Influence of Texture on Ridging and Formability of 16%Cr Ferritic Stainless Steel

J. Mola, D. Chae and B. C. De Cooman

1 Materials Design Laboratory, Graduate Institute of Ferrous Technology, Pohang University of Science and Technology, Pohang, South Korea
2 Stainless Steel Research Group, Technical Research Laboratories, POSCO, Pohang, South Korea

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Abstract. The influence of the texture on ridging and forming properties of transformable 16mass-%Cr steel was studied for two different specific processing routes. In the first route (HACA), hot strips were annealed prior to cold rolling, whereas in the second route (HCA), un-annealed hot strips were directly subjected to cold rolling. Results indicate that compared to HACA, HCA results in an improved surface smoothness, i.e. reduced roping, but a lower mean r-value, as a result of strengthening of the α-fiber texture components. Differences in the roping and forming properties could also be achieved by compositional differences resulting in differences in the fraction of austenite at hot rolling temperatures.

Introduction

Ridging or roping is the formation of corrugations lying parallel to the rolling direction at the surface of sheets during forming operations. Their depth is typically 20-50 µm [1]. They become noticeable after deep drawing operations although they may exist even right after cold rolling. At present, there are two main theories to account for the occurrence of ridging in ferritic stainless steels. The first theory relates ridging to the presence of chemical segregation bands [2,3]. In the second theory, ridges are attributed to the non-homogeneous flow of the steel during cold rolling and subsequent forming operations e.g. deep drawing [1,4-7]. The former theory does not account for the fact that ridging is less pronounced in the transformable ferritic stainless steels in which the formation of compositional bands is more likely when γ forms during hot rolling operations [1,7]. In the latter theory, the non-homogeneous flow is attributed to the arrays of low r-value grain colonies usually possessing α-fiber orientations, i.e. rolling direction//<110>, lying along the rolling direction which are embedded in a high r-value matrix oriented close to the γ-fiber, i.e. normal direction//<111>. The low r-value texture components are believed to originate from as-cast columnar grains with {001}<uv0> orientations, which survive even after numerous processing steps [1,6,7].

Countermeasures against ridging in ferritic stainless steels attempt to eliminate or reduce the volume fraction of these undesirable grain colonies. Hitherto proposed methods are refinement of the solidification structure via electromagnetic stirring [8], rolling of merely equiaxed grains by trimming out the columnar zone of the as-cast structure [1,6], cold rolling of martensite [9], double step cold rolling with intermediate annealing [10,11], and un-lubricated hot rolling [12]. The elimination of the annealing after hot rolling of ferritic stainless steels has also been tried out. This has been found to deteriorate the ridging resistance in the case of non-transformable ferritic stainless steels [11]. In the case of transformable grades it leads to weakly textured sheets having an improved ridging resistance [6]. However, the annealing time after cold rolling of the transformable hot strips is usually not long enough to ensure a homogenous micro-structure of ferrite and carbides. Deep drawability is another important issue for ferritic stainless steels. Any potential processing modification must not only take into account the ridging resistance, but also address formability.
The present work illustrates how the processing conditions of the 16%Cr ferritic stainless steel impact both the texture, and the related normal anisotropy, and the ridging characteristics.

**Experimental Procedure**

The composition of the 16%Cr ferritic stainless steels used in the present study is shown in Table 1. The as-received materials were in the form of hot rolled strips with a thickness of 3 mm, which experienced the following two processing routes. One set of each composition was immediately cold rolled by 80% followed by a prolonged box annealing in a route identified as HCA onwards. Another set of hot strips underwent a processing route denoted by HACA, which consisted of a prolonged box annealing, cold rolling by 80%, and the final recrystallization annealing stage. The sheets produced according to the above schedules were compared in terms of the ridging height by measuring roughness in the direction transverse to the rolling direction. The tensile specimens were taken parallel to the rolling direction and pre-strained by 15% prior to ridge height measurements.

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>N</th>
<th>Cr</th>
<th>Mn</th>
<th>Ni</th>
<th>Si</th>
<th>Ti</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low C</td>
<td>0.022</td>
<td>0.039</td>
<td>16.15</td>
<td>0.54</td>
<td>0.12</td>
<td>0.23</td>
<td>-</td>
<td>Bal.</td>
</tr>
<tr>
<td>Standard</td>
<td>0.040</td>
<td>0.036</td>
<td>16.13</td>
<td>0.39</td>
<td>0.13</td>
<td>0.29</td>
<td>0.01</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

The Lankford parameter (r-value) was used to estimate the deep formability. The r-value was measured during tensile tests on a Zwick/Roell universal tensile testing machine. The r-value in the strain range of 10%-15% was averaged for tensile specimens lying at 0°, 45° and 90° to the rolling direction.

Sample preparation for Electron Back-Scattering Diffraction (EBSD) measurements consisted of SiC paper grinding, polishing using diamond paste down in size to 0.25 µm, and 40 min of colloidal silica polishing followed by a final ultrasonic cleaning stage. EBSD was utilized to perform micro-texture analysis on the RD planes of final sheets to detect the presence of low r-value grain colonies causing ridging. EBSD ODFs were also constructed from the same RD section measurements.

Dilatometry was used to compare the austenite fractions at high temperature. The experiments were done using a Bahr 805 pushrod dilatometer. Reported equilibrium thermodynamic calculations were obtained with the Thermo-Calc software.

**Results**

Roughness measurement results for the pre-strained tensile specimens are shown in Fig. 1. The standard composition is clearly associated with a less pronounced ridging regardless of the processing route. Comparing the two different routes, the HCA leads to a better ridging resistance as evidenced by the smoother surface after HCA processing. This clearly shows that the elimination of annealing prior to cold rolling reduces ridging.

The r-values measured for the different conditions are shown in Fig. 2 as a function of angle to RD. Whereas $r_{45}$ shows the lowest value followed by $r_0$ and $r_{90}$ in the case of the HACA route, the HCA route results in the reversal of the trend of r-value versus angle with $r_{45}$ exhibiting the highest r-value followed by $r_{90}$ and $r_0$. It is also noted that the mean r-values, $r_m$, for the HACA route materials are generally higher than those of the HCA route. Regarding the effect of composition, the low C variant shows higher r-values than its standard counterpart in the HACA route while this difference vanishes by switching to the HCA route.

It is well known that the r-value behavior strongly depends on the texture and that the texture is usually not uniform in the through-thickness direction. Therefore, when the r-value is to be correlated to the texture, EBSD ODFs scanned from the whole RD or TD sections should be preferred to the XRD ODFs which are only representative of a certain depth below the surface.
φ2=45° sections of EBSD ODFs for the different conditions are illustrated in Fig. 3. Whereas in the HACA route the γ-fiber (<111>//ND) is dominant, the HCA processing results in a more uniform distribution of several texture components by adding to the intensity of the α-fiber (<110>//RD).

Fig. 1. Ridging heights measured along the transverse direction of tensile specimens pre-strained by 15% along the RD. Roughness parameter $R_t$ measures the vertical distance between the highest peak and the deepest groove.

Fig. 2. Average r-values in the tensile strain range of 10-15% for the differently oriented tensile specimens. Each point represents the arithmetic mean of at least 4 measurements and the error bars indicate the standard deviation.

Fig. 3. φ2=45° sections of EBSD ODFs measured from the RD planes of sheets. (a) standard composition, HACA route, (b) low carbon composition, HACA route, (c) standard composition, HCA route, (d) low carbon composition, HCA route.

Discussion
The ridging heights measured here (Fig. 1) are smaller than the values reported for the non-transformable ferritic stainless steels [1,7,11]. This is very likely due to the partial breakdown of the
columnar grains, which may otherwise persist and eventually lead to low normal anisotropy colonies in the final sheets. Such a breakdown is especially effective provided the second phase (γ) exists during the hot rolling operations. The difference in the ridging behavior of the two compositions can thus be ascribed to their unequal γ fractions. Fig. 4(a) compares the thermodynamically calculated γ fractions for the two compositions at high temperatures where the standard composition is predicted to have a higher γ fraction. The dilatometry results upon continuous heating of the similarly oriented specimens of both compositions are also shown in Fig. 4(b). The decrease in the instantaneous Coefficient of Thermal Expansion (CTE, i.e. the derivative of the relative displacement-temperature curve) is due to the decrease in the specific volume of specimens upon γ formation. The larger decrease in the case of the standard composition thus signifies a higher γ fraction. Therefore, the higher γ fraction of the standard composition at hot rolling temperatures may account for its superior ridging resistance compared to the low C variant.

In the HACA route, a fully ferritic matrix with a homogeneous array of embedded Cr$_{23}$C$_6$ precipitates undergoes cold rolling while in the HCA route, the as hot-rolled microstructure, which is basically a banded mixture of relatively soft α and hard transformation products of the high temperature γ notably α', is subjected to cold rolling. Presence of the hard second phase during cold rolling of un-annealed strips is expected to further facilitate breakdown of the undesirable grain colonies originating from the as-cast structure as it does during the hot rolling. The HCA route is therefore more favorable in view of the ridging characteristics.

EBSD orientation imaging maps obtained from the RD planes of sheets were examined to search for the grain colonies with large mis-orientations with the matrix, but no clear evidence of such colonies could be found. This is in good agreement with the observed anti-ridging properties.

The r-value trends for the HACA sheets typify those of the commercial ferritic stainless steel sheets after the final recrystallization-annealing step. This trend, i.e. $r_{90}>r_{60}>r_{45}$, is a result of the dominance of grains only slightly mis-oriented from the desirable γ-fiber which is characterized by texture components with a large r-value and a small planar anisotropy. As the calculations based on the relaxed constraint model of crystal plasticity compiled from the literature data [13,14] indicate (Fig. 5), the trends obtained for the HACA sheets can be accounted for based on their corresponding ODFs. The {111}<112> can be considered the major texture component for both compositions in the HACA route. Presence of texture components on the TD fiber (TD//<110>), deviated from

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**Fig. 4.** (a) Thermodynamically calculated γ fractions for the standard and low C compositions based on the Thermo-Calc. (b) Instantaneous CTEs experimentally obtained from the dilatometry.
(111)[112] towards (332)[113] can then manipulate the r-value trend from the ideal {111}<112> towards the experimentally measured trends of Fig. 2. The higher r-values for the low C composition compared to the standard one in the HACA route is simply related to its stronger γ-fiber.

Reversal of the r-value trend by cold rolling of un-annealed hot strips can be attributed to the strengthening of the α-fiber as a result of cold rolling and recrystallization of a non-homogenous deformed microstructure mainly consisted of α' and α since as Fig. 5 demonstrates, α-fiber components act to raise the $r_{45}$. In a study on the r-value behavior of a non-transformable ferritic stainless steel, increasing cold reduction ratio and elimination of annealing after hot rolling, both of which acting to increase the amount of stored energy in the cold rolled sheets, have been found to increase the $r_{45}$ in the final recrystallized state [11]. This was as a result of a shift in the position of peak texture component from {111}<112> to {223}<472>, which is closer to the α-fiber. The relatively intense α-fiber in the case of HCA route sheets in the present study may be a result of the recrystallization of severely deformed ferrite grains in the banded hot strips if the martensite does not deform appreciably and the ferrite alone accommodates the cold rolling strains. Alternatively, the α-fiber components may have developed during the recrystallization of γ transformation products including martensite in the banded structure during the recrystallization in the HCA sheets.

![Fig. 5. Orientation dependence of the r-value for several texture components of importance to ferritic steels calculated based on the relaxed constraint model of crystal plasticity. Redrawn from [13,14].](image)

**Conclusions**

1- Cold rolling and recrystallization of un-annealed hot strips of 16%Cr ferritic stainless steel resulted in an improved ridging resistance but reduced mean r-values compared to when batch annealed hot strips with a homogenous microstructure of α+Cr$_2$C$_6$ are cold rolled and recrystallized.

2- Reversal of the angular dependence of the r-value of final sheets, when the hot strips are directly cold rolled without an intermediate annealing step, can be attributed to the strengthening of the α-fiber texture components.

3- The ridging resistance was quite high for all processing conditions. This is very likely due to the absence of detectable grain colonies based on the EBSD grain orientation maps obtained on RD sections.

4- The increased ridging resistance of steel with a higher carbon content is due to its higher γ fraction during hot rolling which facilitates the breakdown of the as-cast columnar structure.
References