Transformations

Phase transformation from fine-grained austenite (Review)

T.FURUHARA et al.

Microstructure formed by diffusional or martensitic transformation from fine-grained austenite of which grain size is smaller than 5 μm was studied. Grain refinement of austenite was established through two kinds of reversion processes; (1) cyclic transformation between martensite and austenite and (2) reverse transformation from tempered and cold-rolled lath martensite (or pearlite). In the process of (1), the fine austenite structures whose grain sizes of 5–10 μm are obtained. Refinement of austenite grain size results in the increase of hardness. In the process of (2), austenite grain size can be refined down to about 2 μm in low-carbon Mn steels by microalloying through pinning of austenite grain growth by alloy carbides. The ferrite grain size after continuous cooling transformation becomes finer as austenite grain size is refined. However, the grain size ratio of austenite and ferrite, d_α/d_γ, increases by refining austenite grain size. For the austenite of grain size smaller than 5 μm, the ferrite grain size becomes coarser than that of austenite for slow cooling. A similar trend in the change of ferrite grain size by refinement of austenite was recognized for isothermal pearlite transformation in eutectoid alloys. Thus, it is suggested that extensive accelerated cooling is important to obtain fine-grained ferrite by diffusional transformations from the fine-grained austenite. Packet and block sizes of lath martensite in low carbon steels are also refined by decreasing the austenite grain size. Several packets and blocks are formed even from the austenite matrix of 2 μm in grain size.

(cf. *ISIJ Int.*, **48** (2008), 1038)

A descriptive model for the formation of ultrafine grained steels (Review)

P.D.HODGSON et al.

This paper presents a descriptive model to explain the mechanisms involved in the development of ultrafine grained structure in steels through dynamic strain induced transformation. The model considers the microstructural evolution during and after deformation as well as the role of different process variables. A key factor is the competition between nucleation and growth, where it is shown that many potential nuclei can be lost under certain conditions leading to a mixed or coarser grain size.

(cf. *ISIJ Int.*, **48** (2008), 1046)

Ferrite transformation during deformation of super-cooled austenite (Review)

H.-C.LEE et al.

The research results achieved by the Korean national project, HIPERS-21, on the ferrite transformation during the deformation of super-cooled low carbon austenite were summarized. Fine ferrite grains formed during the deformation of austenite, *i.e.* dynamically. The rate of ferrite nucleation was estimated to be accelerated several hundred times by the deformation of austenite. However, the grain refinement could not be explained by the accumulated strain alone. The application of stress during the ferrite transformation is known to effectively weaken the orientation relationship of the ferrite grains with austenite, making the coalescence of the grain difficult during the growth of ferrite and effectively increasing the nominal ferrite nucleation rate. The application of the dynamic ferrite transformation to industrial hot rolling or plate milling was also summarized. The multi-pass rolling technique was introduced to produce a fine ferrite grain structure and controlled cooling was adopted to produce a multiphase structure in order to improve the work hardening rate of fine grained steels.

(cf. *ISIJ Int.*, **48** (2008), 1050)

Crystallography and kinetics of dynamic transformation in steels (Review)

Y.ADACHI et al.

Physical meaning of dynamic transformation was re-considered with a particular attention to the effect of post-transformation deformation on crystallography and kinetics of transformed ferrite. An advanced *in-situ* neutron diffraction experiment was performed to examine the microstructural evolution besides an advanced EBSD measurement. In particular, the deformation behavior in austenite/ferrite two-phase region was investigated as a function of deformation temperature and ferrite volume fraction. Based on these findings, the specific features of dynamic transformation were extensively discussed.

(cf. *ISIJ Int.*, **48** (2008), 1056)

Comments on the microstructure and properties of ultrafine grained steel

J.W.MORRIS, Jr.

The present paper addresses several connected issues that concern the mechanical properties of ultrafine grained martensitic steels. Recent research, particularly including EBSD studies, has clarified the complex microstructure of dislocated martensitic steels and shown the central importance of martensite blocks, which are subvolumes of laths that share a Bain variant of the parent austenite. The block-and-packet structure of the martensite appears well-designed to minimize the elastic energy introduced during the martensitic transformation. The martensite block is, ordinarily, the effective grain size for both strength and cleavage fracture. However, the role of the block in imparting strength is sensitive to carbon contamination of the block boundaries. To optimize strength carbon should be present; to minimize the ductile–brittle transition temperature it should be eliminated. When fine grain size produces high strength, it also causes low elongation. The elongation can be improved by including mechanisms, such as TRIP, that lower the initial work hardening rate.

(cf. *ISIJ Int.*, **48** (2008), 1063)

Deformation/Recrystallization

Regularities of deformation microstructures in ferritic stainless steels during large strain cold working (Review)

A.BELYAKOV et al.

The recent studies on grain refinement in several Cr–Ni ferritic stainless steels during large strain deformation at room temperature are critically reviewed. The paper is focussed on the mechanism of structural changes that is responsible for ultrafine grain development. It is concluded that the development of submicrocrystalline structures results from a kind of strain-induced continuous reaction; that is formation of deformation subboundaries and gradual increase in their misorientations up to typical values of ordinary grain boundaries. Following the rapid reduction at an early deformation, the transverse grain/subgrain size smoothly approaches its final value of the order of 0.1–0.2 μm, depending on alloying extent. The increase in average subboundary misorientation upon processing can be related to the strain as $\Delta\theta \sim K\varepsilon$, with K of about 5°. Therefore, the average misorientation between deformation grains/subgrains is about 20° after processing to total strain of 4 and the corresponding microstructure is composed of 50% of high-angle grain boundaries. The structural refinement of starting material can significantly accelerate the kinetics of ultrafine grain development during subsequent plastic working, while the processing method has a little effect on developing microstructures.

(cf. *ISIJ Int.*, **48** (2008), 1071)

Nanostructured aluminum and IF steel produced by rolling—a comparative study (Review)

X.HUANG et al.

In a comparative study aluminum and interstitial free (IF) steel have been deformed to very large strain by cold rolling and accumulative roll bonding. The deformation microstructure has been analyzed by transmission electron microscope techniques and microstructural parameters have been quantified together with mechanical properties. An analysis of the strain induced change in structure, strength and ductility has shown a very similar behavior for the two materials and also that their mechanical properties can be optimized by introducing a new processing step, post-process deformation.

(cf. *ISIJ Int.*, **48** (2008), 1080)

Microstructure–mechanical properties correlation in ultrafine grained steels processed by large strain warm deformation (Review)

S.V.S.NARAYANA MURTY et al.

Ultrafine-grained steels with grain size of about 1 μm offer the prospect of high strength coupled with high toughness among conventional steel compositions and are attracting the attention of researchers worldwide. Application of these ultrafine grained steels to the fabrication of potential engineering structures demand extensive study of their mechanical properties and reasons for the improvement in order to get detailed insight into their behaviour under operating conditions. While there are many studies on the development of ultrafine grained microstructures *per se*, fewer studies were reported on the more important aspect of evaluating their mechanical properties. This is to verify the basic assumption that the microstructural refinement at bulk level indeed improves the properties offering the prospect of a realistic replacement of the existing conventional steels in the near future. This review article attempts to present a comprehensive picture on the microstructure-mechanical properties correlation of ultrafine grained steels fabricated by large strain warm deformation and reasons behind the improved properties from a micromechanics point of view.

(cf. *ISIJ Int.*, **48** (2008), 1088)

Ultrafine grained ferrite/martensite dual phase steel fabricated by large strain warm deformation and subsequent intercritical annealing

M.Calcagnotto et al.

An ultrafine grained (UFG) ferrite/cementite microstructure was produced by use of large strain warm deformation in two plain C–Mn steels. In order to overcome the characteristic restricted tensile ductility of this steel, an intercritical annealing was applied to obtain an UFG ferrite/martensite dual phase (DP) steel. Suitable intercritical annealing parameters have been worked out using dilatometry. Microstructure evolution during intercritical annealing has been investigated by means of scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD). The study revealed that increasing the Mn content from 0.87 to 1.63 mass% was highly beneficial for the formation of martensite. This effect is explained by the enrichment of Mn in cementite which is partly inherited by austenite. The final microstructure consists of martensite islands embedded in an ultrafine grained polygonal ferrite matrix. The average grain size is 1–2 μm. Small amounts of retained austenite (<1 μm) are finely dispersed. The grain size is hardly affected by the intercritical annealing, whereas the fraction of high-angle grain boundaries in the ferrite matrix is reduced. Tensile tests revealed that strain hardenability is drastically improved by the introduction of martensite as a second phase. The UFG-DP steel exhibits a good combination of high strength and uniform elongation and considerable strain hardenability.

(cf. *ISIJ Int.*, **48** (2008), 1096)

Slip system partitioning as a possible mechanism for ultrafine grain formation in Fe–3%Si bicrystals

D.Dorner et al.

An Fe–3%Si bicrystal was deformed in compression to a strain of 0.9 at ambient temperature. In the interior of deformation bands, characteristic band structures with high orientation gradients and low and high angle boundaries were formed during straining. Furthermore, isolated ultrafine grains were found in the matrix of the deformation bands. The morphology and crystallography of the ultrafine grains indicate that they are caused by slip system partitioning, *i.e.* local activity of a highly stressed slip system that is different from the active slip system in the surrounding crystal volume.

(cf. *ISIJ Int.*, **48** (2008), 1102)

Properties

Tensile behavior of fine-grained steels (Review)

Y.Tomota et al.

With decreasing of grain size in ferritic steels, Lüders elongation becomes larger while work-hardening is lowered, finally resulting in loss of uniform elongation. This drawback can be overcome by introducing the second phase like martensite or metastable austenite. The improvement of strength and uniform elongation balance by the second phase can well be estimated by applying the secant method of micromechanics approach. The stress partitioning between two constituents brings high work-hardening, which is verified by *in situ* neutron diffraction. The influences of strain rate and temperature are described by using the Kocks–Mecking model. It is found that the grain refinement and the above stress partitioning contribute mainly to the athermal stress component of flow stress. Hence the tensile properties obtained at a high speed deformation like 10^3/s is excellent in fine-grained multi-phase steels. As an example of ultrafine-microstructure with 20–30 nm in size, the tensile behavior of severely drawn pearlite steel wires with tensile strength larger than 4 GPa is investigated. In spite of such ultra-high strength, the wire deforms plastically by dislocation motion resulting in dimple fracture. The strengthening consists of isotropic hardening due to microstructure refinement and anisotropic hardening caused by residual intergranular stresses which are determined by neutron diffraction.

(cf. *ISIJ Int.*, **48** (2008), 1107)

Managing both strength and ductility in ultrafine grained steels (Review)

N.Tsuji et al.

Ultrafine grained (UFG) steels provide surprisingly high strength but sometimes show limited tensile ductility. In the present paper, systematic experimental results on mechanical properties of UFG steel with ferrite single phase are shown first. The limited tensile ductility of the UFG ferritic steel was due to very small uniform elongation, which was attributed to the early plastic instability in the UFG microstructures. This basic understanding suggested a way to overcome the low tensile ductility: if the strain-hardening of the matrix is enhanced by any means, both high strength and adequate ductility can be managed even in UFG structures. Actual examples of the UFG steels that could achieve good strength–ductility balance are also presented. Dispersing fine carbides within the UFG ferrite matrix, and making the UFG dual-phase structure composed of ferrite and martensite were both effective to manage high strength and large uniform elongation. It was clearly shown that the future studies on the UFG steels from practical viewpoint should be directed to make the UFG structures multi-phased.

(cf. *ISIJ Int.*, **48** (2008), 1114)

Effect of interstitial elements on Hall–Petch coefficient of ferritic iron

K.Takeda et al.

Yield strength was investigated in iron with different grain size and different contents of carbon and nitrogen. The Hall–Petch coefficient; k_y is originally very small in high purity iron (about 100 MPa$\cdot\mu m^{1/2}$) but it increases with increasing the amount of solute carbon content. The value of k_y is enlarged to around 550 MPa$\cdot\mu m^{1/2}$ by 60 ppm of solute carbon and levels off at around 600 MPa$\cdot\mu m^{1/2}$ in the region above 60 ppm solute carbon. On the other hand, nitrogen hardly influences the k_y value. The mechanism of the change in Hall–Petch coefficient was then discussed in terms of the grain boundary segregation of carbon and nitrogen atoms.

(cf. *ISIJ Int.*, **48** (2008), 1122)

Processing

Grain refinement in steels and the application trials in China

H.Dong et al.

In order to control microstructure and performances of steel products, the investigation has been taken to the ways to refine grains in steels and the mechanisms, the availability in industrial production of ultrafine grain steel products, and the applications of ultrafine grain steel products. It is shown that strength of steels can be increased without detriment to ductility when ferrite grains are refined to less than 4 μm in low carbon steels. Based on the study of deformation induced transformation, a new rolling technology has been developed to refine ferrite grains in plain low carbon steel rebar and strip. Plain low carbon steel rebars of 400 MPa grade, with ferrite grains in the range of 4–8 μm, have been developed as the candidate to replace microalloyed steel rebars. High strength plain low carbon steel strips in the yield strength range from 345 to 420 MPa have been used for components conventionally made of microalloyed steels. Ultrafine grained microalloyed steel strip has also been developed. A new on-line cementite spheroidization softening technology has been studied for the wire rod production of medium carbon bolt steel. It is obvious that deformation could also induce pearlite transformation in eutectoid steel.

(cf. *ISIJ Int.*, **48** (2008), 1126)

Integrated production technologies for ultra-fine grained steel sheets (Review)

M.Kiuchi

A national project was conducted by NEDO and executed by a consortium organized by JRCM with aims to develop integrated production technologies necessary for manufacturing ultra-fine grained steel (UFGS) sheets. In the project, the diverse technologies were concurrently developed relating with (1) high-speed large-reduction semi-continuous hot forging, (2) high-speed short-interval hot tandem rolling, (3) multi-cycle hot bending for strain accumulation, (4) high-strength anti-wear rolls, (5) multifunctional lubricants, (6) mathematical modeling and simulation of ultra-fine grain generation and (7) joining of UFGS sheets. The project succeeded in building up the integration of advanced technologies available for overall steel sheets manufacturing as well as production of UFGS sheets. Utilizing the developed technologies, UFGS sheets of plain low carbon steel having 1.0–2.0 mm thickness, 300 mm width, 1.0 μm grain diameter and 600–700 MPa tensile strength were successfully manufactured and found assuredly formable to practical products.

(cf. *ISIJ Int.*, **48** (2008), 1133)

Super short interval multi-pass rolling process for ultrafine-grained hot strip

M.ETOU et al.

As a process to manufacture ultrafine-grained hot strip or plate of which ferrite grain size was about 1 μm, heavy reduction hot rolling at relatively low temperature, such as larger than 70% reduction per pass at lower than 700°C, had been presented. However, it is quite difficult to apply the process to commercial production because the rolling load is very large. A new process of multi-pass rolling at extremely short interval has been proposed and developed in order to manufacture ultrafine-grained hot strip at ordinary rolling load. Authors named it "Super Short interval Multi-pass Rolling (SSMR) process". Ultrafine-grained hot strip of 1.2 mm thick was successfully manufactured in laboratory with the simple chemical composition of 0.15%C–0.74%Mn. Its grain size was 0.9 μm at 50 μm beneath the surface and 1.2 μm on the average over the thickness. The rolling load in SSMR was smaller than 30 kN/mm and it was relatively small owing to relatively small reduction, smaller than 50% per pass, and relatively high temperature, higher than 820°C. Consequentially it was confirmed that the rolling load in SSMR process could be reduced to half compared to the previously presented process of heavy reduction hot rolling at low temperature.

(cf. *ISIJ Int.*, **48** (2008), 1142)

Grain refinement of C–Mn steel to 1 μm by rapid cooling and short interval multi-pass hot rolling in stable austenite region

T.TOMIDA et al.

A noble grain refinement method to attain ferrite grain size of 1 μm in plain C–Mn steel by multi-pass hot rolling in a stable austenite temperature region has been explored. 0.1%C–1%Mn and 0.16%C–0.7%Mn steels were finish-rolled at about Ae_3 and then rapidly cooled. Special emphases have been placed on the interval, Δt, between the finish of rolling and the start of water spray cooling of more than 1 000°C$\cdot$s^{-1} in cooling rate and the interval between the last two rolling passes. By reducing Δt from 0.5 to 0.05 s alone, the grain sizes near the sheet surface and in the central region were markedly reduced to 1.3 and 2.2 μm respectively. By reducing Δt and the rolling pass interval together, a further reduction in grain size was then achieved. Consequently, the steel sheet in which the ultrafine grain structure of about 1 μm in grain size penetrated from the sheet surface to the depth of a quarter of the sheet thickness and the grain size in the central region was well below 2 μm was obtained. The transformation to the ultrafine ferrite is considered to be static and from deformed γ. The detailed grain refinement mechanisms are discussed based on the microstructure observation of quenched C–Mn steels and a fcc Ni–30%Fe alloy as well as the calculation of prior γ texture by the misorientation distribution function method.

(cf. *ISIJ Int.*, **48** (2008), 1148)