Role of In-grain Shear Bands in the Nucleation of $\langle 111 \rangle$ //ND Recrystallization Textures in Warm Rolled Steel

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Electron Back Scattering Diffraction (EBSD) analysis was carried out on warm rolled Ti-IF and low carbon (LC) steels. The aim of this study was to learn more about the formation of grains with a $\langle 111 \rangle$ axis parallel to the sheet normal (ND fibre grains) during annealing. In-grain shear bands were found to be more prevalent in the deformed microstructure of the IF steel than in that of the LC grade. Consequently, the deformed ND fibre grains were far more fragmented in the IF material. These fragmented ND fibre grains produced ND fibre oriented nuclei in the grain interiors during annealing. It is concluded that the relative absence of in-grain shear banding in the warm rolled LC material is the most likely reason for the absence of an ND fibre recrystallization texture in this steel. It is also postulated that in-grain shear bands are involved in the nucleation of the near $\{554\}\langle 225 \rangle$ textures that are often observed in cold rolled and annealed IF and LC product.

KEY WORDS: warm rolling; shear bands; IF steel; ND fibre; recrystallization texture; grain fragmentation.

1. Introduction

The occurrence of grains with a $\langle 111 \rangle$ axis parallel to the sheet normal (ND) in steel strip is of considerable technological significance. Generally speaking, the greater the number of these grains present, the higher the deep drawability. As a consequence of this, the formation of such grains (abbreviated here on out as ND fibre grains) during the annealing of cold rolled strip has been extensively studied. Fortunately, it turns out that the processes by which these grains are formed are quite robust and ND fibre grains feature prominently in steels processed under a wide range of conditions.¹⁾

However, one processing variable that causes a noticeable departure from the norm is deformation temperature. Various workers have noted that ND fibre grains are relatively absent in annealed low carbon (LC) steels that have been rolled at temperatures above 600°C ^{2–4)} (see Fig. 1).

This phenomenon, and its dependence on the presence of solute carbon, has been ascribed to the direct action of solute carbon upon slip and crystal rotation near grain boundaries during warm deformation.³⁾ It has recently come to light, however, that solute carbon also impacts strongly upon the number of shear bands generated during warm ($600^\circ\text{--}700^\circ\text{C}$) rolling.⁵⁾ The presence of solute carbon seems to retard shear band formation at these temperatures. The comparative absence of in-grain shear bands in warm rolled LC material has consequently been linked with the low number of ND fibre grains formed in this grade during annealing.⁴⁾ This line of reasoning supposes that in-grain shear bands promote

the nucleation of ND fibre grains.

In the present work, EBSD analysis is used to probe further the apparent connection between in-grain shear bands and the ND fibre recrystallization texture in warm rolled LC and IF steel.

2. Experimental

This study was carried out on samples used in a previous work⁵⁾ (to facilitate comparison with existing X-ray textures and optical micrographs). Two laboratory warm rolled ($\sim 65\%$ reduction at $650\text{--}700^\circ\text{C}$) steels were examined, a Ti stabilised IF grade ("IF" – 0.005 wt% C, 0.13 wt% Mn, 0.084 wt% Ti, 0.042 wt% Al, 0.003 wt% N, 0.005 wt% Si, and 0.01 wt% P and S) and a low carbon steel ("LC" – 0.014 wt% C, 0.22 wt% Mn, 0.03 wt% Si, 0.01 wt% S and P, and 8 ppm N).

Sections of the deformed material were cut perpendicular to the transverse direction (TD) for analysis. The IF sample was partially recrystallized in a salt bath at 700°C and also sectioned for analysis. These transverse sections were studied using a Jeol SEM microscope operated in EBSD and BSE modes.

In this study, $\varphi_2 = 45^\circ$ sections of Bunge's Euler space are used to display the texture results. The exact locations of the important orientations in this nomenclature are given in Fig. 2. For practical purposes, ND fibre orientations are defined here as those that have a $\langle 111 \rangle$ axis within 15° of the sheet normal. (It is important to note that this definition allows for considerable misorientations to exist between orientations that fall within the ND fibre.) Various texture software developed inde-

Fig. 1. Recrystallization textures typical of warm rolled (650°–700°C) IF and low carbon steels.⁴⁾ There is only a low degree of ND fibre intensity in the low carbon material ($\phi_2=45^\circ$ ODF sections – intensity levels 2, 3, 4, 5, ...).

Fig. 2. $\phi_2=45^\circ$ ODF plot showing the positions of the main rolling and recrystallization orientations along with the RD, TD and ND fibres.

pendently by P. Van Houtte, J. Savoie and L. Kestens were used in the manipulation of the crystal orientation data.

3. Results

3.1. Deformed State

One hundred orientation measurements were taken (approximately one point per grain) from the mid plane region of both steels using EBSD. The presence of diagonal striations in the immediate vicinity of each measurement point was also noted. Similar diagonal striations have been previously identified as in-grain shear bands, due to their morphology and evidence that localised flow had occurred along them.⁵⁾ The overall textures obtained from the orientation measurements (expressed in ODF form by allowing a 7° Gaussian spread

Fig. 3. Deformation textures of the warm rolled (650°–700°C) steels measured using X-ray diffraction⁵⁾ and EBSD ($\phi_2=45^\circ$ ODF sections – intensity levels 2, 3, 4, 5, ...).

Fig. 4. Percentage of material containing in-grain shear bands (established from optical microscopy and SEM using a point counting technique).

around each orientation) are presented along with the X-ray texture results⁵⁾ in **Fig. 3**. There is reasonable agreement between the X-ray and EBSD data, which suggests that the 100 grains measured are representative of the whole.

The percentages of measurement points falling in the immediate neighbourhood of in-grain shear bands are shown together with optical microscopy results⁴⁾ in **Fig. 4**. The SEM data are higher in value than the optical microscopy figures. This is most likely a consequence of the greater accuracy afforded by the orientation contrast obtained in the SEM analysis. It is clear, nevertheless, that the IF material contains considerably more in-grain shear bands than the LC grade. It should also be noted that the bands in the IF steel are more severe in nature than those observed in the LC material.⁵⁾

The SEM results for the IF steel were examined more closely to see if there was any correlation between the shear band and orientation data. To this end, the Taylor factor (a measure of the total amount of slip occurring per unit of imposed strain) corresponding to each orientation was calculated using a full constraint Taylor model. The average Taylor factor for the points that fell near in-grain shear bands was found to be 3.4, while that

for the non-banded regions was 2.9. This finding is consistent with previous work, which has shown that shear bands occur preferentially in high Taylor factor orientations.⁶⁻⁸⁾

In rolled steel, the most prevalent high Taylor factor orientations are those of the ND fibre.⁹⁾ Significant amounts of banding is therefore expected to occur in ND fibre grains. Indeed, in the present IF sample, 85% of the measured orientations that fell within 15° of the ND fibre were associated with in-grain shear bands. This indicates that the internal structure of most of the deformed ND fibre grains in the IF sample is influenced by shear banding. For the LC grade, the percentage of ND fibre orientations observed in the vicinity of bands was only 35%. The internal structure of the ND fibre grains in each of these two grades is therefore expected to be quite different.

With the aim of assessing this difference, deformed ND fibre grains from both steels were examined using BSE imaging. Typical examples are presented in Figs. 5 and 6 for the LC and IF samples, respectively. A significant difference between the two materials is evident. The ND grains in the IF steel appear to be much more

fragmented than those in the LC grade. In-grain shear banding can also be seen in the IF material.

Stepped EBSD orientation measurements were carried out along the rolling direction to assess the degree of fragmentation. The misorientations between the measurement points shown in Figs. 5c) and 6c) are plotted in Fig. 7. The greater degree of fragmentation in the IF material is readily visible in this figure.

The amount of fragmentation of ND fibre grains was quantified further by carrying out step scans similar to those illustrated in Fig. 7 on 10 ND fibre grains for each steel. The misorientation angles between points 3 µm apart and are plotted in Fig. 8a). The average mis-

Fig. 5. Examples of typical ND fibre grains in steel LC (transverse sections-RD parallel to micron marker).

Fig. 6. Examples of typical ND fibre grains in steel IF (transverse sections-RD parallel to micron marker).

Fig. 7. Misorientations between adjacent points plotted as a function of distance along the RD for the ND fibre grains in Figs. 5c) and 6c).

Fig. 8. a) Misorientations between points 3 µm apart along the RD (established using scans of ~30 µm in the RD for 10 ND fibre grains in each steel grade). b) Misorientations between individual data points and average grain orientation (established using scans of ~30 µm in the RD for 10 ND fibre grains in each steel grade).

orientation over $3\mu\text{m}$ is 8.2° in the IF steel, and 1.4° in the LC grade. The misorientation angles between each data point and the average grain orientation are given in Fig. 8b). All the orientations measured remained within 15° of the ND fibre and no particular pattern was evident. Clearly, the ND fibre grains in the IF material are fragmented, in an apparently “general” manner, to a greater extent than those in the LC steel.

3.2. Recrystallization in the IF Steel

The presence of such high misorientations in the ND fibre grains in the deformed IF steel is expected to enhance nucleation in ND fibre grains during annealing. Indeed, it is a well established fact that deformed ND fibre grains are amongst the first to produce recrystallization nuclei in cold rolled material.^{1,10,11)} It is also known that the new grains thus produced are often of ND fibre orientation.^{1,10,11)} These ND fibre nuclei have frequently been observed at the grain boundaries and, consequently, grain interiors have not been generally considered as sites for the nucleation of ND fibre grains.^{12–14)} However, the fact that in-grain shear bands appear to cause general fragmentation of deformed ND fibre grains suggests that ND fibre nuclei should form readily in grain interiors, as well as at grain boundaries, in the present IF material.

To assess this prediction, EBSD examination of the IF sample in the early stages of recrystallization ($\sim 2\%$) was carried out. The transverse section BSE micrographs presented in Figs. 9a)–9c) show that ND fibre grains do indeed nucleate inside deformed grains, apparently at in-grain shear bands, in this material.

4. Discussion

The current results support the contention that in-grain shear bands play a large role in the nucleation of ND fibre grains during the recrystallization of warm rolled IF steel. It is therefore likely that the low number of in-grain shear bands present in warm rolled LC material is a contributing factor to the relative absence of an ND fibre recrystallization texture in this grade.

The link between shear bands and ND fibre texture formation is not one that has often been made in the cold rolling literature, with the notable exception of a recent paper by Ning *et al.*¹⁵⁾ Shear bands are more commonly associated with the formation of Goss ($\{011\}\langle 100 \rangle$) textures,^{1,16,17)} and ND fibre orientations with grain boundary nucleation.^{12–14)}

Although the present results apply specifically to warm rolled material, it must be mentioned that the bulk deformation and recrystallization textures displayed by the IF grade have been shown to be only marginally different from those of cold rolled material.^{4,5)} And in addition to this, micrographs in the literature show that in-grain shear bands of the type observed in the current work are a common feature of both IF^{18–20)} and LC^{21–23)} cold rolled material. If in-grain shear band stimulated nucleation of ND fibre grains is important in warm rolled IF material, it is likely that similar nucleation takes place in cold rolled IF material. The present observations should therefore be able to be reconciled

Fig. 9. Examples of ND fibre grains that appear to have nucleated at in-grain shear bands in the interior of deformed ND fibre grains in the IF material.

with those in the cold rolling literature. This is attempted below.

4.1. Fragmentation of ND Fibre Grains

The heavily fragmented nature of deformed ND fibre grains evident in the current IF material has been noted in a number of previous TEM studies on cold rolled IF

and LC grades.^{20,24)} In particular, two specific types of fragmentation occurring in these grains have been highlighted; (i) rotations to the Goss in shear bands,²⁵⁾ and (ii) rotations to specific orientations at grain boundaries.^{3,26,27)} The present work clearly shows, however, that significant general fragmentation of ND fibre grains can occur in the grain interiors of warm rolled IF material. This same fragmentation is absent when significant in-grain shear banding is absent, as in the present LC material. It follows that in-grain shear bands cause general fragmentation of ND fibre grains.

In-grain flow localisation, similar in nature to that evident in the shear bands observed in the present work, has been shown to cause general fragmentation in fcc materials.⁸⁾ A hint as to the mechanism by which this may occur can be found in the observation, made by Duggan *et al.*,²⁸⁾ that in-grain shear bands operate only once and seem to develop rapidly to their full width. In materials that readily produce in-grain shear bands, this process is likely to occur repeatedly throughout working. A dynamic picture of deformation can therefore be drawn in which different in-grain shear bands are continuously being activated and deactivated during straining. The new in-grain shear bands will cause crystal rotation in the band in response to slip activated by the shear. The material in the old "dead" bands, on the other hand, will rotate back towards stable rolling orientations. It is easy to imagine that such a dynamic occurring in grains like the one illustrated in Fig. 10 will cause a considerable degree of general fragmentation.

The relative absence of this fragmentation mechanism in the present LC material explains the low levels of ND fibre grain fragmentation observed in this grade (Figs. 5 to 8). This increased homogeneity of deformation also accounts for the sharp deformation texture and coarse recrystallized grain size observed in this grade.^{4,5)}

Observations of the fragmentation of ND fibre grains in warm rolled LC steel have highlighted the influence of lattice rotations towards $\{113\}\langle 110 \rangle$ that were seen near grain boundaries.³⁾ However, in light of the significant influence of in-grain shear bands evident in the present work, it is felt that such lattice rotations are of secondary importance. Nevertheless, examples of a similar phenomenon were seen in the course of the present study. It is quite likely that these rotations are enhanced in LC steel by the increased amount of overall grain rotation that occurs in the absence of localised deformation.⁴⁾ It is also possible that such rotations are present in warm rolled IF material, and that they are more readily observed in warm rolled LC steel simply because they are more easily identified in the absence of shear band fragmentation.

This is not to say, however, that the recrystallization textures produced in LC material are not influenced by specific lattice rotations in the vicinity of grain boundaries. Indeed, the detailed study carried out by Senuma *et al.*³⁾ shows that they are. Rather, it is in the absence of competition from nuclei generated from in-grain shear band induced fragmentation, that nucleation at other sites, like rotated regions at grain boundaries, can have such a strong effect on the final texture.

Fig. 10. Example of extensive in-grain shear banding (IF material, optical image).

It is apparent that more work is needed in the area of ND fibre fragmentation in steel, on both shear band and grain boundary effects, and on material subjected to higher strains than that employed in the present study.

4.2. Nucleation of ND Fibre Grains as a Consequence of In-grain Shear Banding

Grain boundary nucleation in ND fibre grains has often been observed to give rise to ND fibre oriented nuclei.¹²⁻¹⁴⁾ However, the micrographs in Figs. 9a)–9c) clearly show that ND fibre grains also nucleate in the grain interiors of the current warm rolled IF steel. This general phenomenon was also observed by Senuma *et al.*,³⁾ who report that half of the ND fibre nucleation occurring in their warm rolled IF grade took place in grain interiors. Recently Ning *et al.*¹⁵⁾ have shown that $\{111\}\langle 112 \rangle$ orientations can nucleate in shear bands and Vanderschueren²⁰⁾ has observed that grain interiors can yield near ND fibre nuclei in cold rolled steel. Clearly, both grain boundary and grain interior nucleation are involved in the nucleation of ND fibre grains, the latter most likely as a consequence of fragmentation induced by in-grain shear bands.

It is also important to note that the fragmentation arising from in-grain shear bands is as likely to enhance nucleation at the grain boundary as it does in the grain interior. Indeed, the absence of a significant ND fibre texture in annealed warm rolled LC material suggests that both grain boundary and grain interior nucleation of ND fibre grains are decreased in the absence of in-grain shear bands.

The fact that in-grain shear bands lead to the nucleation of ND fibre grains has not been incorporated in the traditional explanations for the influence of hot band grain size and rolling reduction on the recrystallization texture of cold rolled steel. A proper understanding of the influence of these variables should take this into account.

4.3. Formation of Specific Orientations Inside Shear Bands

To this point, only the general fragmentation arising from the activation of multiple in-grain shear bands has been discussed. Below, the specific rotation paths and stable orientations of the material inside the shear bands are considered. To this end, crystal plasticity rationale

(similar to that which has enabled Lee and Chan⁷⁾ to predict fcc shear band inclinations) will be employed.

The most prevalent orientation that readily forms shear bands in steel, is $\{111\}\langle 112\rangle$.^{22,25,29-33)} This is manifest in the present work by the fact that the six non-banded ND fibre grains observed in the deformed IF material, were considerably nearer in orientation to $\{111\}\langle 110\rangle$ than $\{111\}\langle 112\rangle$.

Shear bands in $\{111\}\langle 112\rangle$ orientations have often been observed to give rise to Goss^{17,25,29,30)} nuclei. This holds true for in-grain shear bands in polycrystals as well as for shear bands in single crystals and arises because rotations to the Goss occur in shear bands.²⁵⁾

However, the Goss is rarely present in the recrystallization textures of "normal" cold rolled IF and low carbon steel despite the large numbers of $\{111\}\langle 112\rangle$ grains and in-grain shear bands present in these materials.¹⁸⁻²³⁾ The present work also demonstrates that in-grain shear bands in steel do not always lead to Goss nucleation. The analysis that follows will attempt show that in-grain shear banding in $\{111\}\langle 112\rangle$ orientations can cause lattice rotation to both Goss and near ND fibre orientations, depending on the conditions under which the shear band is formed.

Shear bands most commonly involve simple shear on a plane that has its normal direction perpendicular to the sheet transverse direction. The starting orientation upon which this deformation acts is defined by the inclination of the band to the rolling plane (RP) and the orientation of the grain in which it forms ($\{111\}\langle 112\rangle$ in the present case).

The inclination angles of in-grain shear bands to the RP observed in the present work, and in the steel literature,²²⁾ are in the range 20°–40°. More specifically, single crystal studies have shown that shear bands readily form at angles of 20° and 35° to the RP in $\{111\}\langle 112\rangle$ orientations.²⁵⁾ The specific positioning of these bands with respect to the important slip systems (established from Fig. 9 of Ushioda and Hutchinson's paper²⁵⁾) is illustrated in Fig. 11. It will be assumed here that this arrangement of slip systems and shear bands also holds true for $\{111\}\langle 112\rangle$ grains in polycrystalline material. The occurrence of two sets of in-grain shear bands in a similar manner to that shown in Fig. 11 is evident in the

grain shown in Fig. 10.

Only the 20° shear band is predicted by the criterion for shear band angle determination developed by Lee and Chan,⁷⁾ presumably due to the limited applicability of their fcc based formulation to bcc steel. Nonetheless, the occurrence of bands inclined at both 20° and 35° to the RP in $\{111\}\langle 112\rangle$ steel crystals can be rationalised in terms of the factors considered by these workers. The occurrence of a band inclined 35° to the RP can be understood in terms of its high degree of texture softening (to be discussed below) and its ease of accommodation by slip on the $\{110\}$ plane in the opposite sense.³⁴⁾ The band inclined 20° is most probably formed as a consequence of its particularly low Taylor factor (due to its alignment with the $\{112\}\langle 111\rangle$ slip system). It is possible that the reason the $\{111\}\langle 112\rangle$ orientation forms shear bands so readily is that it contains favourably oriented slip planes that can easily carry, or accommodate, shear band deformation.

An important aspect of lattice rotation in shear bands is that of texture softening. This can be loosely defined as the phenomenon that arises when slip induced lattice rotation results in a lowering of the total amount of slip occurring on the active slip planes (*i.e.* when the Taylor factor decreases with increasing strain). With reference to shear banding, texture softening has been defined in a number of ways.^{7,25,33)} The rate of Taylor factor change occurring in the band, however, seems to be of primary importance. Indeed, this is confirmed in experimental work by Deve and Asaro,³⁵⁾ who have observed rotations inside shear bands that rotate an active slip system into alignment with the band. This type of rotation invariably involves the lowering of the Taylor factor in the band.

Before these considerations can be applied to in-grain shear bands in $\{111\}\langle 112\rangle$ orientations, it is necessary to establish the direction of crystal rotation. Fortunately, the direction of crystal rotation predicted by full constraint Taylor analysis of simple shear in $\{111\}\langle 112\rangle$ orientations is simply that shown in Fig. 11. This is also in agreement with the analysis and measurements carried out by Ushioda and Hutchinson.²⁵⁾

In the case of the shear band inclined at 35° to the RP, it can be seen from Fig. 11 that the $[011]$ axis will be rotated towards the ND as shearing occurs in the band. This is also accompanied by texture softening as the $(211)[-111]$ slip system takes more of the shear and thereby reduces the Taylor factor. Once the $(211)[-111]$ slip system comes into complete alignment with the shear band, a pseudo stable orientation is reached. This orientation is not fully stable due to the fact that a small rotation of the slip plane "past" the shear plane will cause subsequent deformation to induce further rotation of the $[011]$ pole towards the ND (*i.e.* rotations towards the Goss will occur in the band). It is presumably this phenomenon of pseudo stability that lead Hutchinson³⁶⁾ to note that there are no real stable orientations for simple shear. So, for lattice rotations to the Goss to occur in a 35° band, the pseudo stable orientation must be "passed", a certain degree of texture hardening must occur (as the $(211)[-111]$ slip plane rotates "away" from the shear band) and, of course, the band must last

Fig. 11. Schematic of a $\{111\}\langle 112\rangle$ grain showing typical shear band planes (inclined 20° and 35° to the rolling plane) and important slip planes.

Fig. 12. Initial and end orientations for Taylor simulation of shear in shear bands inclined at 20° and 35° to the RP ($\phi_2 = 45^\circ$ ODF sections).

sufficiently long enough for both of these to take place.

The shear band inclined at 20° to the RP shown in Fig. 11 is pseudo stable, because of its alignment with the $(211)[-111]$ slip system. Rotations of the lattice in this band will only occur if fragmentation away from the stable orientation occurs first. The direction of rotation, when it occurs, is the same for the 35° band, *i.e.* the $[011]$ axis rotates towards the ND. The Goss will only be attained in the 20° shear band, however, if considerable texture hardening occurs. This arises from the fact that the Goss has a high Taylor factor for shear at 20°.

It is also worth noting that the current analysis predicts that crystal rotation of the $[100]$ axis towards the ND should occur in shear bands of opposite sense to those considered above (due to a change in the sense of shear). This is confirmed by the fact that $\{113\}\langle 332 \rangle$ orientations have been found to be present in the recrystallization texture of $\{111\}\langle 112 \rangle$ single crystals that have experienced shear banding in both senses.²⁹⁾

So, summarising, the present considerations suggest that in-grain shear bands in $\{111\}\langle 112 \rangle$ are not expected to always give rise to Goss orientations. Rotations to the Goss are, however, more likely to occur in 35° than in 20° shear bands. For Goss orientations to be formed, the deformation conditions must be such that sufficiently high strains are able to be borne by the in-grain shear bands, and that texture hardening and pseudo stable orientations can be “overcome”. These conditions are much more likely to arise in materials where the driving force for flow localisation is particularly high.

Indeed, most of the literature observations that link the Goss with shear band nucleation were made on material which displayed prolific amounts of flow location. This was achieved by rolling in the dynamic strain aging region³⁰⁾ or through the use of large grain size¹⁷⁾ or single crystal^{25,29)} material.

To explore further the effect of low levels of shearing

Fig. 13. $\phi_2 = 45^\circ$ ODF section showing the texture of the in-grain shear band nuclei illustrated in Fig. 9.

in in-grain shear bands, two simple Taylor simulations were carried out. The starting orientations for both are shown in Fig. 12 and are situated near $\{111\}\langle 112 \rangle$. The orientations formed after each of the starting grains were allowed to shear to an equivalent strain of 0.5 at inclinations of 20° and 35° to the RP are also shown in Fig. 12. (Only the orientations that experienced texture softening are illustrated.)

A number of interesting points are evident in these results. All of the final orientations are within 15° of the ND fibre. And the average misorientation between the initial and final orientations is $\sim 10^\circ$ for the 35° band and $\sim 5^\circ$ for the 20° band. This suggests that shear band strains of similar magnitude to that used in the simulation (*i.e.* 0.5) would be sufficient to account for the misorientations observed in the current IF material.

It is also evident that the end orientations are displaced from the ND fibre, from $\{111\}\langle 112 \rangle$ in the direction of $\{554\}\langle 225 \rangle$. Similar “bending” of the ND fibre is often observed in steel recrystallization textures^{1,9)} (see also Fig. 1), and it is probable that in-grain shear band nucleation plays a role in this phenomenon.

The orientations of the shear band nuclei illustrated in Fig. 9 are shown in ODF form in Fig. 13. Together, these orientations make up a strong near $\{554\}\langle 225 \rangle$ texture. This supports the contention that the occurrence of these orientations in steel recrystallization textures is connected with in-grain shear band nucleation.

5. Conclusions

(1) In-grain shear bands play a large role in the general fragmentation of ND fibre grains during the warm rolling of IF steel.

(2) This general fragmentation leads to the nucleation of ND fibre grains at sites situated both within the grain interior and at the grain boundary.

(3) The relative absence of in-grain shear bands in the warm rolled LC material is the most likely reason for the absence of ND fibre orientations from the recrystallization textures of this steel.

(4) If in-grain shear bands are able to be re-introduced into warm rolled LC steel (by alloying element addition, for example), improvements in the ND fibre intensity, and the r -value, of the annealed product may be realised.

(5) Nuclei of near $\{554\}\langle 225 \rangle$ orientation appeared to be generated by in-grain shear banding. This is in agreement with rough theoretical predictions for the orientations expected to form in low strain in-grain shear bands in near $\{111\}\langle 112 \rangle$ grains.

(6) It is probable that in-grain shear bands are involved in the nucleation of the $\{554\}\langle 225 \rangle$ recrystallization textures that are commonly seen in cold rolled steels.

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