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Physical metallurgy of modern high strength steel sheets (Review)

T. Senuma

Lightening of automobile bodies is required from the viewpoint of saving energy which contributes to ameliorating an ecological problem. A useful means of doing this is the application of high strength steel sheets to automobile bodies. The inferior formability of high strength steel sheets in comparison with that of mild steel sheets, however, hinders their broad application. But in recent years, many high strength steel sheets with good formability have been developed using sophisticated physical metallurgy.

In this paper, the recent development of modern high strength steel sheets is reviewed paying special attention to their physical metallurgy which realized the improvement of their formability.

(cf. *ISIJ Int.*, **41** (2001), 520)

Mechanisms and modelling of microstructure/texture evolution in interstitial-free steel sheets (Review)

B. Hutchinson et al.

Evidence relating to mechanisms of recrystallisation and associated texture evolution in low carbon steels is briefly reviewed and some new observations are presented. These viewpoints are taken as the starting point for development of a computer model that can be used to predict the effects of steel chemistry and process parameters on the grain structures and textures of titanium-stabilised interstitial-free steel sheets. The model utilises physical principles as far as possible and combines these with empirical descriptions where necessary, fitting these with the aid of experimental data. Assumptions made in the model are clearly described.

(cf. *ISIJ Int.*, **41** (2001), 533)

Development of steel plates by intensive use of TMCP and direct quenching processes (Review)

C. Ouchi

Historical progress of Thermo-Mechanical Processing (TMP) in steels during a last half century is briefly reviewed in the first part of this paper. Online accelerated cooling process in a wide plate mill was developed by a Japanese steel mill in the end of 1970's, and its equipment was installed into major steel plate mills in Japan and Europe in 1980's. The combination of controlled rolling and accelerated cooling called as TMCP provided a powerful means for microstructural control of hot rolled steel plates. Subsequently, direct quenching (DQ)-tempering process was industrialized, where direct quenching after finish-rolling was performed at the highest cooling rate available in the accelerated cooling equipment. Since then, various new steel plates have been developed by intensive use of TMCP and direct quenching process particularly in Japan. In the latter part of this paper, newly developed steel plates by use of TMCP or DQ process during last two decades were summarized based on classification of line pipe steel, weldable HSLA steel plates used for shipbuilding, offshore construction, building, bridge or penstock, and austenitic stainless steel plate. Various strengthening mechanisms such as grain refinement, precipitation hardening or strengthening due to transformed microstructures have been utilized in development of numerous TMCP and DQ steel plates.

(cf. *ISIJ Int.*, **41** (2001), 542)

Microstructural evolutions with precipitation of carbides in steels (Review)

Y. Ohmori

The studies on the crystallographic features of diffusional transformation of austenite in various steels have been reviewed. A primary ferrite forming at an austenite grain boundary is related to at least one of the austenite grains separated by the boundary with the Bain correspondence. In the case of the microstructures containing both ferrite and carbides such as pearlite, degenerate pearlite, interphase precipitation of alloy carbides, and upper and lower bainites, the crystallographic relationships between ferrite and carbides provide further information to elucidate the transformation mechanisms. In the present report, therefore, the orientation relationships between ferrite, carbide and austenite as well as the habit planes of platelike transformation products and the mechanisms of transformations are discussed.

(cf. *ISIJ Int.*, **41** (2001), 554)

Physical metallurgy of steel weldability (Review)

N. Yurioka

The concept of hardenability used in the welding field differs from that used in the heat treatment. It represents the hardened depth after quenching in the heat treatment while it is related with the welding condition for fully hardened heat-affected-zone (HAZ) in the welding. The effect of steel chemical composition on hardenability is expressed by a multiplying factor for the former and by carbon equivalency for the latter. The metallurgical relation between these two factors can be clarified by a heat conduction analysis of a quenched round bar.

Steel weldability means susceptibility to hydrogen-assisted cold cracking which mostly occurs in the welding of high strength steels. Many carbon equivalents with different coefficients have been proposed to assess the cold cracking susceptibility which is affected greatly by the hardness at HAZ. Since the HAZ hardness is interactively determined by the carbon content and hardenability, carbon equivalency for assessing susceptibility to cold cracking must consider this interactive effect.

Toward the international standardization of the guideline for the avoidance of cold cracking, the methods based on different carbon equivalency are discussed.

(cf. *ISIJ Int.*, **41** (2001), 566)

Microstructure development by thermomechanical processing in duplex stainless steel (Review)

T. Maki et al.

In the case of two-phase alloys, a refinement of matrix phase and a uniform distribution of second phase are important to improve mechanical properties. In this paper, microstructure change of α (ferrite)+γ (austenite) two-phase structure, especially microduplex structure consisting of α and γ in a fine-grained form (1–3 μm), in the duplex stainless steel by various thermomechanical processings and heat treatments is briefly reviewed. Main topics are as follows, 1) formation process of fine-grained $\alpha+\gamma$ structure (microduplex structure) by various thermomechanical processings, 2) nature of microduplex structure and its stability during prolonged aging, 3) microstructure change of microduplex structure by annealing after heavy cold rolling and 4) microstructure change of microduplex structure during superplastic deformation.

(cf. *ISIJ Int.*, **41** (2001), 571)

The influence of nitrogen on microstructure and properties of highly alloyed stainless steel welds (Review)

S. Hertzman

The influence of nitrogen on the microstructure and properties of austenitic and duplex stainless steel welds is reviewed. Three aspects are covered: intermetallic phase formation, nucleation and growth of austenite in ferrite and nitrogen balance in TIG welding.

The effect of nitrogen on the precipitation of deleterious intermetallic phases is analysed for duplex and austenitic steels by thermodynamic means and the differences in response of nitrogen alloying illuminated. Also the replacement of molybdenum by tungsten is discussed.

Nitrogen alloying made the duplex grades weldable. The duplex steels, designed to comprise approximately equal amounts of ferrite and austenite, solidify in a ferritic mode and a rapid transformation of ferrite to austenite is a prerequisite. Nitrogen has a beneficial effect on the austenite reformation in the HAZ (Heat Affected Zones) on cooling. This has been confirmed by both experiments and calculations. Attempts have been made to improve the nucleation of austenite and thus to increase the possibilities for welding by more demanding techniques which involve rapid cooling through the critical temperature range 1 350°C to 1 000°C.

Nitrogen is added to many of the modern stainless steels because of its favourable effects on both strength and corrosion resistance. This implies that the welding procedure must consider the risk of nitrogen escape from the weld pool. Avoiding nitrogen losses may be accomplished by applying *e.g.* nitrogen-containing shielding gas. Applying balanced shielding gases is generally successful but on occasion reproducibility problems may arise. Correcting measures require insights in the process and the mechanisms controlling the nitrogen fluxes in TIG welding. These can be illuminated using a simple process model that accounts for alloy composition, shielding gas nitrogen content, weld pool shape and size. It is suggested that the main reasons for lack of reproducibility may be found in the batch to batch variation in surfactant content that controls the weld pool shape *via* the Marangoni effect and surface mass transfer reactions.

(cf. *ISIJ Int.*, **41** (2001), 580)

Function of hydrogen in embrittlement of high-strength steels (Review)

M.NAGUMO

Various models so far proposed for the mechanism of hydrogen embrittlement (HE) of steels are critically reviewed with respect to the manifestation of hydrogen in the fracture process. Recent studies that elucidate the hydrogen states and their relevance to HE are discussed. Particular attention is paid to the role of deformation-induced defects that interact with hydrogen. A model is proposed in which increased vacancy density and agglomeration lead to the promotion of failure. The model ascribes HE to the context of ductile fracture in which vacancies play the primary role.

(cf. *ISIJ Int.*, **41** (2001), 590)

The limits of strength and toughness in steel (Review)

J.W.MORRIS, Jr. et al.

The ideal structural steel combines high strength with excellent fracture toughness. In this paper we consider the limits of strength and toughness from two perspectives. The first perspective is theoretical. It has recently become possible to compute the ideal shear and tensile strengths of defect-free crystals. While the ferromagnetism of bcc Fe makes it a particularly difficult problem, we can estimate its limiting properties from those of similar materials. The expected behavior at the limit of strength contains many familiar features, including cleavage on {100}, ⟨111⟩ slip on multiple planes, "conditionally" brittle behavior at low temperature and a trend away from brittle behavior on alloying with Ni. The behavior of fcc materials at the limit of strength suggests that true cleavage will not happen in austenitic steels. The results predict an ideal cleavage stress near 10.5 GPa, and a shear strength near 6.5 GPa. The second perspective is practical: how to maximize the toughness of high-strength steel. Our discussion here is limited to the subtopic that has been the focus of research in our own group: the use of thermal treatments to inhibit transgranular brittle fracture in lath martensitic steels. The central purpose of the heat treatments described here is grain refinement, and the objective of grain refinement is to limit the crystallographic coherence length for transgranular crack propagation. There are two important sources of transgranular embrittlement: thermal (or, more properly, mechanical) embrittlement at the ductile–brittle transition, and hydrogen embrittlement from improper heat treatment or environmental attack. As we shall discuss, these embrittling mechanisms use different crack paths in lath martensitic steels and, therefore, call for somewhat different remedies.

(cf. *ISIJ Int.*, **41** (2001), 599)

History of power plants and progress in heat resistant steels (Review)

F.MASUYAMA

During the last fifty years steam pressure and temperature in fossil-fired power plants have been continuously raised to improve thermal efficiency. Recent efforts for raising steam conditions are in response to the social demand for environmental protection as well as energy conservation concerns. Today the steam temperature of 600°C for modern power plants equipped with swing load or sliding pressure demand functions has already been realized, and a goal for the future is the 630°C to 650°C class with ferritic steels. However the 600°C to 630°C class is possible for current construction, based on already developed materials that include ferritic steels for pipework and rotors. Numerous studies on heat resistant steels actively conducted since the early 1970s have allowed great progress in both 9–12%Cr steels and austenitic steels. This paper presents a historical view of developments in steam pressure and temperature of fossil-fired power plants and alloy design for heat resistant steels in the 20th century, particularly over the last several decades, as well as a survey of the current status of steel development for power plants, mainly with regard to creep strengthening and enhancement of corrosion resistance.

(cf. *ISIJ Int.*, **41** (2001), 612)

Design of ferritic creep-resistant cteels (Review)

H.K.D.H.BHADESHIA

Creep resistant steels must be reliable over very long periods of time in severe environments. Their microstructures have to be very stable, both in the wrought and in the welded states. This paper reviews the quantitative methods for the design of steels for elevated temperature applications. A methodology is described for the calculation of complex precipitation reactions over periods extending many tens of years. However, microstructure alone is not enough in the design of alloys. The estimation of the creep rupture stress using a neural network technique is described in the second part of this review. The calculation of the influence of solute-elements on the self-diffusivity of iron, which features in many creep equations, is an emerging area in alloy design. The methodology for such calculations is reviewed in the final section of the paper.

(cf. *ISIJ Int.*, **41** (2001), 626)

Strengthening mechanisms of creep resistant tempered martensitic steel (Review)

K.MARUYAMA et al.

The creep deformation resistance and rupture life of high Cr ferritic steel with a tempered martensitic lath structure are critically reviewed on the basis of experimental data. Special attention is directed to the following three subjects: creep mechanism of the ferritic steel, its alloy design for further strengthening, and loss of its creep rupture strength after long-term use.

The high Cr ferritic steel is characterized by its fine subgrain structure with a high density of free dislocations within the subgrains. The dislocation substructure is the most densely distributed obstacle to dislocation motion in the steel. Its recovery controls creep rate and rupture life at elevated temperatures. Improvement of creep strength of the steel requires a fine subgrain structure with a high density of free dislocations. A sufficient number of pinning particles (MX particles in subgrain interior and $M_{23}C_6$ particles on sub-boundaries) are necessary to cancel a large driving force for recovery due to the high dislocation density. Coarsening and agglomeration of the pinning particles have to be delayed by an appropriate alloy design of the steel.

Creep rupture strength of the high Cr ferritic steel decreases quickly after long-term use. A significant improvement of creep rupture strength can be achieved if we can prevent the loss of rupture strength. In the steel tempered at high temperature, enhanced recovery of the subgrain structure along grain boundaries is the cause of the premature failure and the consequent loss of rupture strength. However, the scenario is not always applicable. Further studies are needed to solve this important problem of high Cr ferritic steel. MX particles are necessary to retain a fine subgrain structure and to achieve the excellent creep strength of the high Cr ferritic steel. Strengthening mechanism of the MX particles is another important problem left unsolved.

(cf. *ISIJ Int.*, **41** (2001), 641)