Textures and Microstructures, 1994, Vol. 22, pp. 199–218
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A METHOD FOR MEASURING STRAIN BY ANALYZING SHARPNESS OF ECP WITH IMAGE ANALYSIS

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(Received 20 September 1990; Received in final form 10 December 1993)

A method for measuring strain by analyzing sharpness of Electron Channeling Pattern (ECP) with Image analysis has been newly developed. The relative value of sharpness of first-order pseudo-Kikuchi line in ECP is used as a parameter of strain. Strain change of Fe-3.25%Si alloy single crystal and polycrystal during deformation and recrystallization was analyzed by this method. This method was compared with the conventional methods; hardness and line broadening of X-ray. This method can be used for measuring strain in material with any crystal orientation.

KEY WORDS: Strain, scanning electron microscope, electron channeling pattern, pseudo-Kikuchi line, image analysis, Fe-3%Si.

1. INTRODUCTION

It is very important for studying deformation, recovery, recrystallization, texture, fatigue and fracture to know strain in steel or other crystalline material. The strain in material has been evaluated commonly by measuring hardness or line broadening of diffracted beams of X-ray or by observing lattice defects, for example, dislocations with Transmission Electron Microscope(TEM). However, the measurement of strain by hardness is affected by solutes and precipitates in material. In the case of measurement of strain by line broadening of diffracted beams of X-ray, beams of X-ray are difficult to focus on such a small area as under 100 μm in diameter. In the case of observing lattice defects with TEM, it is time consuming for the specimen preparation. Accordingly, these methods are not sufficient for measuring strain precisely and efficiently in such a small area as under 100 μm in diameter.

On the other hand, several studies have been done on the measurement of strain in the material by quantifying the contrast of specific pseudo-Kikuchi line in the Electron Channeling Pattern (ECP) (e.g. Joy *et al.*, 1971; Sticker *et al.*, 1971; Schulson, 1971; Davidson, 1974; Ruff, 1976; Davidson *et al.*, 1976; Davidson, 1977; Davidson, 1981; Farrow *et al.*, 1981). The strain in such a small area as 3 μm in diameter in the material can be measured by quantifying the contrast of specific pseudo-Kikuchi line in ECP because beam of ECP can focus on 3 μm in diameter (Nakagawa, 1986). However,

this method is inapplicable to the quantification of strain in the material with an arbitrarily chosen crystal orientation because the kind of pseudo-Kikuchi line in ECP depends on the crystal orientation (Davidson, 1984).

Quite recently, some studies have been done on the measurement of strain in the material by using Electron Back-scattering Pattern (EBSP) (e.g. Quested *et al.*, 1988, Dingly *et al.*, 1990). The strain in such a small area as less than 1 μm in diameter in the material can be measured by quantifying the contrast of EBSP. For measuring strain in a small area less than 3 μm in diameter. EBSP should be used. However, since ECP is more sensitive to strain than EBSP, ECP can be more appropriate than EBSP in the case of measuring small strain.

Then for measuring the small strain in the material with any crystal orientation, a method by analyzing sharpness of first-order pseudo-Kikuchi lines in ECP with Image analysis has been developed in the present study. The relative value of sharpness of first-order pseudo-Kikuchi line is used as a parameter of strain. Fe-3.25%Si alloy single crystal and polycrystal were used as test specimens. Strain change during deformation and recrystallization was analyzed by this method.

2. DEVELOPMENT OF THE METHOD FOR MEASURING STRAIN BY ANALYZING SHARPNESS OF ECP WITH IMAGE ANALYSIS

(1) *The Parameter of Strain*

The outline of analysis flow, the definition of sharpness of ECP (herein after referred as S) and sharpness of first-order pseudo-Kikuchi line (herein after referred as $S1$) are shown in Figure 1, Figure 2, respectively. When every first-order pseudo-Kikuchi is sharp, the value of $S1$ is defined as the ideal sharpness of first-order pseudo-Kikuchi (herein after referred as $S1_0$). $S1$ and $S1_0$ which are defined by eq. (1) and eq. (2)

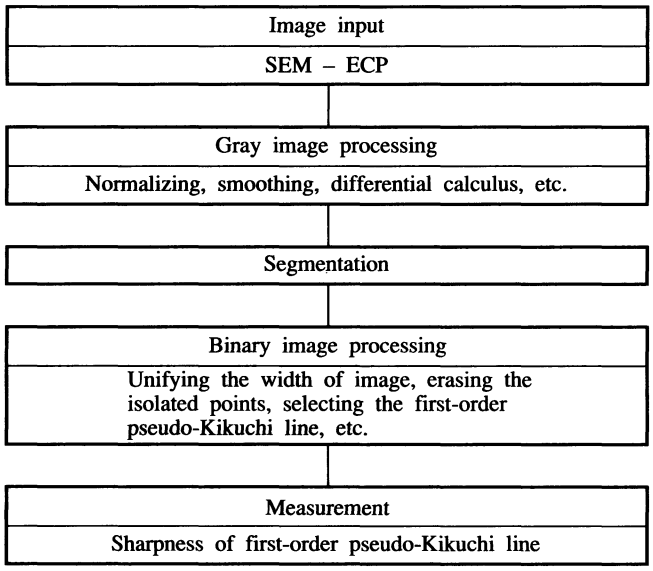

Figure 1 Flow of analysis.

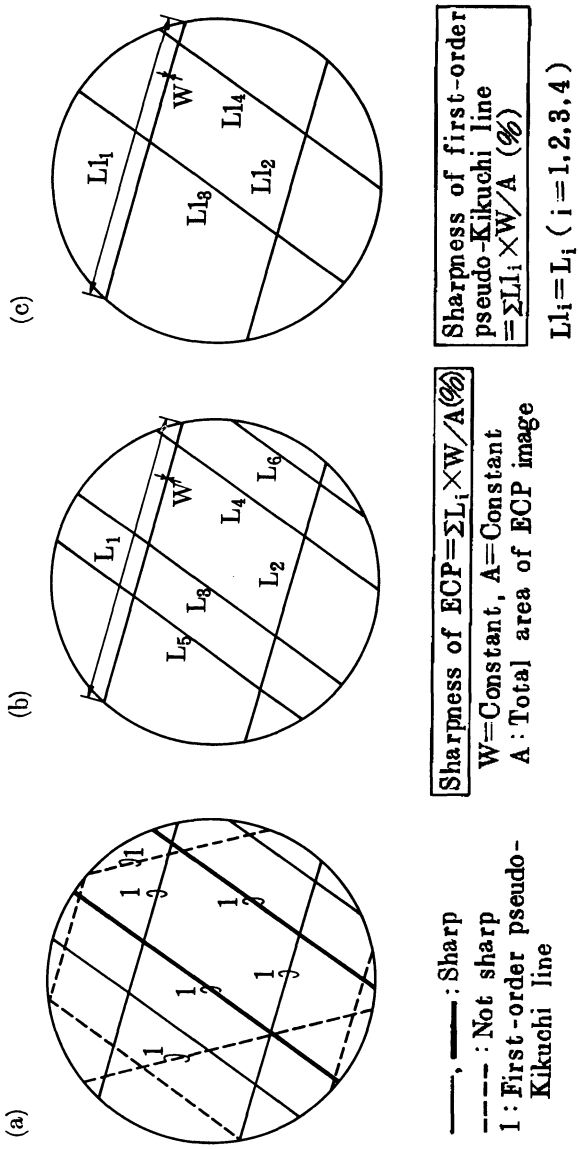

Figure 2 A schematic diagram of sharpness of ECP and sharpness of first-order pseudo-Kikuchi line. (a) ECP, (b) Sharp ECP, (c) Sharp first-order pseudo-Kikuchi line.

respectively are measured. Then, relative value of sharpness of first-order pseudo-Kikuchi line (herein after referred as $S1^*$) is calculated.

$$S1 = \sum L1_i \times W/A \quad (\%) \tag{1}$$
$$S1_0 = \sum L1_{oi} \times W/A \quad (\%) \tag{2}$$
$$S1^* = S1/S1_0 = \sum L1_i / \sum L1_{oi} \tag{3}$$

where $L1_i$ is the length of sharp first-order pseudo-Kikuchi line in ECP, $L1_{oi}$ is the length of first-order pseudo-Kikuchi line in ECP, W, the width of sharp first-order pseudo-Kikuchi line in ECP, is constant, A, the area of ECP image, is constant. $S1$ is measured as the area rate of sharp first-order pseudo-Kikuchi lines in ECP image because the area of crossing points of sharp first-order pseudo-Kikuchi lines in ECP image is so small that it can be neglected. $S1_0$ is also measured as the area rate of first-order pseudo-Kikuchi lines in ECP image. $S1^*$ is used as a parameter of strain in the present study. It is true that $S1^*$ has no information on the strain influence of higher order of pseudo-Kikuchi lines. However, $S1^*$ is practically superior to S as a parameter for expressing the degree of strain in the sense that $S1^*$ can be defined for any crystal orientation but S needs the reference value, for example, the value of S of fully annealed specimen with the same orientation as the test specimen has. To prepare this reference specimen for any orientation is very difficult.

(2) *Procedure*

The analysis flow is shown in Figure 1. First, a SEM-ECP image is transferred to an image analyzer with frame-store averaging. Then, Gray image processing, Segmentation, Binary image processing and Measurement are performed as follows.

1) *Gray image processing*
Smoothing by median filtering, standardizing the gray level by gray-scale transformation and smoothing by selective local averaging are performed. Then, the gray image is transferred to 2-dimensional differential calculus image with Sobel's method (e.g. Matuyama, 1985). This 2-dimensional differential calculus image is made more distinct by performing GAMMA transformation, LOG transformation, GAMMA transformation and smoothing by median filtering in this order.

2) *Segmentation*
Segmentation with constant threshold is preformed to obtain the image of area including the first-order pseudo-Kikuchi lines.

3) *Binary image processing*
Erasing isolated points is performed to delete noise with small area. Then, expanding the figure and shrinking the figure are performed. The operation of expanding the figure is the transformation by which the output picture element has "1" in the case that the input picture element or the picture elements with 8-adjacent relation to the input picture element has "1" and the output picture element has "0" in other cases. On the other hand, the operation of shrinking the figure is the transformation by which the output picture element has "0" in the case that the input picture element or the picture elements with 8-adjacent relation to the input picture element has "0" and the output picture element has "1" in other cases. By these processing, the region comprising the first-order pseudo-Kikuchi line, inserted between two area with high value of 2-dimensional differential calculus in original SEM-ECP image, is obtained. Then, holes in the region

comprising the first-order pseudo-Kikuchi lines are filled. And, thinning by Tamura's method (Tamura, 1978) and expanding the figure are performed to get the image made up of lines with constant width. The operation of thinning is the transformation by which the width of line in the image becomes 1 picture element. Through these processing, the image of sharp ECP described its definition in Figure 2 is obtained. And, each line in the image of sharp ECP is judged to be a sharp pseudo-Kikuchi line. And also, the thin line image just after thinning is defined as the thin line image of sharp ECP. On the other hand, the image included every first-order pseudo-Kikuchi line in ECP is made with the crystal orientation or by manual operation on the basis of the original ECP image. Then, the operation of making the logical product of the image of sharp ECP and the image included every first-order pseudo-Kikuchi line in ECP is performed to get the image made up of sharp first-order pseudo-Kikuchi lines with constant width. This corresponds to the image of sharp first-order pseudo-Kikuchi line described its definition in Figure 2.

4) *Measurement*

$S1$ and $S1_0$ which are defined by eq. (1) and eq. (2) respectively are measured. Then, $S1^*$ defined by eq. (3) is calculated. $S1$ is the area rate of sharp first-order pseudo-Kikuchi lines in ECP image and $S1_0$ is the area rate of first-order pseudo-Kikuchi lines in ECP image.

5) *Approximate method for measuring $S1^*$*

If the other method, for example EBSP, for measuring the crystal orientation of the specimen with some amount of strain is used, $S1_0$ value can be calculated with the crystal orientation. However, in the case that such a method isn't available, it is possible but not easy to measure the value of $S1_0$ of any specimen with any degree of strain. This is because it isn't easy to make the image included every first-order pseudo-Kikuchi line in indistinct ECP by manual operation. Then, the approximate value of $S1_0$ and its error range are measured as follows.

The value of $S1_0$ depends on the Miller index of normal direction. However, it is thought that the specimens with the similar orientation have the similar value of $S1_0$. Then, the mean value of $S1_0$ of each Box which is used in the Vector method (Ruer *et al.*, 1977) for analyzing 3-dimensional crystal orientation distribution is used as the approximate value of $S1_0$ of each Box. And then, the mean value of $\overline{S1_0}$ of 36 Boxes is used as the approximate value of $S1_0$ of any specimen with any crystal orientation and the range between the minimum value and maximum value of $S1_0$ of 36 Boxes is used as the error range of $S1_0$ of any specimen with any crystal orientation. According to this method, the approximate value of $S1_0$ and its error range for any specimen with the same crystal structure and the lattice constant can be given by measuring the values of $\overline{S1_0}$ of 36 Boxes for one fully annealed specimen.

This approximate is a practical way based on the mathematical concept described in eq. (3). This approximate is useful in the case of the system, like our system mentioned below, without the method, for example EBSP, for measuring the crystal orientation of the specimen with some amount of strain.

(3) *Analyzing System*

SEM:JSM-840 with an auto-stage and Image analyzer:TOSPIX-II are used in the present study. JSM-840 has a Selected Area Electron Channeling Pattern Unit (Nakagawa, 1986). TOSPIX-II has 16 bit cpu, two 132 MB HD, two 1 MB FD and 512 × 512 × 8 bit

picture size. ECP image is transmitted as an electrical signal from SEM to Image analyzer.

3. EXAMPLES OF APPLICATION

(1) *Measurement of the Approximate Value and Its Error Range of $S1_0$*

For measuring the value of $\overline{S1_0}$ of each 36 Box, Fe-3.25%Si alloy polycrystal annealed sheet with a grain size range from 10 to 50 μm was used as a test specimen. The orientation distribution of the polycrystal annealed sheet measured by X-ray and ECP for 100 grains is shown in Figure 3. The polycrystal annealed sheet had nearly random orientation except slightly high intensity of crystal orientation near {100}. The mean value of $S1_0$ of each Box in 36 Boxes measured for 100 images of ECP is shown in Figure 4. In the measurement of $S1^*$ mentioned below, these values of $S1_0$ in Figure 4 were used to calculate the approximate value and its error range of $S1_0$. The maximum value and minimum value of $\overline{S1_0}$ for 36 Boxes were 1.2 and 0.8 times as high as the average value of $S1_0$ for 36 Boxes respectively.

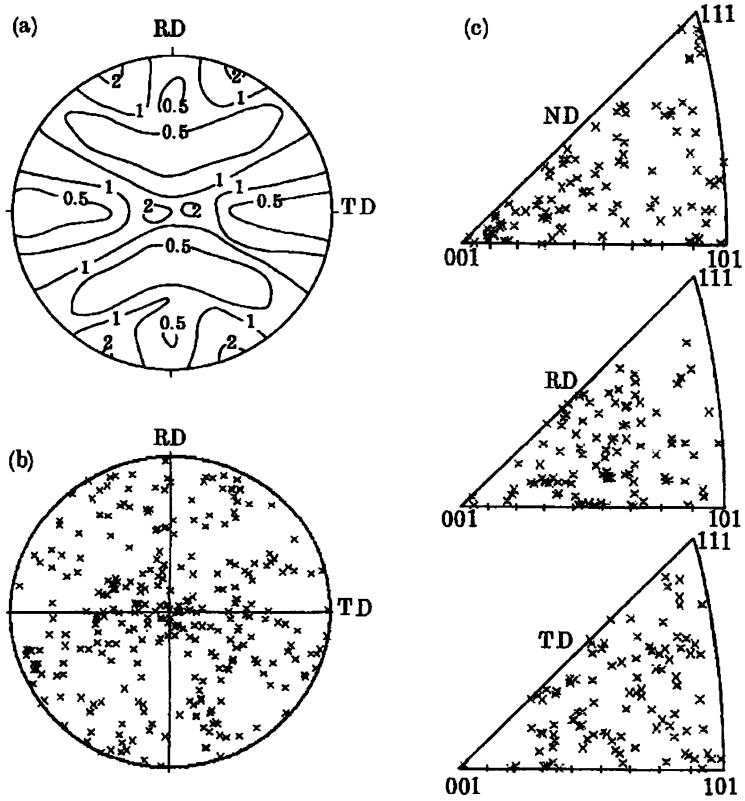

Figure 3 Orientation distribution of Fe-3.25%Si alloy polycrystal specimen. (a) {100} pole figure measured by X-ray. (b) & (c) orientation of 100 grains measured by ECP. (b) {100} pole figure. (c) Standard stereographic triangle projections (inverse pole figures).

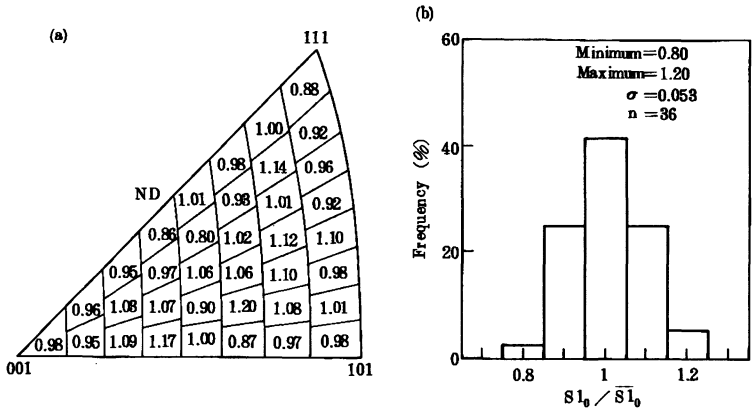

Figure 4 Distribution of ideal sharpness of first-order pseudo-Kikuchi line of Fe-3.25%Si alloy specimen. (a) The mean values of $S1_0/\overline{S1_0}$ in each Box. (b) The distribution of the mean values of $S1_0/\overline{S1_0}$ in each Box. $S1_0$: ideal sharpness of first-order pseudo-Kikuchi line. $\overline{S1_0}$: the mean value of $S1_0$ of 36 Boxes.

(2) *Test Specimens*

For analyzing the strain by deformation, Fe-3.25%Si alloy polycrystal annealed sheet mentioned above and Fe-3.25%Si alloy single crystal annealed sheet were used as the test specimens. The {100} pole-figure of the single crystal annealed sheets measured by X-ray are shown in Figure 5. The single crystals of (110)[001] and (100)[011] orientations were used as the test specimens. The single crystal and polycrystal specimens with various degree of strain were made by cold rolling by 1 pass with reduction from 0 to 17% or by tensile deformation with elongation from 0 to 15%.

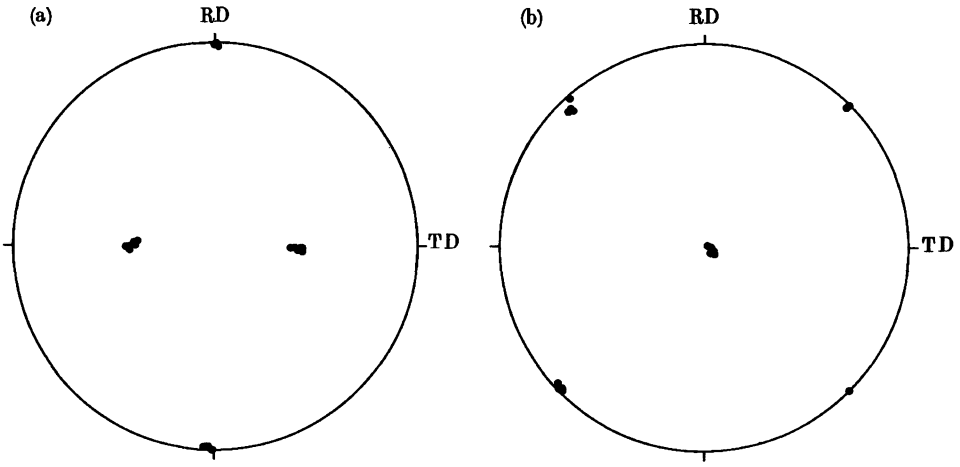

Figure 5 {100} pole figures of Fe-3.25%Si alloy single crystal specimens. (a) (110)[001], (b) (100)[011].

The thickness of specimens before deformation was 0.36 mm. In the case of cold rolling, the lubrication oil was applied to the roll surface and the diameter of the roll was 120 mm. In the case of tensile deformation, the tensile direction was chosen to the same direction with the cold rolling direction.

Then, for analyzing the strain decrease during recrystallization, the polycrystal specimens were prepared as follows. 2.3 mm thick Fe-3.25%Si-0.01%C hot rolled sheet was annealed at 1273 K for 300 s and was cold rolled to 0.285 mm thickness and was heated at a rate of 20 K/s to 1173 K and cooled in air at various temperature during the heating stage.

(3) *Measuring Method*

The specimens were chemically polished to the midplane for measuring S, $S1$ and $S1_0$. ECP at 10 points (2 points parallel to the direction deviating from R.D. by $\pi/12$ rad. $\times$ 5 points parallel to the direction deviating from that direction by $\pi/2$ rad., at 10 μm intervals) and at 50 points (5 points parallel to the direction deviated from R.D. by $\pi/12$ rad. $\times$ 10 points parallel to the direction deviating from that direction by $\pi/2$ rad., at 100 μm intervals) was measured for the single crystal specimens and the polycrystal specimens, respectively. And also, the local inhomogeneity of $S1^*$ was investigated for the single crystals deformed by 1.5% cold rolling and the partially recrystallized polycrystal specimen. Then, the relationship between S and $S1$ was investigated for ECP of polycrystaly annealed sheet and cold rolled sheet. And the grain boundary influence on S was investigated for polycrystal annealed sheet. As measuring condition of SEM-ECP of backscattered electron image, the accelerating voltage of 35 kV. the absorbed specimen current of 9×10^{-9} A, the working distance of 8 mm and rocking angle of $\pm 8 \times (\pi/180)$ rad. were used. The approximate value of $S1_0$ and its error range measured for polycrystal annealed sheet as mentioned above were used in this study. As the threshold for segmentation judging whether pseudo-Kikuchi line is sharp or not, the value of 30 was used.

Several parameters might affect $S1^*$ value. For example, the surface contamination by long-time measurement tends to decrease the $S1^*$ values. However, in this study, ECP is measured only once for the specimen. In addition, this contamination influence on $S1^*$ value can be much weaken by standardizing the gray level of original ECP with gray-scale transformation. The measuring parameters, such as primary beam aperture, size of scan area, gradation (gamma settings) and primary beam voltage, which might affect $S1^*$ value are carefully fixed in measuring ECP. The influence of dislocation cell-wall distribution on $S1^*$ value isn't taken into account in this study.

For comparing this method with the conventional methods, the full width of half-value (FWHV) of (200) diffracted X-ray, the Vickers hardness and the fraction recrystallized were measured. As measuring condition of FWHV, the characteristic X-ray of Mo $K_{\alpha 1}$, the accelerating voltage of 40 kV and the filament current of 20 mA were used. The Vickers hardness of the test specimen was measured with the load of 1 kgf. Then, the fraction recrystallized was measured by point-count method of 100 points with the naked eye for Electron Channeling Contrast (ECC) pictures measured by SEM. For considering the physical meaning of $S1^*$, the relationship between the tensile stress and $S1^*$ was investigated.

(4) *Results*

1) *Crystal orientation dependence on accumulated strain*

The influence of strain on ECP, the image of sharp ECP and the image of sharp first-order pseudo-Kikuchi line of (110)[001] single crystals are shown in Figure 6. ECP became indistinct and the number of sharp pseudo-Kikuchi line decreased with increasing strain. The total length of the sharp pseudo-Kikuchi lines shown in Figure 6, for example, is proportional to S (c, d) and $S1$ (e, f) respectively. The influence of strain by cold rolling on $S1^*$ of single crystals was shown in Figure 7. In Figure 7., the error range of $S1^*$ was caused by that of $S1_0$. According to eq. (3), the error range of $S1^*$ was asymmetric to the approximate value of $S1^*$. $S1^*$ was decreased with increasing strain in the cold reduction range less than 17%. The degree of this influence was affected by the crystal orientation before deformation. In the case of (110)[001] single crystal, $S1^*$ was decreased remarkably by 1.5% cold-rolling reduction and, then, was decreased gradually as the strain was increased in the cold-rolling reduction range from 1.5% to 17%. On the other hand, in the case of (100)[011], $S1^*$ was decreased gradually with increasing the strain in the every cold-rolling reduction range less than 17%.

Si^* is thought to express the mean contrast of all first-order pseudo-Kikuchi lines in the ECP of the specimen. The contract of specific pseudo-Kikuchi line in ECP was decreased as the dislocation density of the specimen was increased (Stickler *et al.*, 1971).

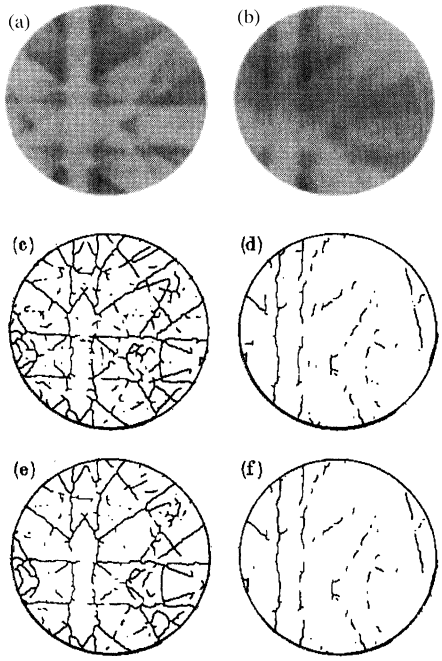

Figure 6 Influence of strain on ECP, sharp ECP and sharp first-order pseudo-Kikuchi line. Specimen : Fe-3.25%Si alloy (110)[001] single crystals at the midplane. a, b : ECP. c, d : sharp ECP made by Image analysis with our study. e, f : sharp first-order pseudo-Kikuchi line made by Image analysis with our study. a, c, e : without cold rolling. b, d, f : 15% cold rolling.

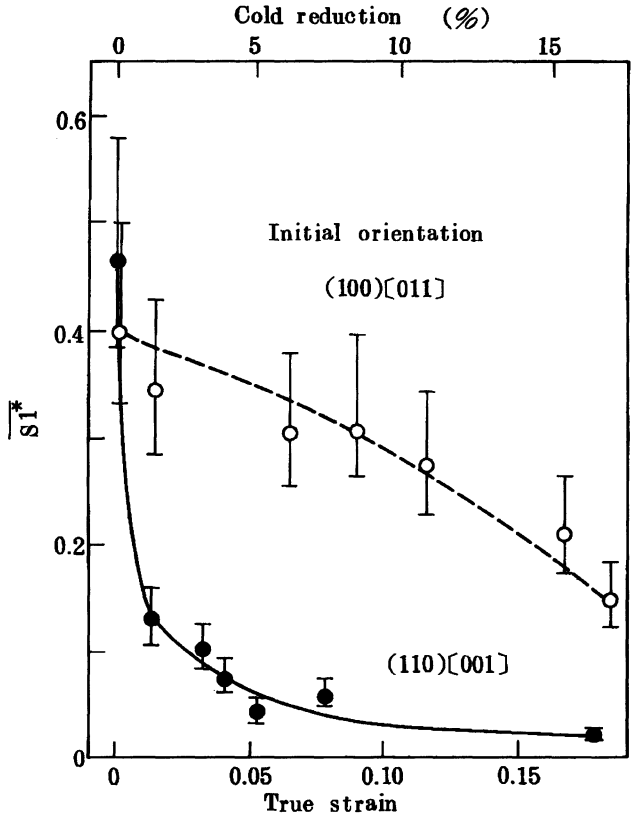

Figure 7 Influence of strain on sharpness of first-order pseudo-Kikuchi line of Fe-3.25%Si alloy single crystals at the midplane. $S1^*$: relative value of sharpness of first-order pseudo-Kikuchi line.

And also, the influence of elastic strain on the contrast (line width) of specific pseudo-Kikuchi lines in ECP was negligible (Davidson, 1982). Accordingly, $S1^*$ is thought to be the value which is decreased with increasing the dislocation density of the test specimen.

The accumulated strain or the dislocation density is influenced by the crystal orientation before deformation (e.g. Dillamore *et al.*, 1967; Takechi *et al.*, 1968). Figure 7 is thought to show the accumulated strain in (110)[001] single crystal is larger than that in (100)[011] single crystal. The relationship between $S1^*$ and the dislocation density of the test specimen is discussed further in the section of Relationship between tensile stress and $S1^*$.

2) *Local inhomogeneity of strain*

The local inhomogeneity of $S1^*$ (110)[001] and (100)[011] single crystals deformed by 1.5% cold rolling is shown in Figure 8, Figure 9, respectively. In the case of (110)[001] single crystal, the deformation band parallel to T.D. was observed. At that deformation band, the rotating angle from (110)[001] orientation around [011] axis parallel to T.D. was larger than that elsewhere. In addition, $S1^*$ at the deformation band was smaller than that elsewhere. On the other hand, in the case of (100)[011]

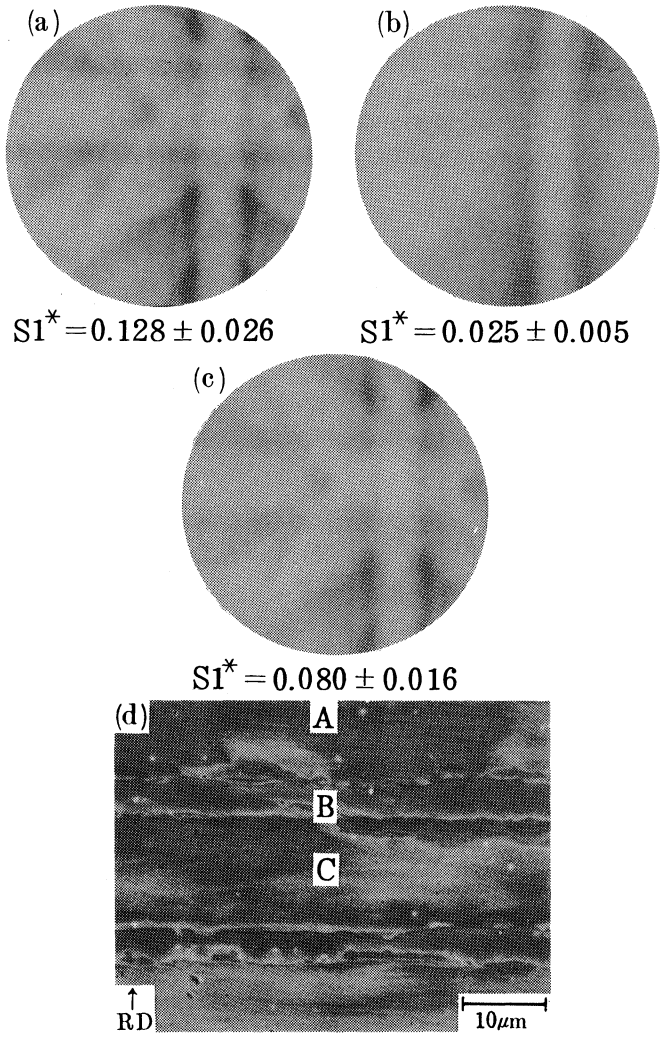

Figure 8 Local inhomogeneity of sharpness of first-order pseudo-Kikuchi line. Specimen : Fe-3.25%Si alloy (110)[001] single crystal at the midplane deformed by 1.5% cold rolling. a, b, c : ECP at A, B, C respectively. d : ECC. $S1^*$: relative value of sharpness of first-order pseudo-Kikuchi line.

single crystal, the deformation band parallel to the direction deviated from R.D. by $\pi/4$ rad. was observed. There was almost no orientation difference between at that deformation band and elsewhere. In addition, $S1^*$ at the deformation band was slightly smaller than that elsewhere.

Figure 8 and Figure 9 are thought to show the local inhomogeneity of accumulated strain or dislocation density in (110)[001] single crystal is larger than that in (100)[011] single crystal because $S1^*$ is thought to be the value which is decreased with increasing the dislocation density of the test specimen.

Next, the local inhomogeneity of the specimens extracted at 923 K and cooled in air during heating stage after 88% cold rolling is shown in Figure 10. In this case, the fraction recrystallized was 20%. $S1^*$ at recrystallization grain (A, B) was remarkably larger than that at recovery grain (C, D). This difference of $S1^*$ is thought to express that the dislocation density at recrystallization grain is much smaller than that at recovery grain.

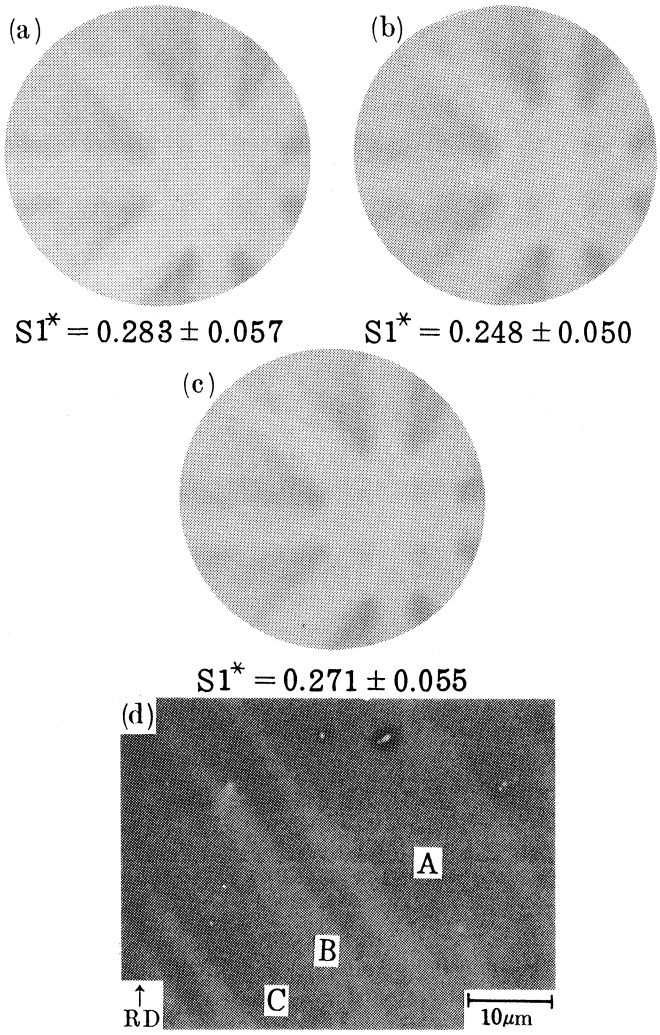

Figure 9 Local inhomogeneity of sharpness of first-order pseudo-Kikuchi line. Specimen : Fe-3.25%Si alloy (100)[011] single crystal at the midplane deformed by 1.5% cold rolling. a, b, c : ECP at A, B, C respectively. d : ECC. $S1^*$: relative value of sharpness of first-order pseudo-Kikuchi line.

3) *Approximation method for measuring S1**

In order to measure the value of $S1^*$ the measurement of crystal orientation or the manual operation for tracing the first-order pseudo-Kikuchi line is necessary. For avoiding these time-consuming operations, the approximate relationship between S and $S1$ expressed in eq. (4) could be used.

$$S1/\overline{S1}_0 = 0.8888 \times S/\overline{S1}_0 - 0.01241 \tag{4}$$

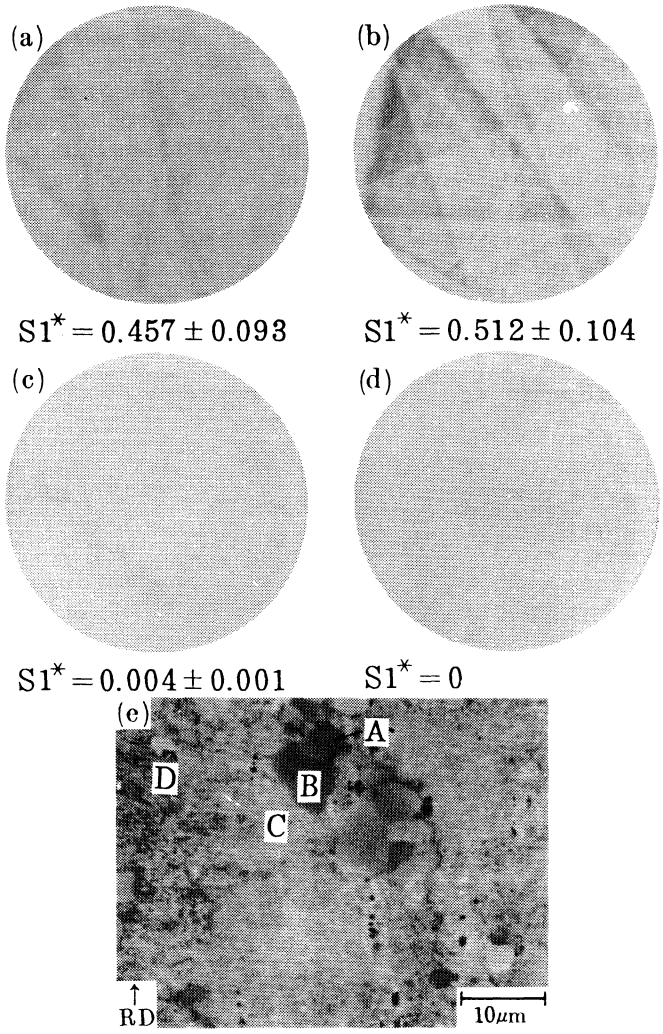

Figure 10 Local inhomogeneity of sharpness of first-order pseudo-Kikuchi line. Specimen : Fe-3.25%Si alloy polycrystal at the midplane at 923 K during heating at a rate of 20 K/s after 88% cold rolling. a, b, c, d : ECP at A, B, C, D respectively. e : ECC. $S1^*$ relative value of sharpness of first-order pseudo-Kikuchi line.

which was obtained by the method of least squares, where $\overline{S1_0}$, the mean value of $S1_0$ of randomly oriented specimen, is constant. The relationship between S and $S1$ of polycrystal annealed sheet and cold rolled sheet is shown in Figure 11. The number of measuring points was 50 and the coefficient of correlation was 0.9972 and the standard deviation was 0.01578. Eq. (4) shows $S1^*$ $(= S1/S1_0)$ can be calculated from S measured without measuring the crystal orientation nor tracing the first-order pseudo-Kikuchi line. However, the error range of $S1^*$ with eq. (4) is increased by its standard deviation.

4) *Grain boundary influence on S*

In the case of measuring S of polycrystal with auto-stage of SEM, the value of S is influenced inevitably by grain boundary. The example of grain boundary influence on ECP of polycrystal annealed sheet is shown in Figure 12. In ECP at grain boundary or triple point, two or three images of ECP of the grains bordering each other were mixed. The grain boundary influence on S of polycrystal annealed sheet is shown in Figure 13. The decrease of S value by mixed ECP at grain boundary or triple point could be estimated about 20% to the average value of S of the grains bordering each other. The relative value of 20% can be considered as the error of S value by grain boundary influence.

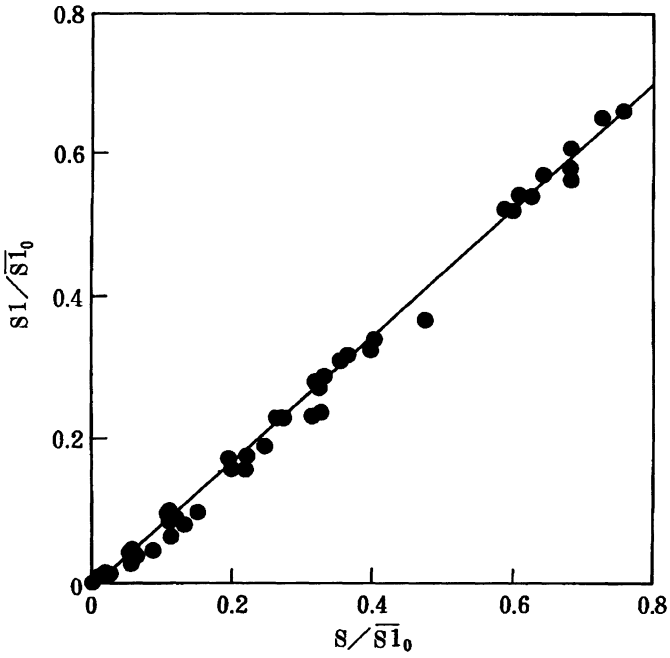

Figure 11 Relation between sharpness of ECP (S) and sharpness of first-order pseudo-Kikuchi line ($S1$). Specimen : Fe-3.25%Si alloy polycrystal annealed sheet and cold rolled sheet at the midplane. $\overline{S1_0}$: the mean value of ideal sharpness of first-order pseudo-Kikuchi line of randomly oriented specimen.

5) *Strain of polycrystal by deformation*
The influence of strain by cold rolling on $S1^*$ and FWHV of polycrystal is shown in Figure 14. In this case, $S1^*$ was calculated by e.q. (4) with S value. The $S1^*$ value was decreased remarkably by 1.5% cold-rolling reduction and, then, it was decreased gradually with increasing the strain in the cold-rolling reduction range from 1.5% to 15%. On the other hand, FWHV was increased gradually in the cold-rolling reduction range less than 15%.

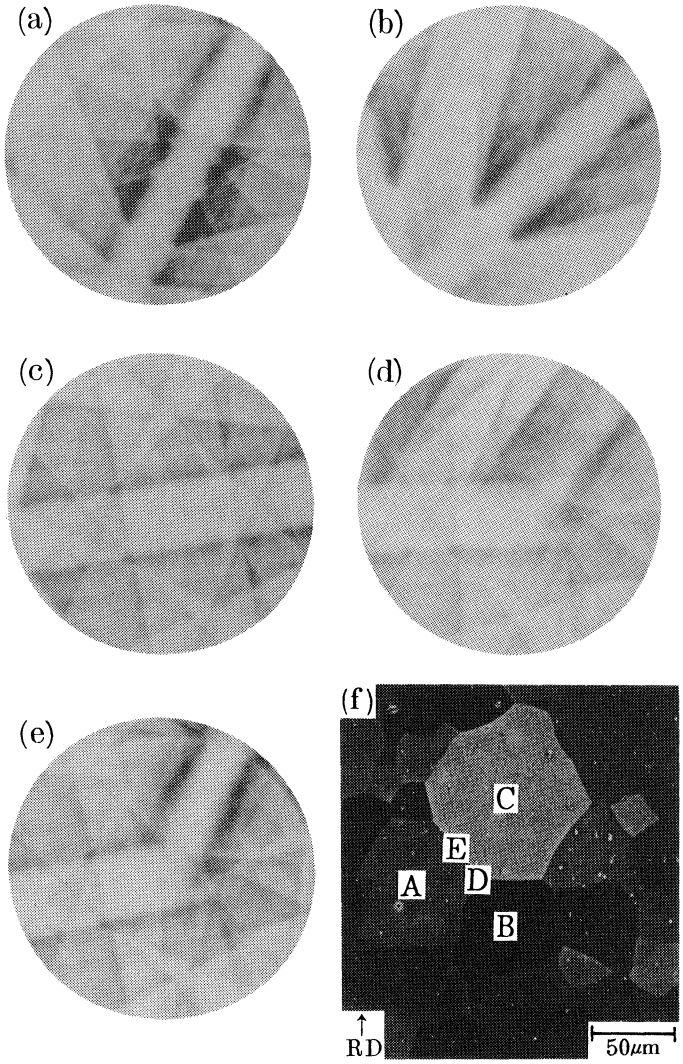

Figure 12 Influence of grain boundary on ECP. Specimen : Fe-3.25%Si alloy polycrystal. a, b, c, d, e : ECP at A, B, C, D, E respectively. f : ECC.

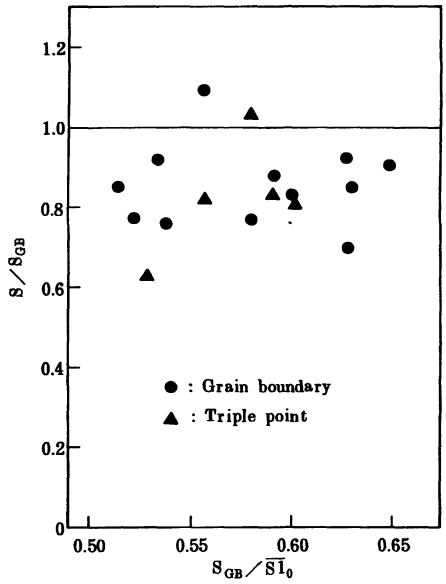

Figure 13 Influence of grain boundary on sharpness of ECP. Specimen : Fe-3.25%Si alloy polycrystal annealed sheet. S : sharpness of ECP. S_{GB} : the mean value of S of two or three grains bordering each other. $\overline{S1}_0$: the mean value of ideal sharpness of first-order pseudo-Kikuchi line of randomly oriented specimen.

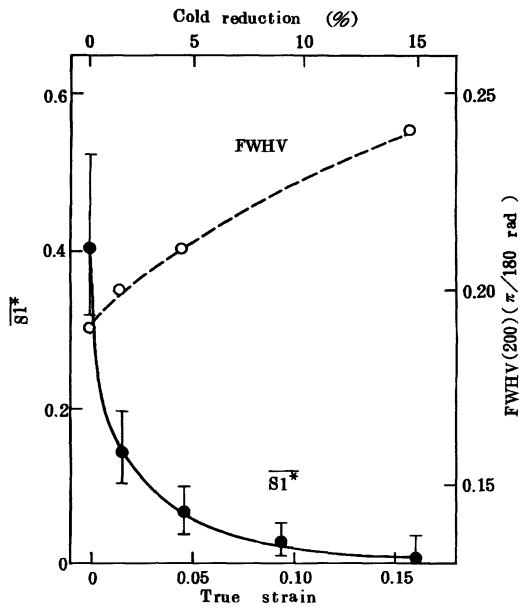

Figure 14 Influence of strain by cold rolling on sharpness of first-order pseudo-Kikuchi line and FWHV (200) by X-ray at the midplane. Specimen : Fe-3.25%Si alloy polycrystal. $S1^*$: relative value of sharpness of first-order pseudo-Kikuchi line.

The influence of strain by tensile deformation on $S1^*$ of polycrystal is shown in Figure 15. The $S1^*$ value was decreased remarkably by small strain and, then, it was decreased gradually with increasing strain to 15% elongation.

6) *Relationship between tensile stress and $S1^*$*
The example of the relationship between tensile stress and $S1^*$ value of polycrystal is shown in Figure 16. The square root of $S1^*$ value was decreased linearly as the tensile stress was increased. The square root of the dislocation density of the specimen is proportional to the tensile stress (e.g. Basinski, 1964). Accordingly, $S1^*$ value is thought to be decreased as the dislocation density is increased.

Strictly speaking, the blurring of pseudo-Kikuchi lines in ECP by dislocation depends on the lattice plane and crystallographic direction in relation to dislocation lines. In addition to the dislocation density, the sharpness of pseudo-Kikuchi lines in ECP depends on the type and distribution of dislocation (Kaczorowski *et al.*, 1991). Therefore, $S1^*$ value might be influenced not only by the dislocation density, but also by their type and distribution. However, based on the relationship between the dislocation density and the tensile stress (e.g. Basinski, 1964), Figure 16 is thought to suggest that $S1^*$ value can be decreased as the dislocation density is increased.

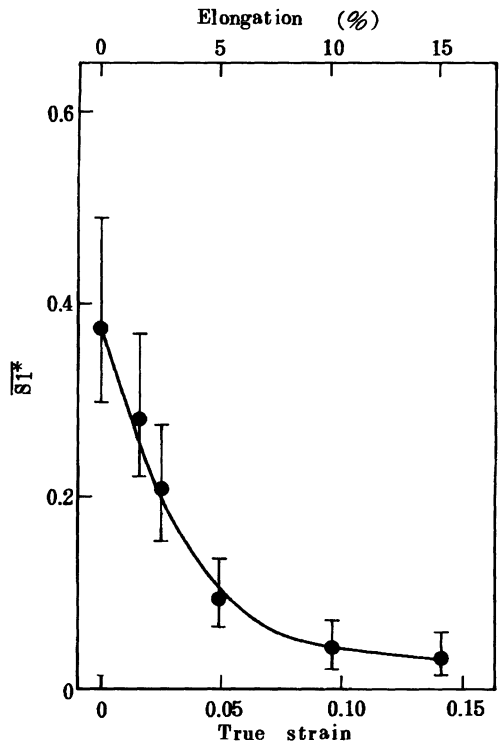

Figure 15 Influence of strain by tensile deformation on sharpness of first-order pseudo-Kikuchi line at the midplane. Specimen : Fe-3.25%Si alloy polycrystal. $S1^*$: relative value of sharpness of first-order pseudo-Kikuchi line.

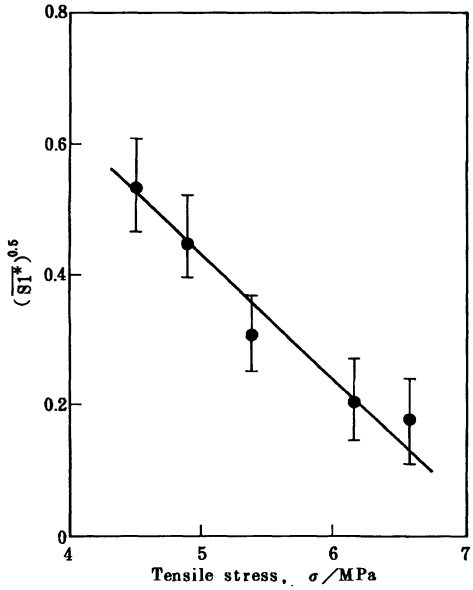

Figure 16 Relation between tensile stress and sharpness of first-order pseudo-Kikuchi line at the midplane. Specimen : Fe-3.25%Si alloy polycrystal. $S1^*$: relative value of sharpness of first-order pseudo-Kikuchi line.

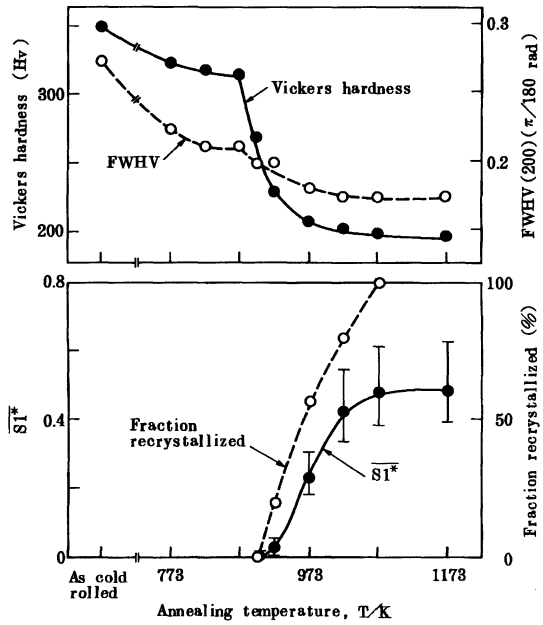

Figure 17 Changes in sharpness of first-order pseudo-Kikuchi line, fraction recrystallized, Vickers hardness and FWHV (200) by X-ray at the midplane during heating at a rate of 20 K/s after 88% cold rolling. Specimen : Fe-3.25%Si alloy polycrystal. $S1^*$: relative value of sharpness of first-order pseudo-Kikuchi line.

7) *Decrease of strain during recrystallization*
The changes in $S1^*$, Vickers hardness and FWHV of polycrystal during heating stage after 88% cold rolling are shown in Figure 17. The $S1^*$ value was increased remarkably during recrystallization. On the other hand, Vickers hardness and FWHV were decreased gradually during recrystallization. The increase of $S1^*$ value during recrystallization is thought to be caused by the decrease of dislocation density.

4. CONCLUSIONS

A method for measuring strain by analyzing sharpness of ECP with Image analysis has been developed. The $S1^*$ value in ECP is used as a parameter of strain. Fe-3.25%Si alloy single crystal and polycrystal were used as test specimens. Strain change during deformation and recrystallization was analyzed by this method. This method was compared with the conventional methods; hardness and line broadening of X-ray. The main results obtained are as follows.

1. The $S1^*$ value decreased with increasing strain in the specimen. This method can be used for measuring strain in material with any crystal orientation. This method could be useful for measuring strain less than 15% cold-rolling reduction or 15% elongation. Its sensitivity for small strain was larger than that of line broadening of X-ray. The $S1^*$ value was influenced by crystal orientation before deformation, especially, in the case of smaller strain. This phenomenon can be considered to be caused by the accumulate strain dependence of the crystal orientation before deformation. The $S1^*$ value was increased during recrystallization. In addition, the change of $S1^*$ value during recrystallization was more distinguished than both that of hardness and that of line broadening of X-ray. The $S1^*$ value can be considered to decrease with increasing the dislocation density in the specimen.
2. It is thought that this method can be useful for analyzing crystal orientation dependence on accumulated strain, decrease of strain during recrystallization and inhomogeneity of strain in the the grain or near the grain boundary.

Acknowledgement

The present authors would like to thank Dr. S. Nagashima, former Professor of Yokohama National University, for his valuable advice on this study. The present authors also would like to express thanks Mr. N. Takahashi and Mr. T. Nakayama of R&D Laboratories III, Nippon Steel Corporation for their constant encouragement and useful advice. The present authors also thank Dr. R. Shimizu and Mr. T. Ariyoshi of R&D Laboratories III, Nippon Steel Corporation for their valuable advice for measuring ECP in this study.

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