（＊掲載記事題目及び掲載頁は変更になる場合があります。）

Fundamentals of High Temperature Processes

The effect of the liquid Fe–C phase on the kinetics in the carburization of iron by CO at 1 523 K

Y.SASAKI et al.

In order to evaluate the effect of liquid Fe–C alloy produced during the carburization on the kinetics of iron carburization, the rates of carburization of iron by CO–Ar gas mixtures have been measured gravimetrically at 1 523 K and the growing rates of the liquid Fe–C layer thickness are also measured. The measurements were made under conditions for which the gas phase mass transfer was negligible. It is found that the weight gains due to the carburization reaction are almost proportional to $t^{2/3}$ within experimental scatters. For all runs except that of 1% CO, the liquid phase is observed after the carburization time of 300 s. The liquid phase thickness is found to be almost constant for the first 3.6 ks. After 3.6 ks, the liquid phase thickness starts to increase almost linearly with time. The mechanism to maintain the constant thickness is briefly discussed. The carburization reaction rate is calculated based on the well established decarburization rates and is reasonably agreed with the experimental carburization rate. Compared the experimental results with the calculated liquid phase diffusion rates and the chemical reaction rates, it is confirmed that the rate-controlling step of the carburization reaction of iron with CO gas at 1 523 K is the chemical reaction $CO+O_{ad}\rightarrow CO_2$ at the surface after the liquid Fe–C phase is produced.

(cf. *ISIJ Int.*, **41** (2001), 209)

Reaction kinetics of desulfurization of molten pig iron using $CaO–SiO_2–Al_2O_3–Na_2O$ slag systems

J.-Y.CHOI et al.

Desulfurization kinetics of molten pig iron were studied using $CaO–SiO_2–Al_2O_3–Na_2O$ quaternary slag systems at 1 350°C. The concentration of Na_2O in slag decreases with time due to evaporation. The rate of desulfurization increases by increasing the Na_2O content in slag, decreasing Al_2O_3 content, increasing the slag basicity, *i.e.*, the ratio of CaO to SiO_2, and increasing the temperature. A mathematical model has been developed which enables the effect of decrease in Na_2O content over time to be taken into consideration. The model provides a rate equation that can represent all conceivable rate controlling steps, such as interfacial chemical reaction, mass transport in the metal phase, and in the slag phase. The apparent rate coefficient—a parameter employed in the model—was dependent on temperature and slag composition, especially Na_2O content. An equation is suggested which relates the coefficient to the sulfide capacity of slag. The activation energy of the apparent rate coefficient was found to be 127 kJ mol^{-1}. It was concluded that the desulfurization of molten pig iron using the present slag system is controlled either by the interfacial chemical reaction or slag phase mass transfer.

(cf. *ISIJ Int.*, **41** (2001), 216)

A volume of fluid (VOF) method for the simulation of metallurgical flows

P.LIOVIC et al.

A finite difference numerical method, based on the VOF approach for tracking interface distortions, is presented. It is capable of accurately simulating the fluid flow of multiple immiscible fluids for metallurgical applications. This volume tracking method is based on piecewise linear reconstructions of interfaces, density distributions based on a shifted grid approach, and a fully kernel-based CSF method for surface force modelling. Second order temporal and spatial accuracy are achieved using improved Euler time-stepping enhancement of a two-step projection algorithm, supported by a multigrid-preconditioned GMRES solver that enabled large density ratios (1 : 30 000) between the fluids and fine scale flow phenomena to be resolved. The code was used to simulate the rise of an air bubble in water and in liquid pig iron and was able to capture the time dependent oscillation of the bubble. The bubble velocity varied with the instantaneous shape of the bubble. The averaged terminal velocity of the gas bubble in water was in good agreement with published experimental data. Splash formation from a top submerged gas injection lance was simulated to illustrate the capability of the code in resolving the break up and fragmentation of liquid drops for possible use in the study of bath smelting processes.

(cf. *ISIJ Int.*, **41** (2001), 225)

Gas dispersion phenomena and mixing characteristics under gas injection through slot nozzle submerged in water

K.OKUMURA et al.

Bubble dispersion and mixing behaviour in a bath with gas injection through a slot nozzle was studied by a cold model. A high speed video recording system was used to measure the bubble diameter and the size of plume cross sectional area. The mixing time was measured by using an electrical conductivity method. Measurements were conducted under various gas flow rates and bath depths. Comparison of mixing time was examined between a slot nozzle and a single circular nozzle. The results were discussed in terms of specific power of injected gas.

At lower gas flow rates, the bubble size distribution was not changed with the vertical distance. At higher gas flow rates, the bubbles detached at the nozzle coalesced immediately and became large. It was found that the slot nozzle led to an increase in plume cross sectional area as compared with a single circular nozzle. The mixing time for the slot nozzle was smaller than that for the single circular nozzle. The plume cross sectional area for the slot nozzle was larger than that for the single circular nozzle. The increase in the plume cross sectional area was connected with the decrease in the mixing time. Effects of the experimental variables on the mixing time were quantitatively examined.

(cf. *ISIJ Int.*, **41** (2001), 234)

Nitride capacities of $CaO–Al_2O_3–CaF_2$ melts at 1 773 K

W.-Y.SHIN et al.

The nitrogen solubility of $CaO–Al_2O_3–CaF_2$ was studied at 1 773 K. It was found that nitride capacity increased with increasing CaO content for a given CaF_2/Al_2O_3 ratio, decreased with increasing Al_2O_3 content for a given CaO/CaF_2 ratio, and increases with increasing CaF_2 content when the CaO/Al_2O_3 molar ratio was less than about 2, but became unaffected by CaF_2 content when the ratio exceeded about 2. These observations were interpreted that CaO depolymerized the Al_2O_3 network, allowing for nitrogen to exist as both free and non-bridging nitrides, and that CaF_2 assisted in depolymerization and hence increased nitrogen solubility, provided that there was a sufficient amount of network to be depolymerized. A diagram of iso-nitride capacity was drawn for the $CaO–Al_2C_3–CaF_2$ ternary system at 1 773 K, and the nitride capacity was related to the optical basicity of the melt to obtain the following correlation equation:

$$\log C_N = 7.442\Lambda - 19.05$$

(cf. *ISIJ Int.*, **41** (2001), 239)

Casting and Solidification

Inclusion particle growth during solidification of stainless steel

M.SUZUKI et al.

Inclusion particles in stainless steel were investigated in continuously cast slabs in a full scale caster and ingots cast in several kinds of molds under laboratory conditions. Under such conditions particle size near slab surfaces was seen to be smaller. However, it was increasing with increasing depth going into the slab interior. In order to understand the mechanism of inclusion particle growth we applied four different mathematical models to predict the size distribution of particles. Of the four, the Ostwald ripening model, usually only applied to aqueous colloid phenomena, provided the best correlation with experimental results. This suggests that particles formed during solidification grow by "diffusion coalescence" due to the difference in solubility of neighboring particles which in turn is dependent on particle size.

(cf. *ISIJ Int.*, **41** (2001), 247)

Forming Processing and Thermomechanical Treatment

Effect of thermomechanical processing on the microstructure and properties of a low carbon copper bearing steel

M.K.BANERJEE et al.

A boron treated copper bearing HSLA steel containing austenite formers like manganese and nickel, somewhat lower in amount than that in HSLA 100 variety of steel is chosen for the study. The role of thermomechanical processing on the microstructure and mechanical properties of the above steel has been investigated. Differential scanning calorimetric study is carried out for understanding the precipitation behaviour of copper in HSLA steel under the influence of boron. The microstructure of the experimental steel is found to consist of laths of marten-

sites and bainite. MA constituents of ribbon like morphology are observed at the lath boundaries. Higher strength properties of the steel are attributed to the presence of finely distributed precipitates of copper and microalloy carbides.

(cf. *ISIJ Int.*, **41** (2001), 257)

Effects of nitrogen, niobium and molybdenum on strengthening of austenitic stainless steel produced by thermo mechanical control process

M.TENDO et al.

Thermo mechanical control process (TMCP) applied to high nitrogen austenitic stainless steels could produce high-strength thick plates with a 0.2% proof stress of higher than 600 MPa. The effects of nitrogen, niobium and molybdenum on the strengthening have been examined by hot compression tests around 1 223 K. The hardness of the compressed specimens linearly increased with increasing the nitrogen content, and the increment in hardness was larger than that of the specimens in a recrystallized state. This could be explained in terms of enhanced work-hardening by nitrogen addition during hot compression. In fact, the flow stress linearly increased with increasing the nitrogen content. The planar dislocation structure observed in the specimens with high nitrogen contents also gave evidence that nitrogen affected the work-hardening behavior. Although it was not clear that nitrogen affected dislocation glide or dynamic recovery, it could be predicted that nitrogen addition was effective in increasing the dislocation density. Since niobium (~0.1 mass%) had a marked effect on retarding the static recrystallization, probably owing to the fine precipitates of NbN, niobium addition is an effective way to prevent softening before accelerated cooling in TMCP.

(cf. *ISIJ Int.*, **41** (2001), 262)

Optimization of hot free forging condition for the uniformity of forged shape by three dimensional rigid-plastic finite element analysis

K.TAMURA et al.

Focusing on the rough forging stage of the hot free forging process, the influence of the operational conditions on the occurrence of concave defects was first numerically analyzed using a three dimensional rigid-plastic finite element method. The validity of the analysis was examined by laboratory experiments using lead billets and the analytical results are in good agreement with experimental results. As a result, the mechanism through which the concave defects appear was clarified, and it was revealed that by applying only a small curvature to a plane surface of an anvil, the concave defects is enormously improved. Moreover, it was found that the new anvil geometry makes it possible to increase the productivity.

(cf. *ISIJ Int.*, **41** (2001), 268)

Surface Treatment and Corrosion

Quantitative analyses of crystalline compositions of iron rust on automobiles under service conditions

S.FUJITA et al.

Quantitative analyses of the crystalline composition of rust that formed on automobiles under service conditions was carried out to investigate the corrosion mechanism of zinc-coated steel panels. The composition of the rust was quantitatively analyzed by X-ray diffraction using the internal-standard technique. The rust compositions in the crevice and on the surface of the outer panels were located within each characteristic region in the α-FeOOH/(γ-FeOOH+Fe_3O_4)/remainder ternary diagram that we proposed in the present study. The rust in crevices contained more (γ-FeOOH+Fe_3O_4) than that on the surface. The largest amount of amorphous iron rust formed in the crevices of galvanized steel panels under zinc corrosion products during the initial stage of steel corrosion. Crystalline β-FeOOH then appeared until the amount reached a maximum content of 13%. The composition of iron rust on zinc-coated steel sheets progresses towards that of the ungalvanized regions. It was found that the production of crystalline iron rust was retarded when zinc corrosion product formed in the crevice of lapped areas.

(cf. *ISIJ Int.*, **41** (2001), 275)

Transformations and Microstructures

Effect of Mo and W on the phase stability of precipitates in low Cr heat resistant steels

K.MIYATA et al.

Effects of Mo and W on creep strength of low Cr heat resistant steels have been investigated from the stand points of the phase stability of precipitates during long-term exposure at the elevated temperatures. The study on 2.25%Cr–Mo–V–Nb (Mo-steel) and 2.25%Cr–W–V–Nb (W-steel) with a same amount of Mo-equivalent has shown that the substituting W for Mo retards the evolution of microstructure, and thus remarkably improves the creep rupture strength. TEM observations have suggested that the most important precipitates strongly affecting the stability of microstructure are M_6C type carbide and MC type carbide in both Mo-steel and W-steel. It is found that the M_6C carbide precipitates with concentration of Mo and W during long-term aging. Therefore, the amounts of solute Mo and W supersaturated in matrix have reduced to the thermal equilibrium levels with changing the substructure from bainite lath structure to sub-grain liked structure. The kinetics of Mo- and W-partitioning between matrix and M_6C carbide has been successfully expressed by a Johnson-Mehl-Avrami type equation and estimated the activation energy for diffusion of solutes; 125 kJ/mol in Mo-steel and 219 kJ/mol in W-steel. Thus the diffusion rate of W is suggested to be definitely lower than that of Mo. Furthermore, Mo- and W-partitioning to MC carbides have also been confirmed to affect the coherency and the growth rate of MC carbides. TEM observations on the strain image have shown that the MC carbide in Mo-steel has already lost the coherency with matrix. On the other hand, the finer MC carbide in W-steel has kept the coherent relationship with matrix even after long-term aging. It is concluded that W-steel is superior to Mo-steel in the stabilization of bainite lath structure and precipitates at elevated temperatures, resulting in the higher creep strength.

(cf. *ISIJ Int.*, **41** (2001), 281)

Effects of alloying elements on mechanical properties and phase transformation of cold rolled TRIP steel sheets

S.C.BAIK et al.

Tensile and dilatation tests were conducted in order to study the effects of Mn, Si and Nb on the transformation behavior in the 0.14C–(2.1~2.4)Mn–(0.5~1.0)Si–(0.00~0.02)Nb TRIP steels. All the specimens for dilation tests were annealed under the condition to form the same austenite fraction, followed by cooling to the austempering temperature. The volume fraction of bainite transformed during austempering, ΔV_B, and the martensite start temperature, M_s, were measured. ΔV_B was dependent on the austempering temperature and a minimum in ΔV_B was obtained at 450°C for all the examined steels. The M_s temperature was linearly decreased as ΔV_B was increased. The decreasing rate of M_s to ΔV_B was not dependent on the steel composition, but on the austempering temperature, exhibiting the maximum value when the austempering temperature was 450°C. It was also observed that volume fraction of retained austenite was linearly increased with the decrease of M_s for the steels austempered at various conditions. The highest elongation was obtained when the rate of M_s to ΔV_B was the maximum. M_s was increased when the amount of Mn was increased from 2.1% to 2.4%. It was because Mn retarded the ferrite transformation rate, so that the soluble C diffused from the ferrite to the austenite was decreased. The addition of Si decreased M_s because it activated the diffusion of C to austenite during the cooling to the austempering temperature. The addition of Nb was observed to give little influence on ΔV_B and the M_s.

(cf. *ISIJ Int.*, **41** (2001), 290)

Mechanical Properties

Influence of microstructural morphology and prestraining on short fatigue crack propagation in dual-phase steels

K.NAKAJIMA et al.

The ferrite–martensite dual phase (DP) steels offer a better combination of strength and ductility than other conventional steels with equivalent static strength which are generally used in the automobile industry. The continuous martensite phase in DP steels seems to play an important role in determining fatigue properties and be a key factor to gain a higher resistance to fatigue. Additionally it is very important from a practical point of view to improve the fatigue properties after prestraining or cold working. The effects of microstructural morphology and prestraining on the propagation behavior of