Effect of Simple Shear Deformation Prior to Cold Rolling on Texture and Ridging of 16% Cr Ferritic Stainless Steel Sheets

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The effect of simple shear deformation by equal-channel angular pressing (ECAP) for one pass on the texture and ridging of ferritic stainless steel sheets with 16 mass% chromium has been investigated. Hot rolled and annealed sheets of 4 mm thickness were ECA-pressed for one pass, prior to cold rolling and final annealing. It was found that grains were subdivided by grain-scale heterogeneous plastic deformation, namely, deformation bands, during simple shear by ECAP. Deformation bands appear to contribute to the fragmenting layered structure after cold rolling and facilitate recrystallization of the so-called colonies having \((hkl)(110)\) texture, which are otherwise difficult to recrystallize in final annealing. In other words, strain energy can be stored more effectively by combining simple shear and cold rolling than by cold rolling alone. Recrystallization occurred at a much lower temperature in the process including ECAP than in a conventional cold-rolling only process, replacing colonized \((hkl)(110)\) grains with more favorable \((111)(hkl)\) grains, thus enhancing its formability and reducing ridging.

KEY WORDS: simple shear; equal channel angular pressing; ridging; texture; ferritic stainless steel.

1. Introduction

Ferritic stainless steel sheets are very attractive with high corrosion resistance and high formability, and they can potentially replace high-cost Ni-containing austenitic stainless steel sheets. However, they exhibit ridging when the sheets are subjected to tensile plastic strain in the rolling direction. The ridging is a kind of rumple, and should be eliminated for good appearance and further formability. The ridging formation mechanism is not completely clarified yet, but several proposed mechanisms agree in that ridging is caused by anisotropic plastic strain in the rolling direction. The ridging is converted into large and highly elongated bands with sharp texture. Hot and cold-rolled texture, especially the \(\{100\}\)\{011\} orientation, is very stable and stores less energy as dislocations during cold rolling. Thus, it is very difficult to recrystallize, and tends to remain as a colony until the final product. They undermine the formability of a sheet, such as deep drawing; thus eliminating the colonies could result in alleviating the ridging and enhancing formability. Alleviation of ridging has been attempted by several approaches, such as modifying the chemical composition, electromagnetic stirring during continuous casting to refine grain size, thermo-mechanical processing, intermediate annealing between cold rolling, and changing the strain path by a unique deformation such as spread rolling. With the advent of electron-back scattering diffraction (EBSD), it has become faster and easier for researchers to measure macro- and micro-texture along with the spatial distribution of crystallographic orientation. We can thus relate more precisely the formation of ridging with the texture.

Equal-channel angular pressing (ECAP) is one severe plastic deformation (SPD) that emerged as a new process for fabricating bulk ultrafine grained (UFG) or nanocrystalline materials. Various metallic materials such as copper and aluminium can be fragmented into an ultrafine grain size after six to eight passes. Compared with other SPD, such as high-pressure torsion (HPT) etc., ECAP has fewer limitations in the shape and size of materials, and it can potentially be applied to structural applications. Additionally, ECAP can be designed for a continuous process and combined with other processing such as cold-rolling. In our previous studies, we found that dense deformation twins and micro-shear bands with local orientation splitting formed in copper during ECAP by one pass. Since activation of slip is limited to slip systems nearly parallel to the macroscopic shear plane, strain hard-
ening tends to be suppressed, resulting in heterogeneous plasticity as a plastic instability. The present authors applied ECAP, which has been mostly applied for billets, to ferritic stainless sheets prior to cold rolling, and demonstrated that the combination of ECAP and cold rolling has a favourable effect for alleviating ridging.\(^{30}\) There have been several reports on the microstructures and mechanical properties of UFG metals processed by the combinations of ECAP and cold rolling.\(^{31\text{-}35}\) Most of them reported that post-ECAP cold-rolling modifies the UFG structures, and have favourable effect on the strength\(^{31,32}\) and superplastic deformation.\(^{33\text{-}35}\) In our study, however, the objective of ECAP is to control the texture and recrystallization by introducing deformation bands prior to cold rolling. Following our previous results,\(^{29,30}\) we further examined the effect of intense simple shear deformation by ECAP for one pass prior to cold rolling in more detail. We focused the role of grain-scale heterogeneous structures, such as deformation bands introduced by ECAP, on the cold-rolled and recrystallized textures and microstructures.

2. Experimental

Hot-rolled sheets of 16% Cr ferritic stainless steel with a thickness of 4.0 mm were fabricated in a conventional industrial plant. The chemical composition is shown in Table 1. They were annealed at 880°C for 10 min in a laboratory furnace. Then, they were ECA-pressed for one pass followed by cold-rolling to a final thickness of 0.6 mm and final annealing at 880°C for 30 s. The die for ECAP has a channel angle of 120°. A schematic diagram and a photo of the ECAP-die designed for processing sheets are shown in Fig. 1. In order to compare with a conventional process, some sheets were cold-rolled without ECAP. Ridging was evaluated after straining in tension by 20% in the rolling direction. For the Lankford values (\(r\)-values) measurement, tensile tests were performed at angles of 0, 45, and 90° to the rolling direction. Microstructures were observed by an optical micrograph and a transmission electron microscope (TEM, JEOL JEM2100F). Macro-textures were determined by means of conventional X-ray analysis. From incomplete pole-figures measured in back-reflection, orientation distribution functions (ODF) were calculated. Micro-texture and spatial orientation distribution were measured by a JEOL JSM-7001 scanning electron microscope with a Schottky field emission gun (FE-SEM) equipped with an EBSD detector from Oxford Instruments.

3. Results

3.1. Microstructure after ECAP and Cold Rolling

Microstructures after hot strip annealing, ECAP and cold rolling were observed by optical microscopy from the TD direction, as shown in Fig. 2. After hot strip annealing, the microstructure appears to be a recrystallized structure with some elongation in the rolling direction. However, there are large and highly elongated bands with a similar crystallo-

| C   | Si  | Mn  | P   | S   | Cr  | Ti  | N   |
|-----|-----|-----|-----|-----|-----|-----|-----|
| 0.004 | 0.12 | 0.12 | 0.025 | 0.001 | 16.1 | 0.28 | 0.010 |

Fig. 1. (a) Schematic diagram of ECAP process, and (b) photo of ECA-die.

Fig. 2. Optical microstructures after hot strip annealing, ECAP, and cold rolling, in conventional and ECAP processes.
graphic orientation, which, during hot rolling, were converted from the columnar grain structures of the as-cast slab. These bands usually transform into grain colonies with a similar orientation during recrystallization in hot strip annealing. After ECAP for one pass, deformation bands nearly parallel to the shear plane were observed inside a number of grains. As shown later, EBSD measurement revealed that these deformation bands accompany the local orientation splitting from the embedding matrix. After cold-rolling, layered structures parallel to the plane were observed in both conventional and ECAP processes. Most importantly, however, these layers of the ECAP process are obviously finer than those of the conventional process. As is discussed later, it is suggested that grain fragmentation by these deformation bands during ECAP may contribute to the fragmentation into finer-layered structures during cold rolling. Figure 3 shows the TEM microstructure after hot strip annealing and ECAP. In contrast with annealed grains in Fig. 3(a), one can see deformed structures of high dislocation density as shown in Fig. 3(b); the photo shows the region between a deformation band and an embedding grain as indicated by arrows. The region consists of clustered so-called microbands with a thickness smaller than 1 μm parallel to the shear plane. In this region, orientation is scattered as indicated by the selected area diffraction pattern, and might change from a band to embedding grains.

3.2. Texture

Textures after each process were represented by ODF by Euler-angle space sectioned at \( \phi_2 = 45 \), as shown in Fig. 4. In the conventional process, the weak texture of hot-rolled sheets developed into a typical sharp texture with peak {112}⟨110⟩ and {111}⟨110⟩ orientation, which are components of the so-called \( \alpha \)-fiber having RD//⟨110⟩, and \( \gamma \)-fiber having ND//⟨111⟩. On the other hand, after ECAP, {113}⟨332⟩ and {011}⟨100⟩ orientations were recognized. These two unusual texture components can be considered to develop as a result of typical shear texture of bcc, namely, {110}⟨001⟩ and {112}⟨111⟩ being parallel to the macroscopic shear plane and shear direction of ECAP, respectively (Fig. 5). In the shear texture of bcc metals, a common (111) become parallel to the shear direction, and {110} become parallel to the shear plane. After cold rolling, the two ODFs seem quite similar, but close examination reveals some differences; \( \alpha \)-fiber components become sharper, while \( \gamma \)-fiber components become weaker in the ECAP process compared with that in the conventional process. It is probable that the fraction of orientation developed in ECAP, for example, the dominant {113}⟨332⟩, rotated to {100}⟨011⟩ and vicinity during cold rolling, and this possibility is discussed later. Such a difference in the rolled texture between the conventional and ECAP processes suggests that the orientation developed in ECAP was not cancelled by the succeeding cold rolling. After final annealing, however, \( \gamma \)-fiber components, especially {334}⟨483⟩ and

![Fig. 3. TEM micrographs after (a) hot strip annealing, and (b) ECAP for 1 pass. Arrows indicate the interface between matrix and a deformation band (BD).](image-url)

![Fig. 4. ODFs of textures after each process. Represented by Euler-angle space \( \{ \phi_1, \phi, \phi_2 \} \) sectioned by \( \phi = 45 \).](image-url)
orientations, became sharper in the ECAP process than those in the conventional process. α-fiber orientations, which are otherwise difficult to recrystallize, were effectively replaced by γ-fiber components during recrystallization.

3.3. Spatial Distribution of Orientation after ECAP and Final Annealing

Orientation maps covering a large area of the cross section perpendicular to the TD were obtained by EBSD after hot annealing and ECAP, as shown in Fig. 6. The individual orientations are color coded according to their crystallographic direction along the ND, and the color code standard triangle is given below the figure. After hot strip annealing, several large grains having near ND//{100} orientations accounted for a high fraction of the measured area. These large {100} grains, if cold rolled, become hard-to-recrystallize banded structures and the origin of the colony. After ECAP, however, grains with a green color near ND//{110} increased, as is also indicated by ODF. A number of grains, especially large grains with reddish color near ND//{113}, as indicated by ODF in Fig. 4, have deformation bands with a different orientation from the embedding grains. In the example shown in Fig. 7, several {112} bands were formed inside the embedding reddish grains of possibly ND//{113}, as indicated by ODF.

Figure 8 shows orientation maps after final annealing measured on the plane normal to ND in half-through thickness. The color code again indicates the direction of ND. In the conventional process shown in Fig. 8(a), one can recognize band structures consisting of the colonies of grains with similar orientation near ND//{111} orientation indicated in blue, and those near ND//{100} by red, alternately. In each colony, a large number of low-angle boundaries are seen. In the ECAP process, these colonies were eliminated, and texture was rather randomized and dominated by {111} orientation as shown in Fig. 8(b).
3.4. Ridging and Formability of Cold-rolled and Annealed Sheets

Theoretical and experimental Lankford values (r-value) of 0°, 45° and 90° from rolling directions were compared as shown in Fig. 9. Theoretically values were calculated following the pioneering work of Kitagawa et al.,36) who calculate r-value from ODF, assuming that all slip systems whose Schmid factors were not less than a certain value were activated, and that an amount of slip in each slip system was proportional to its Schmid factor. Both experimental and calculated values become higher by the ECAP process than by the conventional process. This can be attributed to the higher components of γ-fiber in the ECAP process. Macroscopic appearances of ridging after 20% straining are shown in Fig. 10. The specimen in the ECAP process shows a smoother, yet not perfectly ridge-free, surface. Figure 11 shows the surface profiles of the two specimens. Evidently, the specimen by conventional process depicts a much rougher surface with an average roughness of Ra = 0.94 μm and a maximum roughness of Rt = 7.3 μm as opposed to Ra = 1.3 μm and Rm = 12.7 μm in the sheet by ECAP process. It is evident that ECAP before cold rolling is effective for alleviating ridging.

4. Discussion

4.1. Origin of Deformation Bands

The origin of deformation bands is not yet clarified. One possibility is that the deformation band as referred to in the usual sense, develops when neighboring volumes of a grain deform on different slip systems and rotate to different end rotation.37) When the regions between deformation bands, where the orientation changes from one to the other, have a finite width, they are called a transition band. The microbands shown in Fig. 3 might be part of a transition band. A transition band is therefore a region of a large orientation gradient that is an ideal site for recrystallization.38) The cold-rolled ND//[100] grains changed from the dominant ND//[113] grain embedding the deformation bands, and became easily recrystallized.

The second possibility is that this deformation band is a grain-scale shear band as a manifestation of plastic instability. In this case, it is also one form of deformation band, but is specifically called a micro-shear band. In ECAP, where simple shear deformation occurs in a very narrow region, limited slip systems tend to be activated parallel to the macroscopic shear plane and the shear direction of ECAP.29) With a limited slip system, material deforms with little strain hardening, accompanying plastic instability with strain localization. Thus, micro-shear bands tend to occur in ECAP as a manifestation of plastic instability.29)

4.2. Role of Deformation Bands on the Formation of Texture

Since the X-ray intensity of the main components in α- and γ-fibers was different between the two textures after cold rolling, it can reasonably be considered that the crystal orientation change caused by ECAP was not cancelled by the subsequent cold rolling. In other words, some fraction of the grains rotated to around {113}(332) and {110}(001) after ECAP were rotated to a different end orientation than those without ECAP. According to a study of single crystal experiments,39–42) {110}(001) rotated to a {111}(211) orientation during cold rolling, and {113}(332) to a {100}(011) orientation, while {112}(110) and {100}(011) remained unchanged. Therefore, {110}(001) grains and its vicinity, which are mostly green grains in the orientation map (Fig. 6(b)), possibly rotated to {111}(112) and γ-fiber, whereas {113}(110) grains embedding deformation bands possibly rotated to a {100}(011) orientation.

Since it is technically difficult to track the orientation change of small deformation bands embedded in a grain
during cold rolling, even using high-resolution EBSD, the components of the pressed deformation band in the cold-rolled textures are not identified. Taking the literature data into account,\textsuperscript{39–42} we can speculate, however, that deformation bands having ND//{112} embedded in near ND//{113} grains, as shown in Fig. 7, remain ND//{112} while embedding grains rotated to a dominant ND//{100} orientation. Therefore, after cold rolling, large elongated ND//{100} grains were fragmented by embedding elongated deformation bands as nucleation sites, and became easily recrystallized in the subsequent annealing.

4.3. Softening Behavior During Recrystallization

In order to verify the facilitation of recrystallization during final annealing by grain-scale heterogeneity introduced in ECAP, additional experiments were carried out. Three kinds of specimens were annealed by an infrared furnace (ULVAC MILA3000) at several intermediate temperatures from 600 to 1000°C to examine softening behavior. In Fig. 12, the first specimen, marked ECAP+CR with a square, was ECA-pressed and then cold rolled from 4 to 2.0 mm. According to Fukuno et al.,\textsuperscript{40} an equivalent strain, \(\varepsilon_{eq}\), given by ECAP, is about 0.6, and the sum of \(\varepsilon_{eq}\) is about 1.3. The second specimen, marked CR with a triangle, was cold rolled from 5.0 to 1.4 mm without ECAP. Rolling reduction in the second specimen was adjusted so that an equivalent strain \(\varepsilon_{eq}\) was equal to 1.3. The third specimen, marked CR with a circle, was also subjected to only cold rolling from 4 to 2 mm with the same reduction of the first one (\(\varepsilon_{eq}=0.7\)). The second specimen cold-rolled from 5 to 1.4 mm at a lower temperature than the cold-rolled specimen (4–2 mm) due to the higher reduction in cold rolling. Most importantly, however, the specimen marked ECAP+CR softened at a much lower temperature, namely about 100°C than the cold-rolled specimen in spite of the same equivalent strain. This indicates that by combining ECAP and cold rolling, more strain energy can be effectively stored as heterogeneous structures than by cold rolling alone. These heterogeneous structures serve as nucleation sites and facilitate the recrystallization of {100} grain colonies, which are otherwise difficult to recrystallize.

5. Conclusions

(1) Deformation bands were effectively introduced by ECAP for one pass prior to cold rolling. They have a different crystallographic orientation from the embedding grain. The origin of these bands is not clear, but regions between a band and the matrix consist of microbands with a high orientation gradient.

(2) Microstructures after cold rolling were typical layered structures for ferritic stainless steel. However, they were finer in the ECAP process than in the conventional one. The above-mentioned deformation bands elongate in the rolling direction, and contribute to the fragmentation of the layered structure.

(3) EBSD analysis revealed alternating bands having near {100} and {111} orientations in finally annealed sheets in the conventional process. In the process including ECAP, these bands were effectively eliminated, alleviating ridging.

(4) The recrystallization temperature was lower in the ECAP process by approximately 100°C. The combination of shear by ECAP and cold-rolling is effective for storing strain energy as a heterogeneous structure, thus, facilitating the recrystallization of the colony.

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