Evolution of microstructure and toughness of very tough ferritic stainless steels

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Abstract. In present work, the hot rolling with different finish rolling temperatures and annealing with different annealing temperature are employed with high toughness AISI444 ferritic stainless steel, and different microstructure are generated. It was indicated that low finish rolling temperature could lead to the significant refinement of the rolled and annealed microstructures and decrease the fraction of grains with \{001\} planes which are parallel to notch plane in the annealed microstructure. Therefore, the ductile-brittle transition temperature was lowered from -44.2°C to -48.8°C, resulting in the improvement of toughness after employing the low finish rolling temperature for ferritic stainless steel. When high annealing temperature can be applied, the coarsening of annealed microstructure occurred, but the fraction of grains with \{001\} planes which are parallel to notch plane in the recrystallized microstructure decreased. Thus, the ductile-brittle transition temperature has no significant change after annealing with different temperatures.

1. Introduction

Ferritic stainless steels (FSSs) can replace the conventional Cr-Ni austenitic stainless steels (ASSs) for specific applications, such as heat exchanger shell, because of the face that FSSs has better stress corrosion cracking resistance and lower cost than ASSs \cite{1,2}.

However, as compared with ASSs, FSSs show high ductile-brittle transition temperature (DBTT), especially when their thickness is greater than 5mm because of specimen size effect which means that thicker specimens possess higher DDBT \cite{2}. This poor toughness can results in the cracking during stamping and the significantly decrease of toughness after welding for FSSs medium plate, which will impedes the extensive application of FSSs. Our previous work \cite{1} suggest that the occurrence of ductile-to-brittle transition can be closely connected with the formation of deformation twin: during Charpy impact testing, deformation twins could form in FSSs; a microcrack tend to initiate at the tip of deformation twins and propagate along the boundary of twins, leading to the occurrence of brittle fracture. This suggests that parameters which can impact the occurrence of deformation twinning will influence the DBTT and toughness of FSSs \cite{1}. Based on this work, the alloy design of high toughness
FSSs is developed [2] in terms of refining microstructure and increasing stacking fault energy which can suppress twinning.

In present work, high toughness AISI444 FSS are hot rolled and annealed by different processes for further decreasing the DBTT and optimizing the notch toughness. The effects of hot rolling and annealing on microstructure and toughness were investigated.

2. Experimental procedures
A high toughness AISI444 FSS used in this study has the composition of 0.008% C, 0.0041% N, 0.16% Nb, 0.8% Ni, 0.43% Cu, 0.06% Al, 1.8% Mo, 18.5% Cr, 0.05% Si, 0.01% Mn and the balance Fe. After a homogenization treatment of 2h at 1200°C, the cast ingot was rough rolled at temperature of 1100-1050°C. Subsequently, one of the rough rolled plates was cooled in air to 1030°C and then finish rolled with the finish rolling temperature of 914°C. The other rough rolled plate was cooled in air to 905°C and then finish rolled with the finish rolling temperature of 854°C. The former is denoted as HFT (High finish rolling temperature), and the latter is referred to as LFT (Low finish rolling temperature). After different hot rolling processes, an annealing treatment of 8 min at 1000°C was undertaken for the hot rolled plates HFT and LFT for study the influence of hot rolling conditions on microstructure and property, and the plates LFT were annealed at temperature of 900-1000°C for 8 min for study the influence of annealing conditions on microstructure and property.

The microstructure and microtexture were observed with the optical microscope (OM) and the Electron Backscatter Diffraction (EBSD) system, respectively. The subsize Charpy specimens were machined along the rolling direction (RD) for Charpy impact tests at temperatures of -80-20°C.

3. Results and discussion
Figure 1 shows the toughness of annealed plates with LFT and HFT processing routes and the DBTT vs. plate thickness for AISI444 FSSs. The DBTTs were -44.2 and -48.8°C for the annealed plates HFT and LFT, respectively. This indicates that decreasing finish rolling temperature leads to the decrease of the DBTT. The DBTTs were -50.0, -51.0 and -48.8°C for the annealed plates annealed at 900, 950 and 1000°C, respectively, indicating that the annealing temperature has no obvious influence on the DBTT. AISI444 FSSs medium plate developed in this study has more superior toughness than those using conventional alloy design and processing routes.

![Graph showing DBTT vs. plate thickness for AISI444 FSSs.](image)

**Figure 1.** The toughness for annealed plates with different rolling (a) and annealing (b) processes and the DBTT vs. plate thickness for AISI444 FSSs obtained in present work and reported by other researcher using conventional alloy design and processing routes [3,4] (c)

Figure 2 shows the rolled microstructures observed by OM and recrystallized microstructures analyzed by EBSD after different rolling conditions. Low finish rolling temperature can result in larger accumulated deformation stored energy and lower dynamic softening rate [1], so the hot rolled plate LFT possesses higher dislocation density, more in-grain shear band and finer microstructure than rolled plate HFT, as shown in Figures 2(a) and (c). In the annealed plate HFT, the partial recrystallization occurred and the average grain size is found to be about 240μm obtained by EBSD analysis (Figure 2(b)). By contrast, full recrystallization was observed, the microstructures are consisted of equi-axed grains in annealed plate LHT and the average grain size is found to be about
107μm obtained by EBSD analysis (Figure 2(d)). The annealed plate LHT has finer and more homogeneous microstructure than the annealed plate HF, as shown in Figures 2(b) and (d). This can be due to high dislocation density and fine microstructure in the hot rolled plate LHT, which can increase the recrystallization driving force and nucleation sites of recrystallized grain [3].

![Figure 2](image1.png)

**Figure 2.** The microstructures of the rolled plates ((a),(c)) and orientation maps of all orientations of annealed plates ((b),(d)) with different rolling conditions (a),(b) HFT, (c),(d) LFT

![Figure 3](image2.png)

**Figure 3.** The orientation maps of <001>//RD oriented grains measured from the annealed plates with different rolling conditions (a) HFT, (b) LFT

Figure 3 shows the orientation maps of <001>//RD oriented grains measured from the annealed plates with different rolling conditions. The fraction of <001>//RD oriented grains in the annealed plates HFT and LFT are measured to be 25.5% and 17.1%, respectively, indicating that after low finish rolling temperature the fraction of the <001>//RD oriented grains markedly decreases. Hot deformation at lower temperature can promote the crystal rotation from some <001>//RD orientations such as {100}<001> and {110}<001> towards relatively stable <110>//RD (α-fiber) and <111>//ND orientations (γ-fiber) [5]. Thus, low finish rolling temperature can sharp hot rolled γ-fiber. During annealing, the sharp hot rolled γ-fiber is inclined to increase the number of γ-fiber recrystallized grains [5]. Hence, the low finish rolling temperature can decrease the fraction of the <001>//RD oriented grains. Because subsize Charpy specimens were machined along the RD, the annealed plates with low finish rolling temperature has lower fraction of grains with {001} planes which are parallel to notch plane that with high finish rolling temperature.

Ghosh et al. [6] found that higher fraction of {001} planes which are parallel to the notch plane can promote the propagation of cleavage crack and eventually the increase of DBTT. The lower fraction of {001} planes parallel to the notch plane in the annealed plate LFT can decrease the DBTT. On the other hand, grain refinement can suppress the formation of deformation twins which can promote the initiation and propagation of crack during Charpy impact testing for FSSs [3]. The finer recrystallized microstructure obtained in the annealed plate LFT can decreases the DBTT. Therefore, the annealed plate LFT possesses lower the DBTT and low finish rolling temperature result in the decrease of the DBTT.

Figure 4 shows the microstructures of annealed plates with different annealing conditions analysed by EBSD. The average grain sizes of annealed plates annealed at 900, 950 and 1000°C are measured to be 92, 100 and 107μm, respectively (Figures 4(a), (c) and (e)). This indicates that the microstructure of annealed plates begins to coarsen with increasing annealing temperature. The fraction of <001>//RD oriented grains in the annealed plates annealed at 900, 950 and 1000°C are measured to be 20.5%, 18.7% and 17.1%, respectively (Figure 4(b), (d) and (f)), indicating that the fraction of grains with {001} planes which are parallel to notch plane in annealed plates decreases with the increasing
annealing temperature. During annealing, the $\gamma$-fiber recrystallization grains preferentially nucleate and then these grains will grow by consuming deformed grains or other oriented recrystallization grains, such as <001>/RD oriented grains [5,7]. Increasing annealing temperature is favorable for increasing the driving force for recrystallization grain growth. Hence, increasing annealing temperature can reduce the fractions of <001>/RD oriented grains and {001} planes which are parallel to notch plane and coarsen recrystallized microstructure. As above-mentioned discussion, decreasing the fraction of grains with {001} planes which are parallel to notch plane can decrease the DBTT, while coarsening recrystallized microstructure can increase the DBTT. Therefore, the annealing temperature has no obvious influence on the DBTT.

![Figure 4](image)

**Figure 4** The orientation maps for all orientations ((a),(c),(e)) and corresponding <001>/RD oriented grains ((b),(d),(f)) measured from the annealed plates after different annealing processes (a),(b) 900°C, (c),(d) 950°C, (e),(f) 1000°C

4. Conclusions
The rolling and annealing processes have an obvious influence on microstructure and toughness for the developed AISI444 ferritic stainless steel having superior toughness in this study. Low finish rolling temperature could significantly refine the microstructure in hot rolled and annealed plate and decrease the volume fraction of the <001>/RD oriented grains and corresponding the fraction of grains with {001} planes which are parallel to notch plane in recrystallized microstructure. Therefore, the ductile-brittle transition temperature was lowered from -44.2°C to -48.8°C, and the toughness was enhanced after employing the low finish rolling temperature for developed AISI444 ferritic stainless steel. After annealing with higher temperature, the microstructure in hot rolled and annealed plate coarsened, but the volume fraction of the <001>/RD oriented grains and corresponding the fraction of grains with {001} planes which are parallel to notch plane in recrystallized microstructure decreased. Thus, the ductile-brittle transition temperature has no significant change when high annealing temperature is applied.

5. References
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