Texture Control in Metal Sheet Processing by Innovative Processes

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**Electrical Steels**

**Grain Oriented Grades**
- Grain-oriented electrical steel sheets for high efficiency transformers
- Transformer Sheet

**Non-Oriented Grades**
- Non-oriented electromagnetic steel sheet
- Enlarged view
- Used in drive motors for hybrid vehicles

**Electrical Machines**

**Function of iron core:** magnetic flux carrier

**Requirements:** max. permeability $\mu$, min. iron losses ($P_h$, $P_e$)
Why are magnetic properties of steel texture dependent?

C.W. Chen, Magnetism and Metallurgy of Soft Magnetic Materials, p. 64
E.g. applied field direction $\mathbf{H}$

$$E_a = \text{extra energy required to magnetize unit volume of single crystal in a direction} \neq \langle 100 \rangle \text{ direction}$$

$$E_a = K_1 \left( \alpha_1^2 \alpha_2^2 + \alpha_2^2 \alpha_3^2 + \alpha_3^2 \alpha_1^2 \right)$$

$$+ K_2 \left( \alpha_1^2 \alpha_2^2 \alpha_3^2 \right)$$

$(\alpha_1, \alpha_2, \alpha_3) = \text{direction cosines of applied field}$

$K_1, K_2 = \text{anisotropy constants}$
For BCC materials (e.g. Fe-Si electrical steels):

All important rolling and recrystallization components are represented in \( \varphi_2 = 45^\circ \) section (with boundaries 0-90\(^\circ\))
Average A parameters for various textures

<table>
<thead>
<tr>
<th>A-parameter</th>
<th>Random Texture</th>
<th>Random Cube</th>
<th>$\gamma$-Fibre</th>
<th>$\alpha$-fibre</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>31.8</td>
<td>22.5</td>
<td>38.7</td>
<td>30.1</td>
</tr>
</tbody>
</table>

*phi2 = 45deg

**The best buy !!**
Texture development during conventional processing?
Texture development during NO steel processing?
Non-oriented Electrical steels:

- **Fully Processed Grades:**
  - Hot Rolling
  - Cold Rolling
  - Annealing
  - (skin pass)

- **Semi Processed Grades:**
  - id. Fully Processed
  + additional annealing treatment applied on punched lamellae

![Graphs with A=30.7 and A=31.5](image)
Conventional processing of electrical steels:

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Doorstootoventemp. (°C)</td>
<td>1070</td>
<td>1250</td>
<td>C</td>
<td>0.021</td>
<td>0.055</td>
</tr>
<tr>
<td>Slab reheating Temp (°C)</td>
<td>790</td>
<td>920</td>
<td>Si</td>
<td>0.000</td>
<td>2.153</td>
</tr>
<tr>
<td>Coiling Temp (°C)</td>
<td>580</td>
<td>780</td>
<td>P</td>
<td>0.006</td>
<td>0.032</td>
</tr>
<tr>
<td>HB annealing</td>
<td>niet</td>
<td>wel</td>
<td>S</td>
<td>0.008</td>
<td>0.033</td>
</tr>
<tr>
<td>Line speed (m/s)</td>
<td>150</td>
<td>250</td>
<td>N₂</td>
<td>0.0017</td>
<td>0.0224</td>
</tr>
<tr>
<td>Annealing temp. (m/s)</td>
<td>700</td>
<td>800</td>
<td>Al&lt;sub&gt;met&lt;/sub&gt;</td>
<td>0.011</td>
<td>1.060</td>
</tr>
<tr>
<td>Skin Pass reduction (%)</td>
<td>2</td>
<td>8</td>
<td>Sb</td>
<td>0.000</td>
<td>0.160</td>
</tr>
</tbody>
</table>

25° < A<sub>0</sub> < 31°

No significant improvement possible!
Alternative ways of texture control

**Cross Rolling** (lab scale)

- Hot Rolling in (α+γ) range
- **rotate sheet 90°**
- Cold Rolling (70-80%)
- Recrystallization Annealing
- Cold Rolling (4 - 8 %)
- Recrystallization Annealing
Texture Development during Cross Rolling

Cold Rolled

Static Recrystallization

Additionally Annealed

\( A = 24.3° \)

\( 5x \) {\( \{311\} <136> \)}

\( 156x \)

\( 50x \)
Cold Rolled textures IF steel

*Collaboration with Prof. N. Tsuji (Osaka University)
Recrystallized textures IF steel

Levels: 0.7, 1.0, 1.4, 2.0, 2.8, 4.0, 5.6, 8.0, 11, 16
Proposed strategy: Severe Plastic Deformation

- Si-alloyed ULC Steel

- $T_{\text{reheat}} = 1150°C$
- $T_{\text{coiling}} = 550°C$
- HR 90% (lubrication)
- Recrystallization annealing (900-1200°C)

CR reductions: 91%, 93%, 95%

Total true strain: $\varepsilon = 4.71, 4.96, 5.30$
Texture Evolution During Severe Plastic Deformation

Origin of the \{311\}<136> recrystallized component??

Present study

- Starting deformation Texture:
  \{001\}<110> ✔ → NO <110> 30°
- Survival of \{112\}<110> compt.
- Size advantage of \{113\}<136> in all observed stages of RX (early nucleation)
- No texture change during the GG

Indication of oriented nucleation of \{311\}<136>

Previous study

- recrystallized \{311\}<136>
- \{110\} 30° relationship
- highly deformed \{112\}<110> texture

Oriented growth
Verbeken et. al, Acta Mat (2005)
Observation of cold rolled structure: Ti-IF 60% cross rolled

- ND
- RD

Max 5.6

4 µm

$\{311\}<136>$
Nucleation mechanism of \{311\}<136> orientations

A bands

\[ \text{max} = 70.033 \]
- 60.000
- 32.000
- 16.000
- 8.000
- 5.000
- 3.000
- 1.000

A + B bands

\[ \text{max} = 81.035 \]
- 60.000
- 32.000
- 16.000
- 8.000
- 5.000
- 3.000
- 1.000

A bands

A + B bands
Nucleation mechanism of \{311\}<136> orientations: case A
Shear Bands in Rotated-Goss Orientations?
Can the Cube Component be generated by a shear band in a Rotated Goss component?

Initial Orientation:
Discretized R-Goss with Gaussian width 7°

CP Model: VPSC6 – Multi interaction mode
Strain mode: Rotated Simple Shear
Shear Band Inclination Angle: +35°
Texture evolution - RGoss

- $E = 0.00$
- $E = 0.14$
- $E = 0.29$
- $E = 0.43$
- $E = 0.57$
- $E = 0.87$
- $E = 1.15$
- $E = 1.73$
- $E = 2.31$
Surface texture by annealing in full austenite domain

Recrystallisation: no change
Inter-critical: No change

Transformation: yes

It appears that surface grains are very different in orientation as well as in structure → **surface energy anisotropy**
Surface texture by annealing in full austenite domain

Orientation

\([hkl] \langleuvw\rangle\)

Min

Total Fraction

- \((0 0 1) \langle 1 0 0\rangle\): 0° 0.014
- \((0 0 1) \langle 0 0 1\rangle\): 10° 0.072
- \((0 0 1) \langle 1 0 0\rangle\): 20° 0.178
- \((0 0 1) \langle 0 0 0\rangle\): 30° 0.291

Point-to-point and Point-to-origin graphs.
Surface texture by annealing in full austenite domain

Ar3 decreasing

Pure Iron

ULC Steel

ULC Steel + low Mn and Al (L3)

ULC Steel + high Mn and Al (L2)

α–γ–α anneal surface

Max 6.83

Max 3.73

Max 1.61

Max 1.60

RD

ND

0.80
1.00
1.30
1.60
2.00
2.50
3.20
4.00
5.00
6.40

α–γ–α anneal surface
Conclusions

Appropriate tools for quantifying texture and magnetic quality of texture are available.

**Conventional steel manufacturing**: limited degrees of freedom for magnetic texture control.

**Alternative processing** design was discussed:
- recrystallization texture after severe plastic deformation by accumulation of hot and cold rolling strain; {311}<136> texture can be obtained
- Cube Shear Bands are observed in rotated Goss orientations
- Surface anisotropy controlled texture control favours {001} and {110} surface textures.
Orientation Imaging Microscopy (OIM)
of surface textures in Mn alloyed IF steel


Before double phase tf.

After double phase tf.