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Transformations and Microstructures

Microstructure refinement of structural steel in china (Review)

Y.WENG

In Oct. 1998 Chinese government opened national program: "Fundamental Research on New Generation of Iron and Steel Materials in China" (N.G. Steels). The progress of on-going project has been briefly reported in this paper. In order to get microstructure refinement in structural steels, the following 5 ways have been studied:

For Ferrite+Pearlite microstructure in plain carbon steels and low-alloy steels,

(1) Purified steel-making→Fully equiaxed continuous casting→Rough-mill with higher Zener–Hollman parameter (γ-DRX refinement)→Finishing-mill rolling by Deformation Induce Ferrite Transformation (DIFT) technology.

(2) For thin-slab continuous casting and rolling (CSP) process, ultra-fine sulfides (20–60 nm) and oxides (5–20 nm) controlling technology.

(3) For Low Carbon Bainite (and Ultra Low Carbon Bainite) microstructure (LCB/ULCB) in microalloyed steels, combination of Deformation Induced Precipitation (DIP) and subsequent middle temperature phase transformation controlling.

For quench-temperated martensite microstructure in alloy structural steels:

(4) Ultra-fine γ grains by innovated heat treatment and alloy design;

(5) Carbide-free bainite/martensite microstructure with retained γ films along lath/sub-lath boundaries.

(cf. *ISIJ Int.*, **43** (2003), 1675)

Fundamentals of High Temperature Processes

Sulfur transfer in dynamic conditions of liquid steel drops falling through slag layer

S.-M.KANG et al.

The rate of desulfurization was investigated by allowing liquid iron droplets to fall through a CaO–Al_2O_3–MgO slag layer at 1 600°C. Droplet falling velocity decreased by increasing the sulfur content in the metal. The sulfur transfer was well represented by a first order reaction rate with respect to the sulfur concentration of the metal. The rate of desulfurization during dynamic contact while falling through the slag layer was about two orders of magnitude larger than that of the static contact between the metal and slag. The enhanced rate of desulfurization during the dynamic contact was attributed to the combined effect of (1) the continual contact of fresh slag while falling, (2) enhanced internal circulation in the metal phase, and (3) most importantly, emulsification of the metal/slag interface, which greatly increases the reaction area. The rate of desulfurization was affected to a large extent by slag composition. It was tentatively concluded that slag composition influences the rate of desulfurization by affecting both emulsification of the metal/slag interface and the interfacial reaction of sulfur transfer.

(cf. *ISIJ Int.*, **43** (2003), 1683)

Effect of silicon and carbon on the evaporation rate of copper in molten iron

H.ONO-NAKAZATO et al.

In order to increase the evaporation rate of copper in molten iron, the addition of silicon or carbon, which has a strong affinity with the solvent metal, iron, is considered to be effective, because the activity coefficient of copper can be expected to increase. Accordingly, the effects of silicon and carbon on the evaporation rate of copper in molten iron have been investigated. It is found that the rate constant of copper evaporation has a maximum value at the silicon content of about 3 mass%. The apparent rate constant at 3 mass% Si is about 1.4 times larger than that for Fe–Cu alloy. The apparent rate constant of copper evaporation for Fe–C–Cu alloy monotonically increases with increasing the carbon content. The rate constant at 2 mass% C is about 1.7 times larger than that for Fe–Cu alloy. At a practical reduced-pressure of 133 Pa, the rate constant of copper evaporation which is large enough to be equivalent to that in the case of the chemical reaction rate-limiting for Fe–Cu alloy was attained in the present study.

(cf. *ISIJ Int.*, **43** (2003), 1691)

Characteristics of iron entrainment into slag due to rising gas bubbles

Z.HAN et al.

Iron droplets can be entrained into the slag phase when gas bubbles pass through the molten iron/slag interface. The entrainment phenomena occurring during passage of single bubbles through the interface were investigated by using *in-situ* X-ray transmission (fluoroscopic) techniques and by collecting and measuring the entrained iron droplets. The effects of bubble size, interfacial tension and viscosity of the slag on the iron droplets entrainment were investigated. The results showed that the mass of the entrainment increased with the increasing bubble size, but decreased with increasing interfacial tension and slag viscosity. A dimensionless equation was proposed to describe the relation between the entrainment of metal into slag and the above-mentioned parameters. This information can be used to optimize heat and mass transfer processes *e.g.* in ladle metallurgy and to reduce the financial loss due to metal discard within the slag.

(cf. *ISIJ Int.*, **43** (2003), 1698)

Deoxidation and desulfurization equilibria of liquid iron by calcium

K.TAGUCHI et al.

It is important to reduce the oxygen potential in steel in order to lower the sulfur content, and the addition of the strong deoxidizing agent, such as calcium, is considered to be most effective. The deoxidation and the desulfurization equilibria of liquid iron by calcium have been investigated at 1 873 K. The following thermodynamic values on the calcium desulfurization have been derived from the experimental results in the present study and in the previous studies by others.

$$CaS(s)+\underline{Ca}(\text{mass\%, in Fe})+\underline{S}(\text{mass\%, in Fe})$$

$$\log K=-6.23\ (\pm 0.56)$$

$$e_S^{Ca}=-22.4\ (\pm 6.4),\quad e_{Ca}^{S}=-28.0\ (\pm 8.0)$$

(at 1 873 K)

Using the thermodynamic data derived in the present study, the deoxidation and the desulfurization equilibria of liquid iron by calcium are proposed in the Fe–Ca–O–S system. The deoxidation and the desulfurization limits of liquid iron by calcium are calculated to be 1.6 mass ppm O (at 15 mass ppm Ca) and 3.5 mass ppm S (at 40 mass ppm Ca) under the condition of $a_{CaO}=a_{CaS}=1$ at 1 873 K.

(cf. *ISIJ Int.*, **43** (2003), 1705)

Steelmaking

Reaction model for carbon, manganese, and oxygen in bottom blowing with mixed gas in final stage of steel refining in converter

Y.KATO et al.

A theoretical study of the reaction rates of carbon, manganese, and oxygen was made, and the computational results were compared with experimental results from a commercial plant to enable prediction of the enhancement of the decarburization rate in the final stage of refining by bottom blowing with mixed gas. A reaction model which combines the stoichiometric and equilibrium relationships among carbon, manganese, and oxygen and their mass transfer rates was made for decarburization as a gas–metal reaction and for manganese and iron oxidation as slag–metal reactions. It was assumed that 1) addition of inert gas through submerged tuyeres contributes to bath stirring as well as to a decrease in CO pressure, and 2) all rate determining steps in the gas–metal and slag–metal reactions are the mass transfer of carbon, manganese, or oxygen in the molten steel. Fitting the parameters under a 1/1 oxygen–nitrogen flow rate ratio, the calculated metallurgical properties in ordinary blowing (bottom blowing with pure oxygen) agreed well with the experimental results. Calculations for certain operating factors showed that the decarburization rate increases and the oxidation rates of manganese and iron decrease as the bath temperature increases and the ratio of oxygen to inert gas decreases. The contribution ratio of the gas–metal reaction relative to the slag–metal reaction in bottom blowing with mixed gas is 6 to 9 times larger than that in top blowing with mixed gas.

(cf. *ISIJ Int.*, **43** (2003), 1710)

Casting and Solidification

Numerical simulation of inclusion removal in a billet continuous casting mold based on the partial-cell technique

Y.-H.HO et al.

A mathematical model has been developed to simulate the fluid flow behavior and subsequent inclusion removal rate in a billet continuous casting mold. The model is then used to evaluate the effects

of various nozzle designs and operating conditions on the removal of inclusions originally adhere to the continuous casting mold. The ultimate goal is to obtain the optimal design and operating condition to improve the steel cleanliness.

The numerical technique employed in this study is the SOLA-SURF technique incorporated with the partial-cell scheme, which can better approximate the geometry of the simulated system. Other than simulating the flow field of molten steel in the continuous casting mold, the pathlines of nonmetallic inclusions, which are affected by the interactions of inclusion particles and molten steel, are also calculated to directly access the effectiveness of inclusion removal.

The model is then tested on a circular billet continuous caster, which requires the model to have the capability to treat curved surfaces in the geometry of the simulated system. Various port designs in the submerged nozzle and operating conditions such as casting speed and submerged depth of the nozzle are evaluated with the calculated pathlines of the inclusion particles for their effects on the cleanliness of the steel. Results of this research show that the flow pattern in the mold region is affected by the design of the nozzle and operation of the caster. It also shows that submerged depth of the nozzle has a more profound effect on the efficiency of inclusion removal than the casting speed.

(cf. *ISIJ Int.*, **43** (2003), 1715)

Microstructure and cleanliness of rapidly solidified steels

O.VOLKOVA et al.

In the present work the relations between microstructure, cleanliness and solidification parameters of the low alloyed and high alloyed steels in the case of rapid solidification have been investigated. Rapid solidification was investigated experimentally under laboratory conditions by immersion of a cold copper rod into a steel bath. Samples from the frozen steel shell were investigated under an optical microscope. As a structure-relevant characteristic, the secondary dendrite arm spacing (SDAS) and the nonmetallic inclusion diameter have been obtained as a function of the distance from the contact area and the solidification conditions.

(cf. *ISIJ Int.*, **43** (2003), 1724)

Application of an optical DTA for morphological transition in the Al_2O_3–YAP–ZrO_2 metastable eutectic system

H.YASUDA et al.

This paper presents an optical DTA apparatus which is capable to examine the solidification behavior of the Al_2O_3-based materials. A direct current through the two Mo crucibles effectively heats specimen and reference up to 2 400 K. The small heat capacity of the crucible and the specimen enabled a cooling rate up to the order of 10^2 K/s. Since accuracy of temperature measurement by two two-color pyrometers was not affected by emissivity change to phase transformation, exothermic and endothermic heats in the specimen was efficiently detected at high temperatures. The developed apparatus was used to examine DTA for α-Al_2O_3 and the Al_2O_3–YAP–ZrO_2 metastable eutectic system. The morphological transition from the entangled eutectic structure to the lamellar eutectic structure was observed at a cooling rate around 10 K/s. At a cooling rate more than 70 K/s, α-Al_2O_3 phase started to solidify as a primary phase. Furthermore, the divorced eutectic solidification was recognized at a cooling rate of 360 K/s.

(cf. *ISIJ Int.*, **43** (2003), 1733)

Prevention of slab surface transverse cracking by microstructure control

T.KATO et al.

Slab surface transverse cracking is well known to be induced by strain concentration at film-like primary ferrite, *i.e.* allotriomorphs of ferrite formed along the austenite grain boundaries. In the present study, a new concept for the prevention of transverse cracking by means of microstructure control at continuous casting strand is examined. Three kinds of examinations in charge of each objective were conducted; (a) ingot cooling tests for microstructure control with secondary cooling; (b) hot tensile tests for hot ductility with the microstructure; and (c) continuous casting tests for cracking susceptibility on continuously cast slab. Results obtained are concluded as follows.

(1) Slab surface microstructure could be controlled by secondary cooling condition. Surface structure control (SSC) cooling, providing intensive cooling until less than A_3 transformation temperature just below mold and subsequently reheated up to 1 250 K in secondary cooling, brings film-like ferrite free structure.

(2) Hot tensile tests subsequent to *in-situ* remelting and solidification prove that hot ductility is much improved and ductility trough almost disappeared with that microstructure control. The results also confirm that *in-situ* remelting of specimen is indispensable on the hot tensile test to evaluate the effect of microstructure on susceptibility to transverse cracking.

(3) Continuous casting test confirms that susceptibility to transverse cracking could be alleviated with this microstructure control.

(4) The prevention of transverse cracking and microstructure control is a result of uniform fine precipitates dispersion, such as (Ti, Nb)(C, N), according to SSC cooling.

(cf. *ISIJ Int.*, **43** (2003), 1742)

Evaluation of grain density on the surface of a solidified shell

H.ESAKA et al.

Refinement of the solidified structure is of importance for soundness of cast products. Formation of the grains on the surface is very important for the understanding of evolution of solidified structure. The evaluation method for grain density on the chill plate is proposed in this study.

Using an engineering model for grain selection, which has been separately developed, the number of grain decreases linearly in a first stage of solidification. Therefore, the solidified structure should be observed at least two cross sections. Extrapolating the data to the chill surface, the grain density on the surface can be evaluated.

Validity of the proposed method has been checked using Al–10mass%Cu alloy. A solidified shell, which was produced by dipping a chill plate in a molten alloy, has been closely observed. A grain is defined as a group of the dendrites that have the same orientation. Densities of grains were measured at two cross sections. Extrapolating these data to the surface, the grain density on the surface has been estimated. This estimated value agrees well with the density of grains, which was directly measured on the surface of the solidified shell.

(cf. *ISIJ Int.*, **43** (2003), 1751)

Phase-field modeling of rapid solidification in small alloy droplets

S.G.KIM et al.

Phase field modeling has been applied first to simulate microstructural evolution during rapid solidification of small Al–0.02 mole fraction Cu alloy droplets. We use a phase-field model with the parameters determined at a finite interface thickness condition. Numerical computation is stable over a wide temperature range because same interface energy and interface thickness are applied during computation by using temperature dependence of phase field parameters. For numerical efficiency, we adopted rather thick interface thickness, large interface energy and small interface kinetics coefficient, compared with reported values. Nevertheless, overall features of microstructural evolution presented in this study show close resemblance with the reported theoretical predictions and experimental results; initial dendrite/plane-front transition when the nucleation undercooling is small, plane-front/cell and cell/dendrite transition in high interface velocity regime, complete disappearance of dendritic structure in high heat transfer coefficient and deflection phenomena in cellular growth direction.

(cf. *ISIJ Int.*, **43** (2003), 1758)

Chemical and Physical Analysis

Flow injection analysis of phosphorus in steel using filter tube preconcentration

K.WATANABE et al.

A flow injection analysis (FIA) of phosphorus using coprecipitation with beryllium hydroxide was performed. An on-line preliminary concentration method using a filter tube was developed and this method was applied to the determination of phosphorus in steel. Phosphorus was coprecipitated with beryllium hydroxide by increasing the pH of the medium in the flow tube, and the precipitate was collected with the filter tube (pore size: 1.0 μm, inner diameter: 1.0 mm, length: 7 cm). The precipitate collected was eluted with an acid. The resulting eluate was allowed to react with ammonium molybdate in the presence of antimony, and was then reduced with ascorbic acid. The amount of the phosphorus–antimony–molybdenum ternary complex thus formed was determined spectro-photometrically to be 890 nm. Concentration was performed for 10 min at a flow rate of 0.75 mL/min and the acid

used for elution was 1 M HNO_3. During sample preparation, matrix iron was reduced with sodium hydrogen sulfite and masked with EDTA. The concentration process yielded a sensitivity of analysis about 25 times higher than that of conventional methods. In 0.03 g of steel sample, the method proposed here gave measurements equivalent to those of the phosphorus contents in standard steel samples (JSS 061-6, 230-5, 231-4, and 501-5), and were thus in good agreement with the guaranteed values. The possible range of phosphorus determination is from 0.0021 to 0.017% in steels.

(cf. *ISIJ Int.*, **43** (2003), 1767)

Forming Processing and Thermomechanical Treatment

Investigation of the thermo-mechanical behavior of type 304 stainless slab in hot charge rolling condition by the finite element method

C.G.SUN et al.

A finite element-based, integrated process model is presented for a three dimensional, coupled analysis of the thermal and mechanical behavior of type 304 stainless slab during hot charge rolling (HCR) and cold charge rolling (CCR) processes. The validity of the proposed model is examined through comparison with measurements. The susceptibility on micro-crack initiation or propagation due to the thermal stress in these two different process conditions was examined. The model's capability of revealing the effect of diverse process parameters is demonstrated through a series of process simulation.

(cf. *ISIJ Int.*, **43** (2003), 1773)

Deformation and annealing behavior of nitrogen alloyed duplex stainless steels. Part I: Rolling

J.KEICHEL et al.

The deformation behavior, *i.e.* the microstructure development and the deformation mechanisms in nitrogen alloyed ferritic–austenitic duplex stainless steels were studied by means of microstructure investigations and texture measurements in both phases. By comparison with corresponding single phase bcc and fcc materials and Taylor type deformation texture simulations it was possible to reveal the influence of the complementary phase on deformation of each phase during hot and cold rolling. To determine the effect of nitrogen on the deformation mechanisms the nitrogen content in the investigated steels was varied between 0.15 to 0.62%. The investigations prove that during rolling both phases deform similar to the respective single phase material and that there is a minor influence of the second phase on the deformation mechanisms due to the morphological constraints of the typical microstructure in rolled duplex materials.

(cf. *ISIJ Int.*, **43** (2003), 1781)

Deformation and annealing behavior of nitrogen alloyed duplex stainless steels. Part II: Annealing

J.KEICHEL et al.

The softening behavior of ferritic–austenitic duplex stainless steels (DSS) was investigated separately for both phases by means of microstructure investigations and texture analysis. The results were compared to those of similar single phase materials in order to unveil the influence of the second phase on the specific softening mechanisms during annealing after cold rolling. The microstructure and texture development during hot and cold rolling of the investigated duplex steels was subject of a previous paper.[1] Based on those results this part describes the softening behavior observed during annealing in both a salt bath furnace and a conventional furnace. During annealing the rolled microstructure changes to a more isotropic morphology without pronounced coarsening of the constituent phases. Due to the layer character of the microstructure generated during rolling the recrystallization of the austenite phase is shown to be subject to constrained nucleation conditions and thus leads to textures different from textures of fcc single phase materials. Depending on the degree of deformation and on the initial cold rolling texture the ferrite phase undergoes recovery or recrystallization, but recovery dominates the softening of the bcc phase. Despite of the layered microstructure the active softening mechanisms of ferrite are the same as known from bulk single phase materials and obviously are negligibly influenced by the presence of the austenite phase.

(cf. *ISIJ Int.*, **43** (2003), 1788)

Deformation induced surface roughening of austenitic stainless steels

M.BAYDOGAN et al.

This is an investigation on examination of deformation induced surface roughening behavior of two AISI 304 quality austenitic stainless steel sheets, having ASTM grain size numbers of 7 and 8. In as-received condition, surface roughness of the fine-grained steel was higher than that of the coarse-grained steel, where the roughness increased gradually during plastic deformation. The rate of roughening increased with increasing grain size. Coarse-grained steel exhibited rougher surface than fine-grained steel after longitudinal strain of 11%, during uniaxial tensile loading.

(cf. *ISIJ Int.*, **43** (2003), 1795)

Surface Treatment and Corrosion

Silver containing stainless steel as a new outlook to abate bacterial adhesion and microbiologically influenced corrosion

K.R.SREEKUMARI et al.

Biofouling and microbiologically influenced corrosion (MIC) are alarming processes of material deterioration. The scenario originates from the attachment of microorganisms as quickly as a material is immersed in a non-sterile environment. Stainless steels, in spite of their wide use in different industries and as appliances and implant materials, do not possess inherent antibacterial properties. To make stainless steel antibacterial and thus to mitigate MIC and bacterial infection was the purpose of this study. AISI type 304 stainless steels containing silver as an alloying element and silver coated are tested for the antibacterial efficacy as well as MIC resistance keeping plain stainless steel as control. Experimental coupons were exposed to a dilute nutrient medium containing *Pseudomonas* sp., isolated from a corrosive ground water environment. Coupons were exposed for varying duration (maximum 6 days), and bacterial adhesion was monitored by using epi-fluorescence microscope and quantified with the help of image processing software. In another experiment, free corrosion potential of these materials was monitored for 60 days. The area of bacterial adhesion was found to be significantly lesser in case of silver containing coupons compared to control. Silver alloyed coupons showed better antibacterial effect than the silver-coated coupons. Free corrosion potential showed ennoblement in the case of control coupons, while silver alloyed and silver coated coupons showed substantially lesser fluctuation. SEM observation showed pitting corrosion by 30 days in control coupons, whilst, pits were near nil on silver alloyed and very less on silver coated coupons. The results, thus suggest that silver containing stainless steels possess antibacterial properties and are resistant to MIC as compared to 304 SS. Furthermore, a field study, where the coupons were exposed to a freshwater pond showed that coupons containing silver possessed significant resistance to microfouling build-up until a period of 30 days, suggesting the possibility of using these materials in freshwater environments where microfouling is a persistent problem. As an attempt to investigate the actual damage the silver caused in the bacterium, cell walls and intracellular changes were observed under a transmission electron microscope (TEM).

(cf. *ISIJ Int.*, **43** (2003), 1799)

Transformations and Microstructures

Solubility product of VN in austenite of high Cr heat resistant steel

M.TAMURA et al.

Dissolved V in austenite of 7%Cr–0.4%V–0.09%N steel (hereinafter, % means mass%) was measured and the solubility product of VN was determined as follows:

$$\log([\%V][\%N]) = 4.38 - \frac{8436}{T}$$

where T is the absolute temperature in K. The solubility product obtained is 3 to 5 times larger than those in the literature and about one order larger than that for iron. The decrease in the activity coefficient of nitrogen due to the presence of Cr and V in the experimental steel is responsible for the increase in the solubility product of VN.

(cf. *ISIJ Int.*, **43** (2003), 1807)

Sensitisation and evolution of chromium-depleted zones in Fe–Cr–Ni–C systems

T.SOURMAIL et al.

The development of chromium concentration profiles in austenitic stainless steels, due to the grain boundary precipitation of carbides has been modelled, taking account of multicomponent effects, both in the estimation of the state of equilibrium at

the carbide/matrix interface and in diffusion. A comparison against published experimental data shows that the theory accounts for the development of the depleted zone as well as self-healing, unlike recent work where these effects are treated as separate phenomena. At the same time, the present model preserves local equilibrium at the precipitate–matrix interface and provides a natural explanation for the observation of delays in reaching the minimum chromium content.

(cf. *ISIJ Int.*, **43** (2003), 1814)

Acceleration of low-temperature bainite

C.GARCIA-MATEO et al.

Recent work has shown that bainitic ferrite plates produced by transformation at low temperatures can be as thin as 20 nm with a hardness in excess of 650 HV. However, it may take several days in order to achieve the required degree of transformation at low temperatures. In this work we report methods for accelerating the rate of reaction without compromising strength.

(cf. *ISIJ Int.*, **43** (2003), 1821)

Comparison of precipitation kinetics and strengthening in an Fe–0.8%Cu alloy and a 0.8 % Cu-containing low-carbon steel

A.DESCHAMPS et al.

The precipitation kinetics and associated change in mechanical properties (hardening and strain hardening rate) have been compared in a Fe–Cu alloy and a Cu-containing low-carbon steel of identical copper content (0.8 wt%). A combination of experimental techniques (TEM, Small Angle X-ray Scattering, tensile tests) have been used to quantitatively determine the precipitation phenomena during ageing at 500°C, including the influence of the presence of dislocations prior to the ageing treatment. The precipitation phenomena are shown to be qualitatively identical, in terms of nucleation size, influence of dislocations on the precipitation reaction, or influence of precipitation on the strain hardening rate. However, the growth kinetics of precipitates is shown to be much faster in the steel. Similarly, the time to peak hardness is reduced in the steel. Further, the net precipitation hardening capability is reduced in the steel as compared to the Fe–Cu alloy. The results are discussed in terms of the influence of Mn and C on the precipitation and hardening processes.

(cf. *ISIJ Int.*, **43** (2003), 1826)

Effect of manganese segregation on fine-grained ferrite structure in low-carbon steel slabs

T.YAMASHITA et al.

Using a 100 mm thick continuously cast slab with a chemical composition of 0.10C–0.16Si–0.58Mn–0.01P–0.003S (mass%), we have clarified the effect of the manganese segregation on the transformed ferrite structure when the slab was reheated to make austenite grains equi-axed and smaller and followed by the Grain Refinement Process (GRP) of heavy compression and subsequent controlled cooling. Samples from which the Mn segregation was eliminated were also prepared for comparison. The resultant microstructure was examined for compressive strains between 0.7 and 2.1.

When the austenite grain size is 160 or 120 μm prior to GRP, the ferrite grain size of the samples with the Mn segregation is smaller at the given strain than that of the samples from which the Mn segregation was eliminated. The Mn band formed by the heavy compression is thought to act as a barrier in the form of a relatively stable austenite against the ferrite growth.

Moreover, we found a unique equation to predict the transformed ferrite grain size in the samples with the Mn segregation. Namely, the ferrite grain size can be accounted for according to a parameter, ES (effective spacing): a mean spacing that considers both the pancake austenite grain boundary and the Mn band. We also suggest that the smaller Mn band spacing may make the ferrite structure finer even when the austenite grain size is large.

(cf. *ISIJ Int.*, **43** (2003), 1833)

Effect of chromium, boron and manganese additions on the deformation and recrystallization textures of warm rolled low carbon steels

M.R.TOROGHINEZHAD et al.

The effect of solute carbon content, as well as of chromium, boron and manganese addition, on the warm rolling behavior was investigated. Both the as-rolled and recrystallized microstructures and textures were assessed after rolling at temperatures between 440 and 780°C. In an unalloyed low carbon (LC) steel, intense in-grain shear bands were formed at low rolling temperatures, but this intensity was drastically reduced at higher temperatures. Alloying with chromium and boron significantly enhanced the development of shear bands at the higher rolling temperatures. The intensities of the deformation textures produced were little changed with rolling temperature in the IF steel, but increased markedly with temperature for the LC grade. Conversely, the strength of the LC steel recrystallization texture decreased with increasing temperature. The addition of chromium to the low manganese steel somewhat strengthened the {111} component of the annealing texture at the higher rolling temperatures. However, boron addition resulted in a retained rolling component and severely disrupted the recrystallization textures. A higher manganese level was also detrimental to the development of the ND fibre components. These differences are attributed to variations in the dynamic strain aging and precipitation behaviors of the various materials attributable to their differing alloy contents.

(cf. *ISIJ Int.*, **43** (2003), 1842)

Mechanical Properties

Influence of phosphorus and boron on hydrogen embrittlement susceptibility of high strength low alloy steel

S.KOMAZAZKI et al.

Hydrogen-charged miniaturized Charpy-type specimens were subjected to three-point bending tests to investigate an influence of phosphorus and boron on the hydrogen embrittlement (HE) susceptibility of high strength low alloy (HSLA) steels for bolts. The tests were carried out under wide variety of deformation rate to examine an effect of deformation rate on the susceptibility also. The experimental results revealed that the HE susceptibility increased with decreasing deformation rate. This dependence of susceptibility on deformation rate seemed to be associated with velocity relations between the deformation rate and the diffusion rate of hydrogen. The susceptibility was more pronounced by the addition of phosphorus, even though the phosphorus segregation was not sufficient by itself to cause temper embrittlement. On the other hand, boron had almost no influence by itself on the susceptibility. A cyclic voltammetry and thermal desorption spectroscopic analysis were conducted for understanding the change in HE susceptibility with phosphorus and/or boron from the point of view of hydrogen adsorption/absorption characteristics, respectively. However, it was hardly observed that those elements influenced the hydrogen content and the trapping site of hydrogen in the steel under the present hydrogen charging condition. Consequently, it was considered that the increase in HE susceptibility with phosphorus mainly resulted from the reduction in grain boundary strength due to phosphorous, rather than the variation in hydrogen adsorption/absorption characteristics.

(cf. *ISIJ Int.*, **43** (2003), 1851)