On the Grain Growth by Strain-Anneal in Cold Rolled Silicon-Iron Sheet

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Abstract

In the grain growth by strain-anneal of cold rolled silicon-iron sheet containing 3.30 wt% Si, four kinds of grain growth were found up to 10% of reduction. It was presumed that these were Goss type secondary recrystallization, normal grain growth, cube type secondary recrystallization and grain boundary migration respectively all induced by strain. These grain growth by strain were also explained alternatively by an impurity effect with an additive effect on impurity.

1. Introduction

Many papers have been presented on the recrystallization process of 3.25 percent Si–Fe alloy sheet which was cold rolled and annealed. At the primary recrystallization, materials acquire a preferred texture with an orientation of (110) in the rolling plane and [001] in the rolling direction which is usually referred to as Goss texture.

When these materials after primary recrystallization, are again cold rolled slightly and annealed (strain-annealed), grain growth generally occurs showing the development of preformed Goss texture[1,2,3]. The process of strain-anneal, is of interest for its mechanism as well as for practical application in producing fine oriented or single crystal silicon-iron sheets.

On the mechanism of grain growth by strain-anneal, there have been two leading explanations, one of which is attributed to the primary recrystallization process in which grains grow from primary nuclei and therefore the resultant grain size corresponds to the number of nucleation sites depending on strain, and the other is the proposal by Aust et al. and Dunn[4,5], in which they insisted that (110) [001] grain of lower residual strain energy developed consuming the other with higher residual energy in many slightly rolled bicrystals

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with common [110] crystals and which they referred to as strain-induced grain boundary migration.

These two explanations, however, are based on the premise of existence of only one maximum of growth in strain-anneal and yet it is more complicated and has several anomalies as discussed in the following. It is also reported that growing grains are not always from primary nuclei but rather from some grains originally existing in the matrix[6] which deny the theory based on primary recrystallization.

In the present study, the explanations of the anomalies by strain-anneal were attempted.

2. Experimental Procedures and Results

The material and procedure were as follows; 3.25% Si–Fe was melted in a mill furnace and finally cold rolled to about 60% to a thickness of 0.35 mm (primary rolling) and then annealed at 850°C for 2 hours in a dry hydrogen atomosphere (primary annealing). This was rolled again by a reduction rate ranging from 1% to 10% (secondary rolling) and then annealed in the same condition (secondary anneal). The chemical composition of the material is shown in Table 1.

TABLE 1. Chemical composition of the silicon-iron sheet specimen. (wt%)

Si	C	Mn	P	S	Cu
3.30	0.05	0.17	0.013	0.024	0.25

In the primary process, the sheets acquired (110) [001] main texture generally and yet the grain size was rather fine and the texture was weak. By strain-anneal, there occurred a few anomalies of grain growth including an outstanding anomaly in the reduction rate up to 10 percent.

The representative behaviors between the secondary reduction rate and the grain size are shown in Fig. 1. In two curves, one is of fine grained (standard) and the other is of coarse grained (comparison) starting material with a grain size under 0.05 mm and 1 mm in diameter, respectively. In the curve, the points of anomalies are at 2% of the first maximum, 4% of the minimum, 5% of the minor maximum and 8% of the second maximum of growth, respectively. The detailed behaviors of the anomalies of grain growth were somewhat different with experiments and materials, however, the characters of them were common in all practical materials and seemed to have its significance in recrystallization or grain growth.

The influences of the secondary rolling directions relative to the primary one were also studied for 15 degrees from primary rolling direction to that perpendicular to it. In the process, the first maximum, the minimum and the minor maximum of growth were observed, whereas the second maximum of growth was not.

1) First maximum of growth.

The first maximum of growth found in the lowest reduction rate in Fig. 1 was most remarkable in reduction rate ver'sus grain size curve and the resultant texture developed was (110) [001] in the primary rolling direction. The fact that this maximum was always found regardless of the secondary rolling direction and having a Goss texture in the primary rolling direction, would suggest that it was dependent on the factor inherent in the primary recrystallized material and that is accelerated by strain.

This maximum of growth, therefore, has an essential character of secondary recrystallization of Goss type and is not the growth process proposed by Aust et al. and Dunn which depends on secondary rolling direction with grain.

The reduction rate at which grain growth occurs varied slightly with experiments and specimens and it would be due to the primary grain size and impurities present in the materials.

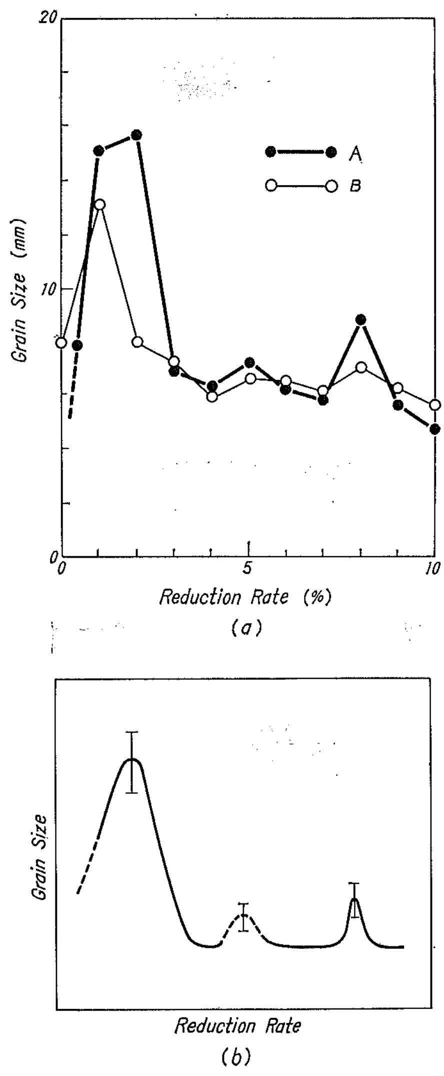

Fig. 1. Grain growth curve by strain-anneal.

(a) Actual growth curve starting from (A) fine grained material for standard and (B) coarse grained material for comparison.

(b) Schematic growth curve.

2) Minimum and minor maximum of growth.

In Fig. 1, the minimum point of the curve is at 4 percent reduction. At this point, the grain growth had practically occurred for the exception of primary coarse grained material and their final grain size was about 5 times of that of sheet thickness in diameter varying slightly with the specimens. Then, in the maximum magnetic torque value ver'sus secondary reduction rate curve of Fig. 2, the torque value at this point equals that of the starting materials and it was supposed that the orientational texture remained unchanged. This suggestion was also verified in Fig. 3(b) of (100) pole-figure in comparison to the primary recrystallized material in Fig. 3(a).

The grain growth without textural development to the order of sheet thickness, would be the typical feature of normal grain growth.

At a slightly higher reduction than this point, there were often observed remarkable developments of cubic crystals as shown in Photo. 1. The development of cubic crystals is expected by surface energy difference[7] after their release of grain boundary energy by grain growth. In this case, the process would occur by two steps: at first, the grain grew up to the comparable order

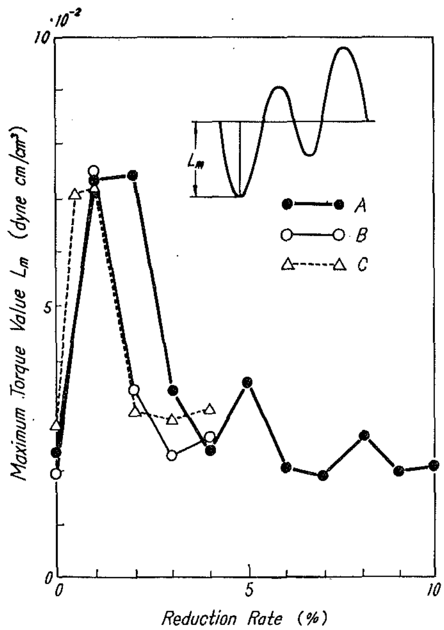

Fig. 2. Curve of secondary reduction rate ver'sus maximum torque value. Typical magnetic torque curve of Goss texture and maximum torque value cited are also shown.

A and B are the same materials in Fig. 1 and C is other fine grained material.

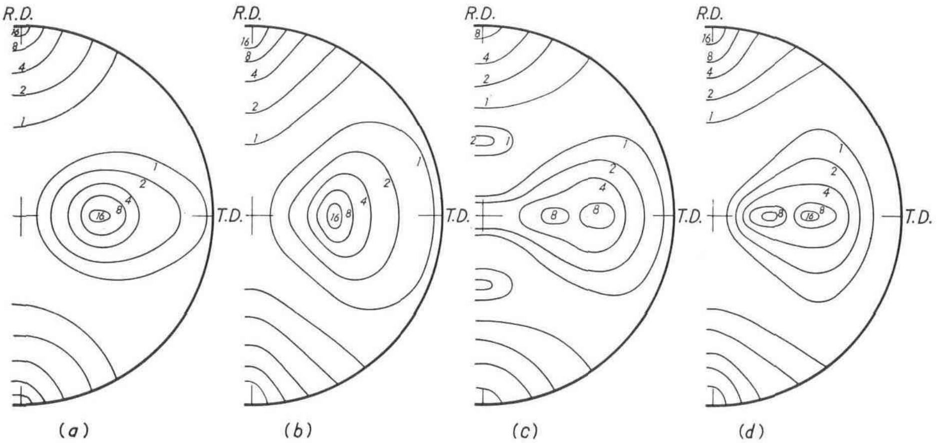

Fig. 3. (100) pole-figures of primary recrystallized and strain-anealed materials. (a) primary recrystallized specimen, (b) growth minimum, (c) cube growth and (d) second maximum of growth.

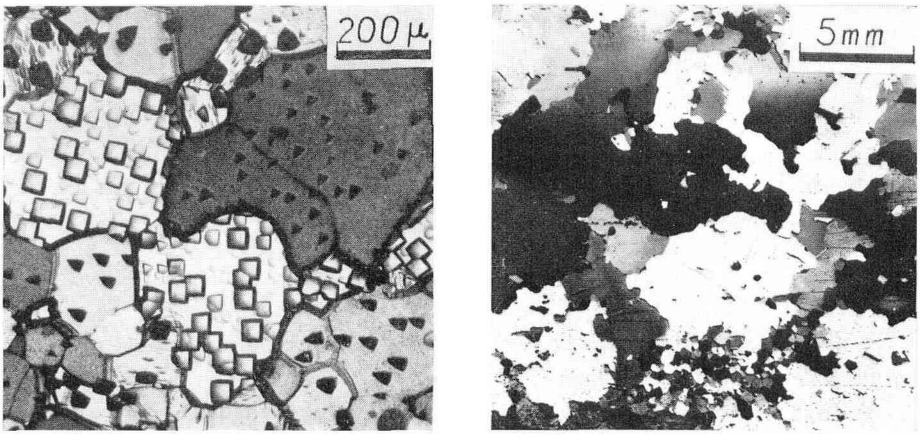

Photo. 1. Cube grains in starting material (grains with cube etch pits on the left) and strain-annealed material by 5% (grains seen bright on the right).

of sheet thickness in diameter by normal grain growth induced by strain and the texture remains unchanged reserving cube grains with the same balance in the starting material (Photo. 1 (left)), and then next, the cubic grain with minimum surface energy would be dominately developed (Photo. 1 (right)).

3) Second maximum of growth.

The second grain growth maximum at the reduction rate of 8 percent is not so remarkable as the first maximum of growth. This was also previously observed by Stanley[8], though he did not relate it meaningfully to recrystallization or grain growth.

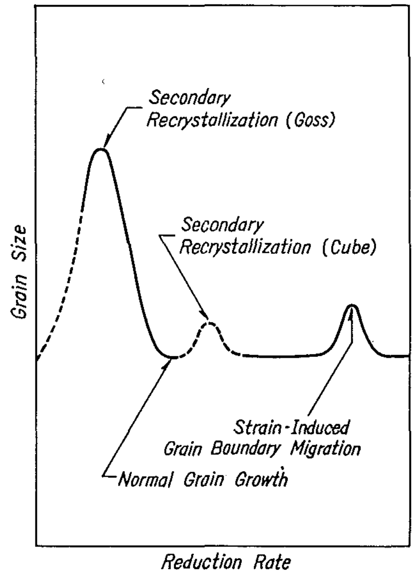

Fig. 4. Summarized character of grain growth by strain-anneal.

As already mentioned, this maximum was only observed with the secondary rolling in the primary rolling direction. It was reduced that the developing texture were as favoured by the orientational relationship between the grains and rolling direction. In Fig. 3 the texture of this maximum growth, has two concentrations near each $(0\bar{1}1)$ and (011), which coincides with the result of Aust et al. and Dunn in the respect that the texture failed to accumulate at exact [110] points.

From the facts that the separation of textural concentration and the reduction rate coincides with the results of Aust et al. and Dunn, the second growth of maximum would be of the same origin of the strain-induced grain boundary migration as proposed by them. Thus, all significant points of grain growth in strain anneal are summarized in Fig. 4 corresponding to their character of growth.

3. Discussion

A discussion will be made here on the results obtained by strain-anneal in cold rolled silicon-iron sheet.

At first, we consider the basic configuration of materials with regard to the impurity effect on grain growth (not by strain-anneal). Generally, impurity affect on the driving force for recrystallization which produces an essential effect on the character of grain growth. Thus, the grain growth scheme can be drawn by the amount of impurity and strain rate alternatively as shown in Fig. 5.

The velocity of grain boundary migration V for a single grain may be expressed according to Dunn and Walter as[9]

$$V = M \cdot P \tag{1}$$

where M is the boundary mobility and P is the driving force. Since the driving force term is expressed in terms of two principal radii of curvature

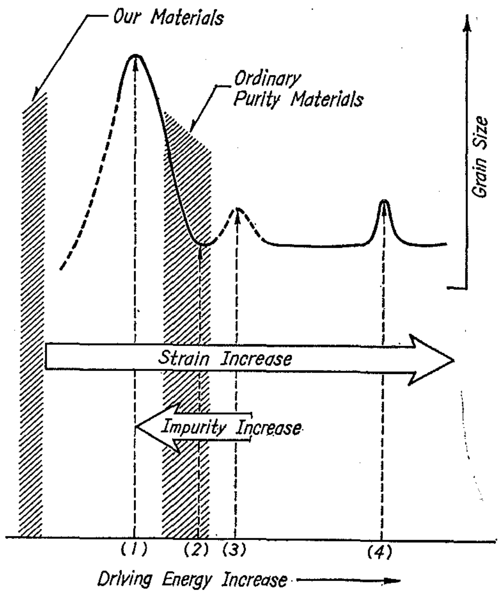

Fig. 5. Scheme of the relation between driving energy and grain growth. (1) secondary recrystallization (Goss type), (2) normal grain growth, (3) secondary recrystallization (cube type) and (4) grain boundary migration all induced by strain.

and impurity drag force (Zener term), above equation becomes

$$V = M\cdot\gamma_b\left\{(1/\rho_1+1/\rho_2)-Z\right\} \tag{2}$$

When the grain practically ceases to grow after primary recrystallization, the term in the bracket becomes

$$(1/\rho_1+1/\rho_2-Z)\fallingdotseq 0 \tag{3}$$

Then, if strain is introduced, the term (3) becomes positive as

$$\left\{(1/\rho_1+1/\rho_2)-(Z-S)\right\}>0 \tag{4}$$

where S is the term related to strain due to secondary rolling.

In Fig. 5, our material may be situated at the left side within (shown as the shaded portion). Then, the material configuration shifts to the right in the scheme at increasing reduction rate showing four sorts of grain growth with regard to the rate or S value in eq. (4). These have the character of secondary recrystallization (Goss type), normal grain growth, secondary recrystallization (cube type) and strain-induced grain boundary migration, respectively.

On cube growth, the energy in the figure means the total energy starting from fine grained material through normal grain growth (induced by strain) to cubic growth, and therefore, the net energy necessary for cubic growth must be far less than that of the Goss type recrystallization.

Pure materials, the laboratory made specimens for example, may be situated at the central portion of the scheme and the maximum development of Goss texture would not be expected. When the strain is added, the growth point shifts further to the right from this position and the kinds of growth decrease.

Then, if the amount of impurity is just at the point of the first maximum, this would act as an inhibitor[10,11,12] resulting in an excellent development of Goss texture without strain.

The fact that alloys containing aluminum e. g. Fe–Al[13] or Fe–Si–Al[14] are active for cube growth and that only aluminum among many elements in Fe–Si improves the activity of the grain growth which means the right shift of the situation in the scheme, may also be of interest.

4. Summary

The grain growth by strain-anneal in cold rolled silicon-iron sheet, was discussed and the following results were obtained.

1) In the reduction rate up to 10%, four types of grain growth were observed having the character of

secondary recrystallization (Goss),
normal grain growth,
secondary recrystallization (cube)
and strain-induced grain boundary migration

on increasing the value of strain, respectively.

2) The results were essentially consistent with those by Aust et al., Dunn and Gokyu et al.

3) The grain growth were explained by an alternative relation between the strain and the impurity effect.

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