Influence of Hot Deformation Conditions on the Annealing Behaviour of Cold Rolled Ultra Low Carbon Steel

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An ultra low carbon (ULC) steel has been deformed in plane strain compression (PSC) using a Gleeble 3500 thermal and mechanical simulator followed by cold rolling and annealing (CRA). Multiple-pass deformation was used to simulate conditions encountered during hot rolling and to study the effect of finish deformation temperature (FDT) on microstructural development during CRA. It was found that a range of ferrite microstructures were produced when FDT decreased from 920 to 600°C, a temperature range which encompasses both austenite (γ) and ferrite (α) deformation. For FDT > 870°C, fine equiaxed ferrite was produced, whereas FDT ~ 850°C produced a coarse-grained microstructure. As FDT was decreased below 850°C, as-deformed ferrite remained with a decreasing propensity for the formation of statically recrystallized grains. At higher FDT, the γ-to-α transformation produced a hot-band texture consisting mainly of (001)(110), and at FDT below the critical transformation temperature the typical body centred cubic rolling texture also developed. Sections of the as-hot-deformed samples were cold rolled to 80% reduction and annealed at 650°C. It was found that the hot deformation microstructure has a strong influence both on the kinetics of recrystallization and texture development during CRA. In particular, a warm-deformed ferrite microstructure (lower FDT) recrystallized most rapidly to produce a strong (111)/ND recrystallization texture (γ-fibre), whereas an initial coarse-grained ferrite microstructure recrystallized most sluggishly to produce a strong (001)(110) texture. The implications of these results in the production of formable sheet steels is outlined.

KEY WORDS: hot deformation; cold rolling; recrystallization; texture; ULC steel.

1. Introduction

The development of microstructure and texture during annealing of low carbon (LC) and ultra low carbon (ULC) steels have been studied intensively with particular focus on the processing parameters: hot deformation temperature, cold reduction, annealing temperature and heating rate.1–10) Several investigations on the effect of hot-band microstructure on the annealing texture of cold-rolled strip have been undertaken using either annealed hot deformed steels,4,5) or employing higher finishing rolling temperatures followed by high temperature coiling to get fully recrystallized hot-bands.11) In both cases, it was found that the microstructure prior to cold rolling can significantly affect both the rolling and annealing textures of ULC interstitial free (IF) steels.10–16)

It has been shown that the hot-band microstructure can be influenced by pre-heating temperature, hot rolling schedule and coiling temperature (see eg. [1]). Among these, the finish deformation temperature (FDT) has been identified as an important parameter affecting grain structure and texture of the hot-band.1,10,17) The purpose of the present work is to study systematically the development of microstructure and texture of an ULC steel during deformation in both the austenitic and ferritic phase fields, and to correlate hot and warm deformed microstructures with the microstructure and texture that develops during cold rolling and annealing.

2. Experimental Procedure

2.1. Materials and Deformation Schedules

An as-cast ultra low carbon steel of composition (wt.%) 0.0036C, 0.03Ni, 0.019Mn, 0.03Al, 0.004Ti and 0.003N was supplied by BHP Steel for use in this study. Rectangular samples of dimensions $8 \times 20 \times 20$ mm were cut from the slab for use in a Gleeble™ 3500 thermal and mechanical simulator. This facility deforms samples in plane strain compression (PSC) and is capable of multiple-pass, high strain rate deformation thus closely simulating the conditions experienced during hot rolling. For example, a sample can be heated at a given rate to the desired ‘soaking’ temperature followed by a series of controlled cooling and high strain rate deformation stages for up to 15 deformation temperatures. After the final pass, the sample is cooled at any given rate to room temperature or held at an intermediate temperature to simulate coiling conditions following hot rolling.
For each sample, thin tantalum and graphite sheets were used as lubricant during PSC and temperature was controlled within 2° of the required temperature by a thermocouple spot welded to the mid-thickness of each sample. **Figure 1** shows the thermomechanical processing schedules used in this study. Each sample was heated initially to 1200°C and solution treated for 300 s, followed by controlled cooling to a temperature above 1000°C in which two deformation passes were carried out at true strain rates of 10 and 20 s\(^{-1}\) respectively to simulate rough-pass rolling. In an attempt to simulate finish rolling and to investigate the effect of FDT on microstructural development, three additional passes were applied at true strain rates of 50, 75, and 100 s\(^{-1}\) respectively at temperatures of 920 to 600°C. The as-deformed samples were subsequently cooled at a rate of 15°C/s to a ‘coiling’ temperature of 600°C, then air cooled to room temperature.

A section of each hot-deformed sample was prepared for microstructural investigation (hot ‘rolled’ state) while other sections were cold rolled to a true strain of 1.6 (80% reduction) in a two-high rolling mill (**Fig. 2**). To simulate continuous annealing, the cold-rolled samples were annealed in a salt bath for various times at 650°C. These series of deformation and annealing steps on the same specimen allows the unambiguous interpretation of the effect of hot-band microstructure on microstructural evolution both during cold rolling and annealing.

### 2.2. Microstructural Examination

The deformation and annealing procedures outlined in section 2.1 produce specimens suitable for both microstructural analysis and texture determination. The microstructures of hot deformed, cold rolled and annealed samples were observed on the polished and 2% Nital etched ND-RD sections using optical microscopy as shown in **Fig. 2**. The average grain size and volume fraction recrystallized, respectively, were determined at the mid-thickness of ND-RD sections by the standard ASTM linear intercept method and with the ASTM point counting technique using a 10×10 grid at 200× magnification.

The development of textures following PSC, cold rolling and annealing were determined by X-ray diffraction. For texture measurement, mid-thickness TD-RD sections were prepared by grinding, polishing and etching in 2% Nital solution. Four incomplete pole figures (\{110\}, \{200\}, \{112\} and \{310\}) were measured using Co K\(_\alpha\) radiation and orientation distribution functions (ODF’s) were evaluated using the Bunge series expansion method.

### 3. Results and Discussion

#### 3.1. Influence of FDT on Hot-band Microstructure and Texture

The microstructures that were produced following deformation at various FDT are shown in **Fig. 3**. More detailed information on the effect of FDT on the development of microstructure and texture are listed in **Table 1**. It may be seen that deformation at a FDT of 920°C produced fine, equiaxed ferrite (**Fig. 3a**), while coarse-grained ferrite was produced at a FDT of 850°C (**Fig. 3b**). As FDT was decreased below 850°C, deformed ferrite remained with a decreasing tendency to form strain-free grains as shown in **Fig. 3c and 3d**. These strain-free grains are likely to be result of static recrystallization (SRX) during slow cooling after the final deformation with the fraction recrystallized decreasing to zero at FDT below 720°C.

**Figure 4** shows flow stress and average ferrite grain size as a function of FDT. In this figure, flow stress represents the maximum stress achieved during the final finish pass and the grain size in the case of FDT below 850°C was measured in recrystallized regions. It can be seen that the minimum flow stress and largest grain size corresponds to the FDT of 850°C. The minimum in flow stress during the final pass at 850°C is probably due to the low strength of transformed ferrite and rapid dynamic recovery between passes. As FDT decreases, flow stress increases due to a decreasing propensity for dynamic recovery of warm-deformed ferrite.\(^6\)

The range of FDT investigated in this study is expected to span three regions:\(^9\) single-phase austenite (\(\gamma\)) above 900°C, single-phase ferrite (\(\alpha\)) below ~870°C, and two-phase \(\gamma+\alpha\) (~870–900°C). As summarised in **Table 1**, deformation at high temperature (\(\gamma\)) produces fine-grained
ferrite by transformation, whereas deformation at low temperature produces mainly (warm) deformed ferrite with some statically recrystallized regions. For final deformations carried out in the vicinity of the two-phase region, an extremely coarse-grained (>100 μm) microstructure is produced. It has been argued that coarse ferrite may form by grain boundary migration of newly transformed or recrystallized ferrite nuclei into the strained ferrite grains. It is clear that nucleation efficiency is low, which results in this type of microstructure. As FDT is decreased further, such as below 820°C, the nucleation of recrystallized grains becomes increasingly more difficult, which results in a de-
crease in the number of recrystallized grains in the as-deformed microstructure (Fig. 4).

The main texture components produced after hot deformation were taken from the ODF data (not shown) and summarised in Table 1. It is clear that FDT has a strong influence on the type of texture produced in the hot-band. For each deformed sample, the maximum intensity of the two dominant texture components: \(\{001\}<110>\) (rotated cube) and \(\{111\}//\text{ND}\) (\(\gamma\)-fibre) were extracted from the calculated ODF’s, and Fig. 5 shows this data plotted as a function of FDT. It can be seen from Fig. 5 that the strength of both texture components increases as FDT is decreased below 870°C. The sharp increase in the strength of \(\{001\}<110>\) and a minimum in strength of \(\{111\}//\text{ND}\) following FDT at 850–870°C coincides with the development of coarse-grained ferrite (Fig. 4). The trends observed in Fig. 5 are generally similar to those of Butrón-Guillén and Jonas\(^{10}\) on a similar steel, but rolled to 90% reduction during the final pass. It is worthwhile noting, however, that these workers did not observe coarse-grained ferrite in their final hot-rolled microstructures.

For FDT greater than 870°C, the hot-band texture was relatively weak (Fig. 5). Final deformation at a temperature well above \(A_r\) is expected to result in static recrystallization of the austenite to produce a considerable volume fraction of \(\{001\}\langle100\rangle\)-oriented grains.\(^{11}\) On subsequent cooling, ferrite grains nucleate mainly at grain boundaries and these grow coherently, according to the Kurdjumov–Sachs relation, to produce a final texture containing a small fraction of \(\{001\}\langle110\rangle\), \(\langle110\rangle\langle001\rangle\) and \(\langle011\rangle\langle110\rangle\) components,\(^{18}\) as observed in this work. However, deformation at 850°C produced a coarse-grained ferrite microstructure exhibiting a strong \(\{001\}\langle110\rangle\) texture (Fig. 5). It has been argued,\(^{17}\) that coarse ferrite is produced during deformation by a strain-induced boundary migration mechanism. However, the reason for the selective growth of certain ferrite grains to produce a coarse-grained microstructure with a moderate \(\{001\}\langle110\rangle\) texture remains unresolved. Further work in the vicinity of this critical temperature is underway to clarify the mechanism of formation of coarse-grained ferrite and its effect on hot-band texture development.

For FDT below 850°C, the final passes are within the ferritic region and as-recrystallized austenite (due to the high temperature roughing passes) transforms to equiaxed ferrite which is subsequently ‘warm’ deformed. Such warm deformation favours the development of the bcc rolling texture as a result of the development of a preferred orientation of the deformed ferrite.\(^{11}\) The strength of this ‘rolling’ texture increases with decrease in the amount of recrystallized ferrite and becomes essentially constant at FDT below 750°C (Fig. 5), which is similar to a previous rolling study.\(^{10}\)

### 3.2 Influence of FDT on Recrystallization after Cold Rolling

#### 3.2.1 Cold Rolling

Optical micrographs are given in Fig. 6 showing the deformed microstructures at three different FDT’s (920, 850
and 700°C) and after cold rolling to a true strain of 1.6 (80% reduction). A high FDT (920°C) produces equiaxed transformed ferrite, which, on subsequent cold rolling, results in the elongation and breakup of these grains (Fig. 6a). In this case, prior ferrite grain boundaries are resolvable and only a small fraction of deformed grains exhibit intragranular shear banding. At the intermediate FDT (850°C), the microstructure consists of coarse ferrite grains which, on subsequent cold rolling, elongate and develop a high density of intra-granular shear bands as shown in Fig. 6b. Cold deformation of the warm deformed microstructure (700°C) results in further elongation and fragmentation of the previously deformed ferrite grains as shown in Fig. 6c.

3.2.2. Annealing Behaviour

Figure 7 shows the progress of recrystallization of cold rolled specimens after FDT’s of 700°C (as-deformed ferrite) and 920°C (equiaxed ferrite) with annealing time. It can be seen that FDT has a significant influence on the sites for nucleation as well as the rate of recrystallization. The kinetics of recrystallization for the three FDT conditions that produced markedly different hot-band microstructures are shown in Fig. 8. A final deformation at either 700°C or 850°C results in the most rapid and sluggish recrystallization, respectively. It can be seen that the initial hot-band microstructure greatly affects the latter stages of recrystallization, with Fig. 9 schematically showing the time required to complete recrystallization as a function of FDT. This sluggish recrystallization behaviour is known to be a result of the orientation dependency of recrystallization, whereby some grains with stable orientations are deformed homogeneously and are therefore difficult to recrystallize.19 The overall kinetics behaviour observed in this study is similar to previous work17 with the recrystallization rate governed by hot-band grain size together with the additional stored energy associated with warm deformation. It is pertinent to note that, despite the marked differences both in the hot-band microstructures and recrystallization kinetics, similar recrystallized grain sizes of ~14 μm were produced after CRA, which indicates that the number of nucleation sites is large after cold rolling to 80% reduction.

Figure 10 shows ϕ₂=45° ODF sections in the fully recrystallized CRA samples following hot deformation at three significant FDT’s: (a) 920°C (fine, equiaxed ferrite), (b) 850°C (coarse ferrite) and (c) 600°C (warm deformed ferrite). The maximum intensity of the two most dominant CRA texture components, {001}<110> and {111}//ND, as a function of FDT are given in Fig. 11. It can be seen that the development of the strongest {111}//ND CRA texture is favoured when FDT is: (i) greater than 870°C (which pro-
duces fine-grained ferrite by transformation), and (ii) below ~800°C (which also produces fine-grained ferrite but with an additional true strain of 0.8 prior to cold rolling). In contrast, a coarse hot-band ferrite grain size (Fig. 4) results in the development of the weakest $\{111\}//ND$ CRA texture, but exhibits a strong $\{001\}^\langle110\rangle$ component due to copious nucleation of grains at shear bands, which is consistent with previous studies. The results herein indicate that FDT has a significant influence on the final texture after cold rolling and annealing and final rolling passes in the ferritic region (warm rolling) is a viable means of strengthening the $\{111\}//ND$ CRA texture which is the favourable texture in the production of formable ULC steel sheet.

3. Conclusions

The development of microstructure and texture in an ultra low carbon (ULC) steel has been investigated systematically during three stages of thermomechanical processing: hot deformation, cold rolling and annealing. It was found that:

- Finish deformation temperature (FDT) has a significant influence on microstructural development. For FDT $>850°C$, uniformly distributed, fine-grained ferrite ($\alpha$) is produced from transformed austenite ($\gamma$), whereas FDT $<800°C$ produces deformed $\alpha$. At an intermediate FDT ($850°C$), very coarse-grained ($>100\mu m$) $\alpha$ is produced possibly by strain-induced migration of $\alpha$ grain boundaries. A FDT in the $\gamma$ phase-field produces a strong $\{001\}^\langle110\rangle$ transformation texture, whereas deformation in the $\alpha$ phase-field develops the typical bcc rolling texture.

- FDT has a strong influence on the rate of recrystallization following cold rolling and annealing (CRA). Warm deformation (low FDT) produces as-strained $\alpha$ and, combined with the additional strain by cold rolling, results in rapid recrystallization. In contrast, coarse-grained $\alpha$ develops at an intermediate FDT and results in sluggish recrystallization, particularly in the latter stages of annealing.

- The strength of the $\{111\}//ND$ recrystallization texture (γ-fibre) after CRA correlates closely with hot deformation microstructure. The $\{111\}//ND$ CRA texture, which is the desirable texture in the production of formable steel sheet, is strongest following FDT either at high
temperatures in the $\gamma$ phase-field (> 870°C) or at low temperatures in the $\alpha$ phase-field (< 800°C). In contrast, the coarse-grained $\alpha$ produced after deformation in the vicinity of 850°C generates, after CRA, the less favourable $\{001\}$$\{110\}$ texture component.

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