Influence of Micro-texture Distribution and Straining Direction on the Ridging of Ferritic Stainless Steels

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Ridging means the appearance of surface profile undulations, i.e. peaks and valleys, as a result of plastic strain. The reasons for the different ridging behaviour of industrially produced, stabilized ferritic stainless steel sheets (EN 1.4509) have been investigated after straining in the rolling and transverse directions with low and high resistance towards ridging. The evolution of macro-texture has been measured by X-ray diffraction (XRD) both before and after ridging tests in the rolling and transverse directions. The macro-texture results showed that straining along the rolling direction strengthened the \( f_{\alpha} \) fibre whereas the \( f_{\gamma} \) fibre was strengthened by grain rotations after straining along transverse direction. Electron backscatter diffraction (EBSD) imaging was used to establish the micro-textural variations over the thickness of the sheets among the high and low ridging materials. Mean orientations of individual grains determined from the EBSD data were utilized to calculate plastic strain ratio \( r \)-values by considering all slip systems weighted according to their Schmid factors. The calculated \( r \)-values were used to predict the ridging surface profile after straining along the rolling and transverse directions. The results demonstrated the influence of local variations in micro-texture on the severity of ridging.

KEY WORDS: ferritic stainless steels; ridging; texture; Lankford parameter; \( r \)-value.

1. Introduction

Ferritic stainless steels (FSS) are used in a wide variety of applications due to their combination of formability, weldability and excellent corrosion resistance. FSS with high chromium contents have become alternatives to the more highly alloyed austenitic steels, which are more expensive primarily due to their nickel content. One drawback sometimes encountered with FSS is a surface defect known as ridging. Ridging occurs along the rolling direction, and its severity is highest when tensile axis is parallel to the rolling direction and lowest along the transverse direction. The height differences between the ridges and adjacent valleys are in the range of 20–50 \( \mu \text{m} \). The phenomenon becomes noticeable for example after deep drawing operations and can result in the need for additional polishing of the drawn product.

Early research proposed that the segregation of alloying elements such as chromium, molybdenum or carbon may be one of the possible reasons for ridging.1–3) Later studies suggested that crystallographic texture is mainly responsible for ridging.4–8) The first concept was proposed by Chao4) for analysing ridging in pure iron, plain carbon steel, 6% (by mass) aluminium steel and AISI 434 and 436 type stainless steels. Chao assumed that the ridges arise due to differences in sheet thickness in adjacent regions, as a result of through-thickness strain variations in cube-on-edge (CE) \{110\} \(<001>\), cube-on-corner (CC) \{111\} \(<011>\) and cube-on-face (CF) \{100\} \(<011>\) texture components. Wright6) modified the Chao model to include a buckling mechanism that led to the prediction of corrugations rather than thickness variations. However, the Wright model is not in agreement with a detailed crystal plasticity finite element study carried out by Shin et al.9) An alternative model by Takechi et al.5) attributes ridging to the banding of grains orientated with a \( (hkl) [011] \) texture component. This model has not received much support because the existence of a texture band with \( [011] \) parallel to the RD has not been convincingly demonstrated.10,11) However, the importance of the shear component is consistent with some of the results presented by Shin et al. Shin et al.9) have carried out crystal plasticity finite element (CPFEM) simulations based on the presence of the bands or colonies postulated by Chao, Takechi and Wright, but actual measured electron backscatter diffraction (EBSD) texture data has not been considered in any modelling.

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With the emergence of the EBSD technique, it became possible to easily identify local texture distributions. Bethke et al.,7) Brochu et al.,10) Shin et al.,9) and Mola et al.,12) used EBSD to reveal local texture distributions in their studies of ridging in ferritic stainless steel sheets. It was observed that spatial orientation distributions on through-thickness sections parallel to both the rolling and transverse directions exhibited inhomogeneity but did not show any alignment of the texture components.

Many experiments have been carried out to reduce ridging height by varying production process parameters or chemical composition. The grain colonies responsible for ridging are believed to originate from as-cast columnar grains with a {001} <uvw> texture, which persists even after numerous processing steps.13,14) Hitherto proposed methods for reducing ridging are the refinement of the solidification microstructure via electromagnetic stirring,15) the reduction or elimination of the as-cast columnar zone,16,17) the cold rolling of α’ martensite,18–20) two-step cold rolling with intermediate annealing,21) cross rolling22) and un-lubricated hot rolling.23) Numerous modelling attempts have been made to correlate the texture and the ridging severity of ferritic stainless steel sheet.9,23–26) Although these models have contributed to a better understanding of the ridging mechanism, they remain qualitative and do not provide practical guidelines to alleviate ridging. CPFEM models have had some success in predicting grain scale deformation behaviour, but accurate comparisons with experimental results at the grain scale are still lacking.

The effect of the straining direction on ridging has been reported but not systematically studied. Previous EBSD studies have reported textures and qualitatively compared the differences between materials with different ridging tendencies. The intensities of the orientations along α-fibre and γ-fibre are correlated to r-values, which affect the overall formability of the material.27–31) Also, it has been suggested that a high γ-fibre intensity gives good resistance to ridging. More importantly, actual grain orientations have never been considered in the CPFEM modelling of the ridging mechanism. The present work was therefore undertaken to clarify the ridging mechanism and evolution of texture during tensile straining in FSS alloys using the actual grain orientations of the material.

2. Materials and Methods

2.1. Materials

Full-width, cold-rolled and annealed samples from various heats of a commercial 18% Cr FSS grade (EN 1.4509/AISI 441) were supplied by Outokumpu Stainless company. The average chemical composition of all the four samples used in the present study is given in Table 1. The materials were produced from continuously cast slabs that were hot rolled (HR) to a thickness of 6 mm, subsequently cold rolled (CR) with an intermediate annealing to a thickness in the range 0.8–1.2 mm and finally annealed. Hot rolling and cold rolling reductions, together with the intermediate and final thicknesses of the samples coded as A, B, C and D are listed in Table 2. The varying cold rolling reductions of the sheet gave different thicknesses to the final sheets. The process conditions were similar, i.e. annealing temperatures after the first and second cold rolling stage were 950 and 980°C respectively for all the coils. The samples were chosen for study due to the regular quality tests that revealed differences in ridging tendency despite the fact that all materials were produced with similar processing parameters.

2.2. Ridging Measurements

Specimens for ridging tests were cut from the final sheet products with the dimensions 300 mm in the rolling direction and 100 mm in the transverse direction, i.e. across the sheet width. They were elongated 15% in a tensile testing machine using special grips. The unfiltered 2D raw surface profile after the ridging tests was measured using a non-skidded bench-top 2D stylus profilometer Zeiss Surfcom 2000 SD3 with stylus tip radius of 2 μm. This raw profile was filtered to calculate the ridging index (RI) a unique index considering the height of the profile and the spacing between the ridges.32)

2.3. Mechanical Properties and Texture Measurements

Metallographic observations on a Zeiss light optical microscope were carried out on the all the samples and grain sizes were evaluated according to the standard ASTM E 112-96. Tensile specimens were cut and tested according to the standard ISO EN 6891-1 on a Zwick Z250/SW5A tensile testing machine. Tensile tests were carried out with the tensile axis oriented at angles 0, 45 and 90° to the rolling direction of the sheet in order to determine the Lankford parameter, or plastic strain ratio (r-value) along the respective directions. The r-value is the ratio of width to thickness strain (εw/εT) in Eq. (1). Materials with higher R-values are resistant to thinning thereby allowing the drawing of deeper parts, while materials with lower R-values are undesirable, since it will thin and possibly rupture.

\[ R = \left( r(0°) + 2r(45°) + r(90°) \right) / 4 \]  

**Table 1.** Average chemical composition of all the samples of the ferritic stainless steel EN 1.4509/AISI 441 (wt.%) used in the present study.

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>N</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Ti</th>
<th>Nb</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.016</td>
<td>0.023</td>
<td>0.520</td>
<td>0.400</td>
<td>17.833</td>
<td>0.211</td>
<td>0.025</td>
<td>0.129</td>
<td>0.395</td>
</tr>
</tbody>
</table>

**Table 2.** Samples and their respective cold reductions and final thicknesses (mm).

<table>
<thead>
<tr>
<th>Sample</th>
<th>HR thickness</th>
<th>1st stage CR thickness</th>
<th>Reduction (%)</th>
<th>Final thickness</th>
<th>2nd stage reduction (%)</th>
<th>Total cold reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>6.0</td>
<td>2.93</td>
<td>51</td>
<td>0.79</td>
<td>73</td>
<td>87</td>
</tr>
<tr>
<td>B</td>
<td>6.0</td>
<td>3.23</td>
<td>46</td>
<td>1.23</td>
<td>62</td>
<td>80</td>
</tr>
<tr>
<td>C</td>
<td>6.0</td>
<td>2.94</td>
<td>51</td>
<td>0.68</td>
<td>77</td>
<td>89</td>
</tr>
<tr>
<td>D</td>
<td>6.0</td>
<td>2.93</td>
<td>51</td>
<td>0.7</td>
<td>76</td>
<td>87</td>
</tr>
</tbody>
</table>
The macro-texture of all materials both before and after the ridging tests was determined by means of conventional X-ray texture analysis using three incomplete pole figures, i.e., (110), (200) and (211). Measurements were made in the parallel beam mode on a Rigaku Smartlab X-ray diffractometer. Specimens were prepared to investigate surfaces parallel to the sheet surface. A normalized thickness parameter (S) is used to denote the layer investigated: 

\[ S = \frac{d}{\sqrt{3}t} \]

where \( d \) is the distance between the mid-thickness and the investigated layer and \( t \) is the sample thickness. Thus, \( S \) varies from 1 (surface) to 0 (center layer). Samples were prepared to investigate surfaces parallel to the sheet mid-thickness, \( S \).

For micro-texture characterization EBSD measurements were carried out in a scanning electron microscope (SEM) (LEO 1450VP). The EBSD data were used to generate texture data using the Oxford HKL acquisition and analysis software. For the EBSD measurements, the SEM was operated at 20 kV and the step size was 1 \( \mu m \). Texture data was acquired on sections parallel to the RD-ND plane, i.e. on the plane normal to the TD direction.

3. Numerical Calculations

Lankford parameter or r-value can be calculated using an approach based on single slip given by Vieth and Whiteley. \( ^{31,35} \)

\[ r = \frac{E_w}{E_t} \frac{[w \cdot d][w \cdot n]}{[t \cdot d][t \cdot n]} \] ........................ (2)

where \( w \) and \( t \) are unit normal vectors in the width and thickness directions, and \( d \) and \( n \) are unit vectors in the slip direction and the direction normal to the slip plane. To calculate the plastic strain ratio from Eq. (2), the operating slip system must be selected, which is taken as that with the highest Schmid factor (SF). Lee et al. \(^{42,43}\) proposed that r-values can also be calculated by considering all the slip systems weighted according to their SFs. Hence Eq. (2) can be expanded to include all slip systems weighted in proportion to their SFs. Considering one grain orientation at a time, like in visco-plastic calculations, \(^{44}\) for the \( i \)th orientation strained at an angle \( \theta \) to the RD we have

\[ r_{ij} = \frac{\sum_{j=1}^{N} [w_{ij} \cdot d_{ij}][w_{ij} \cdot n_{ij}] m_{ij}}{\sum_{j=1}^{N} [t_{ij} \cdot d_{ij}][t_{ij} \cdot n_{ij}]} \] ........................ (3)

where \( j \) is the slip system, \( m_{ij} \) is the SF of the \( j \)th slip system, \( l_{ij} \) is a unit vector along the tensile direction. For the material as a whole, the overall r-value is calculated by summing the contributions of the various orientations weighted according to their intensity in the ODF, i.e.

\[ r_0 = \frac{\sum_{i=1}^{N} r_{ij} f(g_i)}{\sum_{i=1}^{N} f(g_i)} \] ........................ (5)

where \( r_0 \) is the overall plastic strain ratio of the specimen for the direction \( \theta \), \( r_{ij} \) is the plastic strain ratio contribution of the \( i \)th orientation, \( g_i \) is the mean orientation of \( i \)th grain and \( f(g_i) \) is the texture intensity of the orientation which is obtained from the ODF using the MTEX toolbox as units of multiples of uniform distribution (MUD). The r-values are evaluated using all 24 slip systems, i.e. \{110\} \( <11\overline{1}> \) and \{112\} \( <11\overline{1}> \), and in line with the findings of Du et al., \(^{47}\) it is assumed that the critical resolved shear stress for slip on \{110\} and \{112\} planes is identical, i.e. CRSS \( (110) = CRSS (112) \).

4. Results

4.1. Ridging Test Results

Surface views of the samples after 15% elongation along the RD and TD are shown in Figs. 1 and 2 respectively. Ridging indices calculated based on the measured surface profiles are given in Table 3. The ridging indices after straining along RD, indicate that the samples A and B with high ridging (4.94, 1.90) and samples C and D with low ridging indices of 0.93 and 0.68. The ridging indices are low and similar among all the samples when elongated along TD. The ridging profiles of the samples are shown in Fig. 3. The results show that the ridging phenomenon is pre-dominantly dependent upon the direction of straining.

4.2. Grain Size and Mechanical Properties

The grain sizes, mechanical properties and measured r-values are given in Table 4. The grain sizes varied between ASTM 8.5 and 9.5. There is no correlation between grain size, r-value and ridging index. For example, compar-
ing the samples with the highest and lowest ridging indices (samples A and D respectively), grain sizes are very similar. For sample A $\tau$ is 1.86, which is higher than the 1.42 and 1.46 of samples B and C respectively, though A has the highest ridging index.

4.3. Macro-texture

Instead of displaying the entire ODF, textures can be represented in a very condensed way by plotting the orientation intensity along certain characteristic paths or distinct crystallographic fibers. In the case of BCC materials and alloys the most important orientations are in the $\phi_2 = 45^\circ$ section of the ODF as shown in Fig. 4. The ODF’s of specimens A, B, C and D near the surface ($S = 0.8$) and mid-thickness ($S = 0$) RD-TD planes are shown in Figs. 5(a)–5(d) and 5(e)–5(h) respectively. It can be observed that specimen A with severe ridging has a strong $\gamma$ fibre with the intensity peaks at $(111)<121>$ and $(554)<225>$. The maximum intensities are 17 and 19 in $S = 0.8$ and $S = 0$ sections respectively. Specimen D, which has the best ridging resistance, has much sharper texture at similar orientations, 21 and 28 for $S = 0.8$ and $S = 0$ sections. The other specimens B and C have much lower intensities when compared to A and D. Thus, the results indicate that there is no direct correlation between as-received macroscopic texture and ridging index.

The macro-texture of the samples after the ridging tests

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### Table 3. Details of the surface profile parameters and ridging indices after straining 15% along the rolling direction (RD) and the transverse direction (TD).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Straining along RD</th>
<th>Straining along TD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rz ($\mu m$)</td>
<td>Pc (mm$^{-1}$)</td>
</tr>
<tr>
<td>A</td>
<td>19.60</td>
<td>0.25</td>
</tr>
<tr>
<td>B</td>
<td>9.54</td>
<td>0.20</td>
</tr>
<tr>
<td>C</td>
<td>5.37</td>
<td>0.17</td>
</tr>
<tr>
<td>D</td>
<td>4.54</td>
<td>0.15</td>
</tr>
</tbody>
</table>

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### Table 4. Grain size, tensile properties and measured Lankford parameters.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Grain size (ASTM No.)</th>
<th>$R_{p0.2}$ (N/mm²)</th>
<th>$R_m$ (N/mm²)</th>
<th>Ag (%)</th>
<th>A80 (%)</th>
<th>$\tau$-value ($r_0$; $r_{45}$; $r_{90}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>8.7</td>
<td>299±±6</td>
<td>478±±2</td>
<td>20.5±±0.3</td>
<td>31.7±±0.3</td>
<td>1.66±±0.03 (1.66; 1.45; 2.08)</td>
</tr>
<tr>
<td>B</td>
<td>9.6</td>
<td>345±±6</td>
<td>512±±2</td>
<td>19.2±±0.3</td>
<td>29.7±±0.3</td>
<td>1.42±±0.03 (1.38; 1.21; 1.90)</td>
</tr>
<tr>
<td>C</td>
<td>11.4</td>
<td>370±±6</td>
<td>551±±2</td>
<td>17.1±±0.3</td>
<td>24.3±±0.3</td>
<td>1.46±±0.03 (1.29; 1.52; 1.53)</td>
</tr>
<tr>
<td>D</td>
<td>9.7</td>
<td>304±±6</td>
<td>474±±2</td>
<td>20.2±±0.3</td>
<td>31.0±±0.3</td>
<td>1.78±±0.03 (1.85; 1.62; 2.02)</td>
</tr>
</tbody>
</table>

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Fig. 2. Surface images of the specimens (A-D) after straining 15% along the transverse direction (TD).

Fig. 3. Surface profiles of the specimens (A–D) after straining along RD. For better illustration, the profiles of specimen A is adjusted to A+10 $\mu$m, specimen B B−5 $\mu$m, and C to C+5 $\mu$m.

Fig. 4. ODF ($\phi_2 = 45^\circ$) showing the most important orientations in bcc materials.
(elongation 15%) with the tensile axis in the RD are shown in Figs. 6(a)–6(d) at \( S = 0.8 \) and 6(e)–6(h) at \( S = 0 \) sections. Similarly, the results for the tensile axis in the TD are given in Figs. 7(a)–7(d) at \( S = 0.8 \) and 7(e)–7(h) at \( S = 0 \). Interestingly, the behavior of all the samples towards changes in texture is similar. When compared to the ODF’s prior to straining Fig. 6 shows the texture intensities along the \( \gamma \) fibre have decreased significantly and increased towards the \( \alpha \) fibre. It is apparent that 15% strain causes the grain orientations to rotate towards the \( \varphi_1 = \phi = 0^\circ \) corner of the \( \varphi_2 = 45^\circ \) ODF section, i.e. towards cube (001) [101] orientations.

In the case of specimen A, the maximum ODF intensity at \( S = 0.8 \) decreased from 17 to 9.6 and at \( S = 0 \) from 19 to 14. For the remaining specimens a similar although weaker trend is seen.

The changes in the ODF intensities caused by straining 15% along the TD were quite different, for the intensities on the \( \gamma \)-fibre \(<111>\)/\( \text{ND} \) risen significantly for all the samples, as shown in Fig. 7. For specimen A, \( f(g)_{\text{max}} \) at \( S = 0.8 \) increased from 17 to 30 and from 19 to 41 at \( S = 0 \). Similarly, for sample D the maximum intensity at \( S = 0 \) grown from 28 to 39. It is very well known that a
strong {111}/ND intensity means a high r-value. The changes observed after the straining of the material in RD and TD, i.e., decrease and increase of <111>/ND intensities are in correlation with the measured r-values. The measured r-values along RD (i.e., r₀ values) are lower compared to the r-values along TD (r₉₀) as can be seen from Table 4.

4.4. Micro-texture
The intensities of the texture components along the γ-fibre <111>/ND have no correlation with ridging resistance: they are similar in the specimens with both the lowest resistance and highest towards ridging. Hence, specimens A and D were studied in detail using EBSD. Whereas, the XRD macro-textures were measured on the RD-TD planes at S = 0 and S = 0.8, EBSD micro-textures were measured on TD-ND cross sections covering the entire sheet thickness for a distance of 3 mm in the TD. The micro-textures of as-received specimens A and D on the TD-ND planes are shown in Fig. 8. In specimen A, the regions covering the upper and lower 1/3rd of the sheet thickness show a higher frequency of <001>/ND orientations compared to the central 1/3rd. And the lower section which has more <111>/ND orientations. However, specimen D shows more randomly dispersed <001>/ND grain orientations and a higher frequency of <111>/ND oriented grains all through the thickness. These observations give quali-

![Fig. 7](image-url) Macro-textures of specimens after 15% elongation along TD. Contour lines at intervals of 1 unit. Sub-surface (S = 0.8) location shown in (a–d) and center-line (S = 0) in (e–h) Sample A in (a) and (e), sample B in (b) and (f), sample C in (c) and (g), sample D in (d) and (h).

![Fig. 8](image-url) IPF-colored EBSD map showing micro-texture of sample A through the sheet thickness. Coloring indicates the crystallographic orientations of the TD-ND cross sections of (a) specimen A and (b) specimen D. (Online version in color.)
tative information regarding the differences between the specimens that might explain the different ridging behaviour shown in Fig. 1.

5. Discussion

5.1. $r$-value Calculation

In the models of Chao, Takechi and Wright et al., it was assumed that bands of certain textural orientations exist. These models attributed ridging to the different plastic strain ratios that result from cube-on-face or cube-on-edge texture components. Shin et al., verified the results of the above models using CPFEM calculations combined with nominal texture components, but they did not use actual grain orientations that can be obtained EBSD data. All the other models mentioned in the introduction include the essential mechanisms behind the ridging phenomenon, but they too assume ideal grain orientations. However, the micro- and macro-texture measurements shown in Figs. 5–7 indicate that the actual grain orientations deviate substantially from the ideal orientations, which will also have implications for calculated $r$-values.

In this study, $r$-values were calculated for specimens A and D from their actual textures using mean orientations of all the individual grains and weighting slip systems according to their Schmid factors (SF) according to Eq. (5). The threshold SF was set as 0.29 when the strain direction is along RD and TD, and as 0.22 for straining 45° to RD. Figure 9 shows that the measured and calculated $r$-values are in good agreement for both the specimens and all test directions.

5.2. Ridging

To help understand the effect of local texture variations on local $r$-values and the ridging phenomenon $r$-values were calculated for individual orientations in the $\phi_2 = 45^\circ$ section of the ODF covering the Euler angles $\phi_1 = 0^\circ$ to $90^\circ$ and $\phi$ with a step size of $1^\circ$. Figure 10 exhibits the results of

![Fig. 9. Measured vs calculated $r$-values of specimens A and D.](image)

![Fig. 10. $r$-value contours for orientations in the $\phi_2 = 45^\circ$ section of the ODF and $r<1$ black, $1<r<2$ grey, $r>2$ white. (a) straining along the RD, SF limit 0.29. (b) straining along TD, SF limit 0.29. (c) schematic illustration of the effect of straining direction on grain rotations as seen in $\phi_2 = 45^\circ$ section. (Online version in color.)](image)
the calculations made using Eq. (5) considering all 24 slip systems with the SF limits described above, i.e. 0.29 along RD and TD. The r-values that would result for hypothetical, single grained specimens in each orientation of the \( \varphi_2 = 45^\circ \) section of the ODF undergoing an infinitesimal strain along RD or TD. The texture changes caused by 15\% strain depict that straining along RD causes the grains to rotate towards \(<110>/RD\), i.e. \( \varphi_1 = 0^\circ \), while straining along TD causes the grains to rotate towards \((111)/ND\), i.e. \( \phi = 54.7^\circ \), as illustrated in Fig. 10(c). The measured r-values agree with the above findings as the r-values of all the specimens are lower along RD compared to the r-values along TD.

5.2.1. r-value Maps along RD
The individual r-values of the grains for the specimen A and D of the TD-ND section shown in Fig. 8 are again plotted with their corresponding r-values calculated from their mean grain orientations depending upon the strain direction, i.e. RD and TD, as shown in Fig. 11. Grains with different r-values respond to the applied strain differently in respect of the degree to which they contract in the thickness direction: for example, a grain with low r-value contracts more than a grain with high r-value. Since ridging is caused by variations in thinning tendency across the transverse direction, it is reasonable to expect that the clustering of grains with low r-values lies behind the ridging phenomenon. Visual inspection of the grains with r<1 in Fig. 11 shows that they tend to be grouped in colonies in sample A while in D they are more homogenously spread throughout the thickness and across the width of the sample. Brochu et al.\(^{10}\) performed orientation imaging microscopy (OIM) and analyzed grain orientations of the RD-TD and TD-ND planes. They found that the mild ridging behavior is associated with relatively random distributions of the various orientations. However, samples with clusters and bands of approximately width of 100 µm of \(<001>/ND\) and \(<011>/ND\ orienta-
tions showed severe ridging behavior. Park et al.\textsuperscript{14)} reported grain colonies or grain clusters of {001} <110> and {112} <110> orientations located at the mid-thickness region of the sheet samples susceptible high ridging. Their results are in support of Chao\textsuperscript{5)} and Wright\textsuperscript{6)}'s ridging mechanisms that the presence of such grain colonies can cause different r-values compared to the matrix thereby producing ridging. The studies of Shin et al.\textsuperscript{9)} studies also showed that the locations of similar grain colonies found in the center zone agree with their ridging severity. Shin et al.\textsuperscript{9)} modeled the effect of {001} <110>, {112} <110> oriented grain colonies in the randomized texture matrix. The result of CPEM analysis showed that the lower plastic strain ratio of the {001} <110> and differences in shear deformation between {111} <110> and {112} <110> colonies results in ridging. The present results agree with these studies: the r-value map of the sample with poor ridging resistance (sample A in Fig. 11) also shows the presence of colonies of grains with r<1, which explains its lower resistance towards ridging compared to sample D, where such orientations are homogenously spread through the thickness and width of the sample. Comparing the r-value maps of samples A and D for straining along TD, no colonies of grains with similar r-values are apparent in either sample A or D, which agrees with the observation that straining along TD does not result in ridging in either sample.

5.2.2. Simulation of Surface Profile after Straining

Since ridging results from local variations in the plastic anisotropy of the grains, the following simplified approach was used to quantitatively calculate the ridging profile expected in specimens A and D based on the r-values of individual grains as shown in Fig. 11. These r-value plots were divided into equally wide, through-thickness columns. Then the average r-value was calculated for each column for both RD and TD straining directions. From the calculated r-values of each column, the change in thickness caused by 15% strain was calculated assuming a uniform initial thickness of 1 000 µm. The result is shown in Fig. 12. It was assumed that the contiguous columns of grains act individually so that interactions between the columns can be ignored.

The predicted surface profiles of specimen A and D are similar and intertwined when the straining direction was TD. Whereas, when the straining direction was RD, the surface profile of specimen A has a higher amplitude, i.e. it has higher peaks and lower valleys, than that of specimen D. Rt, which is the sum of the highest peak and valley in the surface profile, for specimen A is almost 9.27 µm while for sample D it is only 5.19 µm. The calculated surface profiles are therefore in line with the measured ridging surface profiles.

6. Summary and Conclusions

The reasons for the different ridging behaviour of industrially produced, stabilized ferritic stainless steel sheets (EN1.4509) with low and high ridging were investigated after straining in the rolling and transverse directions. The applied 15 (%) strain along RD and TD and its overall effect on evolution of macro-texture has been studied. Macro-texture studies showed that, compared to the texture of the as received material, the texture was strengthened towards the α-fibre when the applied strain is along RD and the γ-fibre was strengthened during straining along TD. Macro-texture measurements indicated that there was no direct correlation between as-received macroscopic texture and ridging indices.

Micro-textural measurements have been made across the thickness and width of specimens with high and low ridging indices. The material with low resistance to ridging has a larger fraction of grains with {001} //ND and (110)//RD orientations with r-values <1 than the material with high ridging resistance. These grains are in large clusters in sample with high ridging severity, whereas they are less frequent and, more importantly, homogenously dispersed the throughout the thickness and width of the material with higher resistance to ridging.

The overall r-values of the specimens with high and low ridging indices were calculated using the individual grain orientations obtained from EBSD measurements and considering all slip systems weighted according to their Schmid factors (SF) together with minimum SF threshold. The calculated and measured r-values were in good agreement. The individual r-values of the grains were further used to determine the sheet surface profiles after straining 15% along RD and TD.

The resultant profiles were in good agreement with those measured after the ridging test. This demonstrates that the local texture variations causing the ridging defect can be quantitatively calculated using the simple approach of calculation r-values of individual grains based on their actual orientations.

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Fig. 12. Upper surface profile of specimens A and D after 15% strain along RD and TD assuming a uniform initial thickness of 1 000 µm.
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