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Fundamentals and Mechanism of Recrystallization

Block models and (011) [100] recrystallized orientation in cold rolled single crystals of α iron -A critical review-

E.FURUBAYASHI

The block theory for recrystallization nucleation proposed by B.F.Decker and D.Harker (D-H) has been critically reviewed in the light of recent experimental evidence and slip system geometry. Unpublished as well as available data of pole figures of *e.g.* (011) [100]-oriented single crystals of Fe-3%Si have been used for discussion. The experimental results on which the D-H theory was based are found to be incorrect. For example, *Goss* recrystallized texture is developed in crystals rolled at reductions higher than 60 %, while in case of D-H reduction was 40 %.

Operative slip systems on rolling have been estimated using Taylor factor, and lattice rotation has been analyzed. On this basis, existing block models have been discussed and classified into "hard" and "soft" block models in view of the relation between local deformation within blocks and total deformation by rolling. The *Goss* recrystallized orientation was formed from cold rolled {111}⟨221⟩ orientation by a reverse lattice rotation ; *i.e.* the rotation direction is opposite to the direction caused by rolling deformation. This fact has been used to discuss the validity of two models. Preference of the hard model has been emphasized. The D-H model belongs to the soft model, but with this it is not possible to give reasonable explainations.

Relationship between active slip systems and orientations of recrystallized grains in Fe-30Cr alloy

T.OKADA et al.

An Fe-30Cr alloy single crystal sample was deformed in compression along [11$\bar{1}$]direction to a strain of -0.15 at a strain rate of 2×10^{-4}/s at room temperature. Severe shear deformation occurred in a broad band along one of the diagonals of (011) surface of the sample. The Burgers vectors of the screw dislocations activated in and out of the shear band was estimated from the geometry of slip traces and the macroscopic shape of the sample after deformation. After annealing the sample for 240 s at 1 273 K, about 430 recrystallized grains were formed only inside the shear band. The orientations of 70 % of the recrystallized grains were described by the orientation of the band rotated about ⟨110⟩ axes. The recrystallized grains with orientations rotated about [$\bar{1}$01] axis and [110] axis were predominant. Most of the rotation angles were in a range between 20° and 30°and the direction of rotation was counterclockwise. A simple model which describes the formation of recrystallization unclei by the interaction of dislocations introduced during deformation is proposed. The model explains the predominant occurrence of [$\bar{1}$01] and [110] rotations and the direction of rotation.

Origin of recrystallization texture evolution and active slip systems in cold rolled 3%Si-Fe (100) [011] single crystal

T.TŌGE et al.

3 % Si-Fe (100)[011] single crystal was investigated to analyze its texture evolution during rolling and recrystallization. Cold rolled (100)[011] could be fully recrystallized by utilizing dynamic strain aging, and sharp recrystallized texture was obtained.

Rolled texture maintained the initial orientation (100)[011] with TD rotational dispersion. This dispersion is attributed to the action of two kinds of {112}⟨111⟩ slip systems which have the largest Schmidt factor.

Recrystallized texture is composed of eight orientations rotated about 30 degrees around eight ⟨112⟩ axes from the initial orientation (100)[011]. These rotations are attributed to the action of 8 kinds of {110}⟨111⟩ slip systems.

The results of several researchers, showing recrystallized {111}⟨uvw⟩ grains from the rolled matrix having {111}⟨uvw⟩, were also discussed in this paper from the view point of ⟨112⟩-rotation, and an alternative idea on the formation of ⟨111⟩//ND texture has been proposed.

Microscale texture and recrystallized orientations of coarse grained 3%Si-steel rolled at high temperature

Y.OZAKI et al.

Recovered and recrystallized crystal orientations of a coarse grained 3 %Si-steel hot rolled at 1 280°C were examined. Deformed samples exhibited a recovered structure comprised of subgrains. Recrystallized grains with unique orientations emerged along the original grain boundaries during holding at the rolling temperature for 6.5 s. With the aid of the automated EBSD orientation measurement with two dimensional scan, it became possible to map the orientations of the subgrains which were the minimum units of orientation in the present case. Near the original grain boundary, to an extent of several hundreds of microns, the orientation of the subgrains were scattered or continuously rotated due to the constraint by the grain boundary. The orientations of a number of the subgrains near the original grain boundaries in the deformed sample were measured, and the subgrains having large misorientation with the matrix, which were thought recrystallization nuclei, were found. The recrystallize grains in the sample held for 6.5 s at 1 280 ° C, as well as both the recrystallization nuclei and the continuously rotated subgrains near the original grain boundaries in the immediately quenched specimen, often showed a rotational relationship around an ⟨110⟩ axis on ND plane with the deformed matrices.

The relative contribution of different nucleation sources to recrystallization textures of a cold rolled aluminummagnesium alloy

I.SAMAJDAR et al.

Development of recrystallization texture was studied as a function of annealing temperature in a cold-rolled alloy AA5182. A noticeable decrease in rolling texture orientations was observed with increasing annealing temperatures. Particle deformed zones and deformed bands served as the respective sources for PSN (particle stimulated nucleation) and non-PSN nucleation. Although no significant difference between approximate growth rates of different orientations were observed, our studies indicated that PSN grains nucleated first. Thus, increased annealing temperatures favored PSN nucleation, but did not change the number of PSN grains in the rolling texture orientations. In other words, the relative randomization of texture at higher annealing temperatures was mainly caused by reduced non-PSN nucleation and not by changes in the orientations of PSN grains. The global recrystallization textures were simulated from the weighted sum of the PSN and non-PSN nuclei.

An analysis of the solute drag effect of Nb on recrystallization of ultra low carbon steel

M.SUEHIRO

The solute drag effect of Nb on recrystallization of Fe has been investigated using the mathematical model. The calculation result has shown that Nb can retard the migration of grain boundary during recrystallization due to the solute drag effect. The driving force dissipated by the solute drag was compared to that by pinning effect of fine precipitates. The comparison implies that the dominant phenomena are only the pinning effect for small total driving force and the Nb content less than the critical composition, both effects for small total driving force and the Nb content over than the critical composition, and only the solute drag effect for large total driving force and the Nb content over than the critical composition.

Grain Boundary Migration and Grain Growth

Mechanism of orientation selectivity of secondary recrystallization in Fe-3%Si alloy

Y.USHIGAMI et al.

Selective growth behavior of {110}⟨001⟩ grains has been studied utilizing the temperature gradient annealing method. As grains grow, the average deviation angle from the ideal {110}⟨001⟩ orientation becomes smaller and orientation distribution changes corresponding to that of coincidence grains in the matrix. Secondary recrystallization tamperature depends on the orientation of secondary recrystallized grain and sharper {110}⟨001⟩ grains grow preferentially at lower temperatures.

These phenomena are explained by modified Hillert's model of grain growth, which takes the grain boundary characteristics into account. Sharper {110}⟨001⟩ grains, which have higher frequency of coincidence grains in the primary recrystallized matrix, suffer lower pinning force from the precipitates and thus grow preferentially at lower temperatures.

Monte Carlo simulation of grain growth in three dimensions

Y.Saito

The temporal evolution and morphology of grain growth in three dimensions were simulated by Monte Carlo method. In order to prevent impingement of grains of like orientation, new algorithm was adopted. The anisotropy of the grain boundary energy is incorporated into the model. Compared with the case in which no anisotropy of boundary energy is assumed, the suppresion of grain growth was observed at the initial stage of growth in the grain structure with anisotropic grain boundary energy. However, the growth rate is higher at the later stage. The grain size and the face number distributions become broad. To evaluate the profile of the grain size distribution, a parameter called microstructural entropy, S, is defined. It was shown that the characteristics of size distribution profile may be represented by the value S. The average size of n-faced grain is proportional to the grain face number, n. The effect of the anisotropy of grain boundary energy on the n-dependence of the average grain size is not evident. The nearest neighbour face number correlation similar to the Aboav−Weaire relation in two dimension is observed in both grain structures with isotropic grain boundary energy and anisotropic grain boundary energy.

Microstructural Development under Recrystallization

Recrystallization-transformation combined reactions during annealing of a cold rolled ferritic-austenitic duplex stainless steel

W.Reick et al.

Solid state reactions taking place during annealing of 20 % cold rolled ferrite-austenite duplex stainless steel (DIN W.-Nr: 1.4462) have been studied by means of several complementary techniques: optical, scanning and transmission electron microscopy, X-ray dif fraction analysis, microhardness and ultramicrohardness measurements and magnetic phase detection (ferritoscope). It has been found that after cold rolling austenite exhibited more strain hardening and a higher driving force for recrystallization than ferrite. Extensive recov ery took place in ferrite during annealing, while the deformation substructure of austenite remained nearly unrecovered until beginning of recrystallization. The recrystallization kinetics in ferrite was faster than in austenite. Recrystallization in austenite occurred in a more discontinuous manner than in ferrite. The eutectoid transformation of ferrite to sigma phase plus austenite slowed down recrystallization kinetics of both ferrite and austenite phases. A scheme is presented for sigma phase formation during recrystallization annealing.

Effect of carbon on the cold-worked state and annealing behaviour of 18wt%Cr-8wt%Ni austenitic stainless steels

L.F.M.Martins et al.

The influence of carbon on the work hardening, formation and reversion of deformation induced martensite and on the recrystallization of two austenitic stainless steels 18 %Cr-8 % Ni type were studied with the help of different microstructural analysis techniques. Two steels were selected: the first an AISI 304L with low carbon (%C=0.021) content and the second an AISI 304 with higher carbon (%C=0.065) content. Both steels were heat treated to obtain two different initial conditions: one with the carbon completely in solid solution (after a solution annealing treatment at 1 100°C) and the other with practically all the carbon in the precipitated form, as $(Cr,Fe)_{23}C_6$ (after a precipitation treatment at 750°C). The material having higher carbon content, both in solid solution and precipitated, presented in both cases higher strain hardening, smaller tendency to form strain induced martensite and higher resistance to recrystallization. Carbon in solid solution, as compared to the precipitated condition, led to a material with a higher tendency to strain hardening, less susceptibil ity to martensite formation and more resistance to recrystallization. Nucleation of recrystallization preferably occurred in the vicinity of grain boundaries. Based on the results of the kinetics of recrystallization and intergranular corrosion tests it was concluded that the usually recommended annealing tempera tures (1 000 to 1 120 °C) are sometimes unnecessarily high.

Effect of boron on mechanical properties and recrystallization behavior of Ti-added ultra-low carbon cold-rolled steel sheets

J.Haga et al.

Effect of boron (B) on mechanical properties and recrystallization behavior of Ti-added IF steel sheets was studied. Recovery-, nucleation- and grain growth-rates were measured separetely in order to clarify the effect of B on recovery and recrystallization process.

Grain size of hot band was constant regardless of B addition. However, Lankford value (r-value) of annealed steel sheets was lowered with increasing B content. Recrystallization finishing temperature rose remarkably with increasing B content up to 5 ppm, and gradually over 5 ppm. Recovery rate was not varied with increasing B content up to 5 ppm, and decreased over 5 ppm. Nucleation rate of recrystallized grains decreased drastically with increasing B content up to 5 ppm, and slightly decreased with increasing B content over 5 ppm. Growth rate of recrystallized grains decreased progressively with increasing B content up to 16 ppm, and was not varied so much over 16 ppm. The suppression in nucleation and growth was thought to be due to the B segregation to the prior grain boundary of hot band and to the boundary of nuclei, respectively.

Influence of hot rolling and cooling conditions on the grain refinement of hot rolled extralow-carbon steel bands

T.Senuma et al.

In this paper, the effect of various operational parameters in a hot strip rolling process on the grain refinement of hot rolled plain extralow-carbon steel bands has been investigated. The finishing temperature and the onset time of cooling after hot rolling influence the grain refinement significantly. The finishing temperature just above Ar3 is optimum for the grain refinement. The reducing of the onset time of cooling not only refines the grain size, but also decreases the fluctuation of the grain size caused by finishing temperatures different from place to place in a hot strip. The increase in the reduction of the final hot rolling refines the grain size as well. The cooling rate does not affect the grain size of hot bands in the range between 40 and 120°C/sec significantly.

The mechanism of the grain refinement has been discussed with a relation of recrystallization and transformation behavior of austenite and it is concluded that in the case of extralow-carbon steel without Ti and Nb addition, the grain refinement of hot bands is strongly influenced by not only the recrystallization but also grain growth behavior of austenite.

Dynamic recrystallization under warm deformation of polycrystalline copper

A.Belyakov et al.

Structural changes taking place under warm deformation of pure copper were studied in compression at temperatures ranging from 473 to 673 K (0.35 to $0.50T_m$) under strain rates of $10^{-3}-10^{-1}s^{-1}$. Dynamic recrystallization (DRX) takes place fully or partly at temperatures higher than 523 K, while no fine grains are evolved in the pan-caked original grains with serrated boundaries even after high strains at 473 K. The new grains are evolved by bulging mechanism associated with local migration of the original grain boundaries and the evolution of twins and dislocation boundaries. The relationship of peak flow stress to the new grain size evolved under warm deformation can be expressed by a power law function with a grain size exponent of about -0.35, which is different from that for DRX taking place under hot deformation (*i.e.* -0.75). The correlation between the mechanisms of plastic deformation and the structural evolution, such as dislocation densities, cell sizes, and DRX grain sizes, and the mechanisms of low and high temperature DRX are discussed in combination with the analysis of deformation behaviour at moderate temperatures.

Texture Development and Formability

Texture evolution during cold rolling and recrystallisation of IF steel with a strong {111} hot band texture

K.ELOOT et al.

For a new industrially processed, hot rolled Ti+Nb IF steel, finished in the ferrite region and subsequently annealed, the texture development during cold rolling and annealing is investigated. The strong hot band texture is of the {554}<225> peak type. During cold rolling, the absolute maximum shifts from {554}<225> to {111}<112> along the ε-fibre and the local maximum along the α-fibre shifts from {111}<110> to {223}<110>. During recrystallisation, the weaker α+stronger γ-fibre cold rolling texture is transformed to a very strong γ-fibre annealing texture. Hereby, {111}<110> and, to a much lesser extent, {554}<225> develop at the expense of {111}<112>. Orientation Imaging Microscopy (OIM) reveals that γ-fibre grains nucleate and grow in the beginning of recrystallisation by consuming γ-fibre components of the deformed matrix. Already after 23 % recrystallisation, the texture of the recrystallised grains is very similar to the one obtained after full recrystallisation. Moreover, {111}<110> grains are found to be larger and more numerous than {554}<225> grains. The former therefore have an advantage over the latter for consuming the partial α-fibre grains during the final stage of recrystallisation and for further development during grain growth. As a result, a very strong {111}<110> peak type annealing texture is obtained in the present meterial, resulting in extremely good deep drawability.

Cold-rolling and recrystallization texture formation in electro-deposited pure iron with a sharp and homogeneous γ-fiber

N.YOSHINAGA et al.

The formation of the cold-rolling and annealing texture has been investigated in electrolytically deposited pure iron having a sharply developed <111>//ND fiber texture without any anisotropy along γ-fiber nor any orientation density along other fibers. In no respect of cold reduction, {111}<112> texture is formed after cold-rolling. The same texture still remains after the recrystallization in the 65 % cold-rolled sheet, whereas the position of the peak is shifted from {111}<112> towards {111}<110> through recrystallization in the 80 % cold-rolled sheet. The nucleation texture seems to be responsible for the difference of recrystallization texture between the 65 and 80 % cold-rolled sheets. Additionally, it is thought that the growth of the recrystallized grains also plays an important role. It is considered that the recrystallized nuclei with {111}<112> orientation can hardly grow into the deformed matrix of the 80 % cold-rolled sheet because they frequently encounter the deformed grains with nearly the same orientation and thus suffer from a reduced mobility. On the other hand, nuclei with a {111}<110> orientation can easily grow into the deformed {111}<112> grains because of the favorable growth orientation relationship between those. Conversely, in 65 % cold-rolled sheet, the nuclei with {111}<112> are considered to grow more easily since the frequency of pinning due to limited mobility of a low angle grain boundary is rather small, as compared to that of the 80 % cold-rolled sheet. The same mobility argument as applied to the growth of nuclei seems to hold also for the growth of subgrains, namely, nucleation texture formation.

Texture evolution of IF steel due to recrystallization

N.HASHIMOTO et al.

The evolution of texture due to recrystallization was investigated in cold rolled Ti-bearing IF steel sheets using Electron Back Scattering Pattern (EBSP). The aim of this study was to obtain a real picture of the formation of the recrystallization texture of IF steel sheets, which would contribute to proper texture control for improving deep drawability.

The deformed grains can be roughly classified by the following 5 orientation groups: (1) ND//<111> and RD//<112>~<110>, (2) ND//<111>~<335> and RD//<110>, (3) around {112}<110>, (4) around {001}<110> and (5) widely scattered orientations. Their ratios of frequency of finding are approximately 12 : 4 : 4 : 5 : 2. Deformed grains of types (1) and (5) recrystallized at the early stage of recrystallization. The nucleation sites are both grain boundaries and grain interior. The orientations of grains recrystallized from a grain of type (1) are ND//<111> and RD//<112>~<110> while the orientations of grains recrystallized from a grain of type (5) are widely scattered. Most of the deformed grains of types (2), (3) and (4) recrystallized at the later stage of recrystallization. The recrystallization of these grains of types progress through the growth of already recrystallized neighboring grains if the neighboring grains are types (1) and (5). There exist no preferential misorientation axes for migrating recrystallization fronts. Most of the misorientation angles lie between 20° and 55°.

Effect of hot band microstructural factors on recrystallization texture in Ti-added ultra-low carbon cold-rolled sheet steels

I.TSUKATANI

An examination has been made of the effect of hot rolling conditions, considered as thermal history, on the deep drawability and recrystallization texture formation in Ti-added ultra-low carbon cold-rolles sheet steels.

The findings show that the average r-value of IF steel is significantly improved by refining the hot band grains, by decreasing the finish-rolling temperature in large thermal drop, to temperature even below the Ar_3 transformation temperature, during hot rolling process. However, the average r-values of sheets hot-rolled almost isothermally at a finish-rolling temperature below the Ar_3 transformation temperature deviate detrimentally, when compared with hot band of the same grain size. In this study, an attention has paid to the formation of texture throughout the hot rolling, cold rolling and annealing processes, in relation to deep drawability.

Effect of lubrication condition on recrystallization texture of ultra-low C sheet steel hot-rolled in ferrite region

S.MATSUOKA et al.

The application of the EBSD technique with an SEM provides a new approach to the analysis of variations of the recrystallization texture in the thickness direction of ultra-low carbon sheet steels rolled in the ferrite region. A nonuniform recrystallization texture through the thickness is formed due to the additional shear strain introduced by frictional force between the rolls and the material in sheet steel rolled with a friction coefficient over 0.15, <110>//ND recrystallized grains being formed near the surface, and <111>//ND and <100>//ND recrystallized grains being formed at the mid plane. On the other hand, <110>//ND recrystallized grains are not formed preferentially near the surface, and <111>//ND and <100>//ND recrystallized grains are formed uniformly throughout the thickness in sheet steel rolled with a friction coefficient under 0.15. Orientation imaging also reveals differences related to the tolerance of <110>//ND recrystallized grains around the <110>//ND axis in sheet steel rolled without lubrication, in that <110>//ND grains with a small tolerance form at the 1/10 plane from the surface and <110>//ND grains with larger tolerances form at thickness locations from the 1/10 plane toward the surface and center. The r-value depends on the friction coefficient and increases significantly as the friction coefficient decreases under 0.15, resulting in high r-values over 1.2. This change in the r-value with the friction coefficient corresponds to the distribution of the recrystallization texture through the thickness. Orientation imaging allows a more visual and intuitive understanding of the nonuniformity of the recrystallization texture than conventional methods such as optical microscopy and X-ray diffraction measurement.

The influences of the cold rolling reduction on r-value and recrystallization behavior in Fe-36Ni alloy

D.SATO et al.

Recrystallization behavior and grain growth in Fe-36 % Ni invar alloy for shadow masks in color cathode ray tubes were studied. R-value can be increased with increasing (111) surface intensity. In the case of light cold-rolling reduction, nuclei orientation of recrystallized structure after annealing were (011) and the nuclei was surrounded by cold rolled matrices of (011) orientation. On the other hand, in the case of heavy cold rolling reduction, nuclei orientations of recrystallized structure after annealing were (011) and (100). These two nuclei are surrounded by same cold rolled matrices of (011) orientation with light cold rolling reduction.

Numerical analysis on earing behavior in drawn cups of steels based on finite difference of orientation distribution function

K.KOJIMA et al.

Earing behavior in cylindric drawn cups of conventional single-reduced steel sheets and double-reduced steel sheets has been compared with the result predicted by the calculation from the orientation distribution function (ODF) date. Although the earing ratio of the cups of double-reduced steel sheets was larger than that of single-reduced steel sheets, the earing behavior of those steel sheets could be predicted by the same calculating model, in spite of the difference in type of cold-rolling process. This suggests that the second cold-rolling under 15 % reduction little affected the manner in slip deformation during drawing. So it was concluded that the difference of earing behavior among the steel sheets was mainly caused by the difference of their textures.

To discuss the effect of texture on the earing behavior, the finite difference of ODF ($\Delta f(g)$) was defined. A reliability of a result calculated from $\Delta f(g)$ was confirmed by a comparison with a result directly calculated from ODF date. By using the positive and negative parts of the finite difference of the ODF, effects of increased and decreased components on the difference of the earing behavior were separated from each other. It was clarified that the influence of minor components ($f(g)<1$) on the earing behavior was not negligible in quantitative discussion of correlation between texture and earing behavior.

Prediction and control of earing by analysis of texture

H.MURAKAMI et al.

To predict and control the planar anisotropy, it is necessary to clarify the quantitative relationship between the texture, including not only the major orientations but also the minor ones, and anisotropy. In this paper, by three-dimensional texture by vector method and Tucker's deformation model, quantitative evaluation was tried. As the result the justification of the model and the importance of considering of minor orientation have shown. In addition to it, the anisotropy control of the steel established γ-fiber strongly has invested and some mechanism to inhibit anisotropy have been shown.