Development of Cold Rolled Texture and Microstructure in a Hot Band Fe–3%Si Steel

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Hot band Fe–3%Si steel (CRGO or cold rolled grain oriented) was cold rolled with different reductions. The main objective of this study was an overall understanding of deformation texture and microstructure development. Hot band CRGO had a strong α-fiber (RD/(110)) texture. Cold reduction strengthened the α and γ (ND/(111)) fibers, but weakened θ (ND/(100)). All Taylor type deformation texture models were reasonably successful in predicting these bulk texture developments, and the Lamel model seems to be the ‘best-fit’ model, both in terms of a ‘deviation’ parameter (indicating differences between experimental and simulated values of idealized texture components) and a ‘trend’ parameter (indicating the relative change(s) in texture components with strain). The striking feature of the microstructure was the ‘selective’ appearance of grain interior strain localization’s. These appeared at approximately 37° with the rolling direction (RD). Though 37° bands appeared only in orientations with high Taylor factor (M), the absolute value of the Taylor factor alone, was not enough for the appearance of such bands. Negative textural softening or (dM/de) values, on the other hand, were always associated with the appearance of 37° bands, justifying or explaining their formation on the basis of a macroscopic plastic instability theory.

KEY WORDS: cold rolling; texture; grain oriented electrical steel; microstructure; strain localizations.

1. Background

The cold rolled grain oriented (CRGO) steels, with approximately 3% Si in solid solution, are a class of materials where ‘complete’ texture control is implemented.1–3) Fully processed material contains large Goss (011)/(100) grains, with a grain size ranging from millimeters to centimeters depending on the exact processing route. These grains are often ‘slightly’ (3–5°) deviated from the exact Goss orientation.11) The usual thermo-mechanical processing route is the following: hot rolling, typically at a temperature where both austenite and ferrite are stable1–4) and subsequent cold rolling1–8) and annealing under decarburizing atmosphere for primary and secondary recrystallization.1–18) The microstructure of the hot rolled plate, typically contains large and small grains and ‘considerable’ second phase particles.1–4) The general understanding is that the large grains are formed by deformation and recrystallization of the ferritic grains, while the smaller grains are formed by transformation from austenite to ferrite.1) Due to the second factor, small grains are observed to contain larger amounts of second phase particles.1) When the hot band is cold rolled, the extent of cold rolling is dependent on the particular processing route,1–5,8) and past studies10,11) have shown that the development of cold rolling texture and microstructure have a profound influence on the subsequent primary and secondary recrystallization.

Though CRGO processing has attracted considerable academic and industrial interests1,1–22) published literature of systematic studies on cold rolled texture and microstructure developments is almost non-existent. This was the motivation in conducting the present research.

The effects of cold rolling may be generalized in three broad categories: (I) a geometrical change in the size and shape of the deformed grains, (II) deformation texture development and (III) development of dislocation substructure. The geometrical change is in principle directly related to the strain, but it may get affected by the so-called “grain splitting”27,28) or creation of new high angle grain boundaries or lattice curvatures.29) The deformation texture development is relative well understood for bcc low carbon steel.23–27,29–32) In commercial Fe–3%Si with significant second phase dispersions, however, a systematic characterization and modeling of the cold deformation texture development is not so well documented in the domain of published literature. Perhaps the most significant feature of the dislocation substructure in CRGO10,11,18) steel (but also in bcc low carbon steels27,30,34–37) is the development of so-called “grain interior strain localization’s”. In cold deformed CRGO, such strain localization’s were reported to occur mainly at two directions with respect to the rolling direction, namely at angles of approximately 37° and 20°.10,11)
a previous study of the present authors, it was suggested that the relative presence of the respective strain localization’s may determine the frequency and ‘perfection’ of the primary recrystallized Goss grains, perhaps determining the effectiveness of the subsequent secondary recrystallization process. A recent study in low carbon steel has indicated that at least the 57° strain localization’s are first generation micro bands forming on the so-called ‘high Taylor Factor’ orientations. How such strain localization’s may evolve in a cold-deformed CRGO and if both 37° and 20° bands are of the same nature and origin remains to be explored.

2. Experimental Methods

A 200 kg Fe–3%Si steel ingot was hot rolled from 50 to 2.1 mm thickness (pre-heating temperature being 1330°C). The chemical composition of the hot rolled strip is given in Table 1. The hot rolled strip was annealed at 1000°C for 60 s and then quenched. The annealed hot-band material was subsequently cold rolled with a laboratory mill to 5.60 s and then quenched. The annealed hot-band material was then deformation textures were simulated with different Taylor type models and on microstructural and microtextural changes are presented separately.

3. Results

Textural and microtextural changes in the present Fe–3%Si steel were described in terms of the following fibers and texture components: \( \gamma(111) // \text{ND} \), \( \alpha(110) // \text{RD} \) and \( \gamma(111) // \text{ND} \) fibers; \( H\{100\}(011); I\{211\}(011), E\{111\}(011) \) and \( F\{111\}(112) \) components. F and E are typically considered part of \( \gamma \), while H and I are considered as part of the \( \alpha (\text{RD}/(110)) \) fiber. In the OIM measurements, deformed grains were considered as F, E, H or I when they were within 20° of the respective ideal components. When a particular deformed grain (or part of a deformed grain) fell within 20° of more than one ideal component, it was considered as the component of least misorientation. Results on changes in bulk texture, on deformation texture simulations using different Taylor type models and on microstructural and microtextural changes are presented separately.

### Table 1. Chemical composition of the CRGO used in the present study.

| Element | CI | Cu | Al | Mn | P |
|---------|----|----|----|----|---|
| Fe      | 93.1|    | 0.60|    | 0.25|
| C       | 0.60|    | 0.20|    | 0.06|
| Al      | 0.06|    | 0.08|    | 0.02|
| N       | 0.08|    | 0.01|    | 0.00|
| Mn      | 0.25|    | 0.02|    | 0.01|
| S       | 0.01|    | 0.00|    | 0.00|

3.1. Development of Bulk Texture

Figure 1 shows the \( \phi_1=0° \) and \( \phi_2=45° \) sections of the X-ray ODFs for hot rolled and hot rolled plus annealed material and the annealed material after various stages of cold reduction (25%, 40%, 60%, 77% and 88% cold reduction). Figure 2 expands on Fig. 1 by outlining the changes in volume fractions of some important orientations or fibers as function of strain. For the calculation of these volume fractions a spread of 16.5° around the ideal orientations was considered. Textural differences before and after annealing were insignificant in terms of both X-ray ODFs, as shown in Figs. 1(a) and 1(b), or volume fraction estimations. As shown in Fig. 2, changes in volume fractions with strain can be generalized as:

1. Increase in \( \gamma (\text{ND}/(111)) \) and \( \alpha (\text{RD}/(110)) \) fibers, but drop in the \( \theta (\text{ND}/(100)) \) fiber.
2. Increase in E and I, but drop in H.
3. Slight increase in F and drop in Goss. Although these two changes are relatively small and falls in principle within the accuracy of X-ray measurements, consistently similar measurements from several samples strongly indicates a trend of slight increase of F and drop of Goss.

3.2. Deformation Texture Simulations

In order to study the ‘predictability’ of deformation texture developments in the present Fe–3%Si steel, the texture of the hot band (i.e. hot rolled plus annealed) was discretized to 5 000 individual orientations and then deformation textures were simulated with different Taylor type models. For estimation of Taylor factors, only the full constraint (F.C.) Taylor model was used.

OIM samples were prepared using standard techniques. For hot band material as well as material with 25% cold rolling, SEM (scanning electron microscope) with Tungsten and LaB6 filaments were used, while for cold reductions of 40% or more a FEG (field emission gun) SEM was used. OIM data acquisition and analysis were obtained with the standard TSL (Tex-Scan Ltd.) package.
total number of strain states \( (N) \), being 5. The “trend” was estimated by ‘assuming’\(^*2\) a linear relation between textural changes and strain and then obtaining the slope of the best fitting straight line. As shown in Tables 2 and 3, the Lamel model provides the ‘best fit’ with the experimental data. Not only the ‘trends’ were closest, but the deviation parameter for Lamel was also the lowest among all models.

### 3.3. Microstructural Development

Figures 3 to 5 present representative OIM results on 25%, 60% and 88% cold rolling reductions. In each figure, (a) gives the so-called image quality (IQ) map, which is close to an optical microscopic representation of the deformed grains. It represents the relative sharpness of the OIM patterns; this however, does not indicate the accuracy of indexing. Figures 3(b) to 5(b) show the OIM images with low and high angle boundaries indicated by light and dark lines respectively. Figures 3(c) to 5(c) provide the so-called Taylor factor maps. The darkest and lightest regions correspond to respective Taylor factors of 2.2 to 3.9. All the OIM scans were obtained on the so-called long transverse plane containing rolling (RD) and normal (ND) directions;

\*2 Such an assumption is not far from actual experimental observations.
the respective RDs being marked in Figs. 3(a) to 5(a).

Even at the lowest reduction of 25%, the most significant feature of the microstructure is the appearance of 37° bands (approximately at 37°/H1106° with RD) in some particular grains. An example is seen in the bottom grain of Figs. 3(a) and 3(b). Further reduction, as in Fig. 4, enhanced the relative number and severity of 37° bands. At the highest reduction of 88%, see Fig. 5, extreme pancaking did restrict the apparent visibility of the bands, but in small local scans the 37° bands could still be appreciated.

As shown in the OIM images of Fig. 3(b) and 4(b), the bands were typically marked by grain boundaries, often high angle – especially above 25% reduction, mostly with a spatial orientation of 37°±6° with RD. The so-called 20° bands10,11 were only occasionally observed in samples with 60% and 77% reduction, mostly as part of a deformed grain or a grain edge appearing at such an angle. The appearance of the 37° bands seems to be related to the Taylor factor, as they did not form on grains with a Taylor factor of less than 3, see Fig. 3. However, it is interesting to note that only the Taylor factor did not determine the appearance of these bands because it was regularly observed that bands were formed in grains with a particular Taylor factor, while in other grains with the same Taylor factor, no bands were visible, as shown in Fig. 4. This issue will be further discussed below.

4. Discussion

4.1. On the Bulk Texture Development

Mainly because of formability considerations, bulk texture developments in forming grade bcc low carbon steel is a subject of considerable applied and academic interest.23–27,29–32 The deformation texture models, specifically the `Lamel' model,31,32 have been reasonably successful in describing the development of the bulk texture in such material. Hot band CRGO however contains a different microstructure than forming grade material: it has a bimodal grain size distribution and significant presence of second phase particles.1,3,4 The typical hot band texture, as shown in Fig. 1(a), shows a strong α fiber and a weak γ fiber. Such a starting texture is remarkably different from the so-called randomized hot band texture in a forming grade steel. This difference is due to the presence of silicon that suppresses the ferrite–austenite–ferrite transformation, responsible for texture randomization in forming grade steels. In CRGO, the transformation happens only in zones where carbon is segregated. These local phase transformations result in fine grains and hence bimodal grain size distribution.

In the present CRGO, cold rolling increased the strength of both γ and α, see Figs. 1 and 2. In forming grade steels, such as IF (interstitial free)27 or ULC (ultra low carbon),30 with increasing cold reductions, α typically keeps on increasing while γ increases and then stagnates. Interestingly, the trends in the changes of texture components and fibers are reasonably predictable in the present grade of CRGO. As shown in Tables 2 and 3, it is quite evident that the Lamel model31,32 gives the best predictions in terms of both deviation parameter (indicating differences between experimental and simulated values of idealized texture components) and trend (indicating the relative change(s) in texture components with strain).

Table 2. Relative deviation parameter [(Σ(Lc/Vc)²/N)¹/₂, where for a given texture or fiber component “c” – Vc is the experimentally measured volume fraction, as estimated from X-ray ODFs. Lc is the difference between experimental and simulated volume fractions. Each were calculated for rth strain state, or a specific reduction percentage–N or the total number of strain states being 5. FC, RCL, RCP and Lamel stands respectively for full constraint, relaxed constraint lath, relaxed constraint pancake and Lamel models27,29,31,32,42 of deformation texture simulations.

| F.C. | 0.33 | 0.10 | 0.28 | 0.69 | 0.26 | 0.27 | 0.091 | 2.221 |
| R.C.L. | 0.32 | 0.10 | 0.28 | 1.00 | 0.27 | 0.13 | 2.382 |
| R.C.P. | 0.37 | 0.17 | 0.24 | 0.31 | 0.57 | 0.40 | 0.039 | 2.085 |
| LAMEL | 0.21 | 0.034 | 0.096 | 0.64 | 0.25 | 0.10 | 0.064 | 1.302 |

Table 3. ‘Trend’ of change for different texture components as observed/obtained by X-ray diffraction (Expt.) and different Taylor type models (as in Table 2). The trend was obtained from the slope of the best fitting straight line and by assuming that changes in volume fractions (as function of strain) were ‘linear’ and the volume fractions at “zero” strain are equal to the hot rolled volume fractions.

| F.C. | 0.0019 | 0.0036 | -0.0022 | 0.00110 | 0.00070 | -0.0013 | 0.0017 |
| R.C.L. | 0.0017 | 0.0030 | -0.0020 | 0.00110 | 0.00050 | -0.0013 | 0.0017 |
| R.C.P. | 0.0018 | 0.0030 | -0.0020 | 0.00100 | 0.00070 | 0.00072 | 0.0013 |
| LAMEL | 0.0013 | 0.0012 | -0.0013 | 0.00070 | 0.00070 | -0.00050 | 0.0019 |
| EXPT. | 0.0012 | 0.0013 | -0.0011 | 0.00022 | 0.0010 | -0.00049 | 0.0013 |
4.2. Microstructural Features

In CRGO, the frequency and nature (proximity to exact Goss) of the primary recrystallized Goss grains were reported to be related to the spatial orientation of the deformed Goss bands—generalized as bands at approximate angles of 37° and 20° with RD or rolling direction.\(^\text{10,11}\) Goss grains nucleating or growing from 37° bands were more in number but less ‘perfect’.\(^\text{11}\) Primary recrystallized Goss grains are expected to form the nuclei of subsequent secondary recrystallization and hence understanding their relative source or origin is undoubtedly important. The present study clearly outlines ‘selective’ appearance of 37° bands as grain interior deformation heterogeneity’s, while 20° bands seem to originate as part of a deformed grain or a grain edge appearing at such an angle at relatively later stages of deformation.

The so-called 37° bands are also common in low carbon forming grade steel,\(^\text{27,30,34–37}\) albeit for a different reason.

The strength of γ-fiber recrystallization texture seems to depend on the preferential formation of 37° bands in deformed γ grains.\(^\text{30}\) In a typical OIM image\(^\text{27,30}\) these appear as ‘more frequent grain boundaries of higher than average misorientation’ and were generically termed as ‘grain interior strain localization’s’.\(^\text{30}\) Recent studies\(^\text{18,34}\) have shown that the parallel pairs of dislocation walls of 0.1–0.3 \(\mu\)m wide with distinct substructure inside, and borrowing conventions from fcc system,\(^\text{33}\) can be generalized\(^\text{45}\) as first generation or non-crystallographic microbands. It seems that ‘selective’ appearance of such bands in the high Taylor factor orientations\(^\text{30,34}\) may explain the so-called stored energy advantage\(^\text{27,30,34,43,44}\) of the deformed γ-fiber grains.
4.3. Relating Microstructural Features with Macroscopic Parameters

The ‘selective’ appearance of the 37° bands is perhaps one of the most striking features of the deformed microstructure. As shown in Fig. 3, and confirmed by several OIM scans, it seems clear that bands did not form on grains or orientations with low Taylor factors—a similar trend as that of forming grade steel.27,30 Unlike the forming grade material,30 however, a selective appearance of the bands even in grains with nearly identical Taylor factors, was quite apparent. In other words, Taylor factors may indicate a general trend in the appearance of the 37° bands, but this is not enough to guarantee their appearance.

Since 37° bands, irrespective of their origin, may be considered as plastic instabilities or strain localization, a macroscopic45 and much quoted33,42,46,48 way of looking at their formation is through the so-called Dillamore’s plastic instability criteria:

\[
\frac{1}{\sigma} \left( \frac{d\sigma}{d\varepsilon} \right) = \frac{n}{\varepsilon} + \frac{m}{\varepsilon} \left( \frac{d\varepsilon}{d\varepsilon} \right) + \frac{1 + n + m}{M} \left( \frac{dM}{d\varepsilon} \right) - \frac{m}{\rho} \left( \frac{dp}{d\varepsilon} \right) \leq 0
\]

where \(\sigma\) and \(\varepsilon\) are the macroscopic stress/strain, \(n\) and \(m\) are strain hardening exponent and strain rate sensitivity, \(\varepsilon\) is the strain rate, \(M\) is the Taylor factor and \(\dot{\varepsilon}\) is the mobile dislocation density.45 In the present steel, the most likely way to make the left hand term of Eq. (1) negative, is by obtaining a negative texture softening \(dM/d\varepsilon<0\). To explore this possibility, simulations were conducted on different bcc texture components using a full constraint (F.C.) Taylor model and a strain increment of 0.05—see Fig. 6. The components selected have a wide range of Taylor factors—ranging from 2.12 (ideal H) to 3.76 (ideal E). As illustrated in,43 5–10° rotation from ideal texture components does not affect the respective Taylor factors significantly. As in Fig. 6, rotation (depending on the rotation axis and the ideal texture component) may, however affect the numerical value and more importantly the sign (positive or negative) of textural softening or \(dM/d\varepsilon\). For the \(\gamma\)-fiber components of \(F\) and \(E\), except for TD rotation above 3° and 7° respectively, \(dM/d\varepsilon\) values are always negative. For the \(\alpha\)-fiber components I and H, the sign of \(dM/d\varepsilon\) strongly depends on the respective rotation axis even for very small rotations—see Fig. 6.

In real life, as in the case of present cold deformed CRGO, getting an exact ideal texture component is almost impossible. Most of the grains will fall within a certain misorientation along some crystallographic direction from the exact texture components. In a deformed structure, a grain or orientation may go through a process of reorientation, and this process will determine the textural softening or \(dM/d\varepsilon\) value and based on instability criteria45 may determine the relative appearance of plastic instabilities or 37° bands. To test this hypothesis, orientations from individual grains (from respective OIM scans) were selected and screened. A continuous ODF was plotted, at 7° Gaussian spread, and based on maximum ODF intensity an individual orientation was selected as being representative. Respective \(dM/d\varepsilon\) values were estimated (using full constraint Taylor and a strain increment of 0.05) for all such representative orientations. Irrespective of the reduction, as shown in Fig. 7, the sign of \(dM/d\varepsilon\) did correspond to the visual appearance (as in Figs. 3, 4 and 6) of 37° bands. A total of 12 grains with negative \(dM/d\varepsilon\) and 10 with positive \(dM/d\varepsilon\) were analyzed and all followed the pattern of ‘selective’ appearance of 37° bands only with negative textural softening.

From the OIM measurements, the maximum nearest neighbor misorientations (as estimated by point to point misorientation) and maximum long range misorientations (LRMs or point to origin misorientations, see reference42 for further details) were also estimated and are presented in Fig. 7. These were estimated over a distance of at least 10 \(\mu\)m (and often more) along RD. Negative textural softening and a corresponding appearance in 37° bands clearly resulted in significantly larger misorientation and LRM values. Judging the possible effect of the numerical value of \(dM/d\varepsilon\) on misorientation and LRM development is not pos-
sible from Fig. 7, as measurements from different reduction percentages were used. It has to be noted that at any specific reduction no trend could clearly be identified. The procedure for testing $dM/d\varepsilon$ does have some drawbacks. The most important of such drawbacks is that the past history or orientation(s) of the grains are not known.*3 In spite of all this, the present results point towards a correlation between the ‘selective’ appearance of 37° bands and negative textural softening.

5. Conclusions

(1) The hot band CRGO contained strong $\alpha$-fiber orientations. Cold reductions increased the strength of both $\alpha$ and $\gamma$ fibers, but reduced the strength of the $\theta$ fiber.

(2) All Taylor type deformations texture models appeared to be reasonably successful in predicting the cold rolled texture developments of the present grade of CRGO. However, in terms of both the deviation parameter (indicating differences between experimental and simulated values of idealized texture components) and the trend (indicating the relative change(s) in texture components with strain), the Lamel model seems to offer the best predictability of the deformation texture development.

(3) ‘Selective’ appearance of the 37° bands (with an angle of approximately 37° with RD, appearing inside deformed grains) seems to be the most striking microstructural feature of the cold deformed structure. The so-called 20° bands appeared only as part of a deformed grain or a grain edge appearing at such an angle at relatively later stages of

*3 Exact orientation measurements, i.e., no errors in RD, TD or ND rotation, is also difficult in OIM; though maximum precautions were taken in the present study.
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estimated textural softening or dM/de values on individual OIM measured grains or orientations, irrespective of
deformation.

(4) An explanation for the ‘selective’ appearance of the 37° bands was found in the framework of negative textural
softening (dM/de). Though absolute values of the Taylor factor did not necessarily guarantee the appearance of 37°
bands, in all cases negative dM/de did correspond to visible appearance of such bands.

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