Retaining \{100\} fibre texture in electrical steel via strain-induced boundary migration recrystallisation.

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Abstract: In this paper, the feasibility of retaining the preferred \{100\} fibre texture for non-grain oriented (NGO) electrical steel from the as-cast columnar \{100\} grains by encouraging recrystallisation via the strain induced boundary migration (SIBM) mechanism was investigated. Rolling with intermediate annealing stages before the final anneal was used to reduce the stored energy through recovery before the final recrystallisation step. A strong \{100\} fibre recrystallisation texture, i.e. 32\% area fraction, was seen in the sample which was warm deformed to 1.6 strain with 5 intermediate annealing stages then annealed at 950 °C for 5 minutes (to observe the early stages of recrystallisation) or 1 hour. Whereas only 12 - 14\% [100] fibre component was observed after 1.2 strain with a single or with no intermediate annealing stage. It was found that the \{100\} fibre recrystallisation texture was formed in regions adjacent to parental deformed grains with \{100\} fibre texture due to the SIBM recrystallisation mechanism. EBSD imaging analysis was used to follow the recrystallisation process in the same microstructural region using interrupted heat treatments and it was seen that the \{100\} texture grains carried very low stored energy after deformation, which meant the subgrains in these grains bulged into the surrounding grains with higher stored energy. Due to its slow recrystallisation nucleation rate, a low overall stored energy is preferred to encourage \{100\} texture recrystallised grains to form via the SIBM recrystallisation mechanism.

1. Introduction
Texture control is crucial for electrical steel production. For non-grain oriented (NGO) electrical steels, the \{100\} fibre texture is desirable to achieve optimum magnetic properties. It is well known that the \{100\} fibre is typically a minor component after recrystallisation when the subgrain growth (SGG) mechanism occurs due to its low nucleation rate and growth rate [1]. Strain-induced boundary migration (SIBM) is a recrystallisation mechanism where a subgrain with a low dislocation density will bulge into one with higher dislocation density and the dislocations will be swept up during bulging [2]. Hutchinson observed SIBM in bicrystal iron with \{100\}<011> subgrains growing into the neighbouring grain after 72 \% cold reduction [3]. Takashima reported a similar observation in partially recrystallised NGO electrical steel where unrecrystallised grains with \{001\}<210> texture, in the central region of the sheet, grew into the surrounding matrix after light rolling (12\% reduction) [4]. Stojakovic also reported that the \{100\}/ND texture was strengthened by SIBM in electrical steel via light rolling (12 \% reduction) and intermediate annealing at 760 °C [5]. Although numerous studies have been carried out examining texture evolution during recrystallisation in electrical steels, with a general consensus that the \{100\} fibre texture can be enhanced from low strain and / or intermediate annealing prior to recrystallisation, no direct observation of SIBM during recrystallisation has been reported. In this paper, the
recrystallisation behaviour in a high Si content (Fe-6 wt.% Si) has been considered, with direct observation of the recrystallisation mechanism: as-cast thin slab with columnar grains with a strong \{100\} orientation was produced, warm deformed with intermediate annealing, then final annealed.

2. Experiment
Fe-6 wt. % Si was produced in a vacuum induction melting furnace and then cast to 15 mm thick slab, which resulted in material with columnar grains of approximately 1.2 mm width with a strong \{100\} orientation. No equiaxed region was observed. This microstructure is representative of that present in belt cast or twin roll cast material [6]. Cylindrical compression samples, measuring 8 mm in diameter and 12 mm in height, were machined from the columnar grains by electrical discharge machining. The uniaxial compression axis was parallel to the columnar grain growth direction, i.e. the \{100\} direction. Compression tests were carried out in a Gleeble HDS-V40 simulation machine. The samples were heated to the deformation temperature of 450 °C at a heating rate of 20 °C/s, then warm deformed to 1.2 or 1.6 strain, with a strain rate of 1 s⁻¹, in one, two or five passes, with intermediate annealing at 750 °C for 30 seconds between each pass for the multiple pass deformations. Due to the compression load limitation, 1.2 strain could only be achieved for the one / two deformation pass samples, yet 1.6 strain was achieved for the sample with five passes and intermediate annealing, which is more representative of the commercial condition. Final annealing was carried out at 950 °C for either 5 or 60 minutes in an argon atmosphere. A section perpendicular to the compression axis was prepared for microstructure and texture determination. The samples were ground and polished with a Buehler AutoMet polisher. Electron backscattered diffraction (EBSD) analysis was performed in a JEOL 7800 FEG-SEM with an OXFORD instrument EBSD system to examine the micro texture evolution. The step size was 10 µm, and a 15-degree tolerance was allowed to calculate the ideal orientations. The same areas in each sample were examined after the sequential deformation and annealing steps to enable texture evolution measurement.

3. Results and discussion
The microstructure of the samples, which were warmed deformed to strain 1.2 with one or two passes, are shown in figures 1 and 2 respectively. Areas of misindexing are seen in the sample with one pass, figure 1 (a), which is attributed to its high stored energy. The microstructures after 5 minutes of annealing at 950 °C for both samples (same location as deformed image) have also been examined, figure 1 (b) and 2 (b) and show full recrystallisation; the recrystallised grain sizes are inhomogeneous in both samples, which is due to the varying local strain concentration in the deformed material in the initially different oriented grains (based on their Taylor factor), which agrees with literature observations [7].

The microstructure and local misorientation maps of the as-warm deformed (strain 1.6), partially recrystallised samples after holding at 950 °C for 5 and 60 minutes are shown in figure 3. Local misorientation has been used as an indication of the stored energy level and the deformed microstructure, figure 3 (a) and (b) shows strain inhomogeneity with the grain boundary regions being more deformed than the grain interior. The coarse grain at the top left side of the micrographs shows lower local misorientation, i.e. much less stored energy, compared to the finer grains in the centre, which is consistent with previous observations on the effect of grain size and orientation on stored energy after deformation: where small grains are known to have higher stored energy than larger grains; and \{111\}//ND grains (blue grains) have a higher stored energy than the \{100\}//ND grains (red grains) [7, 8]. Therefore, it is expected that the grain boundary regions and the fine grain regions with a \{111\}//ND orientation will recrystallise quicker than the other grains.
At the early stage of recrystallisation (5 minutes), it can be seen from figures 3 (c) and (d) that the more heavily deformed regions start to be replaced by recrystallising grains. In region 1, the recrystallising grains are close to \{111\}//ND and \{011\}//ND (i.e. coloured blue and green respectively). The area along the grain boundaries in region 2 has also recrystallised, but with a smaller recrystallised fraction and the recrystallised grains are close to a \{100\}//ND orientation (mostly red colour). It is generally considered that \{100\} texture grains are the least favourable to form on recrystallisation in bcc material due to their low nucleation rate. However, it can be seen that a high fraction of \{100\} texture grains have nucleated along the grain boundaries in figures 3 (c) and (d), where eleven recrystallising grains with an orientation of \{100\}//ND are present compared to ten recrystallising grains with a \{111\}//ND orientation, which is generally reported to have a high nucleation rate during recrystallisation [8].

It is therefore suggested that the recrystallisation nucleation rate of \{100\}//ND grains is comparable to that of grains with a \{111\}//ND texture in the 6 wt.% Si steel on annealing in this case. This observation of similar number of recrystallisation nuclei for the different textures was seen in other regions that were
examined as well as having been reported in the literature for electrical steel after similar deformation conditions [9]. After annealing for 60 minutes, over 70% of the sample has recrystallised, although the coarse grain on the top left side of the micrograph remains unrecrystallised due to its low stored energy, figure 3(e) and (f). It can be seen in region 3 that the grain with a (100)//ND orientation is bulging into the neighbouring grain, this is indicative of SIBM; this can also be seen in other regions, (indicated by arrows in figure 3(e)).

![Figure 3. EBSD IPF image for as-deformed (a), annealed at 950 °C for 5 minutes (c) 60 minutes (e) Local misorientation mapping for as-deformed (b), annealed at 950 °C for 5 minutes (d) 60 minutes (f)](image-url)
The recrystallised grain size is significantly finer (mode: 100 - 200 µm) in the sample after one / two passes than the sample with five passes (mode: 800 µm) despite the larger total strain imposed, which is attributed to their stored energy difference at the point of recrystallisation (reducing the stored energy by recovery via intermediate annealing). Only 12 - 14% area fraction of {100}//ND texture is present in the recrystallised samples without / with one intermediate annealing step, compared to 32% of {100}//ND texture shown in the sample with five intermediate annealing steps, summarised in table 1.

| Number of passes | Deformed | Recrystallised |
|------------------|----------|----------------|
|                  | {100}    | {111}          | {100} | {111} |
| {1}              | 40%      | 31%            | 14%  | 11%  |
| {2}              | 41%      | 25%            | 12%  | 11%  |
| {5}              | 37%      | 11%            | 32%  | 12%  |

The decreasing amount of {111}//ND texture present in the one / two pass compared to the five passes samples is attributed to the extent of recovery during deformation [10]. The low percentage of both {100}//ND and {111}//ND in the one / two passes samples suggested that recrystallisation did not retain or favour either texture in these cases, i.e. random recrystallisation texture is produced. It is noted that to achieve the desired final grain size for NGO electrical steel magnetic performance (typically 150 µm) a refined starting grain size would be required if low stored energy SIBM recrystallisation is desired to achieve high {100} texture. In summary, it is suggested that the low stored energy sample, i.e. five passes, promoted the formation of {100}//ND texture during recrystallisation via SIBM, with the high stored energy sample (deformed with one or two passes) showing a random recrystallised texture, which is consistent with sub-grain growth recrystallisation.

4. Conclusion

The {100}//ND texture was promoted via SIBM recrystallisation mechanism. The {100} texture grains, which carried very low stored energy after deformation, bulged into the surrounding grains during recrystallisation. Due to its slow recrystallisation nucleation rate, a low overall stored energy is preferred to encourage {100} texture recrystallised grains to form via SIBM recrystallisation mechanism. The SIBM recrystallizing grains have been directly observed from the deformed {100} grains using interrupted EBSD imaging.
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