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UNDERSTANDING THE DEFORMED MICROSTRUCTURE OF COLD-ROLLED IF AND LC STEEL

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ABSTRACT

This paper presents an overview of a series of investigations of the microstructure and texture of cold-rolled IF and LC steel. The investigations made extensive use of orientation mapping using electron backscattered diffraction (EBSD) in a field emission gun scanning electron microscope (FEG-SEM). The effect of grain boundaries on the deformed microstructure was examined by comparing the textures of regions near grain boundaries and in the interiors of grains. A general weakening of the texture, but a strengthening of the {001}<110> component, occurs in the vicinity of grain boundaries. Misorientation angle and axis distributions were used to characterise the fragmentation of grains belonging to different orientation classes. The influence of carbon on the deformed microstructure and nucleation during recrystallization was clarified by examining the microstructures of LC and IF steels during rolling and annealing. The results of the investigations emphasize the important role of shear banding in determining the fragmentation behaviour of ND-fibre grains and the orientations of viable recrystallization nuclei within the deformed microstructure.

1. INTRODUCTION

The formability of cold-rolled and annealed steel is dependent upon its recrystallization texture. In commercial IF and LC steels, the development of the preferred <111>||ND texture is largely nucleation-controlled. Consequently, improving the formability of these steels requires detailed understanding of the deformed microstructure and the factors that influence nucleation during recrystallization.

The main reasons for the dominance of <111>||ND, or ND-fibre, orientations within the nucleation texture are the higher stored energies and orientation gradients present in deformed grains belonging to this fibre, compared with grains of other common orientations. The production of an ND-fibre recrystallization texture is relatively insensitive to many aspects of the steel chemistry and cold-rolling process. Nevertheless, its strength and “shape” may be modified, for example, by the relative availability of certain nucleation sites, such as grain boundaries or shear bands. In extreme cases the dominance of <111>||ND orientations may be lost altogether, as occurs in coarse-grained steels containing significant amounts of solute carbon, where copious nucleation at shear bands produces a Goss recrystallization texture.

While the correlation of certain nucleation sites with stronger or weaker ND-fibre textures is known, the mechanisms which lead to these correlations are only partially understood. In order to further our understanding of this important facet of recrystallization texture development, the authors investigated several different aspects of the deformed microstructures of rolled LC and IF steels. This paper draws together the key results of those investigations and discusses their significance in connection with recent work published in the literature by other researchers.

2. FRAGMENTATION WITHIN GRAINS

During cold-rolling, grains belonging to the ND-fibre become more highly fragmented than those belonging to the RD-fibre. ND-fibre grains develop both smaller cell sizes and higher cell boundary misorientations than RD-fibre grains (Figure 1, see also 4) and have higher stored energies. The combination of higher stored energies and higher boundary misorientations leads to more rapid generation of nuclei within these grains during recrystallization.

![Figure 1: Mean inter-boundary spacing and boundary misorientation for boundaries with misorientations > 1.5° in RD-fibre and ND-fibre regions of a 75% cold-rolled Ti-stabilized IF steel.](image-url)
shear along many of the bands. While the importance of shear bands in producing Goss orientations in coarse-grained steels has been known for a long time, the role of in-grain shear bands in producing the microstructural fragmentation that leads to nucleation of a strong ND-fibre texture has been recognized quite recently.

In a recent investigation of the misorientation axis distributions of ND-fibre grains in a 75% cold-rolled Ti-stabilized IF steel, an important difference was found between spatially-un correlated and spatially-correlated distributions. A strong preference for near-ND rotation axes in the spatially-un correlated distributions (e.g. Figure 2a) indicates that most ND-fibre grains have an overall orientation spread concentrated along the ND-fibre. On the other hand, the spatially-correlated misorientation axes demonstrated a preference for rotation axes located close to the TD-ND plane, but nearer the TD than the ND (e.g. Figure 2b).

Figure 2: Examples of (a) near ND-rotation common in spatially-un correlated misorientation axis distributions and (b) nearer to TD rotations common in spatially-correlated misorientation axis distributions in 75% cold-rolled Ti-stabilized IF steel.

The abundance of local TD misorientations together with an overall orientational spread about the ND can be explained by local TD rotation due to shear banding superimposed on an overall ND rotation produced by homogeneous plane-strain compression. When a shear band forms in an ND-fibre grain, the shear tends to rotate the material within the band about the TD. The material adjacent to the band is likely to rotate approximately about the ND. Once the shear band ceases to operate, the material within the band rotates back towards the ND-fibre but a different location on the ND-fibre to the adjacent material. Consequently, local misorientation axes will be near the TD where shear bands have recently been active but tend more towards ND near “older” shear bands. When misorientations are considered over longer distances (such as in the uncorrelated misorientation axis distribution) the prominence of the local rotations due to shear banding diminishes and the overall ND rotation dominates.

In recent years, a number of different models have been used to simulate texture development during rolling. Taylor crystal plasticity models have been progressively refined and now approximate cold-rolling textures quite well. However, most models do not incorporate spatial information, which is a prerequisite for the subsequent prediction of recrystallization textures. Finite element models offer the potential to simulate the fragmentation of grains within a multi-grain aggregate, although the number of grains in the aggregate and the level to which they can divide is limited by current computer power.

Choi simulated the cold-rolling of IF steel to a reduction of 65% (1.0 true strain) using an FE model. Figure 3 presents a comparison of the dominant rotation axis in uncorrelated misorientation axis distributions produced by the FE model and experimental results. While the comparison is based on a relatively small number of ND-fibre grains (16 experimental and 14 modelled grains), it is clear that the model does not reproduce the strong tendency for ND rotation observed experimentally. Instead, rotations about the RD are more prevalent. This may be partially due to the small difference in the level of strain (1.4 experimentally vs. 1.0 modelled) since it is not unreasonable to expect the tendency for ND-fibre grains to show overall orientational spreads around the ND to increase at moderately-high strains in line with a dominant rotation path along the ND-fibre. However, it is unlikely that this would explain more than a small part of the discrepancy.

Figure 3: Percentage of ND-fibre grains with uncorrelated misorientation axis distributions favouring a particular sample direction. Experimental results are from EBSD measurements on a 75% cold-rolled Ti-stabilized IF steel. Model results are based on FE-modelling data for a 65% reduction.

3. INFLUENCE OF GRAIN BOUNDARIES

With decreasing grain size, both the strength of the \(<111>||ND\) recrystallization texture and the contribution of grain boundary nucleation to this texture increase. Consequently, investigations have been conducted on the grain boundary regions of deformed microstructures in an effort to substantiate the link between the two and discern the reasons for it. A TEM study found rotations towards \{111\}<110> and higher dislocation densities in regions of \{111\}<uvw> grains near their boundaries with \{111\}<110> grains.
However, a study on cold-rolled bi-crystals found no evidence of systematic rotations near grain boundaries. A recent study by the authors used EBSD to compare the textures of grain boundary regions and grain interiors of a 75% cold-rolled interstitial-free steel. The EBSD maps used for the texture study covered 360 μm x 360 μm regions on each of the RD-ND and RD-TD sections containing about 400 grains in total. The textures were segregated by considering all material within 1 μm of a grain boundary to belong to "grain boundary regions" and all other material to belong to "grain interiors". The results of this analysis (averaged results over both RD-ND and RD-TD sections) are presented in Figure 4.

![Figure 4: Variation of ODF intensity along the RD-fibre (φ₁ = 0°, φ₂ = 45°) and ND-fibre (φ₁ = 55°, φ₂ = 45°) for a commercial IF steel cold-rolled 75%, showing the influence of close proximity to grain boundaries (GB).](image)

Overall, the textures of the grain boundary regions are considerably weaker than those in the grain interiors. Against this trend, the grain boundary regions contain a stronger [001]<110> component even though the rest of the RD-fibre is considerably weaker. This result is seen in the textures measured on both the RD-ND and the RD-TD sections and preferential clustering of [001]<110> orientations near grain boundaries can be seen in the EBSD maps. An overall weaker texture, but a stronger [001]<110> component, was also found near grain boundaries in a 70% cold-rolled LC steel with a strong {111}<110> initial texture (Figure 5). The evidence for systematic ND-fibre rotations near grain boundaries is not as clear. When the textures on the RD-ND section are considered separately, the [111]<110> orientations are much weaker near the grain boundaries while the {111}<112> orientations are only slightly weaker. However, on the RD-TD section, both components were weaker by a similar amount. Consequently, the averaged result (Figure 4) shows only a very small difference in the extent to which the [111]<110> and [111]<112> orientations are weaker near the grain boundaries.

![Figure 5: Variation of ODF intensity along the RD-fibre (φ₁ = 0°, φ₂ = 45°) for an LC steel with a strong {111}<110> initial texture cold-rolled 70%, showing the influence of close proximity to grain boundaries (GB).](image)

The strengthening of the [001]<110> component near grain boundaries in contrast to the overall weakening of the texture indicates that the development and stability of this component is favoured by deformation conditions in the vicinity of grain boundaries. In this context, it is interesting to note that in cold-rolled LC steel, the [001]<110> component develops much more strongly than the {112}<110> component at very high reductions (above 95%) and the peak intensity on the RD-fibre shifts from {112}<110> to [001]<110> as a result. It seems reasonable to propose that this is a bulk texture manifestation of the grain boundary effect noted above since at these very high reductions the distance between grain boundaries in the ND is so small that the vast majority of the microstructure becomes affected by them and the [001]<110> component of the bulk texture becomes strengthened.

FE models are not yet at the point where the number of modelled grains and the level to which they can divide
is sufficient to distinctly model texture development in grain boundary regions and grain interiors, although this point may soon be reached. Nevertheless, a comparison between experimental results and the predictions of Taylor plasticity models can be made in the following way. Under one scenario, the material adjacent to grain boundaries is assumed to adhere more tightly to the imposed strain than the material at the centres of grains. Hence, the grain boundary material conforms more closely to the full constraints Taylor model, which predicts a maxima on the RD-fibre near \(\{112\}<110>\), while the grain interiors follow the relaxed constraints model, which predicts a maxima on the RD-fibre at \(\{001\}<110>\). However, the experimental results show the opposite trend. Since grain boundary regions are particularly constrained to conform to the deformation of their neighbours, rather than the imposed strain, the inability of this "combined Taylor model" approach to match experimental observations is perhaps not surprising.

Another possibility is that the grain boundary regions, being much thinner than the grain interiors, follow the relaxed constraints model more closely, separating from their parent grain by deformation banding, a process described by Duggan et al. \(^{37}\). While this explanation would fit the experimental results, further experimental and modelling work is required to ascertain whether this process is responsible for the observed texture difference between grain boundary regions and grain interiors. If this further work leads to a method for reducing the concentration of near \(\{001\}<110>\) orientations at grain boundaries, industrial benefit could be achieved through a reduction in SIBM nucleation of these orientations during recrystallization and a consequent strengthening of the ND-fibre texture.

4. ROLE OF CARBON

Solute carbon promotes the formation of Goss recrystallization textures at the expense of the ND-fibre \(^{9,20,38}\). Many aspects of this relationship have been well established. Goss nucleates in shear bands, mostly in deformed ND-fibre grains and particularly those near \(\{111\}<112>\). Rotation of material from the \(\{111\}<112>\) orientation towards Goss is caused by shear within the bands \(^{14,18}\). The formation of both shear bands and Goss nuclei is enhanced in coarse-grained materials \(^{16,18}\) or when rolling is carried out at temperatures where dynamic strain ageing occurs \(^{37}\). Goss recrystallization textures strengthen with rolling reduction up to about 70%, then decrease \(^{38}\). Recent work by the authors \(^{19,23}\) has concentrated on clarifying some details of the effect of solute carbon, grain size, rolling reduction on shear banding and recrystallization texture. A major focus has been to determine whether it is merely an increased frequency of shear bands or something about their nature or severity that causes a greater production of Goss orientations in coarse-grain steels containing solute carbon.

Figure 7 shows an assessment of the quantity of shear bands present in cold-rolled coarse-grained IF and LC steels at moderately high rolling reductions and the proportion of these bands that remain active. Details of the steels and the experimental method have already been published \(^{19,23}\). The assessment of the quantity of shear bands generated up to 75% rolling reduction was made by point counting the proportion of moderately to severely banded material on etched RD-ND sections. The assessment of the bands that are active between 75 and 80% rolling reduction was made by point counting the proportion of moderately to severely banded material on RD-ND sections that had been polished at 75% reduction before further rolling to a total reduction of 80%. While this provides only a very rough measure of the proportion of bands that are still active between 75 and 80% reduction, it suggests that this proportion is higher for the LC steel than the IF steel. The bands in the LC steel also appear more severe (i.e. carry a larger amount of shear) than those in the IF steel \(^{19,23}\).

![Figure 7](image)

**Figure 7:** Percentage of moderately to severely banded material in coarse-grained IF and LC steels cold-rolled 75% at room temperature. CR 0-75% refers to banded material revealed by etching after a cold reduction of 75%. CR 75-80% refers to banded material on an un-etched surface, polished at 75% cold reduction, after a total reduction of 80%.

These results suggest that either, or perhaps both, of two mechanisms could be responsible for the higher amount of Goss in shear bands in the LC steel. The first is simply that because the deformation was more heavily localised, the greater amount of shear within each band caused more material to be rotated near to the Goss orientation. (Rotation from \(\{111\}<112>\) towards Goss within bands carrying shear is predicted by crystal plasticity theory \(^{14,18}\).) The second possibility is that since less shear bands in the IF steel remain active at high rolling reductions, there is more material within inactive bands that has rotated back towards the \(\{111\}<112>\) orientation. (Orientations between \(\{111\}<112>\) and Goss tend to rotate back towards \(\{111\}<112>\) under plane strain deformation \(^{16}\).)

While the second mechanism seems plausible on the basis of crystal plasticity theory, supporting experimental evidence is indirect (a combination of the knowledge that the strength of the Goss component
increases with rolling reduction at room temperature until 70% and then decreases with further rolling reduction\textsuperscript{35} and the concept that the number of active shear bands decreases at high rolling reductions, as suggested by Figure 7). However, the results of a further experiment confirm that the second mechanism can play a significant role, at least under favourable circumstances.

In this experiment\textsuperscript{35}, the recrystallization texture of an LC steel rolled to a true strain of 1.2 at 300°C was compared to that of the same steel rolled to a true strain of 1.4 at 300°C and that of the same steel rolled to a true strain of 1.2 at 300°C and then to a total strain of 1.4 by further rolling at room temperature following a precipitation treatment. As shown in Figure 8, a small reduction in the amount of Goss occurred with the additional 0.2 strain at 300°C (i.e. within the dynamic strain ageing temperature range, which encourages shear band activity). A much larger reduction in Goss occurred with the additional 0.2 strain at room temperature, where much less shear band activity would be expected due to both the temperature and the reduction in solute carbon provided by the precipitation treatment. This demonstrates that the second of the mechanisms proposed above is viable. It remains to be demonstrated which of the two mechanisms contributes most towards the production of Goss textures in a particular set of circumstances.

![Figure 8: Dependence of the Goss component of the recrystallization texture on strain and rolling temperature. Each texture was measured on an area containing approximately 1000 grains.](image)

5. CONCLUSIONS

Investigations of the microstructures and microtextures of cold-rolled LC and IF steels have confirmed that ND-fibre grains have smaller cell sizes and higher misorientations than RD-fibre grains. More importantly, the investigations have produced several new results. The \{001\}<110> texture component is more prevalent in regions near grain boundaries while the general texture of these regions is weaker than the texture of grain interiors. ND-fibre grains show a preference for local misorientation axes to be nearer TD than ND, notwithstanding the strong tendency for the overall (long range) fragmentation of these grains to be about the ND. A small amount of additional rolling under conditions where shear banding is not favoured can cause a substantial reduction in the Goss component of the recrystallization texture of a steel that has previously been rolled under conditions favourable for shear banding. These results point to the importance of shear band activity in generating the fragmentation in ND-fibre grains that enhances nucleation in these grains during recrystallization and controls the relative strengths of the Goss component and the \{111\}<112> component in the recrystallization texture. They also show that while reducing the hot band grain size may be beneficial in limiting shear banding and the production of Goss orientations, it may also enhance the undesirable \{001\}<110> texture component.

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REFERENCES