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To cite this article: A. Kaijalainen et al 2018 IOP Conf. Ser.: Mater. Sci. Eng. 375 012026

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Development of crystallographic texture under plane and shear strain in ultrahigh-strength strip steels

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Abstract. The effect of centerline and subsurface microstructures on the crystallographic texture of three 8 mm thick low-alloyed hot-rolled and direct-quenched ultrahigh-strength strip steels with yield strengths in the range 800 – 1100 MPa has been investigated. Detailed microstructural features were studied using LCSM, FESEM, FESEM-EBSD. In addition textures and crystallographic features were analyzed using Matlab combined with MTEX software. Rolling to lower finish rolling temperatures increased austenite pancaking leading to the formation of ferritic/granular bainitic and the upper bainitic microstructures at the subsurface. In addition, increased austenite pancaking was found to increase the intensities of \{554\}<225>\alpha, \{112\}<110>\alpha and \{112\}<131>\alpha texture components at the centerline and \{112\}<111>\alpha and \{110\}<112>\alpha/<111>\alpha texture components in the surface layers, especially in upper bainitic microstructures. Parent austenite reconstruction shows that crystallographic texture at the centerline derived from \{112\}<111>\gamma and \{110\}<112>\gamma and the subsurface the shear texture components derived from the \{112\}<111>\gamma and \{110\}<112>\gamma, and the subsurface the shear texture components derived from the \{112\}<110>\gamma and \{111\}<112>\gamma components, as expected. The Matlab reconstruction code was found to work well for martensitic and upper bainitic morphologies even with the highly pancaked prior austenite structure. However, it was less precise for granular bainite and ferrite.

1. Introduction

As previous studies are shown [1,2], the microstructure and crystallographic texture of steel products is greatly influenced by the austenite morphology before phase transformation. Therefore, an understanding of prior austenite morphology is very important for microstructural control in high-strength steels.

The grain reconstruction method is commonly used with martensitic and bainite microstructures [3,4] that have transformed from equiaxed prior austenite with a Kurdjumov–Sachs (K–S) [5] or Nishiyama-Wasserman orientation relationship [6,7]. Furthermore, it is well-known that when austenite is deformed under plane strain conditions below its non-recrystallization temperature, a strong deformation texture develops, the main components of which are \{112\}<111>\gamma (Cu), \{110\}<112>\gamma (Br), and \{110\}<001>\gamma (Goss) as shown in Fig. 1a. The Cu component transforms primarily into \{112\}<110>\alpha, also known as “transformed Cu”, with a much smaller fraction appearing in the vicinity of the “rotated Goss” (\{110\}<110>\alpha) in Fig. 1a. Finally, the Br component transforms primarily into “transformed Br” located in the vicinity of \{111\}<112>\alpha and \{554\}<225>\alpha, with minor
amounts rotating to \{112\}<131>\alpha and \{100\}<011>\alpha in Fig. 1a [8,9]. Similarly, when austenite is deformed by rolling below its non-recrystallization temperature, there are shear texture components in the austenite close to the rolled surfaces, i.e., \{111\}<211>\gamma and \{112\}<110>\gamma. After cooling and transformation to ferrite these lead to the formation of shear components \{112\}<111>\alpha, \{110\}<112>\alpha and \{110\}<111>\alpha, respectively [10] as shown in Fig. 1b.

Therefore, the aim of this study is to use EBSD measurements to reconstruct the prior austenite grain morphology and crystallographic texture in the case of highly pancaked prior austenite to help understand the microstructural transformations that occur during cooling after hot rolling. Such studies can help elucidate the specific reason for the higher intensity of the \sim\{112\}<111>\alpha texture component found in upper bainite in direct quenched steels.

Figure 1. Texture changes resulting from \gamma to \alpha transformation in pancaked austenite as seen in the \phi_{2} = 45^\circ ODF section. (a) Austenite deformed under plane strain conditions, (b) shear-strained austenite.

2. Experimental

The influence of composition and hot rolling parameters on the subsurface microstructure, texture and bendability in various Nb-microalloyed steels having yield strengths in the range 800 – 1100 MPa containing was investigated using hot rolling experiments. The chemical compositions of the steels are given in Table 1. In these experiments, a 210 mm thick continuously cast slab was reheated at 1250 °C and thermomechanically controlled rolled to a final thickness (t) of 8 mm and direct quenched to room temperature at a rate of about 50-70 °C/s. In all, 14 strips were produced with different subsurface microstructures by varying the finish rolling temperatures (FRT) to 920 °C, 880 °C, 840 °C, 820 °C and 800 °C. Each strip was coded according to its chemical composition (A-C) and the finish rolling temperature (920-800).

Table 1. Chemical composition of the investigated steels in weight percent.

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Nb</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>B</th>
<th>Ti</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel A</td>
<td>0.065</td>
<td>1.4</td>
<td>0.2</td>
<td>0.04</td>
<td>1.0</td>
<td>0.02</td>
<td>0.011</td>
<td>0.0013</td>
<td>0.023</td>
<td>0.03</td>
</tr>
<tr>
<td>Steel B</td>
<td>0.076</td>
<td>1.8</td>
<td>0.2</td>
<td>0.04</td>
<td>1.0</td>
<td>0.01</td>
<td>0.017</td>
<td>0.0015</td>
<td>0.021</td>
<td>0.04</td>
</tr>
<tr>
<td>Steel C</td>
<td>0.093</td>
<td>1.1</td>
<td>0.2</td>
<td>0.04</td>
<td>1.1</td>
<td>0.15</td>
<td>0.012</td>
<td>0.0013</td>
<td>0.021</td>
<td>0.04</td>
</tr>
</tbody>
</table>

The prior austenite grain structure was studied using a laser scanning confocal microscope (LSCM) after picric acid etching. General characterization of the transformation microstructures was performed on nital-etched specimens with a field emission scanning electron microscope (FESEM) (Ultra plus, Zeiss). Electron backscatter diffraction (EBSD) measurements (ODF texture) and analysis were
performed using the Oxford-HKL acquisition and analysis software. The FESEM for the EBSD measurements was operated at 10 kV and the step size was 0.2 μm.

In order to reveal the parent austenite grain structure and texture, the EBSD data was subjected to a reconstruction technique that employed Matlab supplemented with the MTEX texture and crystallography analysis toolbox [11]. Briefly, grain maps were initially assembled from the data sets with a grain boundary tolerance of 3-5 degrees. Subsequently, the parent austenite orientation map was reconstructed from this data with a two-step reconstruction algorithm. In the first step of the process, the orientation relationship between austenite and martensite was determined using Kurdjumov-Sachs orientation relationship (K-S OR) i.e. \{111\}_γ/\{110\}_α, <110>\gamma/\langle111\rangle\alpha. There are 4 \{111\}_γ planes which are parallel to a \{110\}_α plane and each \{111\}_γ plane contains 3 <110>, directions each of which is parallel to 2 <111>_α directions. Therefore, 24 different crystallographic variants of bcc structure (bainite/martensite) can form within one former fcc structure (parent austenite). Regarding the variant selection, according to the Morito et al. [12], 24 variants generated by the K-S OR have been classified into four packet groups. In a packet, all variants share the parallelism of the same close-packed planes. Each packet contains six variants with parallel direction relationships on the close-packed parallel planes. This approach has been done for all samples. Although the exact parallelism of planes and directions of the K-S OR cannot be observed in actual crystallographic measurements of martensite, the consistent variant labeling system by Morito et al. [12] has been used to successfully characterize a number of martensitic/bainitic microstructures with varying orientation relationships between fcc and bcc structure. In the second step, the grain map was divided into discrete clusters using the Markov clustering method [13] proposed by Gomes and Kestens [14]. The parent austenite orientation was then calculated for each cluster separately, resulting in a reconstructed orientation map. The average misorientation between the reconstructed orientation for each cluster and the best fit for each individual grain was approximately 2 degrees, indicating a good fit for the reconstructed result. The full details for the reconstructed procedure are available in Ref. [15].

3. Results and discussion
The mechanical properties of the steels are given in Ref. [1]. The longitudinal yield stress (R_p0.2) and tensile strength (R_m) of studied steels vary in the ranges 793-1102 MPa and 933-1247 MPa, respectively.

General findings from the centerline microstructural characterization of the 14 strips can be summarized as follows: (1) a decrease in FRT increased the total reduction (R_tot) in the non-recrystallization (NRX) regime of austenite (i.e. pancaking) (in Fig. 2), (2) a decrease of FRT increased the incidence of granular bainite and ferrite at the expense of auto-tempered martensite and upper bainite. However, the microstructures at the centerline consisted of mostly auto-tempered martensite with some bainite. (3) Prior austenite pancaking increases the intensities of the ~{554}<225>_α, ~{112}<110>_α, and ~{112}<131>_α texture components (Figs. 4-6). More details of the effect of the thermomechanical rolling on prior austenite grain structure, transformation microstructure, texture, mechanical properties and microhardness are discussed in earlier papers [1,16]. The importance of the subsurface observations is discussed in more detail below.

Figure 2. LSCM images of prior austenite morphologies following etching with picric acid: Steel B with (a) 920 °C, (b) 820 °C FRT and (c) Steel C with 820 °C FRT at the centerline.
Specimens consisted of polygonal ferrite interspersed among other carbon-rich microstructural components down to ~50 μm from the surface. This microstructure is seen in Figs. 8 and 9 (bcc EBSD). In the layer from 50 μm to 400 μm, specimens with high FRT (above 880 °C) and Steel B920 mainly comprised upper bainite and martensite with a small fraction of granular bainite. In Steels A and C, with FRT below 840 °C, the subsurface was mainly granular bainite with some upper bainite and ferrite. A decrease of FRT increased the incidence of softer microstructures like ferrite and granular bainite. In addition, increased austenite panckaking increases the intensities of ~{112}<111>, and ~{110}<112>, {110}<111>, texture components in the surface layers. Fig. 3 summarizes the effect FRT on the intensity of the main texture components and microstructures at the centerline and the subsurface. In Fig. 3 the main microstructural components constituting more that 50% of the microstructure are indicated.

Figure 3. Effect of the finish rolling temperature on the intensity of the a) ~{554}<225> texture component at the centerline and b) ~{112}<111> texture component near the sheet surface in various microstructures. Symbols: ♦lath martensite, ●upper bainite, ▲granular bainite.

Figs. 4-6 and Figs. 7-9 present original EBSD maps (above) and reconstructed parent austenite maps (below) together with ODFs for the centerline and subsurface layer, respectively. The parent austenite reconstruction works well for martensite and upper bainite even in the case of highly pancaked prior austenite and a relatively large scanned area (Figs. 4, 5 and 7). However, in the case of granular bainite or even ferrite, the reconstructed grain map (Fig. 6) does not appear feasible due to the presence of intermittent grains and boundaries. Even the change of orientation relationship from K-S to Bain [17], Nishiyama-Wassermann [6,7] or Greninger-Troiano [18] for the austenite to granular bainite and ferrite transformations, cannot be reason for the intermittent grains, because the orientation relationships only differ from each other by a few degrees [8]. In the case of granular bainite, the problems in the reconstruction could be caused by errors in the Matlab code. In the case of polygonal ferrite, the reconstruction algorithm will not work as polygonal ferrite grows into the austenite grains with which it has no orientation relationship. Since, the similar the intermittent grain boundaries and unreconstructed polygonal ferrite can be seen in near surface (50 μm below from surface) in Fig. 8 and even lower from the sheet surface in Fig. 9.

The crystallographic texture at the centerline transformed from {111}<112>, {554}<225>, {112}<131>, and {100}<011>, to {112}<111>, and {110}<112>, as was presented schematically in Fig. 1a. Steel B with 820 °C FRT (Fig. 5) shows irregular transformation between ferrite to austenite texture, while the intense additional {112}<110>, texture component developed at the centerline. In subsurface EBSD measurements, the shear texture components {112}<111>, and {110}<112>, transformed to the {112}<110>, and {111}<112>, components in the parent...
austenite. Additionally, the \{111\}<112>, component can be seen in two locations, (111)[1-21] and (111)[-1-12], for symmetry reasons in the fcc $\phi_2=45^\circ$ ODF.

After austenite reconstruction from mainly martensitic microstructures (in Steel B 920 °C), the maximum texture intensities increased from 5.4 to 14.0 at the centerline and 3.0 to 3.7 in the subsurface layer. For upper and granular bainitic starting microstructures, on the other hand, reconstructed austenite texture intensities decreased. This phenomenon needs to be studied further with different types of orientation relationships as the basis of the reconstructions. Hence, the reasons for the extremely intense bcc texture seen in the mainly upper bainitic microstructures (Steel B 820 °C, in Figs. 5 and 8) cannot be explained by the present parent austenite reconstruction method. Even with the same finish rolling temperature and prior austenite pancaking, for Steel C FRT 820 °C, which consists of granular bainite, the texture intensities are much lower than those of the upper bainite in Steel B.

![Figure 4](image_url)

**Figure 4.** Centerline of Steel B with 920 °C FRT (martensitic). (above) Original EBSD band contrast map with high-angle boundaries (>15°) and IPF colored in the RD direction and bcc $\phi_2=45^\circ$ ODF and (below) reconstructed parent austenite grain map in Euler coloring and fcc $\phi_2=45^\circ$ ODF.

![Figure 5](image_url)

**Figure 5.** Centerline of Steel B with 820 °C FRT (martensitic). (above) Original EBSD band contrast map with high-angle boundaries (>15°) and IPF colored in the RD direction and bcc $\phi_2=45^\circ$ ODF and (below) reconstructed parent austenite grain map in Euler coloring and fcc $\phi_2=45^\circ$ ODF.
Figure 6. Centerline of Steel C with 820 °C FRT (upper/granular bainite). (above) Original EBSD band contrast map with high-angle boundaries and IPF colored in the RD direction and bcc $\phi_2=45^\circ$ ODF and (below) reconstructed parent austenite grain map in Euler coloring and fcc $\phi_2=45^\circ$ ODF.

Figure 7. Subsurface of Steel B with 920 °C FRT (martensitic). (above) Original EBSD band contrast map with high-angle boundaries (>15°) and IPF colored in the RD direction and bcc $\phi_2=45^\circ$ ODF and (below) reconstructed parent austenite grain map in Euler coloring and fcc $\phi_2=45^\circ$ ODF. On the left hand side is located surface of the strip.

Figure 8. Subsurface of Steel B with 820 °C FRT (upper bainitic). (above) Original EBSD band contrast map with high-angle boundaries (>15°) and IPF colored in the RD direction and bcc $\phi_2=45^\circ$ ODF and (below) reconstructed parent austenite grain map in Euler coloring and fcc $\phi_2=45^\circ$ ODF. On the left hand side is located surface of the strip.
4. Summary

The purpose of this research was to investigate the effect of various microstructures on the parent austenite reconstruction and crystallographic texture at the centerline and subsurface of hot-rolled and direct-quenched ultrahigh-strength steels. The main observations and conclusions of the work can be summarized as follows:

- An increase in the total reduction in the non-recrystallization temperature region in conjunction with a lowering of the finishing rolling temperature (FRT) increased austenite pancaking.
- A decrease of FRT increased the formation of softer microstructures such as ferrite and granular bainite in the subsurface layers. At high FRTs, the microstructures at the centerline consisted mainly of auto-tempered martensite especially in the case of higher manganese content. Lowering FRT increased the fractions of granular bainite and ferrite at the expense of martensite and upper bainite in both the central and subsurface parts of the strip thickness.
- Prior austenite pancaking increases the intensities of the plane strain \(~\{554\}<225>_{\alpha}\), \(~\{112\}<110>_{\alpha}\) and \(~\{112\}<131>_{\alpha}\) texture components at the centerline and shear strain \(~\{112\}<111>_{\alpha}\) and \(~\{110\}<112>_{\alpha}\) texture components in the surface layers.
- The current Matlab reconstruction code works in martensitic and upper bainitic microstructures even with the highly pancaked prior austenite morphology, although not in granular bainite or ferritic microstructures. The code also generated the expected austenite crystallographic texture from the bcc textures.
- For martensitic microstructures, the maximum texture intensities increased after austenite reconstruction while the austenite reconstructed from upper and granular bainite had lower maximum texture intensities than the original bcc microstructures.
- No explanation has been found for why upper bainite shows more intense texture than granular bainite even with same prior austenite pancaking.

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