Texture Control in the Production of Grain Oriented Silicon Steels

Munetsugu MATSUO
R & D Laboratories-I, Nippon Steel Corporation, Ida, Nakahara-ku, Kawasaki, Kanagawa-ken, 211 Japan.
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The most successful texture control has been achieved in the production of grain oriented silicon steels. This paper reviews the historical background and current knowledge of texture control for ensuring the high performance of the Goss oriented silicon steel sheets. Special emphasis is placed on the important contributions of textural and microstructural inhomogeneities to perfect secondary recrystallization of the (110)<001> oriented grains, in particular, in the production of high permeability grade products through the single stage cold rolling process. The texture control of grain oriented silicon steels involves the control of local inhomogeneities in texture and microstructure: both potential nuclei of secondary recrystallization and matrix as the favorable surrounding for growth of the nuclei should be optimally provided throughout the processing route. Discussion includes (1) how the (110)<001> oriented grains occur in the primary recrystallization matrix, (2) what qualifies the (110)<001> oriented grains for viable nuclei of secondary recrystallization, and how they can grow at the expense of surrounding grains for perfection of secondary recrystallization, (3) how the (110)<001> oriented potential nuclei originate and survive in the processing, (4) how the texture and microstructure can be controlled in the production of grain oriented silicon steels for improved performance, and (5) what are the main differences between the single and the two stage cold rolling routes in terms of the texture control.

KEY WORDS: grain oriented silicon steel; preferred orientation; texture control; microstructure; hot rolling; cold rolling; primary recrystallization; secondary recrystallization; inhomogeneous structure.

1. Grain Oriented Silicon Steels

1.1. Texture Control for Improved Magnetic Properties

The most successful texture control has been achieved in the production of grain oriented silicon steels. Texture control intends to develop a favorable preferred orientation for the effective use of anisotropy in the physical and mechanical properties originating from the crystallography of materials. Single crystals are anisotropic in physical, chemical, and mechanical properties: the properties depend on the crystallographic direction in which they are measured. Anisotropic property in a polycrystalline material is a certain average value of the property of the individual component crystallites and, therefore, depends on the single-crystal property and on the preferred orientation of the crystallites in the materials.

Iron crystals have a significant anisotropy in magnetization: the easiest magnetization direction is parallel to the (001) axis. If a preferred orientation is developed to align the individual grains so that their (001) axes lie nearly parallel to the rolling direction of a sheet, the grain oriented product has a low core loss and high permeability to maximize magnetic flux passage in the easy magnetization direction and is favorable for applications such as power and distribution transformers.

Two types of preferred orientations can be developed in silicon steels: the cube-on-face or [100]<001> orientation in which the [100] plane lies in the sheet plane, and the cube-on-edge [110]<001> orientation in which the [110] plane lies in the sheet plane. Materials with the [110]<001> preferred orientation are commercially produced on a significant scale. A perfectly [110]<001> oriented material would be magnetically saturated at a value of 2.03 T in an applied field of 800 A/m (B_{sat}). Since the highest B_{sat} value of currently commercial products is about 1.93 T, this is, however, nowhere near the limit of ideally oriented silicon steels and much more improvement may be possible in the future through deliberate tailoring of the texture and microstructure to meet the requirements of the products.

The development of alternate transformer core materials such as amorphous alloys of suitable Bs and extremely low core losses has placed more competitive pressure for improved performance of grain oriented silicon steels. A way for lower core loss is to reduce the eddy current loss by an increase in electric resistance of sheets. The sheets must be provided with lighter gages and higher silicon contents than the conventional products on commercial equipment and at competitive costs. Production of thin gage and high silicon steel sheets imposes increased difficulties in texture control. For commercial production of silicon steels with performance rivaling that of amorphous materials, it may be worthy of reviewing the historical background and the state of the art of texture control for grain oriented silicon steels.

1.2. Conventional and High-permeability Grade Grain Oriented Silicon Steels

There are at present two major grades, conventional oriented grades and high permeability grades, in the products of grain oriented silicon steels. The high permeability grades are characterized by an
average misorientation of the (001) axis 3 to 4 degrees from the rolling direction instead of 7 degrees for the conventional grades (Fig. 1). The sharp preferred orientation brings a B_{90} value of 1.92 T in contrast with 1.83 T for the conventional grades and a decrease in core loss of about 20%. Three types of high permeability products have been developed commercially. The processing and composition of such products are compared with the conventional grain oriented products in Table 1.

The process for conventional grades involves hot rolling a slab after reheating at about 1593 K, and cold rolling in two stages with an intermediate recrystallization annealing. The cold rolled sheet is annealed to decarburize to below 0.003% carbon in a wet atmosphere and at the same time to form a primary recrystallization structure. The sheet is coated with magnesia and subjected to final box anneal in dry hydrogen at 1423 to 1473 K. During the box anneal for development of the (110)(001) preferred orientation, impurities are removed and inclusions of the grain growth inhibitors are dissolved and absorbed in the glass film formed on the surface by reaction with magnesia. Manganese sulfide has been the most common grain growth inhibitor. The process for the first type of high permeability products differs from the conventional process in two important points: (a) the use of aluminum nitride in addition to manganese sulfide as the inhibitor and (b) a single stage cold rolling with heavy reduction. For the second type, (a) antimony or molybdenum is added along with manganese selenide or sulfide as the inhibitor and (b) two stage cold rolling is used with the final stage closer to 70% reduction rather than 50% in the conventional process. The third process differs from the first by the use of boron and nitrogen together with sulfur or selenium as the inhibitor.

General trends and future prospects for production and properties of grain oriented silicon steels are well documented in the recent literature. The present review will focus on the texture control for commercial production of high quality materials.

2. Early Development of Texture Control

2.1. Goss Texture

Patent application by Goss in 1933 marked the beginning of a new approach to the production of electrical steels through texture control: grain oriented silicon steels. (It is interesting to see that the name of inventor, Goss, coincides with the acronym of his invention, Grain oriented silicon steel.) As a result of comprehensive research, Goss found that the maximum permeability at high inductions could be increased to several times the maximum permeability of

![Image](image-url)

Fig. 1. [100] pole figures representing the orientation distribution of secondary recrystallization grains in the conventional grade (left) and the high permeability grade (right). The small circles indicate an angular deviation of 10° from the rolling direction. The central figure shows the Goss texture with a misorientation (α) of (001) axis from the rolling direction.

Table 1. Manufacturing processes of grain oriented silicon steels.

| Conventional grades | High permeability grades |
|---------------------|-------------------------|
| **Steelmaking**     | **Type No. 1**          | **Type No. 2**          | **Type No. 3**          |
| Microalloy (MnS)    | Steelmaking             | Steelmaking             | Steelmaking             |
| Hot rolling         | Microalloy (AlN+MnS)    | Microalloy (MnSc+Sb, Mo)| Microalloy (B+N+S or Sc) |
| Reheating (1593 K)  | Hot rolling             | Hot rolling             | Hot rolling             |
| Annealing (1073-1273 K) | Annealing (1573 K)     | Reheating (1593 K)      | Reheating (1523 K)      |
| Cold rolling (70%)  | Cold rolling (87%)      | Cold rolling (1173 K)   | Cold rolling (65%)      |
| Annealing (1073-1273 K) | Decarburizing          | Annealing (1148-1298 K) | Decarburizing           |
| Cold rolling (55%)  | Boxes annealing (1473 K)| Decarburizing           |                      |
| Decarburizing       | Boxes annealing (1473 K)|                      |                      |
| Box annealing (1473 K, dry H₂) |                      |                      |                      |
products then available. The first breakthrough in texture control was achieved by a proper sequence of cold rolling and annealing to obtain very outstanding magnetic properties in the rolling direction.

It is a surprise to note, however, that Goss failed to realize the true texture of what he invented, as he described in his patent that "...the product is characterized by a high magnetic moment approaching that of a single crystal, and the grains of the material being substantially oriented at random throughout the structure as shown by an X-ray pattern." The same statement was reiterated in his presentation at the 16th Annual Convention of the American Society for Metals to puzzle the audience about the contradiction between random structure and single-crystal property.

The puzzle was cleared up by the X-ray study of Bozorth, who proved conclusively the presence of a sharp [110]<001> preferred orientation in the material prepared by Goss. However, as Bozorth concluded in his paper, Goss' misinterpretation of X-ray data relates in no way to the practical value of his invention. The Goss patent is perfectly valid and marks the starting point of texture control. The significance of his findings is still recognized by general reference of "Goss texture" to the [110]<001> preferred orientation and "Goss process" to the conventional process.

2.2. Secondary Recrystallization

Early progresses in the following years of the Goss invention was reported mainly through patents for obtaining a maximum of [110]<001> preferred orientation and minimum of core loss. However, the mechanism for texture formation was hardly discussed in these patents, although the interests in recrystallization and grain growth should be focused toward understanding the derivation of the texture. There was little scientific reportage on the Goss texture until the late 1940s.

In 1949 Dunn pointed out secondary recrystallization as the responsible process for development of the [110]<001> preferred orientation in grain oriented silicon steels. Secondary recrystallization produces about one large [110]<001> grain among a million of grains in a primary recrystallization matrix through the abnormal and selective growth of the grain during final annealing. As suggested by Beck, the general condition for secondary recrystallization is a small primary grain size achieved through the inhibition of normal grain growth either by second phase particles (impurity inhibition) or through the presence of a sharp primary recrystallization texture (texture inhibition). May and Turnbull showed that secondary recrystallization in commercial grain oriented silicon steels was induced by a fine dispersion of manganese sulfide precipitates; fine particles suppressed the growth of matrix grains, while at the same time [110]<001> grains were able to grow at the expense of the fine grain matrix.

The early work on secondary recrystallization provided the following information. (a) The development of [110]<001> preferred orientation requires the presence of [110]<001> component in the primary recrystallization matrix. (b) Inhibition of grain growth is required to prevent the matrix grains from normal growing during the incubation period for selective growth of the [110]<001> oriented grains. (c) The inhibitors must be present for the selective growth of [110]<001> oriented grains at the incubation temperature; annealing at higher temperatures allows the growth of matrix grains and decreases the driving force for growth of the [110]<001> oriented grains.

3. Approaches to Texture Control of Grain Oriented Silicon Steels

In the following the historical background and current knowledge on texture control of grain oriented silicon steels will be summarized. Problems for breakthrough in texture control will be presented and discussed to give a better understanding on the various approaches to improved performance.

This review represents a viewpoint that a requisite for secondary recrystallization is the presence of microstructural inhomogeneity, since the exclusive growth of a particular grain can not be expected to progress in a homogeneous matrix. The development of a sharp [110]<001> preferred orientation in secondary recrystallization requires a local inhomogeneity in terms of grain size, preferred orientation, and density and morphology of precipitates with an optimum extension in the microstructure.

3.1. Progresses in Methods and Concepts of Texture Research

Along with the commercial interests in silicon steels, search for fundamental understanding continued in the investigation into recrystallization and texture formation mechanism. Intense research and development efforts over the years have led to the commercial production of the high permeability grades. The future innovation in texture control should be guided by a sophisticated understanding of the mechanism involved. As an introduction to the following discussion on current principle and practice of the texture control of grain oriented silicon steels, a brief summary will be given on the historical development in methods and concepts of texture and recrystallization research.

3.1.1. Advances in Research Methods for Understanding of Texture Formation Mechanism

Advances in texture and recrystallization studies are largely dependent on available research techniques. The most significant impact was the information derived from transmission electron microscopy. Observations of the deformed structure and nucleation process by transmission electron microscopy showed that the microstructure resulting from deformation has a decisive influence on the kinetics of primary recrystallization and the evolution of the recrystallized microstructure and texture. It has become widely accepted that recrystallized grains have their origins.
in the inhomogeneities of microstructure introduced by deformation.

Quantitative texture analysis is a prerequisite for texture control. Introduction of the crystallographic orientation distribution function analysis\(^{36}\) has prepared a quantitative basis for pole figure interpretation to describe explicitly the texture of polycrystalline materials. Orientation measurements of individual grains by Kossel\(^{32}\) and electron channeling\(^{33}\) patterns have been made meaningful as a statistical quantity through advances in the measuring and data processing systems.

Texture is considered statistically identical over the whole volume of a material. It is necessary, however, to take into account the occurrence of inhomogeneity in textures in many important cases, especially, in grain oriented silicon steels. Topographic mapping\(^{34}\) of local texture on a significantly large area is achieved by the use of energy dispersive X-ray diffraction that permits rapid acquisition of diffracted intensities from several diffraction planes.

Differences in recrystallization kinetics lead to formation of preferred orientations. Recrystallization processes of individual textural components are followed by X-ray macrography.\(^{35}\) Progresses of both primary and secondary recrystallization are dynamically observed \textit{in situ} by the energy dispersive X-ray diffractometry\(^{36}\) and synchrotron white beam X-ray topography.\(^{37}\) Results of these observations have provided the basis of the following discussion.

3.1.2. Orientation Changes in Cold Rolling and Recrystallization

In the 1950s and 1960s, comprehensive studies were made on cold rolling and annealing of silicon iron single crystals, because an understanding of the mechanism of texture formation in single crystals is a necessary first step toward the understanding of texture control in commercial polycrystalline materials. The easiness of crystal growth in sheet and the ability of controlling the orientation of single crystals made silicon iron ideal for fundamental studies of recrystallization and texture. In addition, well defined starting orientations offered advantages in correlating the orientation changes in deformation and recrystallization and in observing the early stage of grain growth. Many studies were reported on cold rolling and annealing of single crystals, in particular, of the [110] \langle 001 \rangle orientation.\(^{37-47}\)

The orientations of crystals tend to converge into stable orientations in cold rolling to form two types of fiber texture; (1) the component of stable \langle 001 \rangle \langle 110 \rangle orientation with a spread around the \langle 110 \rangle rolling direction extending to include \langle 111 \rangle \langle 110 \rangle and (2) a continuous spread with the \langle 111 \rangle axis parallel to the sheet normal.

One of the principal questions in the single crystal studies has been which of two mechanisms, oriented nucleation and oriented growth, controls the formation of primary recrystallization texture. In the recrystallization textures, orientational relationships were examined between deformed matrices and recrystallized grains in terms of rotations around particular crystallographic axes. As a result of these single crystal studies together with measurements of the orientation dependence of grain boundary mobility, attention was centered on the growth stage of primary recrystallization as the texture governing stage.

Much evidence showed that the mobility of grain boundaries is dependent on their misorientation. Favorable orientation relationships have been established for grain growth; certain special boundaries have greater than average mobility. In principle, this can give rise to recrystallized grains, which satisfy certain orientation relationships with the deformed matrix in which they grow. These relationships correspond with misorientations of 20 to 30 degrees around a common \langle 110 \rangle axis for body centered cubic metals.\(^{48}\) These \langle 110 \rangle rotations are considered to be of selective growth relationship, but these are also the misorientations that can be generated by the dislocation walls in deformation and recovery process.\(^{49}\)

The results obtained from single crystals must be transferred to polycrystalline materials for practical application. The transfer is not always valid for recrystallization texture, since the recrystallization behavior of polycrystalline materials and single crystals is similar only when the deformation texture and the structure of deformed matrix are the same in both materials. Usually, establishment of orientational relationship in recrystallization of polycrystalline materials is difficult because of the complexity of textures. Furthermore, effects of grain boundaries acting as a constraint of slip deformation must be taken into account especially in the \langle 110 \rangle \langle 001 \rangle texture formation of silicon steels, as will be discussed in detail in Chap. 4.

3.1.3. Microstructure and Texture Evolution

Transmission electron microscopy has brought a turning point. Electron microscopic observations showed that the orientation of the recrystallized grain exists within the spread of orientation present in the deformed state and a recrystallized grain forms by enlargement of a cell or subgrain in the matrix.\(^{49-54}\) The cell structure is not homogeneous with a wide variety of cell sizes and misorientations between cells. This represents local variations in the amount of stored energy and crystal rotation in the deformed matrix.

Recrystallization grains nucleate preferentially in the regions of matrix where the orientation and deformation gradients are large. A high local stored energy representing a small cell size can provide a high driving force. Steep spatial gradients of stored energy and orientation allow a growing embryo readily to achieve a high angle boundary for extensive growth. Much evidence indicates that the conditions of preferential nucleation are more readily satisfied in some orientations in a deformed matrix than in others. The extent and the type of dislocation storage depend on the crystallographic orientation in relation to the principal axes of deformation and the frequency of
occurrence is not equal because of the deformation texture. The difference in path and history of the crystal rotation results in the variations of inhomogeneity and stored strain in the deformed microstructure; generally a larger deviation of initial orientation from the stable final orientation represents a higher stored energy.

A clear understanding of the inhomogeneities in deformed state is now recognized to facilitate understanding of the microstructural and textural changes from a deformed to recrystallized state. Knowledge of the nature and formation mechanism of deformed structure may be a basis for understanding of the microstructural and textural change from a deformed to recrystallized state. Various types of microstructural inhomogeneities appear in the deformed state and classified on the basis of its morphological feature and orientation topography. Important microstructures in the texture control of grain oriented silicon steels are transformation bands and shear bands. The orientation of recrystallized grains is known to be dependent on the type of their nucleation sites: grain boundary, grain interior, and second phase interface. Importance of the grain boundary nucleation is recognized in low carbon steels for deep drawing applications. The favorable texture for formability is a high portion of the grains oriented with [111] planes parallel to the sheet plane. In 1960s and 1970s a great deal of work was devoted to the texture control of low carbon steel sheets. Effects of compositions and processing variables on the annealing textures have been extensively studied.

In many cases, the {110} component seems to compete with the components of [111] planar orientation in primary recrystallization: the {110} orientation differs from the [111] orientation in the dependence of recrystallization behavior on reduction in cold rolling and heating rate in annealing as the processing variables, and on initial grain size, nucleation site, and second phase as the metallurgical variables. Therefore, the results of texture and recrystallization studies on low carbon steels have been transferred effectively to the texture control of silicon steels, although the necessary preferred orientation is different. Important differences between silicon steels and low carbon steels are the restriction of cross slips in cold rolling and no complete phase transformation in hot rolling of silicon steels.

3.2. Problems for Breakthrough in Texture Control

The results of fundamental studies must be compiled to be applicable to the texture control in commercial production. Addressing and discussion of the following questions may be a necessary step to understanding of the texture control.

(1) How the {110} oriented grains occur in the primary recrystallization matrix?

Since the development of {110} preferred orientation in secondary recrystallization requires the presence of {110} oriented grains in the primary recrystallization matrix, we must understand the metallurgical and processing factors for evolution of the {110} component as the potential nuclei of secondary recrystallization. As the next step, we need to identify the {110} oriented grains that must have some advantages to get a high capability of grain growth over the other orientations for becoming nuclei of secondary recrystallization and to follow the potential nuclei to their origin. The presence of viable nuclei, however, does not always imply the success of secondary recrystallization, because abnormal growth sometimes ends in imperfection. We must consider both the growing grains and consumed matrix to find the selectivity rule leading to perfect secondary recrystallization.

(2) What qualifies the {110} oriented grains for viable nuclei of secondary recrystallization, and how can they grow at the expense of surrounding grains for perfection of secondary recrystallization?

In the production of grain oriented silicon steels that undergo no complete phase transformation to erase the preceding history, the metallurgical parameters in the early processing stage strongly influence the final texture. Therefore the evolution of microstructure and texture must be followed and controlled through the various stages of processing. We must understand the origin of the potential nuclei and their development in the subsequent processes.

(3) How the {110} oriented potential nuclei originate and survive in the processing?

On the basis of above understandings we can discuss metallurgical and processing factors for the optimum texture control of grain oriented silicon steels.

(4) How should the texture and microstructure be controlled in the production of grain oriented silicon steels for improved performance?

Since the answers to these questions are not generally different for the types of products, the following discussion will be mainly concerned with the single stage rolling process. Finally, we compare the differences in texture formation between the single and two stage cold rolling processes.

(5) What are the essential differences between the single and the two stage cold rolling process in terms of the texture control?

We will discuss these questions in the following sections.

4. Recrystallization Characteristics of {110} - {100} Oriented Grains

The {110} orientation shows very unique behavior in both deformation and recrystallization. Recrystallization characteristics of {110} oriented grains can be better understood on the basis of deformation behavior in cold rolling of single crystals.

4.1. Deformation Behavior of {110} Crystals in Cold Rolling

Deformation structure and texture can be most clearly revealed in the observation of deformed single crystals. First systematic studies were made by Dunn and Dunn and Koh on the rolling tex-
tures of 3.25% silicon iron single crystals prepared with controlled initial orientations and cold rolled to 70% reduction in thickness. Later, other workers extended these studies to include additional orientations and processing variables.\(^{40-47}\)

The change in orientation upon rolling of the (110)<001> crystal can be described as rotations in opposite directions around the [110] axis parallel to the transverse direction of rolling. The two slip systems, (112)[111] and (112)[111], are largest in the resolved shear stress in the initial orientation and can be taken as mainly operative. Operation of these slip systems produces edge dislocations extending in the [110] direction parallel to the transverse direction. The amount of rotation increases with increasing deformation, to be 35 degrees at 70% reduction. These rotations result in two complimentary texture components, (111)[112] and (111)[112]. However, in the later stage of rolling when the two stable orientations are approached, additional slip systems must be operating as well to produce an orientation spread around [111] axis parallel to the normal direction of sheet.

Theoretical analysis\(^{51}\) shows that the (110)<001> orientation is a metastable orientation that is divergent in two ways, as shown in Fig. 2. Deformation of a crystal in the metastable orientation tends to split up the crystal into blocks with different rotations separated by deformation bands. The bands are composed of closely spaced subboundaries, which accommodate cumulative misorientations by bridging an orientation difference between the matrices. Microscopic shear bands form within large grains parallel to the transverse direction with an inclination of about 35 degrees to the sheet surface as a consequence of concentrated shear strain.\(^{25-27}\) In this paper, the shear bands within grain interior are termed as the microscopic shear bands to distinguish them from the macroscopic shear bands that traverse the entire thickness of rolled sheets.

The (110)<001> orientation is a preferred orientation formed in the surface layer of cold rolled iron and steel sheets.\(^{34,55-62}\) The surface texture develops because of high friction between the sheet and the rolls.

Fig. 2. Theoretical prediction on the orientation changes upon cold rolling of iron crystal in a metastable (110)<001> orientation.

4.2. Recrystallization Behavior of [110]<001> Oriented Grains

The following is a summary of the current knowledge on occurrence of [110]<001> oriented grains in primary recrystallization of silicon steels and low carbon steels.

(a) The [110]<001> oriented grains are preferentially formed in primary recrystallization after cold rolling of [110]<001> single crystals at a moderate reduction.\(^{37-47}\)

Primary recrystallization textures of silicon iron single crystals generally contain components derived from the deformed crystals by rotations of 25 to 30 degrees around common [110] axes. In particular, a crystal showing a {111}<112> deformation texture recrystallizes to a strong [110]<001> preferred orientation by a rotation around [110] parallel to the transverse direction. Thus a crystal of initial orientation [110]<001>, which rotates to the [111]<112> in deformation, recrystallizes and returns to its initial orientation. Secondary recrystallization permits the selective growth of grains with approximate orientations of [210]<001>, [121]<012>, and [111]<110>.\(^{35}\)

(b) The [110]<001> orientation recovers and recrystallizes most rapidly in the deformed matrix.\(^{44}\)

Among rolled single crystals of an iron–3.25% silicon alloy which are representative of main components in the rolling texture of this alloy, the crystal with {111}<112> orientation recrystallizes fastest to form a preferred orientation in [110]<001>.\(^{35}\)

(c) The nucleation sites of [110]<001> oriented grains are the bands of heterogeneous deformation.\(^{31,50-57}\)

In the cold rolled silicon iron single crystal initially in [110]<001> orientation, subgrains occur preferentially within striated band structure running perpendicular to the rolling direction. The subgrains grow to be recrystallization grains. The bands have a steep orientation gradient, because lattice rotation during deformation is in different directions on the two sides of the band. A residue of the initial orientation is retained in the center of the transition band. The Goss nuclei occur in the bands for this orientation in a region of sharp lattice curvature with a favorable and symmetrically disposed structure gradient. The nuclei can grow rapidly to form high angle boundaries with the matrix because of the steep orientation gradient.

An analysis of nucleation in deformation bands shows that the most favored orientations for nucleation are [110][001], [001]<110>, and [11, 11, 8]<4, 4, 11> in that order.\(^{63}\) Different types of bands are most favored for nucleation at different strains, and cease to be viable nuclei after heavy deformations.

(d) The [110]<001> component in primary recrystallization texture develops at moderate reductions and weakens with increasing reduction in the preceding cold rolling.\(^{55,64}\)

For moderate cold reductions there is usually a significant amount of [110]<001> component in the recrystallization texture of polycrystalline pure iron. This becomes increasingly prominent with larger grain
size, as shown in Fig. 3. This suggests that the (111)[112] orientation that is the matrix for nucleation of [110]<001> oriented grains [see (a)] is only stable at moderately high rolling reduction and the development of [110]<001> orientation is strongly affected by the presence of grain boundaries.

(c) The [110]<001> orientation stores the highest strain energy in the cold rolled matrix.

Detailed electron microscopy studies show that the cell size and cell boundary misorientation measured by transmission electron microscopy in iron cold rolled to 70% reduction vary in a systematic way according to the deformed grain orientation parallel to the sheet surface. Fine cells with high misorientations represent higher stored energy of deformation. The stored energy increases in the sequence of [001] <[112] <[111], and the highest values of all are found in the small portion of [110] oriented grains. The results of the electron microscopy are generally consistent with the measurement of stored energy in different orientations with X-ray diffraction line broadening of cold rolled polycrystalline iron. Nucleation by subgrain growth within deformed grains is considered most rapid where the stored energy is greatest. The rate of recovery and recrystallization of [110]<001> component is the highest in coarse grained materials, as shown in Figs. 4(a) (recovery of lattice strain as evaluated by X-ray diffraction profile analysis) and 4(b) (number of recrystallization grains as counted by X-ray macrography).

(f) The [110]<001> oriented grains appear in the grain interior, in particular, of coarse grains.

As shown above in (a) and (d), the initial grain size prior to cold rolling and annealing has a significant effect on the nature of recrystallization texture. The [110] component of the recrystallization texture is more seriously affected by difference in the original grain size; this component increases on annealing in the large grained material relative to the small grained material. Appearance of [110]<001> oriented grains in interior of the coarse grained iron is observed by scanning electron microscopy of etch figures in the early stage of primary recrystallization. These features are attributable to inhomogeneous deformation in the grain interior and nucleation of recrystallization in the region of deformation bands. The grain size dependence of deformation band nucleation is expected in such a manner that these bands assume greater significance in coarse grained materials.

(g) Presence of solute carbon in the cold rolling stage promotes development of the [110]<001> component in primary recrystallization texture.

The identification of the roles of carbon has been a primary task of texture control in continuous annealing of low carbon steel sheets. Control for low carbon levels and coarse carbide dispersion is the essential requirement for achieving deep drawability in rapid heating. Higher dissolved carbon levels are associated with formation of textures in which the amounts of [111] components are reduced and those of [110] increased. Strain aging treatment applied between passes of cold rolling produces striated bands as a consequence of clustering of parallel straight dislocations and enhances the development of [110] component. If carbon atoms are not in solid solution, fine dispersion of carbides can release carbon into the matrix to interact with dislocations by a kind of dissociation process. The dissolved carbon forms short

![Fig. 3. Variations of cold rolling and annealing texture of pure iron with the cold rolling reduction and initial grain size.](image)

![Fig. 4. Difference in the orientation dependence of recovery and recrystallization rate in cold rolled pure iron in accordance with the initial grain size prior to rolling.](image)
range ordering of carbon atoms in the stress field of dislocations.

In the cold rolling stage of grain oriented silicon steels, interpass aging during the interval of reverse rolling ensures the high performance of the final products by reproducing a significant amount \{110\}<001> component in the primary recrystallization texture.\(^\text{70}\) Comparison of deformation and recrystallization behavior between the materials rolled with and without interpass aging reveals the characteristics in the occurrence of [110]<001> grains in primary recrystallization, as shown in Figs. 5 and 6. The interpass aging produces a cluster of straight dislocations and an array of striated bands in large grains in the deformation structure. In the early stage of recrystallization, recrystallized grains appear in the grain interior in the aged material and in the vicinity of grain boundaries in the non-aged material. At the completion of primary recrystallization, the grain size is finer and more uniform in the aged material. These are well consistent with the above evidence in particular of (c) and (f).

The effect of interpass aging, which is accelerated by the heat generated by deformation, is most prominent in the materials quenched into boiling water after annealing of the hot rolled sheets.\(^\text{71}\) Boiling water quenched sheets contain a fine dispersion of carbides, while iced water quenched sheets contain solute carbon and martensite. The primary recrystallization texture has a higher amount of the sharp \{110\}<001> component in boiling water quenched material than in iced water quenched material. The finely dispersed carbides probably bring carbon into solid solution by dissociation and favor the stabilization of deformation bands at the most effective stage. The similar evidence on the effects of a fine dispersion of carbides is reported for the two stage route.\(^\text{70}\)

Solute carbon is believed also to suppress selectively the nucleation of [111] grains by lowering the temperature of recrystallization onset.\(^\text{70}\) This possibility of interference of dissolved carbon during annealing must be confirmed for the following points; there remain problems why the presence of carbon or ordering of carbon around dislocations can lower drastically the recrystallization temperature and the interaction of carbon with dislocation rearrangement and annihilation strongly favors towards the development of [110]<001> component which is known to be especially vulnerable to the interference by finely dispersed phases [see (h) below].

As a different viewpoint, hard martensite phase is considered to be essential for production of \{110\}<001> oriented grains.\(^\text{73-77}\) A coarse hard particle produces a highly strained region in the surrounding matrix for preferential nucleation site. However, selective nucleation of the \{110\}<001> grains seems improbable, since the higher performance is attained by processing in the boiling water quenching than the

| Temperature of heating | Not aged between passes | Aged between passes |
|------------------------|-------------------------|---------------------|
| Deformed               |                         | RD                  |
| 823 K                  |                         |                     |
| 848 K                  |                         |                     |
| 973 K                  |                         |                     |
| 1073 K                 |                         |                     |
| 1123 K                 |                         |                     |

Fig. 6. Different recrystallization behavior of a grain oriented silicon steel cold rolled 87% without (left) and with (right) aging between passes, as observed on the section of 20% thickness below the surface of sheet.

Fig. 5. Transmission electron micrographs showing the microstructures in a high permeability grade grain oriented silicon steel cold rolled 87% without (left) or with (right) aging between passes.
Variations of primary and secondary recrystallization texture are evident in accordance with the pre-treatment, as shown on the (100) pole figures of three types of materials after annealing at 1473 K (Fig. 7). Primary recrystallization produces coarse [111]<110> oriented grains by suppression of [110]<001> component in the solution treated material (A). This is very similar to the primary recrystallization structure of aluminum killed steels, suggesting the strong interference of recovery and precipitation during annealing. The coarse grain matrix is retained during the subsequent high temperature annealing without occurrence of secondary recrystallization. The other two crystals form the primary recrystallization texture of [111]<110> and [210]<001>. However, the secondary recrystallization texture differs significantly between the two: [110]<001> in the material (B) and the same orientations observed in the study of single crystals without addition of aluminum and nitrogen in the material (C) [see (a)]. These variations point to the important contributions of aluminum nitride in the control of primary recrystallization for perfect secondary recrystallization.

4.3. Evolution Mechanism of [110]<001> Grains in Primary Recrystallization

All the above evidence can be qualitatively understood on the basis of the characteristic dislocation configurations for [110]<001> nuclei in the microstructure originating from deformation of the initially [110]<001> oriented crystals. The Goss nuclei are embedded in the transition regions of deformation bands or microscopic shear bands. The transition region represents a high dislocation density, accommodating a large misorientation and storing a high energy. In the transition region, subgrains are separated by the walls of tilt boundary composed of an array of edge dislocations having [110] Burgers vector that is parallel to the transverse direction. Accumulation of the tilt boundaries produces an overall rotation around an invariant <110> axis that is perpendicular to the rolling direction.47,50

High sensitivity of [110]<001> nuclei to the effects of solute atoms and fine precipitates can be interpreted on the basis of strong interaction of solute atoms and precipitates with the edge dislocations in tilt boundaries. Locking of dislocations probably favors for the formation of deformation bands as a consequence of pile ups of dislocations in the cold rolling stage. Precipitation of fine precipitates may suppress the en-
largement of subgrains in the bands by climbing of dislocations.

As a summary of the requirements for occurrence of \([110\langle 001\rangle\) oriented primary recrystallization grains in polycrystalline material, the grains prior to cold rolling should be large and have an orientation near to \([110\langle 001\rangle\). The largeness of initial grain size is also favorable for forming the deformation bands in the grain interior and creating a population of \([110\langle 001\rangle\) grains that can be a potential nucleus of secondary recrystallization. The evolution of \([110\langle 001\rangle\) component is enhanced by the presence of solute carbon in the cold rolling process and suppressed by the interference of fine precipitates in the recovery and early recrystallization stage. Processing parameters must be optimally designed to satisfy these requirements. We will discuss the conditions for satisfying such requirements in the single stage rolling route in the following three sections.

5. Perfection of Secondary Recrystallization

5.1. Identification of Viable Nuclei

Secondary recrystallization can occur only when primary recrystallization is complete and normal grain growth is suppressed (matrix stabilization). Furthermore, nuclei are necessary to have an orientation different from the texture in the matrix and a size above a critical value. In grain oriented silicon steels secondary recrystallization nuclei preferentially form in the subsurface layer in the conventional grade\(^{85-89}\) and the high permeability grade sheets processed in the single\(^{84}\) and two stage\(^{86-87}\) cold rolling.

At a depth of 20 to 25\% of the thickness in primary recrystallized sheets, \([110\langle 001\rangle\) grains are found as large grains which include faint traces of the former grain boundaries as shown by the etched figures in Figs. 8(a) and 8(b).\(^{84}\) A transmission electron micrograph in Fig. 8(c) shows a characteristic configuration of grain boundaries upon impingement of a nearly identical orientation. This is very similar to the geometrical coalescence model by Nielsen,\(^{88}\) who originally proposed that, if two or more grains of a very similar orientation come into contact during boundary migration, there will be a geometrical coalescence resulting in a single grain.

The \([110\langle 001\rangle\) component is a minor component in the texture of primary recrystallization after heavy rolling reduction. Therefore, if the \([110\langle 001\rangle\) grains are distributed uniformly in the matrix, impingement of the nearly identical orientation may be rare. A cluster of \([110\langle 001\rangle\) grains must be created in the primary recrystallization matrix. In the initial stage of primary recrystallization, \([110\langle 001\rangle\) grains occur together with several neighboring grains of the nearly identical orientation, as shown in an electron micrograph of Fig. 9.\(^{74}\) This indicates the presence of inhomogeneous local texture in the preceding process.

In hot rolled sheets, large grains that have \([110\langle 001\rangle\) orientation are found at the depth of 20 to 25\% thickness. The interior of these \([110\langle 001\rangle\) large grains is most likely the site for \([110\langle 001\rangle\) primary recrystallization grains, as discussed in Chap. 4. A sufficiently large grain prepares the high probability of impingement of nearly the same orientation grains in the primary recrystallization matrix, as shown in Figs. 8 and 9. These grains may coalesce to get a high capability of growth because of the size advantage over the surrounding grains and act as a viable nucleus for secondary recrystallization.

The coalesced grains grow at the expense of the surrounding matrix. However, the nuclei can not achieve perfect secondary recrystallization, if the matrix is not prepared for extensive growth.

5.2. Matrix for Perfect Secondary Recrystallization

A comparative study of the materials resulting in perfect and imperfect secondary recrystallization reveals the unfavorable matrix for secondary recrystallization.\(^{89}\)

The history of texture and microstructure evolution was followed in the processing of two types of the materials leading to perfect (Material A) or imperfect (Material B) secondary recrystallization in the commercial production. Fig. 10 compares the microstructural changes during final annealing. In both types of materials, extensive grain coarsening starts at a depth of 20 to 25\% thickness below the sheet sur-

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**Fig. 8.** Coalescing grains in the primary recrystallization structure of a grain oriented silicon steel sheet processed through the single stage route: (a) optical (left), (b) scanning electron (center), and (c) transmission electron (right) micrographs showing the coalescence of \([110\langle 001\rangle\) oriented primary recrystallization grains. In (a) and (b), arrows indicate traces of the former grain boundaries and microfacet etch figures reveal the \([110\langle 001\rangle\) orientation.
Fig. 9. Transmission electron micrograph at the initial stage of primary recrystallization of a grain oriented silicon steel sheet cold rolled 87%. The orientations of recrystallized grains and matrix are determined by electron diffraction.

| Specimen | Temperature | Optical micrograph (longitudinal section) |
|----------|-------------|------------------------------------------|
| perfect  | 1293 K      |                                          |
|          | 1323 K      |                                          |
|          | 1393 K      |                                          |
| imperfect| 1293 K      |                                          |
|          | 1323 K      |                                          |
|          | 1393 K      |                                          |

Fig. 10. Perfection (upper) and imperfection (lower) of secondary recrystallization in the final annealing of high permeability grade grain oriented silicon steels processed in the single stage rolling route.

...face. The growth of viable nuclei proceeds anisotropically, most rapidly parallel to the sheet surface in the initial stage. An important difference between Materials A and B is that the growth is hindered from penetration through the sheet at a depth of about 30% of the thickness in Material B.

As evident from Fig. 11 showing the primary recrystallization texture and microstructure of decarburization annealed materials, a remarkable difference is the presence of a layer of relatively coarse grains and a sharp minimum of (111)//ND (normal direction to the surface of sheet) axis density in B at the location where the penetration of abnormal grain growth is strongly inhibited. Crystallite orientation distribution function analysis shows that the (111)//ND component consists mainly of a skeleton of (354) > (111) > (123) to (111) (112) that is related to the (110) <001> grains with the highest rate of growth by a rotation...
of about 30 degrees around the common \langle 110 \rangle axis. Resistance to abnormal grain growth arises especially in the layer where the orientation selectivity to the growing \langle 110 \rangle \langle 001 \rangle grains is not satisfied: the layer with preference of \langle 001 \rangle (\langle 001 \rangle\langle 110 \rangle) in place of \langle 111 \rangle//ND component.

In tracing back the difference in inhomogeneities further to the hot rolled sheets, the principal distinction between the materials, as shown in Fig. 12, is the development of preferred orientation with a strong maximum of \langle 001 \rangle in contrast to a weak \langle 111 \rangle//ND component at a layer of about 30% thickness in Material B. The \langle 001 \rangle component consists mainly of \langle 001 \rangle\langle 110 \rangle orientation that is stable in rolling. The microstructure in the intermediate to central layer of Material B is characterized by the presence of large elongated grains and an irregular dispersion of darkly etched areas that are the transformation product from gamma phase. The large elongated grains are likely a consequence of sluggish recrystallization in hot rolling and are oriented in the stable \langle 001 \rangle\langle 110 \rangle orientation. This structure has a tendency to retain the hot rolling texture after primary recrystallization and to originate a coarse grain structure. The large grains in the central layer of hot rolled sheets are reported to be responsible for the occurrence of streaks of small grains in final annealing, resulting in imperfect secondary recrystallization.\(^{30}\)

5.3. Growth of Secondary Recrystallization Grains

This paper is intended to review the texture control as a prerequisite for perfection of secondary recrystallization, and discussion on inhibitors and their interaction with grain growth is beyond the scope of this review. Progress in simulation and modeling of the grain growth during secondary recrystallization was the subject of a review paper\(^{31}\) in the recent issue of this journal. Only some aspects of grain
growth behavior that is closely related to the inhomogeneous microstructure will be presented in this review.

Usually migrating grain boundaries are considered to absorb dislocations and reduce the total dislocation density during the grain growth process. Direct observation by synchrotron white beam X-ray tomography has revealed that a number of dislocations are left and trailed by migrating grain boundaries during growth of secondary recrystallization grains under a temperature gradient. These dislocations are incorporated in networks to form subgrain structure. The growth fronts move very irregularly with a repetition of burst motion, steady growth, and standstill: the growth velocity ranges from 0 to 0.2 mm/s. One explosive growth consumes an area with an extension of 0.2 to 0.6 mm which seems to be the size of a local inhomogeneity forming a colony of a similar orientation. These observations indicate the important contributions of the local texture to abnormal grain growth besides inhibitor.

The texture control of grain oriented silicon steels involves the control of local inhomogeneities in texture and microstructure. Both potential nuclei and matrix should be optimally controlled throughout the processing route. In the next section the origin of inhomogeneities will be discussed.

6. Generation and Survival of Potential Nuclei

The microstructural and textural inhomogeneities have a significant contribution to preparation of both the potential nucleus of secondary recrystallization and the favorable matrix for its extensive growth. The inhomogeneities are primarily prepared in the hot rolling stage and occur in two ways. One is the local irregularity of grain size and precipitate morphology because of the partial phase transformation in the hot rolling and the subsequent annealing stage. The other source of inhomogeneity is a texture gradient through the thickness of hot rolled sheets: the preferred orientation varies from (110)<001> in the subsurface and intermediate layer to (001)<110> in the midplane of sheets. A good combination of these microstructural and textural inhomogeneities provides the nuclei of Goss orientation for secondary recrystallization. Table 2 shows a general scheme on the contributions of the microstructural and textural inhomogeneities to perfection of secondary recrystallization in the products.

### Table 2. Contributions of the microstructural and textural inhomogeneities to perfection of secondary recrystallization.

| Through-thickness location (z/a) | Subsurface to intermediate layer (1/5 - 1/4) | Midplane (1/2) |
|----------------------------------|---------------------------------------------|----------------|
| Processing stage                | Phase in hot rolling process                |                |
| Structural characteristics      | Ferrite                                    | Austenite      | Ferrite |
| Hot rolling and annealing       |                                            |                |        |
| - grain orientation             | 6.60%                                       | 0.06%          |        |
| - precipitate size density      |                                            |                |        |
| Cold rolling                    |                                            |                |        |
| - heavy reduction               |                                            |                |        |
| Annealing                       |                                            |                |        |
| Primary recrystallization      |                                            |                |        |
| - preferred orientation        |                                            |                |        |
| - grain structure               |                                            |                |        |
| - grain growth inhibition       |                                            |                |        |
| Secondary recrystallization    |                                            |                |        |
| - nucleation                    |                                            |                |        |
| - abnormal grain growth         |                                            |                |        |
| - Goss texture formation        |                                            |                |        |
| Contributions                   | providing source of nuclei                 | preparing matrix for growth | resisting to grain growth |
about three times higher than in alpha phase, so that the gamma phase retains aluminum and nitrogen in solid solution during hot rolling and produce a fine dispersion of aluminum nitrides in the transformation product after annealing of hot rolled sheets. Phase transformation also produces a fine grain structure with a high dislocation density because of the transformation strain. The partial phase transformation produces a duplex structure in the hot rolled and annealed sheets. Typical microstructure appears at a depth of 20% of a hot rolled and annealed sheet: large grains with coarse precipitates and small grains with fine precipitates, as typically shown in Fig. 13. The large elongated grain has the [110]<001> orientation.

A combination of large grains and coarse precipitates arises as a consequence of retention of the ferrite phase. This microstructure, in recrystallization after cold rolling, can favor the formation of colonies in a similar orientation strongly biased to [001]<110> in the interior of prior large grains, as shown in Fig. 8. The largeness of grain size is of primary importance for generating the [110]<001> oriented primary recrystallization grains to act as the source of secondary recrystallization nuclei. The coarse precipitates allow the selective nucleation and growth of [110]<001> component in primary and secondary recrystallization.

The other combination of small grains and finely dispersed precipitates occur as the products of phase transformation from the austenite. After cold rolling and annealing, the small grains produce a matrix of fine recrystallization grains with the [111]<112> preferred orientation which provides the favorable surroundings for extensive growth of the coalesced grains to complete the secondary recrystallization. The preferred orientation is in the favorable orientation relationship for the growth of the [110]<001> grains. The fine precipitates facilitates the inhibition of normal grain growth of the fine grained matrix.

In the processing of boron containing silicon steels (Type 3 in Table 1), one requirement for attaining high permeability is sufficient carbon to assure the presence of some austenite at the hot rolling temperature.4)

6.2. Texture Gradient

It is essential for achieving a strong secondary recrystallization texture in the products to clarify the mechanism of how the coarse grains in the Goss orientation occur preferentially at a depth of 20 to 25% thickness below the surface of hot rolled silicon steel sheets.

The [110]<001> orientation is typically the main component of surface texture in a steel sheet cold rolled with a high friction between the rolls and the sheet. Formation of texture gradients in hot rolled silicon steel sheets has been the subject of a number of research.72,80,89,90,95-103. The preferred orientation in hot rolled silicon steels is [110]<001> in the sub-surfaces to intermediate layers and [001]<110> in the mid-plane with a transition region corresponding to a rotation around the transverse direction. Mechanisms of the surface texture formation have been mainly discussed in terms of lubrication in rolling. A recent paper proposes a formation mechanism of [110]<001> preferred orientation in hot rolling on the basis of slip rotation.104

It is interesting to note that the [110]<001> preferred orientation, which is typically the surface texture of cold rolled sheets, develops most in a layer as deep as 20 to 25% of the thickness of hot rolled sheets. This may suggest that the formation of texture gradient in hot rolling proceeds in more complicated manner because of the high friction in rolling and the concurrent progress of recrystallization that differs with depth below the surface.

In hot rolling the high friction between rolls and sheet produces a shear deformation penetrating into the internal layer of a sheet. The amount of shear deformation occurring on either side of the neutral point varies with the depth below the surface. Near the surface where the shear deformation predominates in the entry side, a redundant shear strain produces a unidirectional rotation of crystals around the transverse direction. The shear is not fully reversed on passing the neutral point.

Evolution of texture gradient in hot rolling was studied29 by rolling in a high-speed laboratory mill equipped with a means for quenching at a predetermined time as short as 10 ms after rolling. Changes in preferred orientation and microstructure were followed in the rolled and quenched specimens.

Hot rolling produces an irregular distribution of plastic strain through the thickness of a hot rolled sheet. In accordance with the amount of introduced strain, the extent of recovery and recrystallization is different with the depth below the sheet surface. Rapid progress of recrystallization takes place near the surface, about 5% of the thickness below the surface, and randomization of the preferred orientation proceeds with subsequent grain growth.

Fig. 13. Inhomogeneous microstructure at a depth of 20% thickness in a hot rolled and annealed high permeability grade grain oriented silicon steel: the [110]<001> oriented large grain, as identified by the microfacet etch figures, seems to be a potential nucleus of secondary recrystallization and the surrounding matrix of small grains is a transformation product from gamma phase. The rolling direction is parallel to the longitudinal direction.
The mode as well as the extent of recrystallization differs across the sheet thickness. At a depth of about 5 to 10% of the thickness, *in situ* recrystallization, or dynamic recovery of the deformed structure, dominates. The subsequent rapid grain growth by high angle boundary migration accompanies an appreciable change in the preferred orientation (Fig. 14). A grains having an orientation which differs significantly from the prevailing preferred orientation of $\{110\}<001>$ will build up sufficiently large misorientations with respect to the surrounding grains (Fig. 15). The highly misoriented grains grow rapidly by migration of the high angle boundaries, leading to randomization of the texture.

On the other hand, transmission electron micrographs of the sections at a depth of 20% thickness below the surface suggest that the coarsening progresses by a mechanism of subgrain coalescence in the intermediate layer. As shown in Fig. 16, the grain growth proceeds by gradual disappearance of the subgrain boundaries to form an elongated structure. Disappearing boundaries are indicated by the arrows in the electron micrographs. The electron diffraction patterns from this region show that these subgrains are preferentially oriented in the $\{110\}<001>$ orientation, which is the dominant textural component of the
section.

The process is different from the high angle boundary migration observed in the surface layer, but it is very similar to the subgrain coalescence. The orientations of the coalescing subgrains are strongly biased to the \{110\}<001> orientation; the subboundaries are of low-angle misorientations. Coalescence of the grains having a nearly identical orientation preserves the preferred orientation of rolling texture after grain growth (Fig. 14). Thus, the generation of coarse grains with the Goss orientation is most likely a consequence of coalescence of subgrains with retention of the \{110\}<001> preferred orientation of the rolling texture in the layer.

7. Structural Control for Perfection of Secondary Recrystallization

7.1. Hot Rolling

The sequence of deformation and recrystallization in hot rolling is very important to provide an optimum inhomogeneities for the perfection of secondary recrystallization. For providing the source of secondary recrystallization nuclei, selection of the rolling conditions in the intermediate to later stage of hot rolling is essential to form the Goss orientation by shear deformation, and grain coarsening by subgrain coalescence. Rolling at a lower temperature produces a higher amount of \{110\}<001> component, but it limits the progress of \{110\}<001> grain coarsening.

The earlier stage is to be controlled for promotion of recrystallization especially in the central layer of sheet to prepare favorable surroundings for an extensive growth of secondary recrystallization grains in the final annealing. Heavy reduction at high temperature produces a fine dispersion of austenite phase which promotes the recrystallization of ferrite and randomizes the texture in the following passes.

7.2. Annealing of Hot Rolled Sheets

Hot rolled sheets are annealed in alpha and gamma region. Annealing produces no appreciable change in the texture gradient. However, the annealing process is important as a conditioning heat treatment for both inhibitor and texture control. In particular, the cooling rate after soaking has a substantial effect on the achievement of perfect secondary recrystallization in terms of texture control. Quenching into boiling water ensures the best results. Controlled cooling promotes the selective coarsening of the large \{110\}<001> grains during the partial phase transformation from austenite to ferrite in the early stage of cooling, because the coarse grains remain ferrite. Furthermore, quenching into boiling water eliminates hard particles of martensite to preserve the potential nuclei through the heavy cold reduction and disperses fine carbides to make the interpass aging more effective by releasing solute carbon to lock dislocations at the most influential stage.

7.3. Cold Rolling and Annealing

The heavy reduction sharpens but decreases the \{110\}<001> component in primary recrystallization texture. The large \{110\}<001> grains must survive the high reduction to be potential nuclei. The interpass aging in cold rolling process retains the potential nuclei within the deformation bands that are stabilized through the locking of edge dislocations by carbon atoms.

In continuous annealing of the cold rolled sheets, primary recrystallization accompanies decarburization. Since the \{110\}<001> grains are originally ferritic, concurrent progress of grain growth and decarburization may affect the growth behavior of the \{110\}<001> grains. No evidence is available on the evolution of preferred orientation in decarburization, which remains as the future research subject.

8. Difference between Single- and Two-stage Cold Rolling Process

Comparative studies of texture formation in the single and two stage rolling routes are not extensively made. Extensive review papers are available on the mechanism of secondary recrystallization texture formation in the high permeability grades processed through the two stage route.

In both processes, the potential nuclei of secondary recrystallization are prepared in the hot rolling stage. Lower reheating temperature and carbon content in the two stage route materials favor the development of higher amounts of \{110\}<001> component in the subsurface layer texture. Microalloying of molybdenum is shown to retard the progress of recrystallization in hot rolling and form large polygonized grains of the exact \{110\}<001> orientation. Strain free areas embedded within these large grains are considered to act as the potential nuclei of secondary recrystallization. These grains perpetuate the texture memory through the two stage rolling in succession of the disappearance in cold rolling and reappearance in annealing. Abundance of the potential nuclei leads to small secondary recrystallization grains ensuring the low iron loss.

As is naturally expected from the difference in the cold rolling route, the most prominent difference in texture appears in the primary recrystallization texture before final annealing. Fig. 17 compares the crystallite orientation distribution functions of primary recrystallization texture between the single stage and two stage process. The Goss orientation is the most populous component in the primary recrystallization texture of two stage route in contrast to the scarcity of the component in the single stage product. The higher reduction in the second stage in the high permeability grade than the conventional grade is to maximize the fraction of Goss grains before the final annealing. This is achieved by promoting the formation of deformation bands by the dispersion of fine carbides in the second rolling stage and strengthening the inhibition of grain growth through the fine dispersion of precipitates and segregates.

These Goss grains can be the most likely grains to
come into contact with a very similar orientation after completion of primary recrystallization. In the final annealing, soaking at a low temperature selects the exact [110]<001> grains for extensive growth during the subsequent heating.

9. Future Prospects

For commercial production of the grain oriented silicon steels with high performance rivaling that of amorphous materials, the products must be provided with lighter gauges and higher silicon contents than the current products at competitive costs. Production of thin gauge and high silicon steel sheets imposes increased difficulties in texture control as well as in cold rolling. Warm rolling can be a way to overcome the difficulties. In the secondary recrystallization, controlled temperature gradient ensures the selective growth of the exact Goss grains. Final annealing under a temperature gradient above 0.3 K/mm is reported to result in a product having a Bs value of 2.0 T. This indicates that much more improvement may be possible in the pursuit of the ideally oriented silicon steel.

As an alternative of the current processes, the rapid solidification process is a promising method for production of thin-gage grain oriented silicon steel sheets. A rapidly solidified 4.5% silicon iron alloy is shown to be cold rolled more than 70%, and to develop a sharp [110]<001> preferred orientation after high temperature annealing in vacuum.

In the research of recrystallization and texture, direct evidence on the selectivity in nucleation and growth is difficult to obtain. A significant part of discussion on the texture evolution must depend on speculation. There is not yet any basis for real understanding of the solute elements and fine precipitates and for prediction of the orientations of recrystallized grains. It is to be hoped that the development of fundamental studies and sophisticated research techniques will increase scientific knowledge. Advances will only be made when the information is acquired on the relationship between the microstructure evolution and the local and global texture formation during plastic deformation and recrystallization. The future innovation in texture control should be guided by a clear and deep understanding of the underlying mechanism.

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