Crystallographic Texture of Warm Caliber-rolled Low Carbon Steel

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The evolution of crystallographic texture with effective strain up to 5.9 is studied in low carbon steel bars fabricated using multi-pass warm caliber rolling. Three-dimensional finite element analysis was carried out to evaluate distributions of effective strain accumulated and strain components introduced with each pass through the rolled bars. The texture at characteristic deformation sites on the cross section in the bars was analyzed using the electron back-scattered diffraction method. Although the texture in the area around the center is dominated by a strong \( \alpha \)-fiber texture, in the other two areas, an \( \alpha \)-fiber texture is not produced. It is clarified that this difference depends on three deformation modes during rolling. Consequently, the areas around the corners, where effective strain of over 5.7 is introduced, are filled with ultrafine ferrite grains of below 680\( \mu \)m, and the texture in the areas is random regardless of the increase of the effective strain under a bi-directional simple compressive condition. [doi:10.2320/matertrans.MA200703]

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1. Introduction

Grain refinement in metallic materials brings about a dramatic improvement in yield strength with a simultaneous increase in toughness without the addition of alloying elements. The plastic deformation is used not only to achieve the required shape but also to impart the desired changes in the microstructure and properties. In particular, the effective strain, \( \varepsilon_{eq} \), introduced in materials by plastic deformation is as important a factor as the working temperature for creating ultrafine-grained (UFG) structures. Since the increase of \( \varepsilon_{eq} \) leads to an enhanced rate of grain refinement, severe plastic deformation (SPD) techniques have been proposed, e.g. equal channel angular pressing (ECAP), accumulative roll-bonding (ARB) and multidirectional deformation (MDD), and the microstructures and mechanical properties of bulk UFG materials fabricated through these techniques have been studied in detail.\(^{1-8}\)

The refinement of crystal grains in plain carbon steel, whose microstructure conventionally consists of ferrite grains and pearlite colonies, is greatly desired because it is the most useful structural material. To achieve ferrite grain refinement in steel, there are mainly two potential routes, the transformation route and the recrystallization (or dynamic recovery) route.\(^{9}\) The former route is the refinement of ferrite transformed from deformed and unrecrystallized austenite. Here, the main purpose of SPD is to increase the density of ferrite nucleation sites. The grain size of ferrite becomes finer with an increase in the strain, \( \varepsilon_{eq} \), and it becomes constant at the strain range of \( \varepsilon_{eq} \geq 2.5 \) regardless of the deformation temperature and the strain rate.\(^{10,11}\) The latter route is the refinement from heavily deformed ferrite accomplished by dynamic recovery occurring at warm working temperatures. Here, the purpose of SPD is to spread the area of the UFG structures into materials. The grain size of ferrite depends on the temperatures and strain rates, i.e., Zener-Hollomon parameter (Z-H parameter), and it becomes finer with increasing the Z-H parameter.\(^{12,13}\) In the former case, the limit of refinement is approximately 2 or 3\( \mu \)m, and, in the latter case, ferrite grains with a size in the hundreds of nanometer are obtained.\(^{3,6,12,13}\) Accordingly, for obtaining fine ferrite grains of 1\( \mu \)m and below, the latter route is applicable. In the case of the recrystallization route, the development of texture would strongly depend on deformation mode (or strain path) because the austenite-ferrite transformation is not utilized. Numerous investigations on the microstructural evolution of UFG ferrite and the production of bulk UFG steels have been conducted. However, the development of texture by introducing strain, \( \varepsilon_{eq} \), using multi-pass SPD processes and the effect of deformation mode on the texture have not been reported systematically.

In this paper, the evolution of crystallographic texture with the effective strain, \( \varepsilon_{eq} \), predicted by three-dimensional finite element analysis (FE analysis) is studied in low carbon steel bars fabricated using a multi-pass warm caliber rolling process. The texture at characteristic deformation sites selected from FE results on the cross section in the rolled bars is analyzed using the electron back-scattered diffraction (EBSD) method. The effect of the deformation mode on the relation between the development of micro-texture and \( \varepsilon_{eq} \) at these sites is discussed.

2. Experimental

A two-high caliber rolling simulator\(^{14}\) with a groove from 40.0 to 7.9 mm square was used in this work. The roll diameter was 368 mm, and the rolling speed was set to be 26 rpm. Figure 1 shows an SM490 steel (0.15C-0.3Si-1.5Mn-0.01P-0.002S) bar of 24 mm square with a ferrite (approximately 20\( \mu \)m)-pearlite microstructure prepared as an initial specimen. The rolling experiments were conducted for square-square passes with a conventional groove shape. The workpiece was soaked at a warm temperature of 773 K for 3600 s to homogenize the temperature and subjected to the rolling simulator. Number of passes was determined according to the strain predicted from FE analysis. The reduction direction was changed in increments of 90\( ^\circ \) by rotating the workpiece a one-quarter turn in each pass. The workpiece was passed through twice for the final groove to control the cross-sectional shape. The workpiece passed through the final groove was immediately water-quenched.
The measurement of the grain boundary misorientation was carried out using the EBSD method with a Schottky type scanning electron microscope (SEM) operated at 15 kV.

3. Numerical Procedure

In the numerical analysis, the FE-code ABAQUS/Explicit ver. 6.2 was employed. The workpiece was assumed to be isotropic and homogeneous, and the roll was regarded as a rigid body. The 8-node linear element was used for the workpiece, and the finite element mesh in the workpiece included 25215 nodes and 22880 elements, as illustrated in Fig. 2. To investigate the difference in the deformation mode at the local site, five elements, the center, quarter, corner-1, corner-2, and side, were selected as characteristic deformation sites. The stress-strain relationships depending on the strain rate and temperature employed in the analysis were measured experimentally by the compression test of a cylindrical specimen. The Coulomb condition with a friction coefficient of 0.3 was used as the frictional condition on the contacting planes between the roll and the workpiece. Furthermore, the roll diameter and the rolling speed were the same, 368 mm and 26 rpm, as those in the experiments.

4. Results and Discussion

4.1 Strain distribution predicted from finite element analysis

Figure 3 shows the contour maps of the accumulative effective strain, \( \varepsilon_{eq} \), predicted by FE analysis after the workpiece was passed through square grooves of 23.5 to 15.8 mm (6-pass), 12.9 mm (8-pass), and 7.9 mm (13-pass) at 773 K and the distributions of \( \varepsilon_{eq} \) in each direction. Note that the final compressive direction corresponds to the y-direction in all cross-sectional shapes shown in this paper. Strain, \( \varepsilon_{eq} \), of 1.2 and above is introduced all over the workpiece, and \( \varepsilon_{eq} \) becomes larger with increasing the number of passes, i.e., the nominal reduction in area, \( r (\%) \). The \( \varepsilon_{eq} \) tends to concentrate around the four corners, and the difference between the strains of the center and the corners becomes larger as the number of passes increases. After the 6-pass rolling corresponding to the nominal reduction in area \( r = 57\% \), \( \varepsilon_{eq} \) of 1.3 is introduced around the center, and maximum strain of 2.2 is introduced around the corners in the y-direction. After the 8-pass rolling corresponding to \( r = 71\% \), \( \varepsilon_{eq} \) around the center is approximately 1.9, and the maximum strain of 3.4 is introduced around the corners in the y-direction. After the 13-pass rolling to \( r = 89\% \), strain larger than 3.2 is introduced all over the workpiece, and the strains introduced to the center, corners in the y-direction, and corners in the z-direction are 3.5, 5.7, and 5.9, respectively. Figure 3 shows that the strain, \( \varepsilon_{eq} \), introduced by warm caliber rolling has a distribution with the maximum around the corners of the workpiece, and \( \varepsilon_{eq} \) is almost homogeneous toward the four sides from the center. Figure 4 shows the variations in \( \varepsilon_{eq} \) with the number of passes on five elements, the center, quarter, corner-1, side, and corner-2, as shown in Fig. 2. In the case of the 13-pass rolling, the elements of corner-1 and corner-2 correspond to the corners in the y-direction and z-direction, respectively. In Fig. 4, the broken line represents the strain calculated simply from changes in the groove shape viz. \(- \ln(1 - r/100)\). It is noteworthy that \( \varepsilon_{eq} \) predicted by FE analysis is larger than the strain calculated simply from the shape change. For this reason, two effects of the lateral spread\(^{14}\) in the z-direction in each pass and friction are considered. As mentioned previously, the workpiece is rotated by 90° with every passing. Therefore, by the effect of the lateral spread the imposed strain becomes so much larger than the value calculated from the shape change that its effect is not considered. In particular, around the corners after
9-pass rolling, the strain predicted is more than 2.5 times larger than the value obtained simply from the shape change.

4.2 Effect of the deformation mode on texture formation

4.2.1 Textures

Figures 5, 6 and 7 present the crystallographic orientation distribution of characteristic sites (center, quarter, corner and side) and corresponding inverse pole figures (IPFs) for the 6-pass, 8-pass and 13-pass rolled bars, respectively. Here, the x-direction and the y-direction (the final compressive direction) correspond to the RD direction and the ND direction, respectively. In addition, Figure 8 shows the variation of the integrated fraction with the tolerance angle on the characteristic orientations of the α-fiber (RD // (101) fiber), RD // (113), the γ-fiber (ND // (111)), and ND // (101), which is one of the main components of the shear texture of bcc metals.\textsuperscript{15,16} at the four sites of the 13-pass rolled bar. At the sites of the center and quarter in the y-direction (Figs. 5(a,b), 6(a,b), 7(a,b)) and the site of quarter in the z-direction (Fig. 7(e)), the orientation images of the RD direction show ferrite grain colonies (region indicated by a green color system) with {101} parallel to the cross section of the bars. The ferrite grains represent the preferred orientations along the RD, i.e., mainly the \( h101i \) crystal orientations spreading to the \( h113i \) and \( h001i \) directions, regardless of the strain, \( \varepsilon_{eq} \). It can be seen from Fig. 8(a), (b) that a strong \( /C11 \)-fiber texture is produced at these sites. At the sites of the corners in the y-direction (Figs. 5(c), 6(c), 7(c)) and in the z-direction (Fig. 7(f)), the texture is clearly different from that at the sites of the center and quarter, and it is almost random regardless of the range of the strain, from 2.2 to 5.9. Hence, the strong α-fiber texture as seen at the sites of the center and quarter, is not produced around the corners (see Fig. 8(c)). In addition, the shear texture, ND // (101), as seen around the plate surface in the sheet rolling, is not produced. At sites s7.9-coy and s7.9-coz where large \( \varepsilon_{eq} \) of over 5.7 is introduced, a significant number of fine equiaxed grains below 1\,\mu m were formed with the fraction of HAGB,\textsuperscript{17} and, at this time, the average grain sizes at sites s7.9-coy and s7.9-coz were approximately 680\,\mu m and 650\,\mu m, respectively. The microstructure at site s7.9-coy shown in Fig. 7(c) seems to be elongated in the z-direction in
Fig. 5  Orientation maps along the rolling direction (RD) and inverse pole figures in RD and in the normal direction (ND) for four sites; (a) s15.8-cen, (b) s15.8-quy, (c) s15.8-coy and (d) s15.8-side, in 15.8 mm square bar after 6-pass rolling.

Fig. 6  Orientation maps along the rolling direction (RD) and inverse pole figures in RD and in the normal direction (ND) for four sites; (a) s12.9-cen, (b) s12.9-quy, (c) s12.9-coy and (d) s12.9-side, in 12.9 mm square bar after 8-pass rolling.
comparison with that at site s7.9-coz shown in Fig. 7(f). This indicated that the effect of the final pass strongly remains. On the other hand, at the sites of the side in the yz-direction (Figs. 5(d), 6(d), 7(d)), the texture at sites s15.8-side and s12.9-side is random in comparison with that at sites s15.8-cen and s12.9-cen. However, as the strain increases, the ferrite grains represent the preferred orientations of \( \text{RD} = \{113\} \). It can be seen from Fig. 8(d) that the \( \text{RD} = \{113\} \) texture is produced at site s7.9-side. Furthermore, Figure 8 shows that the \( \gamma \)-fiber texture, which is typical of recrystallized rolled ferritic steels, and the ND \( \{101\} \) fiber, which is a shear texture, do not appear in the present caliber rolling. This means that the structural changes during severe deformations at warm working temperatures are associated with the strain-induced continuous reaction and that no large shear deformation, as is usually observed in sheet rolling, is introduced near the surface in a caliber-rolled bar.

### 4.2.2 Deformation mode

It is noted from Figs. 5–8 that the developed micro-texture strongly depends on the site on the cross section in the rolled bars. In low carbon steels under plane strain-warm compression testing, as shown in some literatures, the crystallographic texture is characterized by a strong \( \alpha \)-fiber. Similarly, even if such steel is compressed alternately from two directions, such as in the caliber rolling, the \( \alpha \)-fiber texture is produced around center and quarter. However, the texture around the corner is random regardless of the strain. In other words, in the present caliber rolling, the site related to the evolution of the texture can be classified into three areas.

As is well known, the evolution of texture is related to the deformation mode, e.g., the plane strain condition, the simple compressive condition, and the simple shear condition. Therefore, the difference in texture classified into three areas might be brought about by the deformation mode. Figure 9 shows the variations of the strain increment predicted by the FE analysis at five characteristic sites in the 13-pass rolled bar. These strain histories were obtained from the results of strain components in five elements.
corresponding to the center, quarter, corner-1,-2, and side, shown in Fig. 2. Here, $\Delta \varepsilon_1$, $\Delta \varepsilon_2$, and $\Delta \varepsilon_3$ ($\Delta \varepsilon_1 < \Delta \varepsilon_2 < \Delta \varepsilon_3$ and $\Delta \varepsilon_1 + \Delta \varepsilon_2 + \Delta \varepsilon_3 = 0$) denote the minimum, intermediate and maximum principal strains introduced in each pass, respectively. Furthermore, at site s7.9-side, the maximum principal strain $\Delta \varepsilon_3$ corresponds to a strain increment in the x-direction (RD) for all passes.

Based on Fig. 9, at the site of the center, s7.9-cen, the strain increments have a relation of $\varepsilon_{eq}$ = 3.5. However, in the area toward the four sides from the center, the deformed original grains remained, and the texture at the deformed original grains retained, and the texture at the deformed original grains remained. At the site of the quarter (s7.9-quy), the intermediate and maximum principal strains introduced in each pass, respectively. Furthermore, at site s7.9-side, the maximum principal strain $\Delta \varepsilon_3$ corresponds to a strain increment in the x-direction (RD) for all passes.

In the present warm caliber rolling, the area around four corners in the 13-pass rolled bar (nominal reduction $r = 89\%$) was filled with ultrafine ferrite grains with a large misorientation, and the texture in the area was random. However, in the area toward the four sides from the center, the deformed original grains remained, and the texture at the sites of the center and side was dominated by $\alpha$-fiber and RD // (113), respectively. Although ultrafine grains can be formed in the whole area by increasing the total reduction in area, it is more important for process development to design a groove shape where a large strain of 5.7 or above can be introduced to the center with the required deformation mode by using numerical analysis.

5. Conclusions

The effect of the deformation mode on the crystallographic texture with the effective strain $\varepsilon_{eq}$ predicted by threedimensional finite element analysis is studied in ultrafine-grained C-Mn steel bars fabricated through multi-pass warm caliber (square-square) rolling. The basic results and conclusions are given in the following:

![Figure 8](image-url)
In warm caliber rolling which is one of the multi-pass deformation processes for fabricating UFG materials, the effective strain $\varepsilon_{eq}$ has a distribution with the maximum around corners. The $\varepsilon_{eq}$ predicted by the FE analysis is much larger than the strain calculated simply from a reduction in area, $r$; for example, strain in the range of $1.9 < \varepsilon_{eq} < 3.3$ is introduced when $r = 71\%$, and strain of $3.3 < \varepsilon_{eq} < 5.9$ is introduced when $r = 89\%$.

In the warm caliber rolling process, the deformation introduced into materials is classified into three kinds of modes, the bi-directional plane strain condition, the bi-directional simple compressive condition, and the simple tensile condition. At areas around the center and quarter, the texture is dominated by $\alpha$-fiber (RD // (101)) regardless of $\varepsilon_{eq}$ under the bi-directional plane strain condition; at the area around the side, it is dominated by RD // (113) with increasing $\varepsilon_{eq}$ under the simple tensile condition. At areas around the corners, the texture has no preferred orientation regardless of $\varepsilon_{eq}$, i.e., the texture is randomized under the bi-directional simple compressive condition.

The area around four corners where $\varepsilon_{eq}$ of over 5.7 was introduced was filled with ultrafine ferrite grains smaller than 680 nm, and its texture was random.

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(a) Bi-directional plane strain condition

\[
\begin{align*}
\Delta \varepsilon_1 &= 0 \\
\Delta \varepsilon_2 &= 0 \\
\Delta \varepsilon_3 &< 0
\end{align*}
\]

(b) Bi-directional simple compressive condition

\[
\begin{align*}
\Delta \varepsilon_1 &= < 0 \\
\Delta \varepsilon_2 &= \Delta \varepsilon_3 > 0
\end{align*}
\]

(c) Simple tensile condition

\[
\begin{align*}
\Delta \varepsilon_2 &= \Delta \varepsilon_3 < 0 \\
\Delta \varepsilon_1 &= > 0
\end{align*}
\]

Fig. 10 Schematic illustration of three kinds of deformation modes; (a) bi-directional plane strain condition, (b) bi-directional simple compressive condition and (c) simple tensile condition, seen on cross section of caliber-rolled bar and corresponding inverse pole figures in the rolling direction (RD).

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