Original Article

Quantification of texture-induced ridging in ferritic stainless steels 430 and 430LR during tensile deformation

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ABSTRACT

A comparative study has been carried out to assess the effect of rolling and annealing processes on ridging generation of ferritic stainless steels (FSSs) 430 and 430LR after tensile deformation. The results show that FSS 430LR has better ridging resistance owing to the refinement of microstructure and crystallographic texture optimisation. A 30% reduction of ridging height can be achieved using FSS 430LR compared to FSS 430 after tension. Optimal reduction during cold rolling benefits the microstructural refinement and surface quality improvement of FSSs 430 and 430LR. Both theoretical calculations and experimental results indicate that the (112) and the {001} components are responsible for ridging in the FSSs after tension. Through preventing the formation of coarse bands and grains with the {001} component inside the FSSs, the ridging resistance of both FSSs 430 and 430LR can be improved.

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1. Introduction

With high thermal conductivity, excellent mechanical properties and relatively low cost compared to austenitic stainless steels, ferritic stainless steels (FSSs) are commonly used for various applications in industrial fields such as home appliances, medical science and automotive exhaust systems. A rope-like surface roughness profile parallel to the rolling direction (RD), however, can be developed on the surface of FSSs during forming [1]. The undesirable ridges significantly affect the surface finish, and this requires additional polishing operations in order to improve the surface quality of the formed products. RIDGING is commonly described as a series of ridges and valleys along the RD generated upon tensile deformation [2]. During the rolling process, many elongated grain...
colonies with similar crystal orientations nucleate and grow and even survive after annealing. The local strain localisations and banding of the local strain distributions were found due to elongated colonies, promoting increased surface roughness upon forming [3].

Optimisation of microstructure and texture are commonly considered to be effective in order to solve the ridging problem [1–5]. Through prevention of the formation of coarse bands and controlling the texture, the crystallographic anisotropy can be reduced and the differential of plastic deformation can be limited. Patra et al. [6] analysed the effect of coarse grain band on the ridging severity of FSS 409L and reported that hot-band annealing was required at high temperatures in order to improve ridging resistance. Baczynski et al. [7] studied the ridging development of aluminium alloy AA6111 and stated that the spatial distribution of the Goss component was responsible for ridging generation. Further investigation into the microstructure and microtexture evolution during dynamic recrystallisation was carried out by Mannan et al. [8], and it was found that the cube orientation could be dominant due to the low stored energy and its orientation stability during secondary deformation. Zhang et al. [9] evaluated the effects of hot rolled shear bands on surface ridging of a 21%Cr FSS and stated that the formation of shear bands improved the ridging resistance by eliminating the grain colonies in the final sheet. Shin et al. [10] assessed the effect of texture on the ridging generation of FSS 409 and found that the low plastic-strain ratio of the (001) component and differences in shear deformation between the (111) and (112) components contribute to the generation of ridging. The ridging phenomenon of FSS 409L and 430 under various hot annealing conditions were investigated by Park et al. [11], and it was found that ridging could be significantly improved when temperatures were higher than 920°C due to the dissolution of fine precipitates. Engler et al. [12] also evaluated the ridging resistance of FSS 430 and stated that an intermediate annealing would improve ridging resistance. Qin et al. [13] found that the (001) and (112) colonies located at the mid-thickness region were responsible for ridging generation. Viana et al. [3] analysed the ridging in FSS 430 and 434, and concluded that the surface ridging was a result of the differential behaviour of (111) and (001) grain colonies in the FSS sheets. They found that the low R-value of (001) grains caused large differences in the accommodation of the macroscopic transverse tensile strains between the surface and the internal layers, leading to undulation on the surface during subsequent forming processes. Jung et al. [14] assessed the effects of cold rolling and annealing on the ridging of FSS 439, and found that band-like clusters of/ND (normal direction) oriented grains contributed to the ridging generation. Similar results obtained by Li et al. [15] indicated that the ridging was mainly induced by the inhomogeneous distribution of grain clusters of γ-fibre texture formed during recrystallisation in the central layers. The optimisation of the texture structure of FSS during processing, therefore, is considered to be effective to improve the ridging resistance of FSS.

Although the (001) (110) component is considered to be critical in ridging phenomenon, it is commonly acknowledged that the Goss component also contributes to the ridging generation after tensile deformation [16–19]. During the late stages of the rolling process, significant shear deformation occurs at surface layers, promoting the formation of the Goss oriented bands [18,19]. Considering that the Goss bands are formed along with the microbands in FSS, the control of the fraction of Goss component contributes to the refinement of microstructure, giving a rise to the ridging resistance of FSS [20].

FSS 430 is a non-hardenable steel with high corrosion resistance and good formability, and FSS 430LR is a newly developed steel containing Nb, Ti and Sn with the purpose of improving the mechanical properties. As these two FSSs have different compositions and microstructures, they may exhibit diverse ridging phenomena during the formation. Much experimental work has already been conducted in order to enhance the ridging resistance and improve the surface quality of FSS 430 during the subsequent forming process. Few researchers, however, have focused on the microstructure and texture development of FSS 430LR. A comparative study has been carried out in the present study in order to investigate the effects of the rolling and annealing processes on the ridging generation of FSSs 430 and 430LR during tensile testing. The objective of this work is to evaluate the effect of texture and microstructure on ridging generation and develop effective control strategies to improve the ridging resistance of FSSs.

### 2. Experimental procedures

Two FSSs 430 and 430LR were used in the present study, and their chemical compositions are given in Table 1. Fig. 1 illustrates the rolling and heat treatment processes applied in the current study. Both FSSs 430 and 430LR specimens of 5 mm thick were hot-rolled down to 1 mm in four passes, while the rolling temperature was reduced from 1150 to 850 °C in steps of 100 °C, respectively. The hot-rolled sheets were cooled in the air to room temperature, and then they were annealed at 840 °C for 2 h and then cold rolled with different reductions, followed by final annealing at 870 °C for 2 min. For hot rolling experiments, the specimens were cut with the dimensions of 200 × 50 × 5 mm³. In order to avoid oxidation during hot rolling, argon was utilised as protective gas during heating.

To evaluate the anti-ridging performance of FSSs, cross sections of the rolled and annealed specimens were prepared for microstructural observation and texture analysis. The specimens were electro-polished using standard metallographic techniques. Electron backscatter diffraction (EBSD) was

<table>
<thead>
<tr>
<th>Grade</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
<th>Cr</th>
<th>N</th>
<th>Nb</th>
<th>Ti</th>
<th>Sn</th>
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<tbody>
<tr>
<td>430</td>
<td>0.049</td>
<td>0.35</td>
<td>0.23</td>
<td>0.002</td>
<td>0.031</td>
<td>16.24</td>
<td>0.0348</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>430LR</td>
<td>0.0101</td>
<td>0.31</td>
<td>0.19</td>
<td>0.002</td>
<td>0.024</td>
<td>16.58</td>
<td>0.012</td>
<td>0.15</td>
<td>0.11</td>
<td>0.09</td>
</tr>
</tbody>
</table>
performed using a scanning electron microscope (SEM) JEOL JSM-7001F which was equipped with an Oxford HKL Channel 5 software. An area of $2.2 \times 0.4 \, \text{mm}^2$ was scanned for each specimen with a step size of 2 µm. The beam conditions were set to be 15 kV and 7.5 nA. The crystallographic orientations of grains in the scanned area were obtained, and the texture components can be further analysed based on the orientation distribution functions (ODFs). Given that the majority of significant texture components in BCC materials can be obtained on the ODFs on the $\phi_2 = 45^\circ$ section of the Euler space, the effect of major texture components can be analysed based on ODFs inside the $\phi_2 = 45^\circ$ section of the Euler space.

Tensile tests were machined off to evaluate the ridging generation of the FSSs after rolling and annealing. The tensile specimens were prepared along the RD based on the ASTM-E8M Standard [21], and the dimensions of the tensile specimens are shown in Fig. 2. All the specimens were polished at room temperature before the tensile tests. Tensile tests were carried out under displacement control up to 20% extension with a travel speed of 1 mm/min. The tests were conducted three times under each condition and the average value of ridging height was measured and obtained. The stress–strain curves of both annealed FSS 430 and 430LR are shown in Fig. 3.

The ridging profiles of the specimens were measured using a Keyence VK-X100-3D Laser Scanning Microscope. The process flow of how the surface roughness measurements are taken is shown in Fig. 4. The raw data show pronounced undulations with short wavelength. To eliminate the noise of wavelength and waviness, two cut-off values were applied and the profile was filtered based on ISO 4287:1997 Standard [22]. For the measured ridging profile, a discrete Fourier transformation was performed on the original signal and the low-frequency parts of the Fourier spectrum were transformed back, eliminating the errors generated from long-wave features of profile.

3. Results

In this section, the results obtained from EBSD tests and ridging measurement are displayed in order to evaluate the ridging resistance of both FSS 430 and 430LR. In addition, a comparison was made between FSS 430 and 430LR in order to find out the correlation between microstructure, texture and ridging resistance of FSSs.

3.1. Microstructure and texture of cold-rolled and annealed structures

3.1.1. FSS 430

In this section, the microstructure and texture components of FSS 430 are evaluated upon rolling. The inverse pole figure (IPF) maps of the rolled and annealed FSS 430 are presented in Fig. 5.

It is clear that refined ferrite grains at surface layers are formed after rolling and annealing in Fig. 5(a). As the surface
layers are subjected to significant driving force during rolling [6], profound shear deformation on the grains in the surface layers was induced [23,24]. It is known that both high cooling rates and large shearing on the surface layers contribute to the grain refinement [6,23,24]. As a consequence, the grains located on the surface layers are refined during rolling and annealing. The grains in the central layers, on the other hand, are mainly subjected to plane-strain compression which cannot refine the grains effectively unlike the grains in the surface layers. In addition, the cooling rate at central layers is lower than that in surface layers, causing that the coarse grain bands survive even after processing. As shown in Fig. 5(a), many coarse grains can be seen in the central layer under reduction of 60%. As the reduction is increased to 70%, significantly refined grains with better homogeneity are found at the central layers, as shown in Fig. 5(b). With further increase in the reduction from 70% to 85%, a remarkable growth of grains occurs at the central layer because of abnormal grain growth in the central layers [25], as shown in Fig. 5(c). Table 2 shows the average grain size of FSS 430 with different reductions in

![Fig. 4 – The diagram of ridging height measurement using 3D laser microscope.](image)

![Fig. 5 – Microstructure of cold rolled and annealed FSS 430 sheets with reductions of (a) 60%, (b) 70% and (c) 85%.](image)
cold rolling. It can be seen that the grains are refined with a reduction of 70%, and the average grain size increased when the reduction was increased from 70% to 85%. The formation of grain colonies in the central layers promotes the inhomogeneity of grain sizes and will affect the anisotropy of FSS 430.

During the rolling and subsequent annealing process, FSS tend to form typical bcc texture components (i.e. \{112\}[110]) along α-fibre and γ-fibre which can be represented by RD//[110] and ND//[111] orientations, respectively. Texture is defined to be the distribution of crystallographic orientations of polycrystalline materials. To evaluate the effect of texture structure on ridging resistance of FSS, the density of texture component \(f(g)\) was computed from a series of pole figures obtained by EBSD scanning. Fig. 6 shows the ODFs of the FSS 430 after cold rolling and subsequent annealing at different thickness upon rolling. For specimens under reduction of 60%, the \{115\}[110] orientation is quite strong. It is known that the grains at central layers are subjected to plane strain compression, and the ND//[001] orientation rotates to the \{001\}[110] orientation after plane strain compression [5]. As a consequence, the \{001\}[110] bands can form during the rolling process. As the \{115\}[110] component is deviated from the \{001\}[110] component by 16°, the \{115\}[110] component is considered to be transformed from the \{001\}[110] component originated from columnar grains with ND//[001] orientation. However, due to the low Taylor factor and low stored energy of the \{001\}[110] component, the transformation rate is slow and many microbands with \{001\}[110] orientation survive even after rolling and annealing process.

With reduction increasing to 70%, pronounced γ-fibre texture was formed with peaks at the \{334\}[483] and \{111\}[112] orientations on the 45° ODF. Both \{334\}[483] and \{111\}[112] orientations are typical recrystallised textures and they are generated mainly from the \{558\}[110] and \{001\}[110] orientations, respectively. For specimens with reduction of 85%, the maximum strength of texture components grow again and the \{112\}[110] component becomes dominant in FSS 430. \{112\}[110] component is one of the major components in the α-fibre orientation and the \{112\}[110] colonies are considered to be responsible for shear deformation during the subsequent forming process [16,17].

### 3.1.2. FSS 430LR

In this section, the microstructure and texture components of FSS 430LR are evaluated upon rolling. Fig. 7 shows the IFP maps of the cold rolled and annealed FSS 430LR specimens with different reductions during cold rolling. It can be seen from Fig. 7(a) that with a reduction of 60%, the crystal orientations and grain size in FSS 430LR are distributed homogeneously as compared to those in FSS 430 (Fig. 6(a)). As the reduction is increased from 60% to 70%, the grain size shows
no significant change, as shown in Fig. 7(b). When the reduction is increased to 85%, significant refining of grains can be observed. The average grain size of FSS with different reductions in cold rolling is shown in Table 3. It can be seen that the 85% thickness reduction contributes to the most refined microstructure. However, unlike in the 430 grade, the average grain sizes in the 430LR consistently decrease with increasing percent cold roll. It is known that the grain refinement by recrystallisation after cold rolling depends upon recrystallisation temperature, degree of prior deformation and the grain size prior to deformation [26], decrease of the average grain size of FSS can be observed with the increase of reductions during cold rolling.

Fig. 8 shows the 45° ODFs of FSS 430LR after rolling and subsequent annealing at different thickness reductions. It can be seen that the specimen with a reduction of 60% has strong texture along the γ-fibre. When the reduction is increased to 70%, the major components are found along the γ-fibre, especially for {334} and {111} textures, indicating that the specimens have been fully recrystallised. With the further increase of the reduction to 85%, the texture along γ-fibre gradually converts to other texture components, and the intensity of {112} component increases.

### 3.2. Ridging analysis

Fig. 9 shows the 3D surface topology of FSSs 430 and 430LR after 20% tensile deformation on the specimens processed with different reductions in cold rolling. It can be seen that the ridging heights generated on FSS 430LR are lower than those generated on FSS 430 under the same reduction in cold rolling, indicating that FSS 430LR shows better ridging resistance with less undulations and more smooth surface than FSS 430 during tensile deformation.

The dependence of the average ridging height on the reduction of FSS 430 and 430LR is shown in Fig. 10. The results indicate that both groups of specimens show the lowest ridging height with a reduction of 70% and the highest ridging heights with a reduction of 60%. The ridging heights of FSS 430LR can also be around 30% lower than that of the FSS 430, indicating that the FSS 430LR has better ridging resistance than FSS 430.

### 4. Discussion

#### 4.1. The effect of coarse bands on ridging generation

In this section, the effect of coarse bands on ridging generation of FSS is discussed. After cold rolling, the microstructure of FSSs is dominated by elongated grains. After subsequent annealing at 870°C, for FSS 430 with a reduction of 60%, the majority of the grains at the surface layers are fully recrystallised and refined with equiaxed grains while the grains at the central layers are mainly elongated. For specimens with a reduction of 70%, the grains are fully recrystallised and the microstructure is refined with reduced average grain size,
better homogeneity and higher ridging resistance [20]. The different Taylor factors, grain sizes and orientations also promote different plastic deformations of neighbouring grains at different bands, causing a rise in the ridging height after tension [27]. For coarse grain bands, localised plastic slip along specific relatively large grains causes undulations on the surface of FSS 430 during subsequent forming process [20]. To further investigate the impact of coarse bands on the ridging of FSS 430, the texture of coarse and fine grains is analysed (as shown in Fig. 13). It can be seen that a strong \{112\} \{110\} texture exists in coarse bands of FSS 430 while the intensity of this component in fine grains is much lower. It can also be seen that large grains have similar texture, yielding a peak at that location, causing that the \{112\} \{110\} component is dominant in both coarse and whole grain set. The effect of textures on the ridging severity of FSS 430 will be further discussed in the following section.

During hot rolling, the grains at the surface layers are subjected to pronounced shear deformation and plane-strain compression and the grains at central layers are subjected to plane-strain compression. With the driving force, the grains at surface layers are broken down by recovery and recrystallisation during the annealing process [20]. For grains in the central layers, the plane-strain compression could not break down the coarse bands and refine the grains in the central layers. Though profound refinement can be achieved after cold rolling and subsequent annealing, many coarse bands in the central layers survive and give rise to the different plastic anisotropy.

### 4.2. The effect of texture on ridging generation

The ridging phenomenon is mainly generated due to the different plastic deformations within individual grains during the subsequent forming process [27–31]. During rolling and the subsequent annealing processes, the shear-deformed layers are formed at the surface layers, whilst elongated grains are generated due to the plane-strain compression at the central layers. This means that pronounced texture components are generated with strong \{001\} \{110\} and \{112\} \{110\} components at central layers and Goss component at surface layers.

To further analyse the effect of texture components on ridging generation, the volume fraction of major texture components in FSS 430 are displayed in Fig. 12. For FSS 430, with the increase of reduction during cold rolling, the brass, \{112\} \{110\} and \{114\} \{110\} components exhibit significant decrease whereas concurrent increase in fraction is noted for copper component. Given that the fraction of copper component is low in FSS, the impact of copper component on ridging is minimised. The volume fraction of both \{001\} \{110\} and cube components decreased initially and increased afterwards. With reduction of 70%, the fraction of \{001\} \{110\} component remains only 6.44% with the lowest ridging height after 20% tensile deformation. Thus, the decline of \{001\} \{110\} components is considered to benefit the ridging resistance of FSS 430. Remarkable improvement of ridging was observed with FSS 430LR after tensile deformation. With the increase of reduction values, a remarkable reduction of brass
Fig. 9 – 3D surface topology of (a, c, e) FSS 430 and (b, d, f) FSS 430LR after 20% extension: (a, b) reduction of 60%, (c, d) reduction of 70%, and (e, f) reduction of 85%.

As discussed above, one of the most effective methods to enhance ridging resistance is to improve the texture structure of specimens. Fig. 13 shows the volume fraction of \{001\} \{110\} component in FSS 430 and 430LR. A remarkable decrease in volume fraction of \{001\} \{110\} component in FSS 430 can be observed compared with that in FSS 430LR. With the decrease of \{001\} \{110\} texture, the ridging resistance of both FSS 430...
Fig. 11 – $\phi2 = 45^\circ$ ODF sections of cold rolled and annealed sample: (a) microstructure of strips with 60% reduction, (b) coarse grains, (c) fine grains and (d) complete grain set.

Fig. 12 – Volume fractions of different textures of (a) FSS 430 and (b) FSS 430LR with different reductions in cold rolling.

Table 4 – Calculated R-value of texture components.

<table>
<thead>
<tr>
<th>Texture component</th>
<th>R-value (RD)</th>
<th>R-value (45°)</th>
<th>R-value (TD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>{001} (110)</td>
<td>0.00</td>
<td>1.00</td>
<td>0.00</td>
</tr>
<tr>
<td>{011} (100)</td>
<td>1.00</td>
<td>0.40</td>
<td>Infinite</td>
</tr>
<tr>
<td>{001} (100)</td>
<td>1.00</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>{112} (110)</td>
<td>0.11</td>
<td>6.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Copper</td>
<td>1.00</td>
<td>5.99</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Fig. 13 – The volume fraction of {001} (110) texture component in FSSs 430 and 430LR.

and 430LR are found to be enhanced and the ridging heights reduces during the subsequent forming process.

Table 4 shows the calculated plane-strain ratio (R-value) of different texture components in FSSs. R-value is commonly utilised to evaluate the plastic anisotropy of major texture components and thus assess the ridging resistance of FSS [32]. For specimens stretched along RD, the R-value for {001} (110), {112} (110) component was lower compared to the matrix, causing the non homogeneous plastic deformation of grains with different crystal orientations [33]. Thus, reducing the fraction of {001} (110) and {112} (110) component in FSS would improve the ridging resistance and enhance the surface quality during forming process. The results from theoretical calculation match well with the results from EBSD tests.
It can therefore be concluded that \{001\} \langle 1 1 0 \rangle component contributes to the ridging generation of FSS.

5. Conclusions

A comparison of FSSs 430 and 430LR was made to investigate the effect of the rolling and annealing processes on ridging generation during tension. The impact of coarse bands and major texture components on ridging resistance was discussed. The following conclusions can be drawn:

1. The effect of the \{001\} \langle 1 1 0 \rangle component on ridging generation of FSS is dominant. With reduced fraction of \{001\} \langle 1 1 0 \rangle component, 30% decrease of ridging height can be achieved with FSS 430LR compared with FSS 430.

2. The coarse grain bands promote the incomplete breakdown of crystals and lead to inhomogeneous grain sizes at different layers. The coarse grain bands are also generally formed combined with \{1 1 2\} component and low Taylor factor, causing different plastic deformation of neighbouring grains at different layers.

3. For both FSSs 430 and 430LR, the best ridging resistance is achieved with the reduction of 70% in cold rolling, which contributes to the refined microstructure and optimal texture structure and crystallographic diversity.

4. The effect of the coarse grain band at the central layer can be critical in ridging generation, but the coarse grain band can be eliminated by optimisation of the rolling parameters.

Conflicts of interest

The authors declare no conflicts of interest.

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