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## Social and Environmental Engineering

### Considerations on steel manufacturing process (Review)

*Y.RUIYU*

The comprehensive influence on the overall integration of steel manufacturing process is discussed in this paper, which influences not only the target group of technique and economy, but also the process emission and environment.

The evolution of steel manufacturing process for a long period is reviewed, which can be summarized as from simplicity to complication and then from complication to simplification. It is pointed out that the essence of steel manufacturing process is a production system which is combined mass state transformation, mass property control and mass flow control. It is a multi-dimensional mass-flow control system.

In fact, the optimization of steel manufacturing process is the analysis-optimization of the collection of procedure's function, the harmony optimization of the collection of procedure's relations and restructuring optimization of collection of procedures in the process. Based on above theory, the linkage optimization of function–structure–efficiency for steel plants will be realized and the mode of steel plants will be improved.

It is proposed that the social/economic role of steel plants should be positioned actively. The function of manufacturing process at the steel plants should be evolved from metallurgical function mainly to a multi-functional, which has both energy conversion and environmental treatment of social wastage. The steel plants may be an important part of the ecological industry zone in the future.

(cf. *ISIJ Int.*, **42** (2002), 1061)

## Fundamentals of High Temperature Processes

### Chloride capacities of $CaO–SiO_2–Al_2O_3$(–FeO, MgO, MnO) slags and their application in the incineration processes

*M.MIWA et al.*

Thermodynamic properties of chlorine in the $CaO–SiO_2–Al_2O_3$(–FeO, MgO, MnO) and $CaO–SiO_2$–FeO slags have been investigated. The experiments were carried out under relatively high oxygen partial pressure, using gas–slag equilibrium, controlling both $P_{O_2}$ and $P_{Cl_2}$ simultaneously ($P_{O_2}=10^{-5}–10^{-13}$ atm, $P_{Cl_2}=10^{-7}–10^{-10}$ atm at 1 673 K) by flowing gas mixture of $H_2$, $CO_2$, HCl and Ar gases, and the solubility of chlorine in the 40mass%CaO–40mass%$SiO_2$–20mass%$Al_2O_3$ slag was found to vary in proportion to $P_{O_2}^{-1/4}$ and $P_{Cl_2}^{1/2}$, which was the same relationship observed in the reducing conditions. Accordingly, chloride capacity ($C_{Cl^-}$) is used to evaluate ability of slags to absorb chlorine. The $C_{Cl^-}$ values were observed to increase with increasing slag basicity, and showed a reasonable relationship with that of $C_{S^{2-}}$. Based on the result obtained in the present study, chlorine distribution during incineration with slags was predicted quantitatively.

(cf. *ISIJ Int.*, **42** (2002), 1065)

### Activity measurement of silicon in molten Cu–Si binary alloy

*T.MIKI et al.*

The activity of Si in molten Cu–Si alloy was determined by a new experimental technique, that is, the combination of chemical equilibration technique and mass spectrometry.

The ion current ratio of SiO to Cu at 1 600–1 700 K was measured for Cu–Si alloy equilibrated with $SiO_2$ by mass spectrometry. Since the vapor pressure of Si is relatively low, the formation reaction of volatile sub-oxide, SiO, was utilized in the present work. The activity coefficient of Si in liquid copper at 1 623 K was also determined by equilibrating a Cu–Si alloy with $SiO_2$ saturated $CaO–Al_2O_3–SiO_2$ slag in a graphite crucible under CO atmosphere. From these results, the activity coefficient of Si in copper at 1 600–1 700 K was determined. The thermodynamic property of Cu–Si alloy was assessed and it was confirmed that the present work agreed with the reported phase diagram of Cu–Si binary system.

(cf. *ISIJ Int.*, **42** (2002), 1071)

## Ironmaking

### Control of $CO_2$ peak position by dual lance air curtain method

*M.ICHIDA et al.*

A phenomenon that a $CO_2$ peak position or temperature peak position of combustion ($CO_2$ or temperature peak position) in the raceway of blast furnace approaches a tuyere in step with the increase of pulverized coal rate (PCR) changes a gas flow at the lower part of the furnace into a peripheral flow or lowers the temperature at the raceway end, which may be one of the factors making the furnace operation unstable. Therefore, a pulverized coal combustion method (dual lance air curtain method) which interrupts temporarily a contact of pulverized coal and hot air in the vicinity of lance tip by injecting cold air through an opening between inner and outer tubes of the dual lance was examined by performing a hot model experiment and a single tuyere test of actual furnace. The hot model experiment results have revealed that with the increase of the flowing velocity of cold air sent from the outer tube of dual lance, the temperature around the tuyere tip falls and the temperature ranging from the raceway and to a dead man surface rises. According to the examination results of gas temperature under the raceway conditions of actual furnace with the use of one-dimensional raceway model, an estimated value of the moving distance of $CO_2$ or temperature peak position of combustion toward the dead man side is 480 mm when the dual lance air curtain method has been taken this time at Kimitsu No. 2 blast furnace. The combustion efficiency of pulverized coal could decrease due to movement of $CO_2$ or temperature peak position of combustion to the dead man side. And in the actual furnace test conducted this time with a single tuyere, the increase range of unburnt char ratio at the inside of dead man is as small as less than 1% relative to −1 mm fine and the packing structure of dead man surface has been improved.

(cf. *ISIJ Int.*, **42** (2002), 1077)

## Casting and Solidification

### A mathematical model for prediction of thickness of mould flux film in continuous casting mould

*A.YAMAUCHI et al.*

A mathematical model of mould flux infiltration and heat transfer through the flux film has been developed. The model considers the effect of static pressure of molten steel, temperature dependency of flux viscosity and determination of liquid flux thickness with pressure gradient. Present model gives the results that agree well with actual plant data such as mould flux consumption, mould friction and the heat transfer. The results of the model give remarkable effect of static pressure of molten steel as follows: decrease of the static pressure causes increase of liquid and total flux film thickness, reduction of heat flux and decrease of friction force on solidified shell.

(cf. *ISIJ Int.*, **42** (2002), 1084)

### Cooling behavior and slab surface quality in continuous casting with Alloy 718 mold

*A.YAMAUCHI et al.*

In order to decrease surface defects of continuously cast slab, a newly designed innovative mold to realize uniform mild cooling has been developed. Nickel base super alloy, Alloy 718, characterized by high strength at elevated temperature and low thermal conductivity was applied as the material of mold plates instead of conventional copper. Casting experiments of medium carbon steel have been performed with pilot scale continuous caster. The following advantages of the new mold with 40% decrease of meniscus heat extraction and 75% decrease of its fluctuation were confirmed in comparison with conventional copper mold. 1) Index of longitudinal surface crack decreased by about 50%, 2) Frequency of hook (over flow type oscillation marks) appearance on which non-metallic inclusions are likely entrapped decreased by 50%, 3) Depth of "hook" decreased by 20 to 45%, and 4) Average of oscillation mark depth decreased by 35% and its fluctuation also decreased by about 50%.

(cf. *ISIJ Int.*, **42** (2002), 1094)

### Analysis of mold level hunching by unsteady bulging during thin slab casting

*U.-S.YOON et al.*

In order to analyze the phenomenon of mold level hunching (MLH) during thin slab casting process, the variation of the mold level and the bulging of strand were measured and analyzed using Fast Fourier Transform (FFT) spectrum analysis. Both of mold level hunching and bulging had the same frequency and the specific frequency corresponded to the main roll pitch of the thin slab caster. The unsteady bulging was found to be a main reason of mold level hunching. The unsteady bulging profile through the full range of the caster and the height of mold level hunching were calculated using a heat transfer model and a continuous beam model. The effects of process variables on mold level hunching and the process condition of reducing mold level

hunching were studied. The amount of mold level hunching increased as unsteady bulging increased due to the hunching of casting speed. An aperiodic roll pitch between segments could be effective in reducing mold level hunching.

(cf. *ISIJ Int.*, **42** (2002), 1103)

## Forming Processing and Thermomechanical Treatment

### Continuous heating system using electric resistance heating for the hot rolling of stainless steels

*Y.ASANO et al.*

Electric resistance of metals increases according to the elevation in temperature. Non-uniform temperature distribution in cross-section can be automatically sacrificed if we use electric resistance heating, and uniformly distributed cross-sectional temperature can be easily obtained. A continuous heating system using electronic resistance heating is developed, and its characteristics to the heating of stainless steel are examined through a series of basic experiments. Through the investigation, it has become clear that uniform continuous heating of stainless steel can be realized by proposed heating system. Although the composition of heating system is quite simple, high rate in temperature elevation can be obtained. Also, we can precisely control the temperature distribution in feeding (rolling) direction by continuous electric resistance heating, because temperature of metals can be rapidly changed only by changing the degree of electric current and time to impose electric current.

(cf. *ISIJ Int.*, **42** (2002), 1112)

## Transformations and Microstructures

### Determination of upper limit temperature of strain-induced transformation of low carbon steels

*L.DU et al.*

Two quenching methods were applied in the experiments carried out on Gleeble 1 500 thermomechanical simulator: (1) spurting water; (2) making the samples drop into water, and the cooling rate distributed un-uniformly in the samples quenched by the former and uniformly by the latter. The critical cooling rate of preventing ferrite precipitation was determined, and the microstructure observation position in which the microstructure could be frozen to room temperature in the samples quenched by spurting water was also determined, and using this method the $A_{d3}$ was determined to be about 830°C for tested materials. Using second quenching method, single-pass deformation experiments at different temperatures were carried out, and the microstructure analysis indicates that, as the deformation temperature decreased, the ferrite morphology changed from Widmanstätten and allotriomorphs to equiaxed at about 800°C. Combining the dilation–temperature curves measured during cooling process after deformation at different temperatures, the $A_{d3}$ was determined to be also about 830°C for tested materials.

(cf. *ISIJ Int.*, **42** (2002), 1119)

### A numerical modeling of metallo-thermo-mechanical behavior in both carburized and carbonitrided quenching processes

*C.LIU et al.*

A finite element modeling for the simulation of metallo-thermo-mechanical behavior and for the diffusion of carbon and nitrogen during carburized or carbonitrided quenching has been developed. In this modeling, both effects of the diffusion of carbon and nitrogen on transformation kinetics, and of the lattice expansion by the interstitial solutes on the constitutive relations of stress/strain are taken into account. Based on the modeling, prediction of carbon and nitrogen contents, microstructure and stress/distortion in cylinders after carburized or carbonitrided quenching are performed. The effects of carbon and nitrogen contents on the distributions of microstructure and residual stresses are discussed. The calculated results show a good agreement with the measured residual stresses. The agreement proves that the finite element modeling proposed in this paper is effective for numerical simulation of carburized or carbonitrided quenching.

(cf. *ISIJ Int.*, **42** (2002), 1125)

### Observation of $\gamma \rightarrow \alpha$ transformation in ultralow-carbon steel under a high temperature optical microscope

*J.LEE et al.*

The basic composition of IF steel is Fe-ultralow-carbon (<0.02 mass%). There is little research on the transformation behavior and microstructures of ultralow-carbon steel compared to low-carbon steels, and the details, for instance, transformation mechanism and the ratio of grain sizes of $\gamma$ and $\alpha$, remain unclear. Therefore, *in situ* observation of the $\gamma \rightarrow \alpha$ transformation in an Fe–0.004%C steel was performed at a cooling rate of 0.5–18°C/s under a high-temperature optical microscope. The main microstructure of ferrite was $\alpha_q$, and with an increase in the cooling rate, the fraction of Widmanstätten ferrite-like structure and ferrite having a severely ragged interface increased. The growth rate of $\alpha_q$ was $1\times10^{-4}$–$9\times10^{-4}$ m/s which increased with the cooling rate. The growth rate of $\alpha_q$ decreased to about half when the amount of carbon increased to 0.01%. The ratio of $\gamma$ grain size to $\alpha$ grain size was about 1.2, and this value is considerably smaller than the values reported for the low-carbon steels. $\alpha_q$ crossed $\gamma$ grains frequently and some $\alpha_q$ grains were larger than $\gamma$ grains. Usually the curvature of the $\alpha_q/\gamma$ interface did not change at the intersection of the boundaries of $\alpha_q$ and $\gamma$. This shows that $\alpha_q/\gamma$ interfaces are usually incoherent in ultralow-carbon steels. Transformation temperature was in the single-phase region of $\alpha$. Therefore, the $\gamma \rightarrow \alpha_q$ transformation observed in the present research is thought to be massive transformation. The terminology of mechanisms of $\gamma \rightarrow \alpha$ transformation in ultralow-carbon steels and the microstructures of generated $\alpha$ was discussed.

(cf. *ISIJ Int.*, **42** (2002), 1135)

### Three-dimensional morphology and growth kinetics of intragranular ferrite idiomorphs formed in association with inclusions in an Fe–C–Mn alloy

*K.M.WU et al.*

The three-dimensional (3-D) morphology and growth kinetics of intragranular ferrite idiomorphs formed in association with MnS(+VN) inclusions were studied in an Fe–C–Mn alloy. Ferrite idiomorphs began to be formed at a temperature ~40°C lower than the grain boundary allotriomorphs, and the highest temperature of the formation of intragranular ferrite plates was ~60°C below the Widmanstätten start temperature of grain boundary sideplates ($W_s$). The 3-D shape of ferrite idiomorphs was more equiaxed than grain boundary allotriomorphs. Measured growth rates were smaller than those calculated assuming spherical growth, similar to those of grain boundary allotriomorphs previously reported. The possible reasons for the retardation of growth, *e.g.* deprivation of carbon supersaturation by grain boundary ferrite allotriomorphs and solute drag *etc.*, are discussed.

(cf. *ISIJ Int.*, **42** (2002), 1144)

### Effects of Mo addition and austenitizing temperature on hardenability of low alloy B-added steels

*H.ASAHI*

The hardenability change by an addition of B to 0.15%C–Ti added steel was investigated considering the effect of Mo in order to understand one of the peculiar characteristics that austenitizing at higher temperatures reduces the hardenability effect of B. Hardenability monotonically increases with increasing B content up to the optimum B content without the effect of Mo. The optimum B content increases with increasing Mo; 6 ppm, 9 ppm, 13 ppm for 0% Mo, 0.25% Mo, 0.50% Mo. The addition of Mo retards the precipitation of $M_{23}(CB)_6$ and thus more B in solution that contributes to hardenability can exist along grain boundaries by Mo. The optimum B content is reduced with increasing temperatures because much more B concentrates along grain boundaries through non-equilibrium segregation mechanism during cooling from an elevated temperature and thus precipitation of $M_{23}(CB)_6$ easily occurs.

(cf. *ISIJ Int.*, **42** (2002), 1150)

## Mechanical Properties

### Creep rupture properties of an austenitic steel with high ductility under multi-axial stresses

*L.-B.NIU et al.*

Using tubular specimens of austenitic steel SUS310S with high ductility, creep rupture tests are conducted in tension, torsion and combined tension–torsion stress states at 700°C. It is found that the maximum principal stress determines the multiaxial creep rupture life of the steel. The reasons are assumed to be that many voids nucleated in the early stages of creep, and that at any creep stress states this steel showed larger deformations and continuous nucleating of voids during creep testing. Furthermore, by observing on the scanning electron micrographs, the specimens ruptured at various stress-

es are found to exhibit different fracture modes. These creep fracture modes and their formatting factors are discussed in detail. It is assumed that at a multi-axial stress state, the von Mises equivalent stress promotes creep deformation and nucleation of creep voids, meanwhile the growth of the voids should be restrained by the large creep deformation. It is further suggested that in a specimen with existing of the mean stress and a smaller equivalent stress, a brittle intergranular fracture should occur easily.

(cf. *ISIJ Int.*, **42** (2002), 1156)

### Effects of heat treatment and Si addition on the mechanical properties of 0.1 wt% C TRIP-aided cold-rolled steels

*C.G.Lee et al.*

The purpose of the present study was understanding the effects of heat treatment and silicon content on the microstructure and mechanical properties of low-carbon TRIP-aided cold-rolled steel sheets. Two steels of the same base composition, 0.10%C–1.5%Mn–Si–0.5%Cu (hereafter all in weight percent), but containing 0.94% Si and 1.48% Si were cold rolled to 1 mm thick sheet. The sheets were intercritically annealed and isothermally treated in the temperature range of bainite reaction in order to vary the volume fraction of retained austenite and the mechanical properties. The fractions of retained austenite increased with decreasing intercritical annealing and isothermal treatment temperatures, resulting in the improvement in tensile strength, elongation, and the strength–ductility balance. In the steel having the higher silicon content, a higher fraction of retained austenite and better mechanical properties were achieved than in the steel having the lower silicon content. The findings indicate that partitioning of C and Mn to the austenite during intercritical annealing, together with a higher Si content, increase the stability of the austenite and affect the optimum intercritical and isothermal heat treatment temperatures.

(cf. *ISIJ Int.*, **42** (2002), 1162)

### Effects of alloying elements on creep properties of 9Cr–3.3W–0.5Pd–V, Nb, N, B steels

*H.Okada et al.*

Owing to the fine precipitations of FePd $L1_0$ type ordered phase $\alpha''$, Pd addition to 9Cr ferritic heat resistant steel improves the creep strength by not only reducing the creep rate but also extending the creep rupture life. In this study, effects of alloying elements on creep properties of Pd added 9Cr ferritic steels have been evaluated with 10 kg-ingots in order to search for substitutional element for the precious metal Pd. Among the metals from VIIA to IB except Fe and Tc, some elements were found to harden the steels aged at around 823 K, which is the precipitation temperature of $\alpha''$. Corresponding to the hardness change, some elements were found to improve the creep properties also. Among such elements, especially Re addition prevented the growth of Laves phase and remarkably reduced the minimum creep rate at lower stress level. From these results, pipe fabrication and welding tests were performed on Pd and Re-added 9Cr steel using 180 kg-ingots. It was found that this steel could easily be welded by gas tungsten arc welding and formed into pipe without harmful defects.

(cf. *ISIJ Int.*, **42** (2002), 1169)

## Social and Environmental Engineering

### A mathematical modeling and validation study of $NO_x$ emissions in metal processing systems

*G.K.Malikov et al.*

The model is based on separate calculations of prompt and thermal $NO_x$ and is accomplished using CFD code for flow, temperature and concentration fields in the combustion system. Thermal $NO_x$ is calculated with the Zeldovich model. The prompt $NO_x$ is considered to be independent of residence time and is computed with detailed kinetic data based GRI-Mech version 2.11 and CHEMKIN code by assuming that every computational cell is a perfectly stirred reactor. Three main parameters are considered to be critical in $NO_x$ production: 1) air equivalence ratio, 2) temperature, and 3) mixture dilution with combustion products. All of these parameters and methane oxidation reaction rates are readily available in every cell of the CFD domain. Once $NO_x$ emission index is computed by GRI-Mech in every cell, $NO_x$ reaction rate is easily evaluated by multiplying it with the methane oxidation reaction rate. The $NO_x$ concentration field is then calculated using known CFD transport parameters. Comparison of model predictions with measurements is made for a wide range of industrial natural gas-fired burners installed in combustion chambers and furnaces. The flame temperatures were in the range of 1 400–2 100 K, velocities were in the range of 10–200 m/s, burner nozzles were in the range of diameters 5–550 mm, and the combustion chamber or furnace internal equivalent size in the range of 0.05–3.5 m. Good agreement has been obtained in most cases.

(cf. *ISIJ Int.*, **42** (2002), 1175)