Effect of Texture Components on the Lankford Parameters in Ferritic Stainless Steel Sheets

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Two ferritic stainless steel (FSS) sheets were produced to display different recrystallization textures. The in-plane variation of the Lankford parameter $R(\alpha)$ was calculated from the sheet textures and compared to the $R$-values determined experimentally. The textures of the FSS sheets were further decomposed into a number of individual texture components to clarify the effect of the main texture constituents on $R(\alpha)$. The in-plane variation of $R(\alpha)$ is mainly governed by the main texture component, while minor texture components generally reduce the overall level of $R(\alpha)$. A desirable high normal anisotropy $\overline{R}$ and small in-plane variations of $R(\alpha)$ are obtained for texture components with an Euler angle $\phi$ lying in the range $50^\circ \leq \phi \leq 60^\circ$, which comprise the $\gamma$-fiber orientations close to {111}/ND.

KEY WORDS: texture; anisotropy; $R$–value; Lankford parameter; ferritic stainless steel.

1. Introduction

Sheet formability is often characterized by the Lankford parameter ($R(\alpha)$–value) which defines the ratio between the in-plane and through-thickness strains associated with a tensile test performed at an angle $\alpha$ with respect to the rolling direction (RD) of the sheet.1,2) Since there is a strong relationship between the crystallographic texture and formability of the metal sheet,3,4) control of the texture is essential to optimize the formability of sheet metals.

In the interstitial-free (IF) steels used for automobile panel applications, a suitable combination of cold rolling and subsequent recrystallization annealing leads to the formation of a favorable $\gamma$-fiber texture comprising the orientations with $\{111\}$ parallel to the sheet normal direction (ND). This texture gives rise to the desired high $R$–values and good deep drawability of IF steel sheets.5,6)

In ferritic stainless steel (FSS) sheets, the main recrystallization texture component is found at $\{334\}<483>$ instead of the $\gamma$-fiber orientations.9,12) The FSS sheets are produced by a series of thermo-mechanical processes including continuous casting, hot rolling, cold rolling and recrystallization annealing, all of which affect the formation of texture and sheet formability of the final FSS product.12,14) Raabe and Lücke suggested that the formation of the particular recrystallization texture $\{334\}<483>$ in FSS can be explained by a preferred growth of this component into the $\{112\}<110>$ rolling texture component by way of a mechanism called ‘selected particle drag’.15,16) Work by the present authors also showed that a growth selection out of the scattered rolling texture regions into the $\{112\}<110>$ matrix orientation leads to the formation of the $\{334\}<483>$ component in FSS.12,13,17) Because of this peculiar recrystallization texture, the sheet formability of FSS is generally inferior to that of IF steels.

There are numerous papers on the correlation of anisotropic properties with the crystallographic texture, and for steel sheets it is straightforward to derive the in-plane variation of the $R$–value from sheet texture.12,13,17) However, analysis of the full sheet texture does not allow to differentiate the impact of certain orientations or texture components on the resulting anisotropy. That is to say, it is not straightforward to assess which orientations in a given texture improve and which impair the formability of metal sheets. The literature has seen a few attempts to calculate the $R(\alpha)$–values of individual orientations and texture components.18–20) Recently, Jung, Mola, Chae and De Cooman interpreted ridging and formability of FSS sheets by calculating $R$-values from the textures.21,22) However, a detailed quantification of the texture by texture components and a study of their effects on anisotropy and formability of FSS sheets is still lacking.

In this study, two FSS sheets were prepared with and without annealing after hot rolling. From an earlier study it was known that hot band annealing significantly altered the subsequent cold rolling and recrystallization textures and, accordingly, the resulting $R(\alpha)$–values.17,23) Firstly, the textures of the recrystallized FSS sheets were used to simulate the $R(\alpha)$–values of the two different sheets. Then, the two sheet textures were decomposed into sets of individual texture components, which allowed to study the impact of certain texture components on the $R(\alpha)$–values. Eventually, these findings may be utilized to improve the formability of...
2. Experimental Procedure

In the present study a commercial ferritic stainless steel (FSS), in which most of the interstitial atoms in the ferrite matrix are scavenged by additions of titanium, was used. The chemical composition of the FSS sheet is given in Table 1. For improving the formability of FSS, the contents of sulfur and phosphorus should be minimized. The present material possessed sulfur and phosphorous contents typical of commercial grade FSS.

In order to achieve two samples with different recrystallization textures, two process routes were pursued. The first sample was used in the as-received hot rolled state; this material will be referred to as the HR sample hereafter (HR – hot rolled). The second sample was given an additional hot band annealing treatment at 950 °C for 60 s, and is denoted as the AHB sample (AHB – annealed hot band). Both hot band samples were then reversibly cold rolled with a thickness reduction of 80% to a final thickness of 0.7 mm with lubricant oil. Finally the cold rolled sheets were recrystallized annealed at 800°C for 20 s.

The microstructure of the starting samples was analyzed by electron backscattered diffraction (EBSD). The measurements were carried out in a scanning electron microscope equipped with a Schottky field-emission gun (FEG-SEM). The crystallographic textures of the sheets were determined by measuring pole figures in a standard X-ray texture goniometer. X-ray texture measurements were carried out at three different layers of each specimen. The three-dimensional orientation distribution functions (ODFs) were calculated using the series expansion method, where the ODFs \( f(g) \) are expanded in a series of generalized spherical harmonic functions \( T_{lm}^{\alpha} (g) \) with the series expansion coefficients \( C_{lm}^{\alpha} \) (\( l_{\text{max}} = 22 \)).

\[
f(g) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \sum_{n=-l}^{l} C_{lm}^{\alpha} \cdot T_{lm}^{\alpha} (g) \quad \text{.................................. (1)}
\]

The orientations \( g \) are expressed by a triple of Euler angles \( \varphi_1, \Phi, \varphi_2 \) (Bunge’s notation). Since all relevant orientations and fibers found in the textures of steel sheets reside in the \( \varphi_2 = 45^\circ \) section of the Euler space, all ODF representations are confined to this section. Details of the measurement and representation of texture data are reported in the literature. Tensile tests were employed to determine the \( R \)-values of the recrystallized samples. Standard tensile specimens were strained by 15% at a constant cross-head speed of 5 \( \times 10^{-4} \) \( \text{s}^{-1} \). To obtain the \( R(0^\circ) \), \( R(45^\circ) \) and \( R(90^\circ) \) values, tensile tests were carried out at angles \( \alpha \) of 0°, 45° and 90° to the sheet rolling direction (RD). \( R(\alpha) \)-values for the experimental and the synthesized textures were calculated from the series expansion coefficients \( C_{lm}^{\alpha} \) using Bunge’s method.

3. Experimental Results

3.1. Initial Textures and Microstructures

As mentioned above, two different samples were used as the starting materials in this experiment, \( i.e. \) the as-received hot rolled material HR and the hot band annealed sample AHB. Figure 1 shows the microstructures of the longitudinal sections of the two starting materials observed by EBSD measurements from the transverse direction (TD). In the following, the layer within the sheet is indicated by the thickness parameter \( s \), with \( s = 1.0 \) and \( s = 0.0 \) denoting the surface and center layer of the sheet, respectively, such that \( s = 0.5 \) identifies the quarter layer.

The EBSD inverse pole figure (IPF) maps in Figs. 1(a) and 1(b) show the through-thickness microstructural features of the hot rolled HR sample consisting of strongly elongated large grains in the inner thickness layers and small grains in the outer surface layers. Thus, the starting microstructure of the HR sample for this experiment was
quite inhomogeneous. The IPF maps further indicate that the small grains in the outer layers are fairly randomly oriented, while the large elongated grains in the inner layers are oriented mostly in the α- or γ-fibers. Here, the α-fiber comprises the orientations with a common <110> direction parallel to the rolling direction (RD), i.e., the orientations \{hkl\}<110>, and the γ-fiber comprises orientations with \{111\}<uvw>. The blue grains in the ND IPF map in Fig. 1(a) and the green grains in the RD IPF map in Fig. 1(b) are oriented in the γ-fiber and α-fiber, respectively.

The microstructure and texture of the hot band changed notably during annealing at 950°C for 60 s. As evident from Figs. 1(c) and 1(d), the annealed hot band AHB displayed coarsened, rounder grains than the non-annealed sample HR. In the layers close to the sheet center (s = 0.0) large grains with sizes ranging from 100 to 300 μm prevailed, while in the outer layers close to the surface (s = 1.0) small equiaxed grains with sizes of approximately 50 μm were observed. The IPF maps of the AHB sample indicate that the grains in this sample were almost randomly oriented. It is noted that the microstructure and texture in the AHB sample were much more uniform throughout the thickness layers than in the HR sample.

3.2. Formation of Cold Rolling and Recrystallization Textures

The two different starting samples HR and AHB were cold rolled to a thickness reduction of 80%, and Figs. 2 and 3 show the ϕ2 = 45° sections of the resulting cold rolling textures. Texture measurements were carried out at the center (s = 0.0), quarter thickness (s = 0.5) and surface (s = 1.0) layers. Subsequently, the integral sheet texture was obtained by averaging the textures of the three different layers.

The cold rolled HR sample displayed a strong rotated cube orientation \{001\}<110> at (0°, 0°, 45°) together with \{001\}/ND orientations and some <110> RD α-fiber orientations (Fig. 2). This type of cold rolling texture is not usually observed in low carbon steel sheets. Rather, the strong starting texture prior to cold rolling had a pronounced impact on the development of the cold rolling texture in the HR sample. The \{001\}/ND texture in FSS is inherited from the microstructure of the as-cast ingots, which are usually comprised of a columnar grain structure with the fast-growing \{001\} direction aligned parallel to the ND.\(^\text{12,13,17,23}\) The as-cast ingot of the present material displayed equiaxed grains in the middle layer and columnar grains with a length of 10 to 40 mm in the outer layers. The center layer comprising equiaxed grains took about 60% of the ingot thickness. Accordingly, both the hot strip and the cold rolled material of the HR sample showed appreciable texture gradients through the thickness layers.

The AHB sample displayed a cold rolling texture resembling the typical rolling textures of low carbon steel sheets, in which the orientations are assembled along the α and γ-fibers (Fig. 3). In contrast to the strongly textured HR sample, the hot band annealed AHB sample had a nearly random texture prior to cold rolling. This initial texture in the AHB sample provided the conditions for the grains to rotate to develop the typical cold rolling texture.\(^\text{5–8}\) The texture maximum in the cold rolled AHB sheet was observed at (0°, 45°, 45°). This component is deviated by 45° from the rotated cube \{001\}<110> (0°, 0°, 45°) which was the main component in the HR sample. That is to say, hot band annealing effectively reduces the rotate cube texture in FSS.

Finally, the cold rolled samples were annealed at 800°C for 20 s for recrystallization. After annealing, the texture gradients through the thickness layers diminished in both HR and AHB samples, as shown in Figs. 4 and 5, respectively. Therefore, the integral textures presented in Figs. 4(d) and 5(d) appropriately represent the average textures of the whole sheet thickness.

As expected, the HR and AHB samples displayed remarkably different recrystallization textures. The maximum orientation density f(g) in the texture of the HR and AHB samples was observed at (20°, 45°, 45°) and (30°, 50°, 45°), respectively; scattering from the main texture peak was also different. In the HR sample the main texture component was observed at (20°, 45°, 45°) with an anisotropic scatter in two directions (Fig. 4). Furthermore, the HR sample possessed

![Fig. 2. Cold rolling texture of the HR sample. (a) s = 0.0, (b) s = 0.5, (c) s = 1.0, (d) averaged texture by merging three thickness layers.](image)

![Fig. 3. Cold rolling texture of the AHB sample. (a) s = 0.0, (b) s = 0.5, (c) s = 1.0, (d) averaged texture by merging three thickness layers.](image)
This texture corresponds to the peculiar {334}<483> recrystallization texture of FSS sheets mentioned in the introduction.

The main texture peak of the AHB sample is observed at \((30°, 50°, 45°)\) with significant scattering along the \(\gamma\)-fiber (along \(\Phi = 55°\)) (Fig. 5). In addition, the AHB sample displayed minor intensities of the cube texture \((45°, 0°, 45°)\). This texture is comparable to the recrystallization textures that are typically obtained in regular plain-carbon steel grades. The observed differences in the final recrystallization textures of the HR and AHB samples can be attributed to the differences in the up-stream hot and cold rolling textures of the two samples.\(^{14,22}\)

### 3.3. \(R(\alpha)\)-values

Tensile tests were employed to determine the \(R(\alpha)\)-values of the recrystallized samples. To obtain the experimental \(R(0°), R(45°)\) and \(R(90°)\) values, tensile tests were carried out at angles \(\alpha\) of \(0°, 45°\) and \(90°\) to the RD, respectively.

The average value \(\overline{R}\) is commonly calculated by:

\[
\overline{R} = \frac{1}{4} \left( R(0°) + 2 \cdot R(45°) + R(90°) \right)
\]  \(\text{(2)}\)

Figure 6 shows the evolution of the experimental \(R(\alpha)\)-values as a function of the in-plane angle \(\alpha\) (open symbols). The AHB sample shows much higher \(R(0°)\) and \(R(90°)\) values than the HR sample, while the \(R(45°)\) value in the HR sample is somewhat higher than that in the AHB sample. For the HR sample, this leads to an average value \(\overline{R}\) of 1.35, whereas the AHB sample has an average \(\overline{R}\)-value of as much as 1.62 (see Table 2).

High formability and most notably good deep drawing properties further require a low planar anisotropy of the sheet, that is to say, a low variation of the \(R(\alpha)\)-value in the sheet plane. This is commonly quantified by the parameter \(\Delta R\) which is defined as:

\[
\Delta R = \frac{1}{2} \left( R(0°) - 2 \cdot R(45°) + R(90°) \right)
\]  \(\text{(3)}\)

The HR sample has a negative value of \(\Delta R = -0.7\), while in the AHB sample \(\Delta R\) is positive, \(\Delta R = 0.45\) (Table 2). Note that the absolute value of \(\Delta R\) of the AHB sample is smaller than that of the HR sample. This fact, together with the higher average \(\overline{R}\) value, points at a higher formability of the AHB sample.

### 4. Correlation of Texture and Lankford Parameters

#### 4.1. Computation of \(R(\alpha)\)-values from Texture

It is commonly accepted that crystallographic texture is the main cause for the occurrence of plastic anisotropy in steel sheets.\(^{3,4}\) In order to quantify the impact of the two dif-
different textures of the HR and AHB samples on the resulting \( R(\alpha) \)-values (Fig. 6, Table 2), the two sheet textures (Figs. 4 and 5) were used to compute the in-plane evolution of the \( R(\alpha) \)-values with the Taylor model.\(^3\)\(^2\)\(^5\)\(^2\)\(^6\)

In order to determine \( R \)-values with the help of the Taylor model, the sheet texture (expressed by its \( C^{\alpha \beta} \) coefficients) is subjected to the external strain rate \( D \) for which a tensile test along direction \( X_1 \) can be expressed as:

\[
D = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -q & 0 \\ 0 & 0 & (1-q) \end{pmatrix} \Delta \hat{c} \quad \text{............................ (4)}
\]

(\( \Delta \hat{c} \): step width). It is seen that the strain rate is controlled by the contraction ratio, \( q \). Thus, determination of the correct strain rate acting upon tensile deformation – and therewith prediction of the resulting \( R \)-values – requires the determination of the correct value of \( q \). This can be achieved under the assumption that the most probable value of \( q \) is defined by minimum internal work for the tensile test.\(^3\)

Thus, the Taylor factor \( M(q) \) is computed according to the Taylor model for a series of different values of \( q \), with \( 0 \leq q \leq 1 \). The value of \( q \) that results in the minimum value of \( M(q) \) then readily gives the \( R \)-value:

\[
R = \frac{D_{c2}}{D_{c3}} = \frac{q}{1-q} \quad \text{............................ (5)}
\]

The above discussion applies for tensile deformation along direction \( X_1 \), which usually relates to the former sheet rolling direction, RD. In order to determine the variation of the \( R(\alpha) \)-value in the sheet plane, the strain rate has to be rotated by angle \( \alpha \) about the common normal direction, ND = \( X_3 \).

Figure 6 shows the evolution of the simulated \( R(\alpha) \)-values as a function of the in-plane angle \( \alpha \) in steps of \( \Delta \alpha = 10^\circ \) (Table 3). Comparison with the experimental \( R(\alpha) \) values (open symbols) proves a very good fit between the texture-based simulations and the experimental \( R \)-values in both samples. Table 3 lists the calculated \( R(\alpha) \)-values for 0°, 45° and 90° together with the resulting formability parameters \( \bar{R} \) and \( \Delta \bar{R} \). Comparison with the experimental results (Table 2) shows that the simulations tend to predict slightly higher (absolute) values of both \( \bar{R} \) and \( \Delta \bar{R} \). This is attributed to the fact that the experimental \( R \)-values were determined only for the three angles of \( \alpha = 0^\circ, 45^\circ \) and 90°, whereas the simulations were performed in much finer 10° steps. This always leads to some residual errors when maxima and minima of the \( R(\alpha) \) curves do not exactly coincide with the angles of \( \alpha = 0^\circ, 45^\circ \) and 90° (see Fig. 6).

### 4.2. Decomposition of Textures into Elliptical Gauss Components

In the preceding section it has been shown that the different \( R(\alpha) \) of the HR and AHB samples can fully be accounted for by the differences in their respective textures (Figs. 4 and 5). However, analysis of the full sheet texture does not yield information on the impact of certain orientations or texture components on the resulting anisotropy, which impairs the improvement of materials properties through dedicated texture control.

In order to assess the contribution of the various texture constituents – i.e. the major components in the sheet textures – on \( R(\alpha) \), the experimental textures of the FSS sheets (Figs. 4 and 5) were decomposed into distinct sets of texture components. This is routinely done by fitting the experimental texture by a number of Gauss-shaped distributions with a (half) scatter width \( \psi_0 \).\(^2\)\(^7\)\(^2\)\(^8\) An isotropic spherical Gaussian distribution is fully prescribed by three parameters, viz. its center position, scattering angle \( \psi_0 \) and volume fraction. However, anisotropic texture components, i.e. those having different scattering in different directions, cannot be properly modeled by isotropic spherical Gaussian distribution.

An anisotropic Gaussian distribution with different scattering in three directions is described by means of the multivariate Gaussian distribution (MGD). In a three-dimensional space, parameters determining the position, direction, density, size and shape are required for defining the MGD. The shape of the MGD is governed by the variance-covariance matrix comprising 3 × 3 elements. When the distribution contains certain symmetries, the number of parameters can be substantially reduced. Especially, for an elliptical Gaussian distribution with one major axis and two mutually perpendicular minor axes, the elements in the variance-covariance matrix reduce to two independent parameters, viz. the major and minor scattering angles \( \psi_{\text{major}} \) and \( \psi_{\text{minor}} \).\(^2\)\(^9\)\(^3\)\(^\circ\)\(^3\)\(^\circ\)\(^1\) Thus, in total, an elliptical Gaussian distribution requires five parameters, including the center position, major and minor scattering angles, major scattering axis and volume fraction. Accordingly, use of elliptical Gaussian texture components gives more flexibility and, therewith, facilitates the description of non-isotropic texture components like the characteristic fiber-type textures of bcc steel sheets.

In order to illustrate the difference between the two approaches, Fig. 7 gives examples of the spherical and elliptical Gaussian distributions of a texture component with a central position \( \psi_0 \) at \((15°, 35°, 45°)\). The spherical distribution has an isotropic scattering angle of \( \psi_0 = \pm 15° \) along all three scattering axes, while the elliptical distribution has a scattering angle of \( \psi_{\text{major}} = \pm 20° \) along the major axis (here \(-[1 \ 0 \ 0]\)) and \( \psi_{\text{minor}} = \pm 10° \) along the two minor axes. Subsequently, the elliptical Gaussian distribution was fitted with a number of isotropic individual orientations. In both cases the set of orientations constituting the central texture components was augmented with an equal number of randomly

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Table 3. \( R \)-values calculated from sheet textures.

<table>
<thead>
<tr>
<th>Sample</th>
<th>( R(0^\circ) )</th>
<th>( R(45^\circ) )</th>
<th>( R(90^\circ) )</th>
<th>( \bar{R} )</th>
<th>( \Delta \bar{R} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR</td>
<td>0.5</td>
<td>1.9</td>
<td>1.2</td>
<td>1.37</td>
<td>1.05</td>
</tr>
<tr>
<td>AHB</td>
<td>1.7</td>
<td>1.4</td>
<td>2.3</td>
<td>1.70</td>
<td>0.60</td>
</tr>
</tbody>
</table>

![Fig. 7.](image-url) (a) Spherical and (b) elliptical Gaussian distributions of the texture components at \((15°, 35°, 45°)\).
oriented orientations, such that the distributions shown in Fig. 7 relate to textures that are composed of 50% of the main texture component plus 50% random orientations.

With the help of the elliptical Gaussian distributions the experimental recrystallization textures of the HR and AHB samples (Figs. 4(d) and 5(d)) were decomposed into sets of only three or four texture components, respectively. The optimum values of the parameters defining the elliptical Gaussian texture components were derived according to the following procedure.

1) As described in Sec. 2, the ODFs $f(g)$ of the experimental textures were calculated in the regular $(\varphi_1, \Phi, \varphi_2) = 5^\circ \times 5^\circ \times 5^\circ$ grid in the Euler space of $(0^\circ \leq \varphi_1, \Phi, \varphi_2 \leq 90^\circ)$.

2) The maximum value of $f(g)$ in the ODF gives the center position $(g_0)$ of the main texture component.

3) By analyzing the major scattering from $g_0$, one can determine the scattering directions toward $g_1$ and $g_2$ in the Euler space. The major scattering axis is obtained by calculation of the rotation axis connecting $g_0$, $g_1$, $g_2$. The two minor scattering axes are then positioned perpendicular to the major axis.

4) The remaining texture components are located separately in the Euler space. Therefore, center position and major and minor scattering axes of the minor texture components can be derived independently from the main texture component.

5) After the determination of the center positions and scattering axes of the three or four most important texture components, the resulting ODFs are recalculated with various values for the major scattering angle $\Psi_{\text{major}}$ and volume fraction, while for the minor scattering angle $\Psi_{\text{minor}}$ a constant value of $10^\circ$ was chosen. The best fit between the recalculated texture and the experimental texture then provides the parameter values of the quantified texture components.

Table 4 lists the modeled texture components of the HR and AHB samples, where each texture component is characterized by its central position $\varphi_1, \Phi, \varphi_2$ in Euler space, major scattering axis and angle $\Psi_{\text{major}}$, minor scattering angle $\Psi_{\text{minor}}$ and its volume fraction. The peak positions of the two main texture components of the HR sample are found at $(20^\circ, 50^\circ, 45^\circ)$ and $(15^\circ, 35^\circ, 45^\circ)$. These two large components together with a small component at $(0^\circ, 0^\circ, 45^\circ)$ form the texture of the HR sample. In the AHB sample, the main texture component with a large fraction of 35% is found at $(30^\circ, 50^\circ, 45^\circ)$ which coincides with the maximum of the experimental texture. Additionally, three small texture components are identified in this sample. Note that the textures of the HR and AHB samples further contained fractions of random orientations of 35 and 37%, respectively, which were modeled by adding the appropriate number of randomly oriented orientations.

Figures 8 and 9 show the textures which were determined from the individual texture components for the HR and AHB samples (Table 4). Obviously, the recalculated ODFs resemble the experimental ODFs of the HR and AHB samples in Figs. 4(d) and 5(d), which demonstrates the validity of the present approach of texture quantification with the help of elliptical Gaussian distributions.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Central position of texture component in Euler space $\varphi_1, \Phi, \varphi_2$</th>
<th>Major scattering axis</th>
<th>Major scattering angle $\Psi_{\text{major}}$</th>
<th>Minor scattering angle $\Psi_{\text{minor}}$</th>
<th>Volume fraction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR</td>
<td>$(0^\circ, 0^\circ, 45^\circ)$</td>
<td>[001]</td>
<td>$15^\circ$</td>
<td>$10^\circ$</td>
<td>5</td>
</tr>
<tr>
<td>HR</td>
<td>$(15^\circ, 35^\circ, 45^\circ)$</td>
<td>$-110$</td>
<td>$20^\circ$</td>
<td>$10^\circ$</td>
<td>30</td>
</tr>
<tr>
<td>HR</td>
<td>$(20^\circ, 50^\circ, 45^\circ)$</td>
<td>[525]</td>
<td>$15^\circ$</td>
<td>$10^\circ$</td>
<td>30</td>
</tr>
<tr>
<td>AHB</td>
<td>$(45^\circ, 0^\circ, 45^\circ)$</td>
<td>[001]</td>
<td>$20^\circ$</td>
<td>$10^\circ$</td>
<td>5</td>
</tr>
<tr>
<td>AHB</td>
<td>$(20^\circ, 30^\circ, 45^\circ)$</td>
<td>[122]</td>
<td>$20^\circ$</td>
<td>$10^\circ$</td>
<td>10</td>
</tr>
<tr>
<td>AHB</td>
<td>$(20^\circ, 50^\circ, 45^\circ)$</td>
<td>[141]</td>
<td>$15^\circ$</td>
<td>$10^\circ$</td>
<td>13</td>
</tr>
<tr>
<td>AHB</td>
<td>$(30^\circ, 50^\circ, 45^\circ)$</td>
<td>[323]</td>
<td>$20^\circ$</td>
<td>$10^\circ$</td>
<td>35</td>
</tr>
</tbody>
</table>

Fig. 8. Texture components for the HR sample. Components at (a) $(0^\circ, 0^\circ, 45^\circ)$, (b) $(15^\circ, 35^\circ, 45^\circ)$, (c) $(20^\circ, 50^\circ, 45^\circ)$, (d) recalculated texture of the three texture components (plus random background).

Fig. 9. Texture components for the AHB sample. Components at (a) $(45^\circ, 0^\circ, 45^\circ)$, (b) $(20^\circ, 30^\circ, 45^\circ)$, (c) $(20^\circ, 50^\circ, 45^\circ)$, (d) $(30^\circ, 50^\circ, 45^\circ)$, (e) recalculated texture of the four texture components (plus random background).
4.3. Effect of Texture Components on $R$–values

As described in detail in the previous subsection, the recrystallization textures of the HR and AHB samples were decomposed into a set of three or four individual components with elliptical Gaussian distributions (Figs. 8 and 9). For these components the in-plane variations of $R(\alpha)$ were calculated and compared to those derived from the full textures (Fig. 10). Again, the orientation sets constituting the main texture components were augmented with an equal number of randomly oriented orientations. Subsequently, the $C^m\alpha$-coefficients of the textures were computed according to the series expansion method 3,24 and input in the code for modeling $R(\alpha)$–values.

For the HR sample the variation of $R(\alpha)$ is most similar to that of the component at $(15^\circ, 35^\circ, 45^\circ)$, with low $R(0^\circ)$– and $R(90^\circ)$–values and a maximum at $45^\circ$ (Fig. 10(a)). The minor component at $(0^\circ, 0^\circ, 45^\circ)$ shows a similar evolution, yet it substantially lowers the $R(\alpha)$ curve. The second main component at $(20^\circ, 50^\circ, 45^\circ)$ slightly raises the $R(\alpha)$–values, but it displays a different shape of the curve.

In the AHB sample the variation of $R(\alpha)$ is reproduced by the main component at $(30^\circ, 50^\circ, 45^\circ)$ and the minor component at $(20^\circ, 50^\circ, 45^\circ)$ (Fig. 10(b)). The other two minor components at $(45^\circ, 0^\circ, 45^\circ)$ and $(20^\circ, 30^\circ, 45^\circ)$ reduce the overall level of the $R(\alpha)$–values.

From the above discussion it follows that the overall level of $R(\alpha)$ is generally raised by texture components with higher Euler angle $\Phi$. To visualize the impact of $\Phi$ on $R(\alpha)$, the variations of $R(\alpha)$ were calculated for several texture components along $(0^\circ, \Phi, 45^\circ)$. Here a spherical Gaussian distribution of $\gamma_0 = \pm 15^\circ$ was assumed and, as detailed above, the calculation was again carried out with a half of the orientations situated in the texture component and the other half oriented randomly. The results, presented in (Fig. 11(a)), prove that the variation of $R(\alpha)$ indeed strongly depends on the Euler angle $\Phi$ of the texture component. The lowest level of $R(\alpha)$–value < 0.8 is obtained for the component $(0^\circ, 0^\circ, 45^\circ)$, i.e. $\Phi = 0^\circ$. The component at $(0^\circ, 30^\circ, 45^\circ)$ shows a large variation of $R(\alpha)$ ranging from $R(0^\circ) < 0.4$ to $R(50^\circ) > 2.2$. The minimal in-plane variation of $R(\alpha)$ around 2.0 is observed for the component at $(0^\circ, 55^\circ, 45^\circ)$, while the component at $(0^\circ, 80^\circ, 45^\circ)$ displays the largest variation of $R(\alpha)$ with $R(\alpha) > 2.0$ at $0^\circ \leq \alpha \leq 20^\circ$ and $R(\alpha) < 0.8$ at $50^\circ \leq \alpha \leq 75^\circ$.

As already alluded to earlier, high formability and most notably good deep drawing properties mandate a high average $R$–value, commonly expressed by the $\bar{R}$ value (Eq. (2)), together with a low in-plane variation of the $R$–value in the sheet plane, i.e. a low value of $\Delta R$ (Eq. (3)). Figure 11(b) shows the dependency of both parameters $\bar{R}$ and $\Delta R$ as a function of the Euler angle $\Phi$ for the texture components $(0^\circ, \Phi, 45^\circ)$. Note that the definitions for $\bar{R}$ and $\Delta R$ in Eqs. (2) and (3) are based on the experimental $R$–values obtained at angles $\alpha$ of $0^\circ$, $45^\circ$ and $90^\circ$, while for assessment of formability it is advantageous to relate $\Delta R$ to the exact maximum and minimum $R(\alpha)$–values. It is seen that the minimum $\bar{R}(\Phi)$–value is observed at $\Phi = 0^\circ$, i.e. the rotated cube orientation $\{001\}<110>$. The $\bar{R}(\Phi)$–value increases with increasing $\Phi$ angle up to $\Phi = 50^\circ$ and levels at high values of $\bar{R}(\Phi) \geq 2.0$ for texture components with $\Phi \geq 50^\circ$. For small $\Phi$ angles ranging from $0^\circ$ to $40^\circ$ $\Delta R(\Phi)$ first decreases from $-0.7$ to $-1.7$, before it sharply raises up to $\Delta R(\Phi) > +3.0$ for $\Phi = 90^\circ$ (Fig. 11(b)). Low absolute values of $\Delta R(\Phi)$ are found in the range $50^\circ \leq \Phi \leq 60^\circ$.

In summary, proper control of the texture in FSS sheets for improving the overall deep drawability and uniform sheet formability requires increasing the $\bar{R}$ value and decreasing the absolute $\Delta R$ value. According to Fig. 11, the optimum texture of the FSS is composed of the texture components lying at $50^\circ \leq \Phi \leq 60^\circ$ which comprise the $\gamma$-fiber orientations close to $\{111\}$/ND.

5. Conclusions

Two ferritic stainless steel (FSS) sheets displaying distinctly different recrystallization textures were prepared and the in-plane variations of the Lankford parameter ($R(\alpha)$–values) were determined experimentally and calculated using the textures. The textures of the two different FSS samples were quantified by means of a new method of decomposing the sheet textures into a small number of texture components having elliptical Gaussian distributions. The effect of these main texture components on the resulting $R(\alpha)$–values was analyzed, proving that the variation of $R(\alpha)$ is controlled by the main texture components, while the minor texture components tend to reduce the overall $R(\alpha)$–values.

Optimum sheet formability and, especially, overall deep drawability is achieved in sheets characterized by a high
normal anisotropy (i.e. high $\bar{R}$ value) and a low planar anisotropy (i.e. low $\Delta R$ value). The present assessment shows that texture components having Euler angles $\Phi \geq 70^\circ$ give a desirable high but an undesirable large $\Delta R$. Both high $\bar{R}$ and small $\Delta R$ are obtained in textures with their main components lying at $50^\circ \leq \Phi \leq 60^\circ$, which includes the $\gamma$-fiber orientations close to $\{111\}\langle ND \rangle$.

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REFERENCES