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Modes of Grain Growth by Strain-Anneal in Si-Fe Alloy

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Abstract

In the grain growth of cold rolled 3.25% Si-Fe alloy sheet by strain-anneal, a marked maximum of growth and a few minor growths, were observed and were given a descriptive explanation in which they are characterised as the secondary recrystallization in (110) [001] orientation, normal grain growth, secondary recrystallization (100) [011] orientation, and the growth due to the strain difference among grains.

In this paper, they are explained as the residual strain produced by slight cold rolling in a dislocation pile-up along grain boundaries with the inclusions activating the grain boundary movement in increasing rate with misfit angle of boundaries and volume of impurities.

For further straining, the growth is considered to be ascribed to the strain difference between florae formed by a group of similarly oriented grains rather than between each grain.

Introduction

In pure metals, the grain boundary energy increases generally with the misfit angle according to the dislocation theory on a tilt boundary model. If the metals contain impurities such as sulphides, they are gathered together along grain boundaries in an increasing rate with the boundary misfit angle which will exert a drag force on the boundary driving force possibly in a form of inclusion with an essential effect on the growth behaviour.

The strain given by slight cold work such as rolling, could be formed rather by the pile-up of dislocations chiefly along grain boundaries and around inclusions than the distributed dislocations within a grain1). The densities of pile-up of dislocations would become larger in an increasing rate with misfit angle of grain boundary and the size of inclusions. The tendency given by strain would rather be against the effect of impurity along grain boundaries and affect the growth behaviour.

The present article is a supplementary to the previous one2) by the authors who gave a descriptive explanation of grain growth on the basis of the balance of grain boundary energy, and here discussions will be made on the behaviours by cold rolling from a view point of dislocation pile-up along grain boundaries carrying impurities.

Discussion

In cold rolled Si-Fe alloy sheet, the primary recrystallization texture was composed of several components of (110) [001], (111) $[1\bar{1}0]$, (111) $[11\bar{2}]$ and others. The

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grains with similar orientation exist as a group forming a flora or a colony, in which the (110) [001] component is predominant with the least orientation fluctuation between grains in a group. The impurities, sulphide in this case, gather together at the grain boundary exerting a drag force on bundary migration at an increasing rate with the misfit angle. At raising temperature, the grain growth takes place at first among the grains in (110) [001] flora dominantly and then, grains from the (110) [001] florae grown into one grain absorb other oriented florae. These are the essential features of secondary recrystallization for the development of the (110) [001] component in cold rolled 3.25% Si-Fe alloy sheet explained by the authors[3]. In the grain growth by strain-anneal, a growth similar to the secondary recrystallization with the growth of (110) [001] component and other minor growth are seen.

As for the explanation of growth by strain-anneal, a basic proposal in which the strain can rather be of pile-up of dislocations along grain boundaries and around inclusions whicn elevate the activity of the grain boundary will be made. The dislocation pile-up, could then, increase with the increasing misfit angle of boundary and the sizes of inclusion. In lower reduction, however, no marked strain differences between grains as the motivating force for grain growth could be expected because of a high crystal symmetry. A sign of dislocation pile-up along grain boundary produced by rolling is shown in Photo. 1 revealed by dislocation etching.

Photo. 1. Dislocation pile-ups along grain boundary produced by cold rolling. Aged at 200°C for 10 hr and etched with Morris etchant.

Now, it may be written for the driving force P*,

$$P=(1/\rho_1-1/\rho_2)\left[\gamma_B(\theta)-\gamma_B(\theta, z)-\gamma_B(\theta, \sigma)\right] \tag{1}$$

Here γ_B is the grain boundary energy, θ the misfit angle between adjacent grains, D the impurity term and σ the strain induced. The misfit angle θ could be

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[*] In the equation of the velocity of grain boundary migration for single gain, $V=MP^{4)}$, if the boundary can migrate against impurity drag force by introducing strain,

$$P=[(1/\rho_1+1/\rho_2)-(Z-S)]>0,$$

Here, P is the driving force, M the boundary mobility, ρ_1, and ρ_2 the two principal radii of curvature, Z the impurity term and S the strain term.

expressed by the angle between representative crystal planes (as (110) or (100)) measured on a stereographic projection.

The textural shift due to growth may be assumed as,

(1) the texture shifts to the component of flora formed by the grains with large misfit angles when the grain boundary migration rate increases with the misfit angle (in high purity)
(2) the texture is unvaried when the grain boundary migration rate does not vary with the misfit angle
(3) the texture shifts to the component of flora formed by the grains with small mifit angles when the grain boundary migration rate decreases with misfit angle (by impurity effect).

The effect of strain may, therefore, be complementary to impurity, i. e. have a tendency to cancel out the effect arising from impurity. The grain growth behavior by strain-anneal is shown schematically in Fig. 1, in which impurity drag force and strain effect are expressed as a alternative or complementary relation. Fig. 2, the grain boundary energy, boundary mobility and migration rate against impurity and strain are also shown. These effects will, after all, shift the process shown by arrows as $\overrightarrow{(1)\ (2)\ (3)}$ in increasing impurity and $\overrightarrow{(3)\ (2)\ (1)}$ in increasing strain.

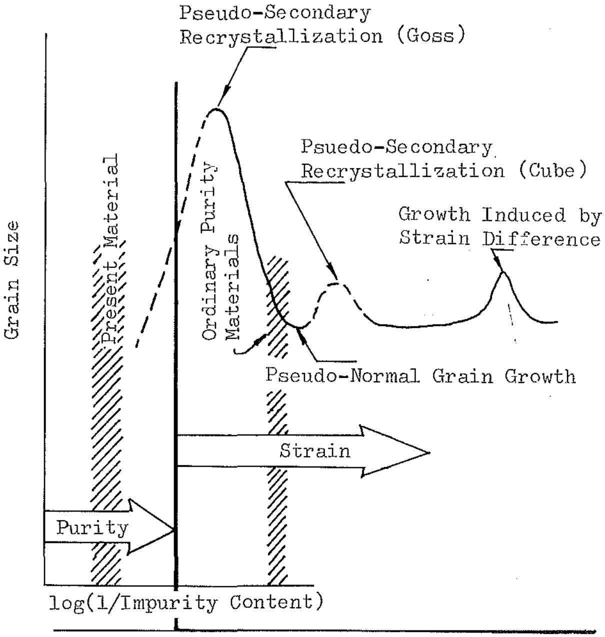

Fig. 1. Schematical representation of modes of grain growth. Grain size against impurity content (C) with strain complementary to it.

Then, the representative behaviors in the grain growth by strain-anneal will be discussed in the sequence of the first maximum, the minimum, the minor maximum and the second maximum of growth respectively.

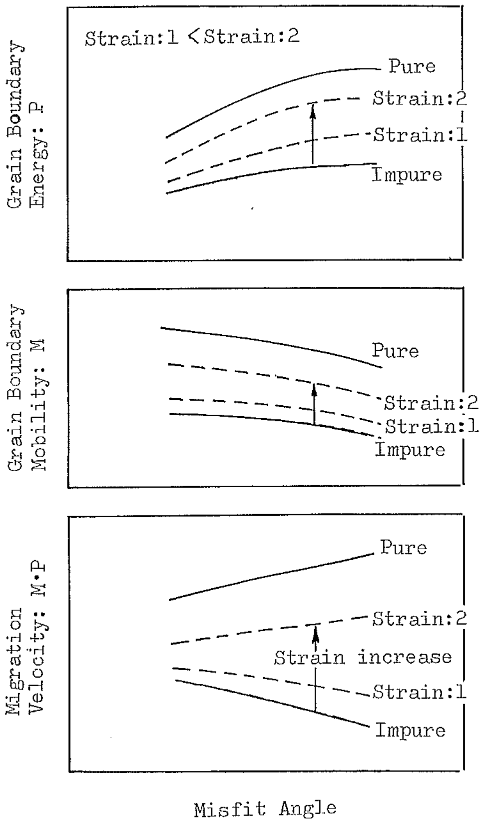

Fig. 2. Grain boundary energy, grain boundary mobility and migration velocity against misfit angle. All with parameter of impurity content.

(1) The first maximum of growth

The first maximum of growth which is found at the least reduction and of which the most marked is characterized by the development of (110) [001] component which is one of the main component of primary recrystallization texture, and this will be referred to a similar process as the secondary recrystallization (Pseudo-secondary recrystallization). The growth can occur when the potential leveled up with the dislocation pile-up produced by the reduction overcomes the impurity drag force and still retains the character of growth of secondary recrystallization. The reason why the growth by strain-anneal took place at a lower temperature level as the primary recrystallization (700–800°C) might be due to the fact that the process proceed by simple diffusion of dislocation pile-up, whereas the process due to secondary recrystallization was introduced by the diffusion of impurity atoms into the matrix after the melting of sulphide such as FeS thereof (melting temperature of 988°C).

The strain would tend to lower the effect of impurity, hence the texture was usually dispersed as compared with that attained by secondary recrystallization. In the course of the shift from (3) to (1) in increasing strain, i. e. $\overrightarrow{(3)(2)(1)}$, the

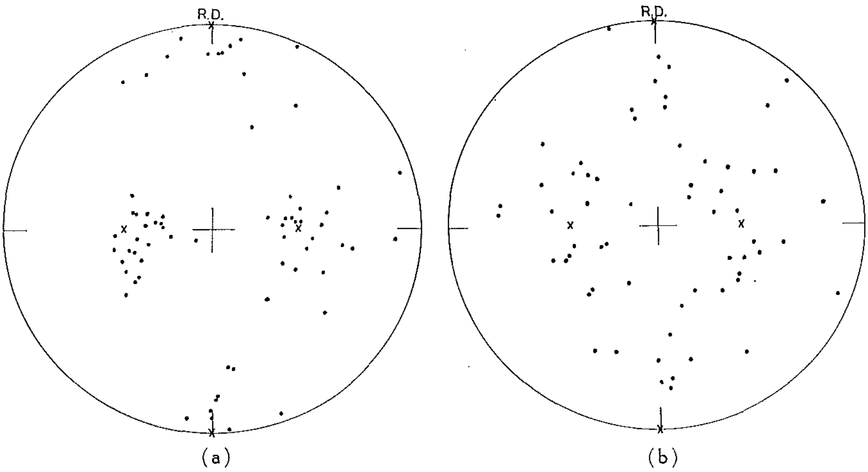

Fig. 3. (100) pole figures of grown grains. Strained by (a) 2.5%, (b) 5.7%. (×) showing (110) [001] orientation.

texture could be of a defect of the (110) [001] component in accordance with some impurity and strain balance as shown in Fig. 3, with the results simiar to that obtained by Dunn[5),6)]. This may also be the reason why the single crystals obtained by strain-anneal have orientations slightly off the exact (110) [001] orientation in spite of the fact that they are classified as having (110) [001] orientation.

(2) The minimum and the minor maximum of growth

The growth minimum appearing next to the first maximum in the grain size against the reduction curve is characterised by the fact that the growth took place at the order of sheet thickness (approx. 5 fold) without any accompanying textural shift. The process may, therefore, be similar to normal grain growth (pseudanormal grain growth). For this reason, the migration volocity may be balanced in any grain boundaries by the increased strain hence a balanced growth occurred among the grains or florae of all orientations. The final size of grown grains may be smaller because of the presence of more grains or florae for nucleation sites as the case may be.. It may also be reasonable to consider that the growth took place at the level of grain size of normal grain growth by strains over 3% to 10% as seen in the growth curve.

At reduction sowewhat higher than this, then, the minor growth maximum was observed which accompanied a marked growth of the (100) [001] component, i. e. cube texture. The process could be explained as follows. If the grain boundary energies were balanced among grains or especially around the regions of the (100) [001] component during growth, the surface energy term in the energy balance equation would become dominant and contribute to the growth although no grain boundary energy diminished to zero. The energy balance E could be expressed for grain boundary migration,

$$E=\frac{\gamma_b}{r}-\Delta\gamma_{st}-\frac{\Delta\gamma_{su}}{t} \qquad (2)$$

Here, γ_b is the boundary energy, r the radius of boundary curvature, $\Delta\gamma_{st}$ the strain energy difference, $\Delta\gamma_{su}$ the surface energy difference and t the specimen thickness. Then, E may be extended to the region of appreciable number of grains,

$$E=\sum_i e_i=\sum_i \gamma_b l_i \frac{m_i}{g}+\sum_i v_i \Delta\gamma_{st}+\sum_i \frac{\Delta\gamma_{su}}{t} \qquad (3)$$

where $\frac{m_i}{g}$ is the vector corresponding to misfit angle, l_i the length of boundary measured on specimen surface, and v_i volume constant. According to the above considerations, $\Delta\gamma_{st}$ and $\sum_i l_i \frac{m_i}{g}$ practically become zero, then the third term predominates which means the growth of (100) [001] grains with the lowest surface energy. These considerations might supply a clue for describing the dominant growth of cube texture in some other alloys7),8).

(3) The second maximum of growth

If cold reduction increases, e. g. up to 7–8%, the boundary could no longer be sharp, but would become broad. They will, therefore, fail to continue as the dominant controlling role in grain growth and the stress dfference induced by cold rolling would exert its influence on the growth in the form of stress difference between florae rather than between grains.

As for the cause of stress difference between florae, it may be considered that the flora of grains with the least orientation fluctuation, i. e. (110) [001] flora can have a small residual stress while the flora of grains with large orientation fluctuation, i. e. (111) [$1\bar{1}0$] and (111) [$11\bar{2}$] and others have a large residual stress. Then, the (110) [001] florae would grow absorbing the other oriented florae.

In the reduction range of 1–10%, no primary recrystallization based on the primary nucleation could be expected to exert its influence as the main factor for the growth because of its very low nucleation frequency.

Conclusion

The grain growth behaviours by strain-anneal has reasonably explained from the view point that the dislocation pile-up is formed along grain boundaries by rolling in increasing rate with the misfit angle which increases the appearent grain boundary energy and activates the grain growth. The proposal which insisted that the certainly oriented grains were remained as the least strain and absorbed other oriented grains could hardly explain the details of grain size against reduction curve and the texture shift observed both by gonioscope and torque magnetometer even if the single growth point was explained by it.

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