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Citation: J. Appl. Phys. 109, 07A325 (2011); doi: 10.1063/1.3560895
View online: http://dx.doi.org/10.1063/1.3560895
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Evolution of magnetic properties and crystallographic texture in electrical steel with large plastic deformation

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(Submitted 16 November 2010; received 24 September 2010; accepted 21 December 2010; published online 1 April 2011)

Deformation leads to a hardening of steel due to an increase in the density of dislocations and a reduction in their mobility, giving rise to a state of elevated residual stresses in the crystal lattice. In the microstructure, one observes an increase in the contribution of crystalline orientations which are unfavorable to the magnetization, as seen, for example, by a decrease in $B_{50}$, the magnetic flux density at a field of 50 A/cm. The present study was carried out with longitudinal strips of fully processed non-oriented (NO) electrical steel, with deformations up to 70% resulting from cold rolling in the longitudinal direction. With increasing plastic deformation, the value of $B_{50}$ gradually decreases until it reaches a minimum value, where it remains even for larger deformations. On the other hand, the coercive field $H_c$ continually increases. Magnetometry results and electron backscatter diffraction results are compared and discussed.


I. INTRODUCTION

In this work, the magnetic and microstructural properties of electrical steel sheets are analyzed after undergoing large plastic deformations due to cold rolling. Plastic deformation leads to a worsening of the magnetic properties of electrical steel, where one observes an increase in magnetic losses and a reduction in permeability. Deformation leads to a work hardening of the material due to an increase in the dislocation density and a reduction in their mobility, leading to a state of elevated residual stress in the lattice. This was discussed previously in a direct comparison between $H_c$ and the measured hardness of deformed electrical steel and has been considered in depth by Cullity. In the microstructure, one observes changes in the crystallographic texture and an increase of the crystalline orientations, which are unfavorable for the magnetization, and this is reflected in a reduction in $B_{50}$. The value of $B_{50}$, the magnetic flux density at a field of 50 A/cm, can be regarded as a measure of crystallographic texture favorable to higher magnetization values.

The dislocations give rise to pinning of the domain walls during the magnetization process and their movement is restricted until the magnetic field reaches a certain critical value. The coercive field $H_c$ increases with deformation since the dislocations make wall movement more difficult.

II. EXPERIMENT

Samples were prepared by cold rolling strips of fully processed NO electrical steel to various thickness reductions until small cracks began to appear. Strips of approximately 3 cm in width and 10 cm in length were then cut out. In Table I some of the principal characteristics of the steel are given.

In order to obtain greater resolution, the thickness of each sample was determined from values of the length, width, mass, and density. The deformation of the strips was quantified in terms of the thickness reduction $r_{esp\%}$, calculated from the values of the initial ($e_0$) and final ($e$) thicknesses using

$$r_{esp\%} = \left(1 - \frac{e}{e_0}\right) \times 100.\quad (1)$$

The magnetic characterization for static fields was carried out with a single-sheet tester installed in a Brockhaus MPG-100D system equipped with a fluxmeter. The hysteresis loss $P_h$ and the coercive field $H_c$ were measured for a maximum induction of 1.5 T under quasistatic conditions, whereas the induction $B_{50}$ was obtained with a magnetic field of 5000 A/m at 60 Hz.

Small pieces of the samples were set in bakelite and reduced to half-thickness by grinding. Afterward the samples underwent a metallographic polishing with diamond paste and a final polish with colloidal silica. Crystallographic texture was obtained in a FEI/Quanta 200 scanning electron microscope (SEM) equipped with an electron backscatter diffraction (EBSD)/TexSEM Laboratories (TSL) system and software OIM Analysis version 4.51.

<table>
<thead>
<tr>
<th>Steel</th>
<th>Density (kg/m³)</th>
<th>Si (%)</th>
<th>Al (%)</th>
<th>$J_c$ (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50F684M</td>
<td>7710</td>
<td>2.0</td>
<td>0.27</td>
<td>2.06</td>
</tr>
</tbody>
</table>

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(orientation imaging microscopy), obtained from a combination of images from three different regions, is shown in Fig. 1. The “good-point” ratio before performing the clean-up database operation was greater than 99%. The clean-up operation applied to the EBSD data was “grain dilation” with a tolerance angle of $5^\circ$ and minimum grain size of 2 $\mu$m. These measurements were used to calculate the volume fraction (VF) of the fiber represented by: $\{111\}(1\overline{1}0)$; $\{111\}(1\overline{2}1)$; $\{111\}(0\overline{1}1)$, and $\{111\}(\overline{1}0\overline{1})$, which are unfavorable directions for magnetic properties.

### III. RESULTS AND DISCUSSION

Table II contains the results obtained for the magnetic characterizations as well as the volume fractions calculated from the EBSD data.

The graph of Fig. 2 shows $H_c$ increasing continually as the deformation increases, indicating that $H_c$ is strongly influenced by the number of dislocations present in the material. The hysteresis loss $P_h$ increases with the deformation as expected, and follows the $H_c$ behavior.

In Fig. 3 $B_{50}$ is reduced to a small value with deformation and remains at that level despite the fact that the deformation continues to increase. The deformation leads to the rotation of the crystalline orientations in the steel, leading to

<table>
<thead>
<tr>
<th>$r_{exp%}$</th>
<th>$P_h$ (J/m$^3$)</th>
<th>$H_c$ (A/m)</th>
<th>$B_{50}$ (T)</th>
<th>VF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>243</td>
<td>31</td>
<td>1.702</td>
<td>0.090</td>
</tr>
<tr>
<td>2</td>
<td>543</td>
<td>101</td>
<td>1.669</td>
<td>0.079</td>
</tr>
<tr>
<td>7</td>
<td>681</td>
<td>127</td>
<td>1.642</td>
<td>0.096</td>
</tr>
<tr>
<td>23</td>
<td>999</td>
<td>190</td>
<td>1.547</td>
<td>0.114</td>
</tr>
<tr>
<td>29</td>
<td>1210</td>
<td>216</td>
<td>1.518</td>
<td>0.115</td>
</tr>
<tr>
<td>46</td>
<td>1591</td>
<td>279</td>
<td>1.459</td>
<td>0.123</td>
</tr>
<tr>
<td>48</td>
<td>1628</td>
<td>291</td>
<td>1.453</td>
<td>0.164</td>
</tr>
<tr>
<td>52</td>
<td>1775</td>
<td>309</td>
<td>1.447</td>
<td>0.164</td>
</tr>
<tr>
<td>61</td>
<td>1903</td>
<td>342</td>
<td>1.451</td>
<td>0.164</td>
</tr>
<tr>
<td>68</td>
<td>1921</td>
<td>347</td>
<td>1.456</td>
<td>0.165</td>
</tr>
</tbody>
</table>

FIG. 1. (Color online) Typical OIM (sample with $r_{exp\%} = 23$) obtained from a combination of images, with and without tilt correction, from three different regions, and the color legend.

FIG. 2. $P_h$ and $H_c$ increases with deformation.

FIG. 3. $B_{50}$ decreases until a minimum value and then remains constant, whereas $H_c$ continues to increase with deformation.

FIG. 4. The behavior of $B_{50}$ compared with that of $VF^{-1}$. The plateaus of both curves begin around $r_{exp\%} = 48$. 

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an increase in the $\gamma$ fiber. In Fig. 4, to facilitate a comparison, there is a plot of the inverse of the VF of the $\gamma$ fiber versus deformation showing that for $r_{\text{exp}}% \geq 48$, $VF^{-1}$ also stabilizes. From the results obtained in this material, one verifies that after a certain value of the deformation, the volume fraction of the $\gamma$ fiber no longer changes with deformation. However, the material is still able to accommodate a deformation through an increase in the density of dislocations and their movement. Comparing the behavior of $B_{50}$ and $VF^{-1}$ in Fig. 4, one observes that the plateaus begin as of the same value of deformation, consolidating the notion of a strong relationship between $B_{50}$ and the texture of the material.

IV. CONCLUSION

The worsening of magnetic properties with deformation of the sample is correlated with the development of $B_{50}$, and is associated with the behavior of the $\gamma$ fiber volume fraction. For large deformations this volume fraction stops increasing at $r_{\text{exp}}% = 48$, at a maximum value, and this effect is reproduced in the values of $B_{50}$. The deformation causes an increase in dislocation density and movement, which will pin the domain walls during magnetization of the material. The dislocations hinder domain wall movement, and this is associated with a continuous increase of $H_c$, even for deformations greater than $r_{\text{exp}}% = 48$. We conclude that the effect of crystallographic texture on the magnetic properties is present up to a maximum strain, whereas the dislocations and their movement always affect the magnetic properties.

ACKNOWLEDGMENTS

The authors wish to acknowledge the financial support of FINEP, CNPq, and FAPERJ. The electrical steel was furnished by Arcelor-Mittal.