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Steelmaking

A review of slag splashing (Review)

K.C.MILLS et al.

This review critically evaluates the factors affecting the process of slag splashing. Two mechanisms are involved in slag splashing, namely 'slag wash coating' and 'slag ejection coating'. Our knowledge of slag splashing is largely based on physical modelling studies. It is necessary to optimise the following for good slag splashing:

(ii) The characteristics of the nitrogen blow (Gas flow, Lance height, Lance angle, Slag depth); and

(iii) Slag composition.

It is important that the slag contains the right blend of low-melting and high-melting phases. The low-melting (FeO-rich) phases ensure good adhesion between the slag and refractory whereas the high-melting phases provide erosion resistance and a thermal barrier. Good slag properties are obtained with a FeO content of *ca.* 13% and MgO should be supersaturated (>8% MgO) to ensure that the slag is MgO-saturated rather than CaO-saturated so that high-melting $MgO \cdot Fe_2O_3$ is formed rather than the low-melting calcium ferrites.

The factors affecting the uniformity of the slag-splashed layer are discussed.

(cf. *ISIJ Int.*, **45** (2005), 619)

Fundamentals of High Temperature Processes

Observations of the reduction of FeO from slag by graphite, coke and coal char

S.L.TEASDALE et al.

The reduction of FeO from iron-saturated FeO–CaO–Al_2O_3–SiO_2 slags by graphite, coke and coal char at 1 673 K has been investigated using a sessile drop technique. Metallographic analysis of samples quenched from the reaction temperature, and "*in situ*" observations of the reaction interface, reveal significant differences in the slag/carbon contact, and in the morphologies of the product iron and its composition; these differences were found to depend on the carbon type used in the reduction. In particular it has been shown that, in the case of graphite and coke, liquid Fe–C droplets were rapidly formed at the slag/C interface. Reactions of the slag with coal chars, in contrast, result predominantly in the formation of solid iron. These observations indicate that the reaction pathways, and hence reaction kinetics, are dependent on carbon type.

(cf. *ISIJ Int.*, **45** (2005), 634)

Kinetics of reduction of FeO from slag by graphite and coal chars

S.L.TEASDALE et al.

The rates of reduction of FeO from iron-saturated FeO–CaO–Al_2O_3–SiO_2 slags by graphite, coke, bituminous coal and anthracitic coal chars at temperatures in the range 1 673–1 873 K have been measured using a sessile drop technique. The extents of reaction were determined using EPMA analysis of quenched samples, and on line gas analysis using a quadrupole mass spectrometer. The reaction rates have been shown to be dependent critically on carbon type. For the reaction geometry used in this investigation the reduction rates of graphite and coke are observed to be faster than with coal chars. This unexpected finding is shown to be associated with differences in the dominant chemical and mass transfer mechanisms occurring at the reaction interface. High reaction rates are observed to occur with the formation of liquid Fe–C alloy product and the associated gasification of carbon from the alloy. The rates of reduction by coal chars are determined principally by the chemical reaction at the carbon/gas interface and slag phase mass transfer.

(cf. *ISIJ Int.*, **45** (2005), 642)

A model for estimation of viscosity of molten silicate slag

M.NAKAMOTO et al.

A model to evaluate the viscosity of silicate melts is proposed on the basis of the bonding states of oxygen, *i.e.* non-bridging oxygen and free oxygen ions, in the silicate structure, considering the flow mechanism of the melts with the network structure. Gaye's model is applied to evaluate the bonding state of oxygen ions using thermodynamic databases. The present model can reproduce the composition dependence of the viscosities for silicate melts in binary systems with a single model parameter, as well as the composition dependence of the viscosities for ternary systems in a wide composition range.

(cf. *ISIJ Int.*, **45** (2005), 651)

The effect of grain boundaries on the surface rearrangement during wüstite reduction within its range of existence

M.BAHGAT et al.

Dense polycrystalline wüstite samples equilibrated with 50%CO–CO_2 gas mixture for 432 ks has been reduced at 1 073 K using 60%CO–CO_2 gas mixture to study the effect of grain boundaries on the surface rearrangement process. Orientations of surface grains on the wüstite specimens are measured by applying electron backscattering pattern technique. The development of the surface arrangement away from grain boundaries is significantly larger than that near grain boundaries. Quick establishment of the equilibrium with the reacting gas in the region near grain boundaries at the early stage of the reduction makes it difficult to continue the transportation of Fe^{2+} ions into deep interiors of wüstite by the volume diffusion process. As a result, the surface rearrangement is retarded at the surface near grain boundaries after the equilibration of the surface. The transportation of Fe^{2+} ions at the surface layer away from grain boundaries by volume diffusion is small but not negligible so that the surface rearrangement away from the grain boundary is possible to continue until almost the whole sample is equilibrated.

(cf. *ISIJ Int.*, **45** (2005), 657)

Ironmaking

A thermodynamic study of silicon containing gas around a blast furnace raceway

J.GUSTAVSSON et al.

The equilibrium conditions for silicon transfer from ash to the liquid metal phase *via* SiO gas have been discussed by several authors. However, no published calculations have been found using the most modern thermodynamic models available. Since there are major differences in the results of calculations using different thermodynamic models and the models are continuously being improved, new equilibrium calculations on SiO and SiS gas formation have been performed using the recently developed models. Different ingoing compositions of coke ash, coal powder ash and blast air were used in the calculations. The compositions chosen represent blast furnace no. 3 at SSAB in Luleå, Sweden. Temperature was found to be the major factor influencing the equilibrium silicon level in the gas phase. At low temperatures (below 1 600°C) the total gas pressure was also seen to influence the silicon content in the gas phase. The main reason for this is that below 1 600°C, the amount of liquid slag at equilibrium increases with the total gas pressure. Liquid slag contains large amounts of silica that then can not be found in the gas phase. Higher carbon activity is usually expected to result in higher SiO gas levels in the blast furnace. The equilibrium calculations show that increased carbon activity increases the amount of silicon in the gas phase at temperatures up to about 1 600°C, but that at higher temperatures SiC is formed that decreases the equilibrium silicon level in the gas phase.

(cf. *ISIJ Int.*, **45** (2005), 662)

A three-dimensional mathematical modelling of drainage behavior in blast furnace hearth

K.NISHIOKA et al.

Stable blast furnace operation is required to reduce energy consumption in iron and steelmaking industry. For the stable blast furnace operation, precise controlled drainage is one of the important factors. However, the effects of the various in-furnace conditions on the stable operation were not examined well. Therefore, in this work, basic characteristic features of drainage in a blast furnace hearth were examined.

Two- and three-dimensional mathematical model were developed based on the finite difference method to simulate molten iron and slag flow in a hearth of a blast furnace. Pressure drop evaluation model in a taphole was developed to reflect pressure variation in a blast furnace hearth on drainage rate of molten iron and slag for the three-dimensional mathematical model.

The two-dimensional mathematical model results were validated with measured interfaces shapes obtained using an experimental model. The three-dimensional mathematical model results were validated with measured total, iron and slag drainage rate of Chiba No. 6 blast furnace. The results indicate that the drainage behavior and residual iron and slag volume were affected by the conditions in the hearth. The taphole conditions dominate the total drainage rate under the term of assumed blast furnace conditions. In order to reduce the residual slag volume, the taphole diameter change during the tap should be controlled. The decrease of the coke diameter causes increase of the residual slag volume,

decrease of the residual iron volume.

(cf. *ISIJ Int.*, **45** (2005), 669)

Steelmaking

Modeling of mixing in ladles fitted with dual plugs

M.MADAN et al.

A physical and mathematical modeling study has been carried out to investigate mixing in a gas stirred ladle fitted with dual plugs, located diametrically opposite at ±1/2 R positions. While conductivity measurement technique was applied to record 95% mixing times, mathematical modeling was carried out *via* the commercial CFD package FLUENT® wherein, a two phase flow calculation procedure based on discrete phase approach was adapted. It was demonstrated that numerically predicted flow and mixing times in general agree reasonably well with the corresponding experimental measurements.

In addition to the above, a relatively simple, quasi single phase flow calculation procedure, developed in-house, was also applied to predict mixing times and thereby, assess an earlier work. It is shown that the quasi single phase model, despite its simplicity, is reasonably effective in simulating mixing phenomena in such system. A comparison between different modeling approaches *vis a vis* experimental measurements is also illustrated in the text.

(cf. *ISIJ Int.*, **45** (2005), 677)

Casting and Solidification

Improvement of hot ductility in the Nb-microalloyed steel by high temperature deformation

F.ZARANDI et al.

Loss of hot ductility at the straightening stage of the continuous casting of HSLA steel is attributed to different microalloying elements, in particular Nb. However, such elements are essential for the desired mechanical characteristics of final product. Since the chemistry cannot be altered to alleviate the problem, thermomechanical processing was studied in order to improve the hot ductility. A Nb-microalloyed steel was examined. The thermal history occurring in the continuous casting process was taken into account as well. Firstly, it was noticed that the steel has a low hot ductility after being subjected to *in situ* melting followed by the thermal schedule. Then, the effect of deformation applied in the vicinity of the $\delta \rightarrow \gamma$ transformation, while the thermal schedule was being executed, was investigated. Such deformation appeared to improve the hot ductility considerably. Finally, the mechanism of such improvement in the hot ductility was discussed.

(cf. *ISIJ Int.*, **45** (2005), 686)

Instrumentation, Control and System Engineering

Design of heat-treated alloy steels using intelligent multi-objective optimisation

M.MAHFOUF et al.

In this paper, a new mechanism is presented to address the multi-objective optimal alloy design problem, which consists of finding the 'best' processing parameters and the corresponding chemical compositions to achieve certain pre-defined mechanical properties of steels. Fuzzy modelling has been used to establish the required mechanical properties which facilitate the Particle Swarm based multi-objective optimisation mechanism. Hence, an adaptive weighted PSO algorithm is developed to improve the performance of the standard PSO algorithm. Based on the established tensile strength and impact toughness fuzzy prediction models, the proposed algorithm has been successfully applied to the optimal design of heat-treated alloy steels. The experimental results have shown that the algorithm can locate the constrained optimal solutions quickly and provide a useful and effective guide for alloy steels design.

(cf. *ISIJ Int.*, **45** (2005), 695)

Forming Processing and Thermomechanical Treatment

Enhanced plasticity of a tool steel near α-γ transformation

B.M.MOGUTNOV et al.

Phase transformations, high-temperature mechanical properties of a tool steel as well as its structure before and after rolling were studied with the aim of clarifying why high-carbon highly-alloyed steels can be rolled with rather high degrees of deformation at moderately low temperatures (~800°C). Three factors were found to bring the steel mechanical properties to the level that makes this type treatment possible. They are: 1) higher plasticity and lower strength of α-phase as compared with γ-phase at the same temperature; 2) stability of the ferrite–carbide state up to temperatures exceeding 800°C; 3) plasticity induced by $\alpha \rightarrow \gamma$ transformation in the process of rolling.

(cf. *ISIJ Int.*, **45** (2005), 701)

Local austenite grain size distribution in hot bar rolling of AISI 4135 steel

H.-W.LEE et al.

In this paper, the local distribution of austenite grain size (AGS) was experimentally determined by conducting single round-oval and square-diamond pass hot bar rolling experiments of AISI4135 steel. The rolling experiments were carried out using the laboratory mill. The local distribution of AGS was also determined numerically. In order to predict AGS distribution, the AGS evolution model was combined with three dimensional non-isothermal finite element analyses by adopting a modified additivity rule. AGS evolution model was experimentally determined from hot torsion test according to Hodgson's model. The predicted results were in a reasonably good agreement with experimental results.

(cf. *ISIJ Int.*, **45** (2005), 707)

Analysis of the effect of Mn on the recrystallization kinetics of high Nb steel: An Example of Physically-based Alloy Design

H.S.ZUROB et al.

Strip casting and thin slab casting are new near net-shape technologies, which have successfully emerged in steels because of significant energy savings, substantial reduction in green house gas emissions and cost benefits. Extensive research was undertaken aimed at integrating microalloying technology with near net-shape casting technology, using a base chemistry of low carbon (0.03 wt%) and high niobium (up to 0.1%wt), which is a well established chemistry for higher grade pipeline steels.

In the present contribution, physically-based modelling is used to optimize the Mn content and the processing conditions for the application of strain-accumulation in the new steels. The results of the modelling confirm the distinct advantage of the low Mn chemistry for the application of plate rolling which is carried out in the high temperature window using small to medium deformation passes. The high Mn chemistry is found to be more advantageous when the rolling is carried out in the low temperature window and using large pass reductions. This result is in agreement with recent rolling simulations and mill trials which show that the high Mn chemistry is superior to the low Mn chemistry for the application of near net-shape strip-rolling.

(cf. *ISIJ Int.*, **45** (2005), 714)

Welding and Joining

Process monitoring method with window Technique for clinch joining

Y.TAN et al.

This paper describes investigations of a process monitoring system—window monitoring for clinching techniques. This window technique was used in the study of evaluating the quality of joints. In the research a clinching machine from the type Eckold, steel DC04 with different thicknesses and steel H340 with a thickness 1.00 mm as well as a window monitoring system Digiforce 9306 were utilized. Monitoring functions were investigated under different applying conditions: change of clinched materials, change of sheet metal thicknesses and change of clinching machine tools *etc.* The results showed that the window monitoring method had an outstanding capability of monitoring changes of applying conditions so that a reproducible quality of joints could be ensured. Comparing with the conventional tolerance monitoring method window monitoring method has two extra advantages: one is its short time consume during a monitoring phase, another one is that with windows there is more information about a monitoring situation, to distinguish which errors occur during a clinch joining.

(cf. *ISIJ Int.*, **45** (2005), 724)

Cr_2O_3 film formed by surface oxidation of stainless steel irradiated by a Nd-YAG pulsed laser

J.YANG et al.

Nd-YAG pulsed laser was applied to the rapid oxidation of stainless steel to form a Cr_2O_3 protective film. Different metal oxide formed by the irradiation of the Nd-YAG pulsed laser. Cr_2O_3 film can form on the stainless steel when the scan velocity was controlled correctly. Different metal oxide growth mechanisms of the laser oxidation and the annealing

oxidation in the oven were discussed. The oxidation reaction rate and the sequence of metal elements in stainless steel with oxygen under the laser irradiation were studied respectively. The lattice diffusion and short-circuit diffusion are the main mechanism of the annealing oxidation in the oven.

(cf. *ISIJ Int.*, **45** (2005), 731)

Transformations and Microstructures

Grain structure of Fe–0.3mass%C–9mass%Ni steel processed through $\alpha \rightarrow \gamma \rightarrow \alpha'$ transformation caused by spontaneous reverse transformation

T.YOKOTA et al.

$\alpha \rightarrow \gamma \rightarrow \alpha'$ (ferrite→austenite→martensite) transformation caused by spontaneous reverse transformation (SRT) in Fe–0.3C–9Ni mass% steel has been demonstrated using laboratory rolling mill, and grain structure of the plate has been investigated. SRT is a new process to obtain an ultra refined austenite, and resulting ultra refined transformation products, which occurs due to adiabatic heating caused by deformation at temperatures in ferrite phase field. SRT occurred all through the plate thickness by intensive rolling with 90% reduction and final microstructure was ultra-refined martensite. Mean lineal intercepts of the martensite grains were 0.90 μm at mid thickness and 0.83 μm at quarter thickness. Ultra-refined grain structure attributes to enhancement of austenite nucleation due to the intensive rolling before $\alpha \rightarrow \gamma \rightarrow \alpha'$ transformation. The martensite texture after the $\alpha \rightarrow \gamma \rightarrow \alpha'$ transformation caused by SRT composed of RD//$\langle 1\,1\,0 \rangle_{\alpha}$ and ND//$\langle 1\,1\,1 \rangle_{\alpha}$ fibers. However, these were not sharp, thus crystallographic grain orientation was quite randomised in spite of the intensive rolling. Two consecutive transformations weakened the initial ferrite rolling texture remarkably. Randomization of the grain orientation was more prominent at the quarter-thickness than at the mid-thickness due to a shear strain.

(cf. *ISIJ Int.*, **45** (2005), 737)

Texture development during grain growth in nonoriented electrical steels

J.-T.PARK et al.

Nonoriented electrical steels should have both low core loss and high permeability. These magnetic properties are largely affected by grain size and texture. The research on grain size optimization during grain growth has been very extensive whereas little attention has been paid to texture transformation during grain growth. In the present study, based on obtained experimental results, a mechanism of texture development during grain growth in nonoriented electrical steels is proposed. In the 2% Si specimens, the major texture components, Goss and $\{111\}\langle 112 \rangle$ components, are weakened during grain growth. In the 1% Si specimens, the main texture components, $\{111\}\langle 112 \rangle$ and $\{111\}\langle 110 \rangle$, are strengthened. It is proposed that for a texture component to be continuously strengthened during grain growth, the grains of the specific orientation should have not only a size advantage over those of other orientations, but also a higher frequency of high angle, high energy grain boundaries.

(cf. *ISIJ Int.*, **45** (2005), 744)

Fabrication of ultrafine grained ferrite/martensite dual phase steel by severe plastic deformation

K.-T.PARK et al.

Processing of ultrafine grained ferrite/martensite dual phase (UFG F/M DP) steel by equal channel angular pressing (ECAP) and subsequent intercritical annealing was described in detail. Along with strain gradient plasticity concept in which an introduction of a high density of geometrically necessary dislocations attributes to enhance strain hardenability, the aim of the present study was fabrication of UFG F/M DP steel exhibiting extensive strain hardenability, which other UFG materials hardly exhibit, in addition to ultrahigh strength and good uniform elongation. By selecting the optimum ECAP and intercritical annealing conditions, it was possible to fabricate UFG F/M DP steel in which isolated UFG martensite islands were uniformly embedded into UFG ferrite matrix. The formation of such a unique microstructure under the present processing conditions was discussed in terms of microstructural evolution during ECAP. Room temperature tensile properties of UFG F/M DP steel were superior to those of coarse grained counterpart. More importantly, in spite of an UFG structure, the present UFG F/M DP steel exhibited extensive strain hardenability from the onset of plastic deformation in association with grain size independent strain gradient plasticity, unlike other UFG materials.

(cf. *ISIJ Int.*, **45** (2005), 751)

Three-dimensional observation of ferrite plate in low carbon steel weld

M.ENOMOTO et al.

The early stages of the formation of acicular ferrite in a low carbon steel weld were studied by serial sectioning and computer-aided three dimensional (3D) visualization. The specimens were taken from the weld of low carbon steel, containing 0.08% C, 0.9% Si, 1.57% Mn and 0.032% O, and were austenitized and isothermally reacted at 600 and 570°C for less than 10 s. Very thin and long plates were formed initially and thickening occurred probably after lengthening was hampered due to impingement on prior austenite grain boundaries and/or pre-formed ferrite plates. Multi-variant ferrite plates were nucleated at inclusions and grew radially in the directions close to $\langle 110 \rangle_{\gamma}$ with habit planes near $\{111\}_{\gamma}$, thus forming a characteristic "Widmanstätten star" noted earlier in a medium carbon steel on polished surfaces.

(cf. *ISIJ Int.*, **45** (2005), 757)

Mechanical Properties

A comparative study on the Θ projection and the Ω method

S.FUJIBAYASHI

Nowadays, most of plant owners have sought for a deterministic technique to assess the remnant life of their old components. In the case of high temperature equipment serviced in the creep regime, the life assessment is more difficult than that for other damage like corrosion since the accumulated damage is not necessarily detectable. In order to predict the materials' response at high temperatures, a constitutive equation precisely describing their creep behavior is required. In the current work, the Θ projection and the Ω method have been examined using creep data for 1.25Cr–0.5Mo and 2.25Cr–1Mo steel. Two different tertiary creep behaviors were observed in experiments, namely, proportional rise in strain rate with strain assumed in the former methodology and exponential rise in strain rate with strain assumed in the latter. The Θ projection has unexceptionally described the creep behavior well when the strain was lower than 10%, whereas the tertiary creep behavior observed in not a few experimental cases, in which the proportionality of strain rate–strain correlation is retained in almost the whole tertiary regime, cannot be explained by the Ω method. The apparent exponential rise in the tertiary creep rate found in the final stage of creep should be attributable to the experiment using a constant load technique, in which cross-sectional stress is increasing with strain. The creep behavior of actual components, which are exposed to the condition under the constant stress rather than constant load, would be more precisely described by the Θ projection.

(cf. *ISIJ Int.*, **45** (2005), 764)