Study of potential recrystallization nuclei in the cold-rolled microstructure of an electrical steel by electron backscatter diffraction

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Abstract. Strain induced boundary migration (SIBM) is widely recognized to be the main mechanism corresponding to recrystallization in metals of low or medium amount of deformation. The nucleation process in recrystallization of heavily deformed metals is, however, less understood for key issues such as how the nuclei are formed and where they are located. The evolution of texture from deformation to recrystallization cannot thus be explained well. In this study, an attempt was conducted to identify the potential recrystallization nuclei (PRN) in the cold-rolled microstructure of an electrical steel by electron backscatter diffraction (EBSD). This work demonstrates that the SIBM mechanism can be the main mechanism corresponding to recrystallization nucleation in a heavily deformed steel. The same area in both the cold-rolled and partially recrystallized states was analysed using EBSD to obtain the correlation between the recrystallized grains and the cold-rolled substructures. The deformed grains having high stored energy were first selected, followed by identifying substructures surrounded entirely or partly by high angle boundaries in these heavily deformed grains. The deformation induced grains having low intra-granular misorientation of $2^\circ$ or less exhibit a very similar orientation distribution to that of the recrystallized grains and are proposed to be the PRN in subsequent recrystallization.

1. Introduction
The process of recrystallization of plastically deformed metals and alloys is extremely important for controlling the texture, and therefore optimizing the corresponding physical and mechanical properties. In recrystallization, the key issue concerning the formation of new grains (or nuclei) has not been explained well. It is well recognized nowadays that the new grains indeed grow from small regions, such as subgrains and cells that are likely surrounded by high angle grain boundaries [1]. According to this idea, the orientations of the recrystallization nuclei are inherent in the deformed microstructure. The small regions that are capable of growing into new grains are therefore called the potential recrystallization nuclei (PRN). Once the PRN can be identified in the deformed microstructure, the texture of a deformed metal after recrystallization can be predicted accordingly.

Strain induced boundary migration (SIBM) has been widely accepted as the main mechanism corresponding to recrystallization in metals subjected to a low or medium amount of deformation [2, 3]. According to this mechanism, a high angle boundary (HAB) present prior to deformation, can bulge out from the low stored energy side toward the high stored energy side. However, the nucleation process in
heavily deformed metals was suggested to rely on different mechanisms, such as subgrain coalescence and subgrain growth [1, 4]. Based on the fact that more and more HABs can be generated in the grain interiors with increasing the deformation, the role of SIBM might have to be re-examined for recrystallization in heavily deformed metals [5, 6]. In our previous work [7], electron backscatter diffraction (EBSD) observations confirmed that recrystallization was preferentially evolved from areas having high local misorientation. The recrystallization nuclei in a partially recrystallized specimen were observed to be directly related to the areas having high kernel average misorientation (KAM) values in the deformed grains. However, the KAM method is a pixel-based technique and cannot be related directly to the PRN. In this study, we report a subsequent effort to identify the PRN from the cold-rolled microstructure based on a modified SIBM model.

2. Experimental methods
An electrical steel after cold rolling was used for EBSD analyses. The composition and hot-rolling conditions of the steel are reported elsewhere [7]. After cold-rolling from 10 mm to 3 mm, the microstructure of the rolled plate was analyzed by EBSD in at least six areas of 230 × 172 μm² each, with a step size of 0.25 μm. The cold-rolled sheets were also annealed at 903-983 K for one minute to reach a partly or fully recrystallized state. The microstructure and texture prior to, and after annealing, were analyzed by EBSD for the same area. Some EBSD orientation image maps (OIMs) were acquired at a smaller step size of 0.05-0.1 μm to reveal the detailed microstructure in the cold-rolled state. The EBSD analyses were carried out using an Oxford Nordlys detector mounted on a Zeiss Supra 55 scanning electron microscope. EBSD data were analyzed using the Channel 5 software.

3. The modified SIBM model
Due to the heavy deformation, one or several subgrains in a cold rolled plate can be surrounded partly or entirely by HABs, as shown schematically in Figure. 1(a), and are called the deformation induced grains (DIGs). The pressure driving a HAB to migrate outward is expressed as [5, 6]:

\[ \Delta P = P_E - P_l - P_r \]  \hspace{1cm} (1)

where \( P_E = 2 \gamma_b / \lambda_E \) is the outward drag force due to the sub-boundaries in front of the HAB, \( P_l = 2 \gamma_l / \lambda_l \) is the inward drag force due to the sub-boundaries behind the HAB, and \( P_r \) is the inward drag force due to the curvature of the HAB. Also \( \gamma_b \) is the surface tension of the sub-boundaries in front of (behind) the HAB and \( \lambda_E (\lambda_l) \) is the average size of the subgrains in front of (behind) the HAB. Figure. 1(a) shows that \( R_b \) is the plane radius of a HAB cap which is free to bulge and \( x \) is the height of the cap. The existence of the DIGs, which are surrounded by deformation induced HABs was examined by EBSD for the steel studied in this paper. Figure. 1(b) shows the EBSD OIM (ND inverse pole figure coloring) acquired with viewing direction along the transverse direction (TD) of the cold rolled plate in a fine step size of 0.05 μm. The corresponding boundary map is shown in Figure. 1(c), indicating that HABs (red lines) are distributed in the interior of a deformed, <111>/ND grain. Some subgrains, surrounded mostly by HABs and free from sub-boundaries internally, can be identified such as A1 and A2 labeled in Figure. 1(c) for examples. Subgrain groups, having larger sizes, surrounded by HABs are also observed such as B1-B3 in Figure. 1(c). Low angle boundaries are distributed in the interiors of B1-B3. The EBSD result verifies the existence of DIGs in the deformed microstructure. Accordingly, there are three factors which determine whether any given DIGs can be a PRN. First, the outward drag force \( P_E \) or the stored energy in the surrounding area is large. Second, the internal drag force \( P_l \) is small, and finally, the HAB that is free to bulge exhibits a relatively large radius of curvature.

4. EBSD Results and discussion
Figure. 2(a) shows a ND OIM acquired from TD. HABs (>15°) are highlighted in dark lines and distributed heterogeneously in the deformed structure. Some deformed grains are free of intragranular
HABs but others contain HABs with a moderate to high density. The deformation heterogeneity can be demonstrated clearly by constructing a map of high misorientation regions (HMRs, see Figure 2(b)) according to the suggestion given by Mishin et al. [8]. It is noted that all the intragranular HABs are located in the HMRs and the crystal orientations of HMRs were found to be mainly in the \( \gamma \)-fiber orientations with a high intensity near \{111\}<112>. Since results in Figure 1 demonstrate the existence of DIGs, the DIGs in the analyzed areas are identified using a 15°-5° criterion and illustrated in Figure 2(c). These DIGs are mainly distributed along the original grain boundaries and on shear bands in the grain interiors. It is noted that the DIGs possess orientations which are different from those of the cold-rolled matrix. Figure 2(d) shows the OIM of the recrystallized grains in the same area after the steel was annealed at 923 K for 60 s. The recrystallization fraction of this area is 25%. The figure indicates that the regions having high density of DIGs are mostly replaced by recrystallized grains with similar orientations after annealing. On the other hand, those regions containing no DIGs remain unrecrystallized.

**Figure 1** (a) A schematic drawing for the deformation induced grains (DIGs) which are grayed out, and EBSD (b) ND OIM + boundary map (white: 5-15°, dark: >15°) and (c) boundary map (gray: 1-5°, dark: 5-15°, red: >15°) for the 70% cold-rolled electrical steel showing the observed DIGs. The scan step size was 0.05 \( \mu \)m.

**Figure 2** EBSD (a) ND OIM + boundary map (dark: >15°), (b) HMR map and (c) DIG map for the 70% cold-rolled electrical steel, and (d) OIM showing the recrystallized grains for the steel annealed at 903 K for one minute. The scan step size was 0.25 \( \mu \)m.
Figure. 3 shows the $\phi_2=45^\circ$ ODF sections derived from EBSD OIMs for the cold rolled and annealed (923 K for 60 s) plate. The ODF section for the cold-rolled plate (Figure. 3(a)) shows a strong $\alpha$-fiber, mainly from \{001\} <110> through \{112\}<110> to \{111\}<110>, and a strong $\gamma$-fiber (\{111\}//ND) both of which are typical for low carbon steels. The ODF section for the HMRs in the cold-rolled structure is shown in Figure. 3(b), confirming that the HMRs are mainly in the $\gamma$-fiber. The orientations of the DIGs (see Figure. 3(c)) distribute rather randomly over the $\gamma$-fiber, the $\theta$-fiber (<100>//ND), the partial <110>//TD fiber and the partial <110>//RD fiber. Finally, the ODF section for the recrystallized grains in the annealed sample is shown in Figure. 3(d). For this annealed state (923 K, 60 s), the average recrystallization fraction is 40 % and the recrystallization nucleation is nearly saturated. It has been reported that the recrystallization proceeds by continuous growth of the recrystallized grains into the remaining deformed grains with low stored energies as the samples were annealed at higher temperatures [9]. It is worth pointing out that the orientation distribution of the DIGs in the cold-rolled structure (Figure. 3(c)) is qualitatively similar to that of the recrystallized grains (Figure. 3(d)), but the recrystallized grains show much higher intensities in the cube (\{100\}<001>), Goss (\{110\}<001>) and \{111\}<11-2> orientations and lower intensities in the rotate cube (\{100\}<011>) and \{110\}<1-10> orientations.

Figure. 3 ODF $\phi_2=45^\circ$ sections derived from 6 EBSD OIMs for each of the following conditions: (a) the cold rolled plate, (b) the HMRs in the cold rolled plate, (c) the DIGs in the cold rolled plate, and (d) the recrystallized grains in the annealed (923 K for 60 s) plate.

According to the discussion above, the DIGs are all distributed in the HMRs having high stored energies. The high stored energies of the matrix generate high outward drag forces on the HABs surrounding the DIGs. Accordingly, as long as the inward drag forces remain low, the DIGs can grow...
into nuclei during annealing. It is, however, tedious to examine the drag force, $\Delta P$, of each DIG to distinguish whether it is a PRN or not. Alternatively, a proper criterion may be chosen to identify the PRN in a statistical manner. Figure 4 shows the intra-granular misorientation as a function of the equivalent diameter each DIG. The intra-granular misorientation is calculated by the Channel 5 software based on the grain orientation spread (GOS) principle [10], and is used to evaluate the inward drag force of the DIGs. Ideally, large DIGs having low intra-granular misorientation values are ideally suited as PRN for recrystallization. However, Figure 4 shows that the misorientation increases with increasing DIG size. A higher misorientation means a higher energy of the substructure and therefore also of the inward drag force. On the other hand, only a portion of the DIGs has intra-granular misorientation values less than 2 degrees. All of these are indeed less than 2 μm in diameter. The traditional theory based on subgrain growth, however, suggests that substructures having large sizes have an advantage doing growth competition. To verify these two ideas, the ODF sections of DIGs having low intra-granular misorientation ($<2^\circ$) and of those having large size ($>3$ μm) are shown in Figure 5. It is evident that the ODF of DIGs having low intra-granular misorientation shows stronger cube, Goss and $\{111\}<112>$ orientations compared to that of all DIGs, and is therefore closer to that of the recrystallized grains. On the other hand, the ODF of the large-size DIGs exhibits a high density of rotated cube orientations and low densities of cube and Goss orientations. As a result, the DIGs having low interior misorientation should be the PRN.

In order to confirm the inference given above, the drag force as a function of the misorientation angle ($\theta_i$) of the sub-boundaries surrounding DIGs is calculated for small DIGs which are free from interior sub-boundaries and large DIGs having a high intra-granular misorientation ($\theta_i$) of $5^\circ$. The results are shown in Figure 6. For the small DIGs, the drag force is positive as the surrounding substructures have boundaries whose misorientation angles are larger than $3^\circ$ for $4$ μm-diameter DIGs and $6^\circ$ for $2$ μm-diameter DIGs. These values are reasonable for steels rolled to $70\%$ [12]. Moreover, the drag force due to the curvature effect decreases with increasing size of the DIGs. On the other hand, the large DIGs with average diameters of $6-10$ μm do not have a positive drag force unless the outside substructures exhibit a large misorientation of $7^\circ$ or above. The small DIGs with a low intra-granular misorientation can therefore grow continuously on annealing, whereas the growth of large-size DIGs is easily be hindered by surrounding substructures having relatively low stored energies.

![Figure 6](image-url)

**Figure 6** Outward drag force as a function of the misorientation angle ($\theta_i$) of the substructures outside the DIGs for (a) small DIGs which are free from interior sub-boundaries and (b) large DIGs having an intra-granular misorientation ($\theta_i$) of $5^\circ$.

Table 1 lists the total number and average number density of the DIGs, PRN and recrystallized grains (RXG) after annealing at $903$ K and $923$ K obtained from the EBSD analyses. The results indicate that one in four of the DIGs is a PRN. It also seems that one out of two PRNs will grow successfully into a recrystallization grain. However, it should be noted that the present result is obtained from a two dimensional EBSD analysis, whereas the recrystallized grains shown in the annealed samples can result
from PRN hidden below the surface that could not be detected. As a result, it is reasonable to believe that the number of PRN analyzed using the method suggested in this study is approximately one order of magnitude higher than the recrystallization nuclei actually formed. The overestimation of the PRN can be attributed to several reasons. First, the outward drag force, which determines the mobility of the HAB, is not considered in our analysis, but can indeed be different for each PRN. Second, this drag force varies with the movement of the HAB. Third, nearby PRN of similar orientations might impinge with each other and then grow more slowly due to the orientation pinning effect [12]. All these factors might cause a portion of PRNs to be merged on growth competition. Further effort is needed on this issue. Moreover, it worth emphasizing that the orientation distribution of the PRN will never be exactly the same as that of the recrystallized grains even if the PRN can be identified more accurately, since they will grow to recrystallized grains with very different sizes.

Table. 1 Total number and average number density of the DIGs, PRN and recrystallized grains (RXG) after annealing at 903 K and 923 K from the EBSD analyses.

|               | DIG     | PRN (<2°) | RXG (22%) | RXG (40%) |
|---------------|---------|-----------|-----------|-----------|
| Number of OIMs| 14      | 14        | 9         | 6         |
| Total number  | 24294   | 6603      | 1120      | 1314      |
| Number density, 1000 μm² | 42 | 12 | 3 | 6 |

5. Conclusion

This work demonstrates that strain induced boundary migration can be the main mechanism for recrystallization nucleation in a heavily deformed steel. The same area in both the cold-rolled and partially recrystallized states was analyzed using EBSD to obtain the correlation between the recrystallized grains and the cold-rolled substructures. The deformed grains having high stored energies were first selected, followed by identifying the substructures surrounded entirely or partly by high angle boundaries in these heavily deformed grains. The deformation induced grains, having low misorientation of 2° or less, exhibit very similar orientation distribution to that of the recrystallized grains and are proposed to be the potential recrystallization nuclei in subsequent recrystallization.

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