. The SS is considered to precipitate in lower temperature ranges on the other pre-formed inclusions such as MnS, oxide and also $Cu_{2-x}S$. The NS is considered to form in the low temperature range of γ-Fe and especially in α-Fe phase as very fine particles due to the high supersaturation, low diffusivity of component elements and the coherency with the α-Fe matrix.

Based on this classification, formation stage of oxide, MnS and Cu_2S was clarified and described as like TTT diagram.

(cf. *ISIJ Int.*, **46** (2006), 744)

Development of a hot-rolled low carbon steel with high yield strength

H.-L.YI et al.

A high strength steel with yield strength on the order of 700 MPa had been developed successfully with the addition of titanium alloy element based on a low-carbon steel. The results show the hot deformation accelerates ferrite and pearlite transformation and retards bainite transformation under continuous cooling condition. The strengthening factors of this steel are attributed to the tiny interlocked distribution of bainite laths and titanium carbide precipitation. When the amount of bainite is more than 70%, the yield strength of steel is higher than 700 MPa, and simultaneously ratio of tensile of yield is more than 1.07, and good mechanical performances are obtained. As a result of the presence of finely dispersed cementite particles which improve the work hardening capacity, the ductility of steel is improved, with the steel's elongation being about 19%. Many tiny TiC precipitates are observed under transmission electron micrograph (TEM), and these particles result in precipitation strengthening.

(cf. *ISIJ Int.*, **46** (2006), 754)

Formation of ferritic products during continuous cooling of a Cu-bearing HSLA steel

S.S.GHASEMI et al.

A continuous cooling transformation (CCT) diagram was constructed by a combination of dilatometry and metallographic methods for a Cu-bearing HSLA steel, which is a low carbon low alloy variant of the ASTM A710 type structural steel. It was found that the decomposition of austenite was significantly depressed to lower transformation temperatures resulting in a prominent transformation region for bainitic structures, at temperatures intermediate between those of diffusional products and the displacive transformation to martensite. Polygonal and quasi-polygonal ferrite were observed to grow across and eliminate the prior austenite grain boundaries at relatively low cooling rates. At a cooling rate ranging from 0.35 to 20°C/s, the structure was characterised by a mixture of quasi-polygonal ferrite, Widmanstätten side-plate ferrite, and bainitic structures associated with minor dispersed islands of martensite and/or retained austenite which were dark etching on preparation for optical microscopy. This microstructure develops by the following processes. The Widmanstätten side-plate ferrite nucleates from the ferrite grain boundary allotriomorphs at the early stage of transformation, together with the bainitic ferrite plates which nucleate directly at the prior austenite grain boundaries. On further cooling, the neighbouring plates of Widmanstätten and bainitic ferrite each tended to coalesce and the volume of untransformed austenite decreased and the shapes of the enclosed γ volumes evolved into residual islands between the ferrite plates. Provided the cooling rate was greater than 20°C/s, the bainitic ferrite plates nucleated directly at the prior austenite grain boundaries, and the plate morphology was revealed by regions of elongated retained austenite or its decomposition products. At the fastest cooling rate obtained by dilatometry (~375°C/s), the structure was largely characterised by a mixture of bainitic ferrite and martensitic packets surrounded by retained austenite films. Dilatometric and metallographic examination of the martensite and bainitic ferrite formed on rapid cooling failed to find a clear microstructural distinction between the two products. The packets of bainitic ferrite plates were generally nucleated directly from the prior austenite grain boundaries, whereas the martensite was characterised by thinner ferritic units with a higher dislocation density. There also appeared to be a larger number of variants of lath packets and apparent intragranular nucleation in the case of martensitic ferrite.

(cf. *ISIJ Int.*, **46** (2006), 759)

Z-phase formation during creep and aging in 9–12% Cr heat resistant steels

K.SAWADA et al.

The precipitation behavior of the Z phase was investigated after long-term creep exposure in ASME-T91, T92, T122 without δ-ferrite, and T122 with δ-ferrite through elemental mapping using EF-TEM. The Z phase was identified by comparing the Cr map with the V map. Most of the Z phase was observed around prior austenite grain boundaries and/or packet boundaries in all of the steels examined. In T122 with δ-ferrite, the Z phase also precipitates around the δ-ferrite. In particular, the number of MX carbonitrides was very small in T122 with a large amount of the Z phase. The main metallic composition of the Z phase in T91 was the same as that in T92. In T122, the Z phase contained a lower Nb content. The main metallic composition of the Z phase around the δ-ferrite was the same as that in the other areas. There was no large difference in the size distribution of the Z phase among the steels. The mean diameter of the Z phases for T122 with δ-ferrite was relatively large in spite of a shorter creep exposure in contrast with T91 and T92. The number density of the Z phases increased with increasing creep exposure time except in the case of T91. The order of the number density was T122 with δ-ferrite, T91, T122 without δ-ferrite, and T92. In crept samples, the amount of Z phase in the gauge portion was higher than that in the grip portion, meaning that stress and/or strain promotes the formation of a Z phase during creep exposure.

(cf. *ISIJ Int.*, **46** (2006), 769)