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Fundamentals of High Temperature Processes

Reduction behavior of hematite to magnetite under fluidized bed conditions

C.FEILMAYR et al.

Reduction kinetic tests of Mt. Newman hematite ore from Western Australia were carried out in a laboratory-scale fluidized bed reactor at temperatures from 623 to 873 K and an absolute pressure of 10 bar. The reducing gas mixture was thermodynamically in equilibrium with magnetite and consisted of a mixture of H_2, H_2O, CO, CO_2 and CH_4. The effect of temperature and residence time was studied. The original ore and its mineralogical and petrographical changes with increasing reduction time were analyzed. A reflected-light microscope technique with CCD-camera was used to determine the progress and the mechanism of reduction. According to the mineralogy and texture the ore could be classified in four types (coarse hematite, microplaty hematite, limonite and martite) with different reduction characteristics. Limonite and martite showed better reducibility than coarse and fine hematite.

At all ore types the growth of dense magnetite rims was observed. The thickness of these layers was found to be linear proportional to reduction time. After analyzing the single steps of the reduction process the phase interface reaction turned out to be rate controlling between 673 and 773 K. Its activation energy is 91 kJ/mol.

(cf. *ISIJ Int.*, **44** (2004), 1125)

A thermodynamic study on the inclusion formation in ferritic stainless steel melt

W.-Y.CHA et al.

A type 430 stainless steel melt containing different Al levels was equilibrated with an AOD type slag saturated with Al_2O_3 or MgO to clarify the formation mechanism of slag-type inclusions containing $MgO \cdot Al_2O_3$ spinel. The Al–O deoxidation equilibrium in the stainless steel melt was examined as a function of melt temperature to check the validity of available thermodynamic data, and to estimate the secondary deoxidation by Al picked up from the ladle slag. During the temperature drop from AOD to tundish, a small amount of entrapped AOD slag particles in molten steel can easily change their composition to a level where the $MgO \cdot Al_2O_3$ spinel can crystallize. The refractory material, MgO or Al_2O_3 for a ladle, is one of critical factors to affect the Al level in the melt, and hence the formation of $MgO \cdot Al_2O_3$ spinel inclusions in the final products.

(cf. *ISIJ Int.*, **44** (2004), 1134)

Ironmaking

Solid behavior in shaft and deadman in a cold model of blast furnace with floating-sinking motion of hearth packed bed studied by experimental and numerical DEM analyses

H.KAWAI et al.

One of recent discussions is on the floating and sinking motion of packed bed in the hearth part of blast furnace while the molten liquid is stored in and tapped out of the hearth. Such a repetition motion might be profoundly related to the renewal of deadman particles. Thus, further analysis for deadman motion with the iron liquid is necessary to develop a method for controlled or stable furnace operation. In this study, the experiment is performed using a two-dimensional cold model with foaming polymer particles and water. Gas flow is not considered. The particle descending velocity in the shaft of the model is found to decrease with floating of the hearth packed bed and increase with the sinking motion. The deadman renewal rate that is the solid moving rate forced into raceway from the inside of deadman, is estimated by subtracting the descending rate from the total particle discharge rate being controlled at a constant rate. The numerical treatment called Discrete Element Method is also carried out to clarify the renewal mechanism with storing/tapping liquid. It is confirmed from both the experimental and numerical that the deadman particles move gradually into the raceway while storing/tapping liquid is repeated and the renewal of particles occurs in such a way that the older particles are forced to go out of deadman by buoyancy and the new particles comes in to fill deadman through near the top of the deadman during tapping the liquid. The simulation indicates also that the wall normal contact force in the hearth part increases considerably when the particle bed floats.

(cf. *ISIJ Int.*, **44** (2004), 1140)

Application of binder in stamp charge coke making

S.H.KRISHNAN et al.

Successful and sustainable implementation of Stamp Charging Technology in Tata Steel has given it an edge over conventional Top Charging Technology in terms of production of superior quality of Blast Furnace grade coke from a wide range of coal base, even permitting use of inferior coals. But, the stability of stamped coal cake and the additional thermal energy necessary to drive the extra quantity of water (3–4%), added intentionally to the coal blend to impart requisite coal cake strength, have always been the two haunting issues associated with this technology. This paper describes the role of coal tar pitch, used as a binder to the coal blend that not only imparts required strength and stability to the coal cake even at lower moisture level and thereby, reducing energy consumption, but also improves the rheological properties of coal blend that contributes to the quality of coke produced from inferior coals. This paper also describes the laboratory scale experimentation and its results followed by commercial plant-scale trials that confirmed the R & D findings on the use of coal tar pitch.

(cf. *ISIJ Int.*, **44** (2004), 1150)

Steelmaking

An improved model of cored wire injection in steel melts

S.SANYAL et al.

Mathematical models for tracking the melting of cored wire during its injection into the steel bath have been developed in the past though important aspects of the formulations have not been discussed in sufficient detail. As a result, it is difficult to use the results of these models to derive benefits for a specific steel melting shop.

A general purpose mathematical model has been developed at R & D, Tata Steel, using the finite difference approach with a fully implicit scheme to simulate the process of cored wire injection taking into account the different operating practices encountered in the steel shop. Numerical simulation of this kind of problem, involving moving boundary, typically suffers from the limitation that the progressive solidification of frozen layers that takes place is not made part of the thermal balance till it attains the size of a full node and thus the heat gained or lost by this "partial node" is not accounted for till such time. An alternative numerical formulation has been developed to rectify this.

Owing to the difficulty in making a direct validation, this model has been verified through a novel approach. This work suggests that the use of different wire dimensions (13–18 mm diameter and 0.4–0.6 mm casing), depending on the steel grades to be processed, is necessary in order to extract the maximum benefit.

(cf. *ISIJ Int.*, **44** (2004), 1157)

Effect of mechanical vibration on the microstructure, impact toughness and thermal fatigue behavior of cast hot working die steel

Y.G.ZHAO et al.

The cast hot working die steel is treated by mechanical vibration (MV) with a frequency of 50 Hz during the solidification process. The experimental results indicate that the MV may break off the dendrites growing from mould wall towards center in the steel during solidification. Therefore, the growth of the dendrites is restrained and the microstructure in the steel is refined; furthermore, MV can decrease the amount of defects such as shrinkage cavity and inclusion and enhance the compactness of the steel. The impact toughness of the steel treated with MV is as 1.5 times larger as that of the untreated steel. During thermal fatigue (TF) test, it is found that TF crack is longer and wider and the chap are more severe in the untreated steel than in the steel treated with MV. Simultaneously, the average velocity of crack propagation is 1.7 times faster in the untreated steel than in the steel treated with MV.

(cf. *ISIJ Int.*, **44** (2004), 1167)

Casting and Solidification

FEM/FDM-joint simulation for transport phenomena in directionally solidifying shaped TiAl casting under electromagnetic field

Y.BAI et al.

Numerical techniques for FEM/FDM joint simulation of solidification heat, mass and momentum transport phenomena in directional solidification processes of shaped alloy castings under electromagnetic (EM) fields are developed. In the present joint computer modeling for the EM-fields coupled solidification transport processes, the relevant EM-

fields are calculated using a FEM-scheme-based computer code, while the changing fields of temperature, solid-fraction, concentrations, pressure and flow velocity of liquid phase are simulated by the FDM-based numerical methods extended from a previous numerical solidification model of the authors. Specific data-processing techniques are proposed for the conversion of FEM-based EM-fields results to those in the FDM format. The sample computations for EM-fields influenced solidification transport processes of directionally solidified γ(TiAl)–Al% castings are performed to demonstrate the feasibility and effectiveness of the proposed solidification model and numerical methods.

(cf. *ISIJ Int.*, **44** (2004), 1173)

Mechanical properties of thin wall ductile iron-influence of carbon equivalent and graphite distribution

P.DAVID et al.

This work focuses on the study of the mechanical properties and microstructure of plates of thin wall ductile iron, cast in sand moulds of vertical and horizontal configuration. All tests were carried out on ferritised samples. Melts of carbon equivalent values ranging from 4.06 to 4.85 were used to cast plates of thickness ranging from 1.5 to 4 mm. The results show that irons having carbon equivalent values greater than 4.6 exhibit a marked tendency to develop exploded graphite shapes and agglomeration of graphite nodules. As a result, these irons show scattered values of mechanical properties. As irons are produced with carbon equivalent values below 4.6%, the mechanical properties improve, reaching levels that satisfy the requirements of standards developed for ferritised ductile irons sand cast in Y-blocks.

(cf. *ISIJ Int.*, **44** (2004), 1180)

Forming Processing and Thermomechanical Treatment

Recovery processes in the ferrite phase in C–Mn steel

A.SMITH et al.

The static recovery kinetics in ferrite were investigated by means of the stress relaxation technique. Samples were deformed in compression for a variety of temperatures, strains and strain rates.

The internal stress was found to decrease as recovery proceeded. In addition for a given relaxation time, the internal stress was found to decrease with increasing temperature. The results were analysed using a model previously proposed in the literature, the main parameters being activation energy and activation volume. At temperatures between 150 and 300°C the activation energy for recovery was close to that for dislocation core diffusion, whilst between 450 and 600°C it was close to the value for lattice diffusion of α-Fe. The activation energy was found not to depend on strain and strain rate.

The activation volume for the lower temperature regime was approximately constant whilst for the higher temperature regime it decreased with increasing temperature. The activation volume was found not to depend on strain or strain rate.

Analysis of the activation energies and activation volumes suggests that above 450°C, the rate controlling recovery mechanism is due to thermally activated glide of jogged screw dislocations, which are decorated with carbon solute atoms.

(cf. *ISIJ Int.*, **44** (2004), 1188)

Machining and heat treatment effects on distortion and residual stresses in an industrial application of ADI

A.D.SOSA et al.

The machining and heat treatment, employed in the fabrication of ADI parts, produce distortions and residual stresses that can increase the scrap rate. In the present study, dimensional changes, shape distortions and residual stresses due to machining and austempering were determined on internal gears of different chemical compositions, as-cast microstructures and machining-thermal cycle sequences. The influence of chemical composition and as-cast microstructure on dimensional change were found to be in accordance with the predictions obtained by Fuzzy modelling. Shape distortion resulted in an ovalization, whose magnitude depends upon the variation range of the residual stresses due to machining. Whereas residual stresses due to austempering were found to increase when the ovalization increases.

The lack of information about the topics here studied, turn these results into a useful contribution to improve the fabrication quality of ADI internal gears. Besides, most of them can be applied to ADI parts in general.

(cf. *ISIJ Int.*, **44** (2004), 1195)

Welding and Joining

Influence of pre and post weld heating on weldability of modified 9Cr–1MoVNb steel plates under SMA and GTA welding processes

P.K.GHOSH et al.

Welding of modified 9Cr–1Mo(V–Nb) steel plates has been carried out by shielded metal arc (SMA) and gas tungsten arc (GTA) welding processes. The welding has been carried out using different preheating temperatures followed by employing post weld heat treatment (PWHT) at different temperatures. The microstructures of the weld and heat affected zone (HAZ) of the weld joints have been studied under optical microscope and correlated with the temperatures of the pre and post weld heating. The property of the weld joint has been primarily characterised by studying variation in hardness across the weld joint. Average hardness of the weld and different regions of HAZ are evaluated and also correlated with the temperatures of the pre and post weld heating. The tensile and C_V-impact toughness properties of the weld joints are also studied and correlated to the preheating and PWHT temperatures. At a given preheating the tensile and impact toughness properties of the SMA and GTA weld joints observed under different PWHT are compared and correlated to their microstructures. The increase of preheating and PWHT coarsened the microstructures of weld and HAZ and significantly influenced the properties of the weld joints. The moderate preheating and PWHT at about 523 K and 1 023 K respectively gave optimum tensile properties of the SMA welds. The toughness of weld deposit of 9Cr–1Mo grade alloy was improved by PWHT at high temperature in presence of its modification by addition of V and Nb.

(cf. *ISIJ Int.*, **44** (2004), 1201)

Transformations and Microstructures

Effects of heavy warm deformation on microstructure and mechanical properties of a medium carbon ferritic–pearlitic steel

L.STOROJEVA et al.

The study of medium-carbon steel (0.36% C) with deformation induced spheroidized cementite produced by heavy warm deformation (HWD) was carried out as a potential substitution of conventional quenching and tempering (QT) or soft annealing (SA).

After austenite deformation the HWD samples were cooled and heavily deformed ($\varepsilon \sim 1.6$) at the temperatures below the γ–α transformation with a subsequent simulated coiling. To estimate the treatment sensitivity the effect of the heating due to the heavy deformation on the mechanical properties was studied using both isothermal and adiabatic processing routes.

The mechanical properties after the various treatments show that the strength–ductility relation after HWD and QT are superior to that after CC or SA. The reason is in the presence of lamellar pearlite in the microstructure after CC and also partially after SA that deteriorates the reduction of area. A similar effect is observed after the adiabatic HWD treatment: the deformation heating at high HWD temperatures may lead to partial pearlite-austenite-pearlite transformation, which results in some lamellar pearlite in the final microstructure.

HWD at 670°C with subsequent coiling simulation allows to get a microstructure with dispersed spheroidized cementite distributed homogeneously in fine grained ferritic matrix with an average grain size of 2 μm and an amount of high angle grain boundaries (HAGB) of about 65%. The features of ferrite and cementite after both HWD and QT have some important resemblances: fine homogeneous distributed cementite and fairly high amount of HAGB. As a result, the mechanical properties of the HWD samples are well comparable to those after QT.

(cf. *ISIJ Int.*, **44** (2004), 1211)

Modelling of microstructure and heat transfer during controlled cooling of low carbon wire rod

S.KUNDU et al.

The microstructure of TMT (Thermo-Mechanically-Treated) rebars consists of four phases, tempered martensite, bainite, ferrite and pearlite. These four phases are non-homogeneously distributed across the cross section of the wire rod which gives rise to a complex hardness distribution. A coupled heat transfer and phase transformation model has been developed at the R & D Division of Tata Steel

that can predict the temperature profile and the fraction of various phases in this type of wire rods efficiently. A fully implicit finite difference scheme has been used for solving the heat transfer equation in cylindrical coordinates; the recalescence due to phase transformation has been taken into consideration that makes the model suitable for use in any industrial application. A model has also been developed based on the volume fraction and strength of the individual phases to predict the hardness at different sections of the wire rod. The predicted hardness distribution has been found to agree well with the micro hardness measurements at various points across the section of the wire rod.

(cf. *ISIJ Int.*, **44** (2004), 1217)

The static and metadynamic recrystallization behaviour of an X60 Nb microalloyed steel

P.D.HODGSON et al.

A rapid method has been developed to determine recrystallization kinetics of Nb microalloyed steels by interrupted hot torsion test. The softening behaviour was achieved as a function of different processing parameters. The method clearly identified three regions, where the strain dependency of the recrystallization rate varied. Firstly, at large strains the rate of recrystallization was not a function of strain; this is generally ascribed to metadynamic recrystallization. At lower strains the time to 50% recrystallization showed a power low relationship with strain, characteristic of static recrystallization. A further break point exists on the time for 50% softening curve when strain induced precipitation occurs in the material. The onset of strain induced precipitation was at strains below the strain to the peak stress at temperatures below 900°C. The experimental results were used to estimate the time for 50% softening and to anticipate the onset of the strain induced precipitation for the alloy of this study. Grain refinement of the recrystallized austenite continued to strains significantly beyond the peak stress and beyond the static to metadynamic recrystallization rate transition.

(cf. *ISIJ Int.*, **44** (2004), 1224)

Prediction model for the austenite grain size in the coarse grained heat affected zone of Fe–C–Mn steels: considering the effect of initial grain size on isothermal growth behavior

S.UHM et al.

The austenite grain size in the coarse-grained heat affected zone (CGHAZ) was predicted by analyzing isothermal grain growth behavior of Fe–C–Mn steels which were designed to investigate the effect of alloying elements. A procedure was proposed to prevent inappropriate neglect of initial grain size (D_0) and misreading both time exponent and activation energy for isothermal grain growth. It was found that the time exponent was almost constant, irrespectively of temperature and alloying elements, and activation energy increased with the addition of alloying elements. From quantification of the effect of alloying elements on the activation energy, an isothermal grain growth model was presented. Combining with the additivity rule, the austenite grain size in the CGHAZ was predicted.

(cf. *ISIJ Int.*, **44** (2004), 1230)

Mechanical Properties

Influence of zirconium on the recovery process in heat-resistant Al alloys

N.JAUKOVIC et al.

Influence of zirconium on structure and properties of aluminium alloys used at elevated working temperature are given in this paper. By following changes in micro-hardness as a function of time for different temperatures and at different zirconium contents, activation energy of the recovery process, which served as an indicator of the creep resistance of the alloys, was determined. A mathematical model which enables to evaluate and predict required quality of alloys was also defined.

(cf. *ISIJ Int.*, **44** (2004), 1238)

Effect of nitrogen content on microstructural aspects and creep behavior in extremely low carbon 9Cr heat-resistant steel

K.SAWADA et al.

Effects of nitrogen content on microstructure and creep strength in extremely low carbon 9Cr ferritic steel were investigated, focusing on the dislocation structure and the distribution of precipitates. The creep strength of the high nitrogen steels was lower than that of the base steel, even though the initial lath width and prior austenite grain size in the high nitrogen steels are finer and larger, respectively. MX nitrides as well as large Cr_2N particles were distributed along lath, block, packet and prior austenite grain boundaries in the high nitrogen steels after tempering. The large particles occupy the MX nitride precipitation sites. The coarsening of the MX nitride during creep exposure in the high nitrogen steels was faster than that of the base steel. The presence of large Cr_2N particles after tempering and the higher coarsening rate of the MX nitride in the high nitrogen steels cause an increase in mean interparticle spacing on boundaries, leading to a decrease in creep strength. The Z phase formation was observed after creep exposure in the gauge portion of all the steels. The Z phase formation in the high nitrogen steels occurs at relatively short term in contrast to the base steel. The short term precipitation of the Z phase in high nitrogen steels can contribute to a decrease in creep strength since the Z phase forms at the expense of the MX nitride which is a main strengthening obstacle.

(cf. *ISIJ Int.*, **44** (2004), 1243)

Fractal analysis of three-dimensional fracture surfaces in metals and ceramics

M.TANAKA et al.

Three-dimensional images of fracture surfaces formed by different mechanisms were reconstructed by the computer-aided stereo matching method on metals and ceramics. The fractal dimension of the three-dimensional fracture surface was estimated by the box-counting method using the height data generated by the stereo matching method. The ductile fracture surface (stage I fatigue) had the larger fractal dimension compared with the brittle-type fracture surface (stage II fatigue) in a Cu–Be alloy. However, it was difficult to classify the type of fracture, namely, ductile fracture or brittle-type fracture, in different materials only by the fractal dimension of the fracture surface, since even fractal dimensions of brittle-type fracture surfaces exhibited different values with different materials, depending on the fracture mechanisms of materials. There was a good correlation between the results of the three-dimensional fractal analysis and those of the two-dimensional fractal analysis on materials. The value of the fractal dimension of the three-dimensional fracture surface depends not only on the size of the analyzed area but also on the algorithms of the fractal analysis. The fractal dimension estimated in a given length scale range can be correlated with specific microstructures in materials.

(cf. *ISIJ Int.*, **44** (2004), 1250)

Use of recycled steel machining chips and aluminum can shreds for synthesizing iron aluminide intermetallic alloys

K.MATSUURA et al.

Some iron aluminide intermetallic alloys based on Fe_3Al or FeAl have been synthesized from recycled raw materials of steel machining chips and aluminum can shreds. The former was an industrial waste made at a bearing case maker, and it had a spiral shape and a length less than 1 mm and contained 0.87 wt% C, 0.21 wt% Si, 1.53 wt% Cr with some other minor elements. The latter, on the other hand, was made by shredding used aluminum cans, and it had a flaky shape and a edge length of 2 to 3 mm and contained 2.3 wt% Mg, 0.36 wt% Fe, 0.88 wt% Mn with some other minor elements. When compacts of the steel and aluminum mixture were heated in a crucible in an argon atmosphere, they exothermically reacted and produced iron aluminide intermetallic alloys. For comparison, similar alloys were produced from pure iron and aluminum by melting them in the same heating apparatus. The bending strength, fracture toughness, Vickers hardness and wear resistance of the alloys synthesized from the recycled raw materials were more excellent than or similar to those of the alloys produced from pure iron and aluminum.

(cf. *ISIJ Int.*, **44** (2004), 1258)

Static and dynamic strain aging at high temperatures in 304 stainless steel

G.R.STEWART et al.

Commercial 304 austenitic stainless steel was deformed at high temperatures. The experiments involved 2-hit hot compression and multi-pass hot torsion testing; the experimental variables included strain rate, temperature and interpass time. The relationship between these variables and the degree of interpass softening produced unexpected results. Specifically, the normal effect of temperature on the static softening kinetics was reversed at intermediate interpass times: the fractional softening decreased with increasing temperature for these times. The diffusion kinetics and segregation mechanics of the

substitutional impurities in the material, combined with the experimental results, suggest that the temporary non-equilibrium segregation of phosphorus (and/or sulphur) to dislocations is responsible for the observed behaviour. Additionally, the observed trend in strain rate sensitivity with increasing deformation temperature indicates that dynamic strain aging was taking place.

(cf. *ISIJ Int.*, **44** (2004), 1263)