Texture Development and Formability of Strip Cast 17% Cr Ferritic Stainless Steel

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In order to optimize the formability of ferritic stainless steel (FSS), control of the crystallographic texture is essential. In the present work, texture development of cast strips with different initial solidification structure during rolling and subsequent annealing and the formability of final sheets were investigated. Fully equi-axed and columnar grained cast strips of Fe17%Cr FSS were fabricated by a pilot twin-roll strip caster. The equi-axed and columnar grained bars cut from a conventional continuous cast slab were used as comparable specimens. It was shown that in the cold rolled and annealed sheet of fully equi-axed cast strip, uniform and strong γ-fiber recrystallization texture was formed and {001}(110) component was almost eliminated. By contrast, the recrystallization texture in the conventional sheets with equi-axed and columnar initial solidification structures exhibited typical shift towards high-index (334)(483), which led to a reduced r-value as compared to that of the equi-axed cast strip. The final annealed sheet of fully columnar cast strip, however, showed weaker γ-fiber recrystallization texture and lower r-value than those of conventional sheets. It is, therefore, believed that twin-roll strip casting can improve the formability of 17% Cr FSS only under the precondition that appropriate solidification structure is obtained.

KEY WORDS: ferritic stainless steel; twin-roll strip casting; solidification structure; texture; formability.

1. Introduction

Ferritic stainless steel (FSS) is believed to be a reasonable replacement of austenitic stainless steels to save expensive element of Ni, and has found wide applications in kitchen wares, electrical appliances, automobile parts and construction materials due to its good corrosion resistance, high thermal conductivity and beautiful surface gloss.

Sheets of FSS are conventionally manufactured by continuous casting, hot rolling, pickling, cold rolling and annealing. However, the continuous cast slabs usually contain developed columnar grains with strong {001} texture parallel to the normal direction (ND), which leads to {001}(110) and {001}(010) textures in the hot rolled bands and cold rolled sheets. Furthermore, unlike in low carbon steel, FSS undergoes no or merely limited gamma-to-alpha phase transformation and recrystallization during hot rolling. Accordingly, the hot bands of FSS usually display pronounced textures and strong through-thickness gradients in both microstructure and texture, which deteriorates the deep drawability and surface quality of final cold rolled and annealed sheets.

Strip casting, a “near-net-shape” forming process to bypass hot rolling, is considered to be able to compete with sheet production with conventional continuous casting and thermo-mechanical processing. Extensive work on texture development of strip cast stainless steels has been carried out by Raabe and co-workers, which indicated that initial textures in the cast strip were nearly random and homogeneous through thickness. The final cold rolled and annealed sheet of strip cast FSS was also shown to exhibit good deep drawability, and could avoid surface ridging phenomenon.

However, by using a fast dip apparatus to simulate twin-roll strip casting, Hunter and Ferry indicated that columnar grains with sharp {001}/ND texture could be easily formed in cast strips of FSS, which could be detrimental to the formability of final sheets. Therefore, there are still inconsistencies regarding of the texture development in cast strips of FSS.

In our most recent work, we showed that cast strips of FSS with different solidification structures could be fabricated by carefully controlling processing parameters such as melt superheats. The fully equi-axed strip exhibited weak and random texture, and the columnar strip possessed strong {001}/ND fiber texture through the sheet thickness.

The evolutions of texture, microstructure and properties in cast strips during processing (cold rolling and annealing), therefore, still need to be further clarified in comparison with the conventionally processed FSS, because little work has so far been systematically performed to understand the texture development of strip cast FSS and its effect on the formability of final sheet.

In the present work, fully equi-axed and fully columnar strips of 17% Cr FSS were fabricated by using a pilot twin-roll strip caster. The texture developments of the two differ-
ent strips in cold rolling and annealing were studied. Equi-axed and columnar bars were cut from a continuous cast slab, and hot rolling, hot band annealing, cold rolling and final recrystallization annealing were performed for both bars to simulate the industrial processes. The texture developments of the two bars were also studied and compared with those of cast strips to understand the evolutions of microstructure, texture and properties in the cast strips.

2. Experimental Procedures

Fe17%Cr FSS with a composition of Cr, 16.9; Ni, 0.114; C, 0.03; Mn, 0.154; Si, 0.243; P, 0.016; S, 0.004 (in mass%) was used. Cast strips were produced by using a pilot twin-roll strip caster, in which the molten steel was poured into a preheated tundish under Ar shield to flow through a nozzle into the rotated water-cooled rolls. The casting speed was set up to be 0.25 m/s and the initial roll gap was set to be 1.5 mm to produce strips with thickness of about 1.8 mm. The pool melt temperature was measured by a thermo-detector installed above the melting pool. In the present work, pool melt superheats were controlled to be about 140 K and 20 K, respectively, to produce fully columnar and fully equi-axed cast strips, Fig. 1. The average diameters of columnar and equi-axed grains were about 400 μm and 200 μm, respectively. Both strips were cold rolled by using a laboratory rolling mill with a thickness reduction of 80%, and were annealed at 860°C for 2 min.

Columnar and equi-axed bars in the size of 250L×110 W×45 T (mm) were cut from a cast slab of Cr17 FSS, Fig. 2. The average diameters of columnar and equi-axed grains were about 7 mm and 2 mm, respectively. They were reheated to 1200°C, held for 2 h and hot rolled by five passes to a thickness of 3.5 mm by using a laboratory rolling mill. The hot rolled bands were annealed at 850°C for 3 h, with the average grain sizes being about 55 μm and 40 μm, respectively. They were cold rolled to the final thickness of 0.7 mm by ten passes with the total reduction of 80%. Finally, the cold rolled sheets were annealed at 860°C for 2 min.

After processing, specimens from longitudinal sections of the strips were prepared for electron backscatter diffraction (EBSD) analyses attached to a scanning electron microscope (SEM). Bulk texture analyses for the center layer of rolled and annealed samples were performed via the measurement of three incomplete pole figures {110}, {200} and {112} by using X-ray diffraction on a Philip PW3040/60 diffractometer with Co Kα radiation at 35 kV and 40 mA as an X-ray source. The textures were measured at the end of each process, denoted as cast strip (CS), hot-rolled and annealed (HRA), cold-rolled (CR), and cold-rolled and annealed (CRA). Bcc steels tend to develop two characteristic fiber textures (α-fiber and γ-fiber) during the various processing stages. It is thus convenient to represent relevant orientations and fibers on ϕ2 = 45° section of orientation distribution function (ODF), Fig. 3. The standard specimens at angles of 0, 45 and 90° to rolling direction (RD) were cut from the sheet, and tensile tests with these specimens were performed for the r-value measurements.

Fig. 1. Typical EBSD micrographs of 17% Cr FSS cast strips. (a) Fully columnar strip, (b) fully equi-axed strip, (c) color coded map type [001] inverse pole figure.

Fig. 2. Solidification structure of a continuous cast slab.

Fig. 3. φ2=45° section of the Euler space with locations of some important ideal orientations and fibers.
The $r$-value was determined as the ratio between the in-plane and the through-thickness strains, and the average $r$-value was calculated to be $r = (r_{0°} + 2r_{45°} + r_{90°})/4$.

3. Experimental Results

3.1. Texture Developments in the Columnar and Equi-axed Bars from Conventional Cast Slab

Figure 4 show the texture developments of columnar (a to c) and equi-axed (d to f) bars cut from conventional cast slab ($\phi_2=45°$). (a) and (d) HRA; (b) and (e) CR; (c) and (f) CRA.

The $r$-value was determined as the ratio between the in-plane and the through-thickness strains, and the average $r$-value was calculated to be $r = (r_{0°} + 2r_{45°} + r_{90°})/4$.

3.2. Texture Developments of Fully Columnar and Equi-axed Cast Strips

Figures 5(a) and 5(b) show the initial textures of fully columnar and equi-axed cast strips, respectively. The fully columnar strips exhibited remarkable $\{001\}/ND$ fiber texture. The fully equi-axed strips revealed weak and nearly random texture, which was in good agreement with the results given by Raabe et al. (13).

Figure 6 shows the cold rolling and annealing textures in both fully columnar strips and equi-axed cast strips. In the cold rolled sheet of the columnar strip, the texture was dominated by the $\{001\}/\{110\}$ cube texture. In the cold rolled sheet of equi-axed strips, to contrast, the cold rolling texture was characterized by both relatively intensified $\alpha$ and $\gamma$-fiber textures. After annealing, uniform $\gamma$-fiber recrystallization textures were formed in both final sheets, with the cold rolled and annealed sheet of the equi-axed strip showing more intensified $\gamma$-fiber texture than that of the columnar strip. Also, the $\{001\}/\{110\}$ component almost disappeared in both final sheets.

3.3. Texture Gradient

Figure 7 shows EBSD micrographs of two cold rolled and annealed sheets. It can be seen that the final cold rolled and annealed sheet of conventional equi-axed bar contained a large number of band-like grain colonies, which were parallel to the rolling direction, Fig. 7(a). However, grain colonies were greatly eliminated in the final sheet of equi-axed cast strip, Fig. 7(b). Figure 8 shows the texture gradient along sheet thickness for the cold rolled and annealed...
sheets of equi-axed cast strip and equi-axed bar. It can be seen that the final sheet of equi-axed cast strip possessed lower texture gradient than that of conventional equi-axed bar.

3.4. $r$-values of Cold Rolled and Annealed Sheets

Table 1 shows the $r$-values of the final sheets. The final sheet of equi-axed cast strip possesses the highest $r$-value among the four sheets. However, that of columnar cast strip displays the lowest $r$-value. By contrast, the final sheets of conventional columnar and equi-axed bars show medium $r$-values. And it is obvious that the final sheet of equi-axed bar shows slightly higher $r$-values than that of the columnar bar.

4. Discussion

4.1. Texture Developments during Conventional Processing

Investigations have been performed on the texture development of FSS produced by conventional processes.5–7,16,21–23) During hot rolling, FSS undergo no or merely phase transformation and rapid recovery occurs instead of recrystallization. Hence, strong $\{001\}/H_{110}$ component can be easily formed in the center layer of hot rolled band due to easy crystal rotation toward stable orientation during rolling. However, in the present work, it was observed that the grains with $\{001\}/(110)$ orientation did not change significantly upon annealing and could be retained easily in hot rolled and annealed band due to their low recrystallization rate. The hot rolled and annealed bands of columnar and equi-axed bars both showed strong $\{001\}/(110)$ components, Figs. 4(a) and 4(d), respectively. After cold rolling with an 80% reduction, the $\alpha$-fiber texture was further intensified due to the crystal rotation towards stable orientation during cold rolling, and the devel-
opment of γ-fiber texture was slow, which was different from interstitial free (IF) steels. Figs. 4(b) and 4(e). The maximum orientation intensity in the two cold rolled sheets was both at \(\{001\}/(110)\), indicating that this strong deformation texture remained stable during cold rolling. Another important orientation, \(\{112\}/(110)\), turned to be more pronounced. It should be noted that the cold rolled sheet of columnar bar exhibited much stronger α-fiber densities than that of equi-axed bar, especially for the \(\{001\}/(110)\) orientation, which could be attributed to the original fully columnar solidification structure with strong \(\{001\}\) ND texture. After final recrystallization annealing, instead of forming strong and uniform γ-fiber texture in low carbon steels, both cold rolled and annealed sheets displayed shifted γ-fiber textures with a significant shift towards high-index \(\{334\}\) (483), Figs. 4(c) and 4(f), which deviated about 9° from exact \(\{111\}/(112)\) orientation.

Raabe and Lücke suggested that the formation of high-index component such as \(\{334\}\) (483) in recrystallized FSS be explained by a preferred growth of this component into the \(\{112\}/(110)\) rolling texture. In this paper, the \(\{334\}\) (483) and \(\{112\}/(110)\) components were calculated to obey an approximate 26°(110) orientation relationship, close to the orientation relationship of coincidence site lattice (CSL) \(\Sigma\)19a (27°(110)) grain boundaries, which display high mobility. Therefore, \(\{334\}\) (483) recrystallization texture could have been developed from the scattered cold rolling textures by a 26°(110) selective grain growth in the vicinity of the pre-existing high-mobility CSL-grain boundaries. In the present work, remarkable \(\{112\}/(110)\) component was formed in the two cold rolled sheets of columnar and equi-axed bars, which might support this argument to some extent. It is generally agreed that the deformed grains near \(\{001\}/(110)\) orientation store low energy, and recovery occurs rapidly during annealing together with homogeneous deformation structures, causing the slow approach to final recrystallization to result in incomplete removal of the pronounced \(\{001\}/(110)\) component after annealing.

4.2. Texture Developments in Columnar and Equi-axed Cast Strips

The initial solidification structure was mainly controlled by using different melt superheats in the melt pool. When the melt superheat was 140 K, the temperature gradient in front of the solid phase was high enough to satisfy the segregation growth during solidification and resulted in preferred columnar structure with remarkable \(\{001\}\) ND fiber texture and the maximum close to \(\{001\}/(010)\). When the melt superheat was controlled to be 20 K, heterogeneous nucleation occurred and growth selection was restrained, to fully equi-axed strips, which exhibited weak and random initial textures.

After cold rolling, the cold rolled sheets of both columnar and equi-axed cast strips displayed weaker textures than those of the conventional cold rolled sheets. In the cold rolled sheets, the dominant \(\{001\}/(010)\) cube texture was found to be caused by initial pronounced \(\{001\}/(010)\) texture of the solidified columnar grains, Fig. 6(a). This is in good agreement with the result of Tsuji et al. that the \(\{001\}/(010)\) oriented grains were difficult to rotate and maintained their initial orientation during cold rolling. Figure 9 shows the EBSD characterization of the microstructure in ND plane of the cold rolled columnar cast strip with a reduction of 80%. It can be seen that a large number of low angle grain boundaries (LAGBs) existed in the deformed \(\{001\}/(010)\) grain interiors, especially along initial grain boundaries, which were caused by significant number of multiple slips to accommodate the shape change of the \(\{001\}/(010)\) oriented grains during rolling to stabilize the \(\{001\}/(010)\) orientation against rolling deformation. On the other hand, during cold rolling, the columnar grains might also be broken to form the randomized texture, leading to the formation of weak cold rolling texture. By contrast, the initial equi-axed crystals with nearly random orientations had almost same rotation tendencies towards \(\{001\}/(110)\), \(\{112\}/(110)\) and \(\{111\}/(110)\) orientations during cold rolling, which resulted in relatively weak α-fiber and clear γ-fiber as compared with the conventional cold rolled sheets, Fig. 6(c), in agreement with the predictions by Huh and Engler. Because the orientation density of \(\{112\}/(110)\) component in the cast strips was lower than that in conventional cold rolled sheets, the selective growth of high-index textures such as \(\{334\}\) (483) into this component might have been eliminated and the uniform γ-fiber recrystallization texture was formed in both sheets after annealing.

Due to the formation of relatively intensified γ-fiber in cold rolling textures, the final sheet of equi-axed strip showed much more intensified γ-fiber recrystallization than that in the columnar strip, Figs. 6(b) and 6(d). In the work by Raabe and co-workers, the uniform γ-fiber recrystallization texture had also been found in the final sheets of cast strips. The orientation densities along γ-fiber, however, were weaker (center layer: \(f(\theta)_{max}=5.4\); sub-surface layer: \(f(\theta)_{max}=3.3\)) than those in the present work. Although they did not show the microstructure in their paper, it could be deduced that the weaker γ-fiber texture might have been caused by the initial solidification structure with the mixture of equi-axed and columnar grains because the \(\{001\}\) ND fiber texture close to the surface of the strip was also found. Figure 10 shows the EBSD characterization of the cold
rolled sheet of equi-axed cast strip after annealing at 860°C for 10 s. It can be seen that the cold rolled structure consisted of alternative bands of $\alpha$ and $\gamma$-fiber deformed grains. During cold rolling, it is believed that crystals along initial grain boundaries rotate preferentially to $\{111\}//ND$, accompanied by a remarkable increase of misorientation and dislocation density. In this work, similar observation has been obtained, as shown in Fig. 10(a). Preferential nucleation of $\{111\}//ND$ recrystallized grains took place along the initial grain boundaries at the early stage of recrystallization, as shown in Fig. 10(b), possibly by the mechanism of in-situ recrystallization in the sense that nuclei originated from single sub-grains according to Vanderschueren et al. It can also be seen in Fig. 10(a) that large misorientations existed in the regions close to boundaries between deformed grains and newly recrystallized nuclei, which might show the evidence that the subsequent growth of these $\{111\}//ND$ nuclei was sustained by consuming the nearby deformed grains with other orientations during the subsequent recrystallization. Therefore, the final uniform $\gamma$-fiber recrystallization texture was formed by the preferred nucleation of $\{111\}//ND$ grains in the early stage of recrystallization and their subsequent growth, rather than by the preferred growth of $\{334\}\{483\}$ into $\{112\}\{110\}$. In both cold rolled sheets of cast strips, $\{001\}\{110\}$ component exhibited very low density, leading to the complete removal of this component in the final sheets after annealing, Figs. 6(b) and 6(d).

### 4.3. Recrystallization Textures and $r$-values of the Final Sheets

$r$-value of a FSS sheet depends on a number of factors including the shape and orientation density of the $\gamma$-fiber recrystallization texture, the remnant $\alpha$-fiber texture (in particular $\{001\}\{110\}$ component), and the through-thickness texture gradient. Figures 11(a) and 11(b) show the orientation densities along $\alpha$ and $\gamma$-fiber textures of the cold rolled sheets, respectively. The conventional cold rolled sheet shows pronounced $\alpha$-fiber texture such as $\{001\}\{110\}$–$\{112\}\{110\}$ orientations and relative weak $\gamma$-fiber, which is believed to be the main cause for the formation of shifted $\gamma$-fiber recrystallization texture towards $\{334\}\{483\}$ orientation and remnant $\{001\}\{110\}$ component after recrystallization. By contrast, the cold rolled sheets of cast strips displayed weak $\alpha$-fiber but clear $\gamma$-fiber texture, therefore, the $\{111\}//ND$ preferred nucleation could prevail during recrystallization and led to the formation of uniform $\gamma$-fiber and less $\{001\}\{110\}$ components in the recrystallization texture. Figures 12(a) and 12(b) show the orientation densities along $\alpha$ and $\gamma$-fiber textures in the annealed sheets after cold rolling, respectively. The final sheet of equi-axed cast strip possesses the highest $r$-value among the four sheets, which may be attributed to the formation of uniform and relatively strong $\gamma$-fiber and weak $\alpha$-fiber (especially $\{001\}\{110\}$–$\{112\}\{110\}$) in the recrystallization texture. By contrast, although the final sheet of columnar cast strip also possesses the uniform $\gamma$-fiber and weak $\alpha$-fiber textures, it has the lowest $r$-value due to its weakest orientation densi-
tices of γ-fiber in the recrystallization texture. The final sheets of columnar and equi-axed bars display shifted γ-fiber recrystallization textures towards {334} [483] orientation and remnant {001} [110]–{112} [110] orientations, exhibiting lower r-values than that of the equi-axed cast strip. The final sheet of equi-axed bar shows slightly higher r-value than that of the columnar bar due to its higher densities of γ-fiber recrystallization texture.

Raabe calculated r-values for the cold rolled and annealed sheets of cast strips from the first four Fourier coefficients of the harmonic ODF, and indicated that its high r-value might have been another reason for its higher texture gradient than that of conventional bars. However, the fully columnar cast strip exhibited remarkable {001}/ND fiber texture. After cold rolling and annealing, it possessed weak γ-fiber recrystallization texture and lower r-value than conventional final sheets. Therefore, equi-axed solidification structure in the cast strip is the pre-condition for the improvement of formability of 17% Cr FSS by twin-roll strip casting.

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