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Nonoriented Magnetic Steel with Improved Texture and Permeability

H. Huneus, K. Günther, T. Kochmann, V. Plutniok, and A. Schoppa

In nonoriented silicon steel, high-field permeability usually decreases with decreasing core loss. Recently developed steel grades offer higher magnetic polarization and medium-to-low total loss due to improved crystallographic texture.

Keywords
magnetic steel, magnetic steel strip, nonoriented magnetic steel

1. Introduction

THE magnetic properties of nonoriented magnetic steel strip are characterized by the specific total loss and polarization values for various field strengths that determine magnetic permeability. Commercially available grades are shown in Fig. 1.[1-5] The aim is to lower specific total loss and to increase magnetic permeability by low-cost processing steps and hence to reduce the manufacturing and operating costs of electric machines.

H. Huneus, T. Kochmann, and **A. Schoppa,** EBG Gesellschaft für elektromagnetische Werkstoffe mbH, Bochum, Germany; **K. Günther** and **V. Plutniok,** Thyssen Stahl AG, Duisburg, Germany.

2. Basic Aspects

The main factors influencing magnetic properties are strip thickness, concentration of the main alloying elements silicon and aluminum, grain size, level of impurities, and crystallographic texture.

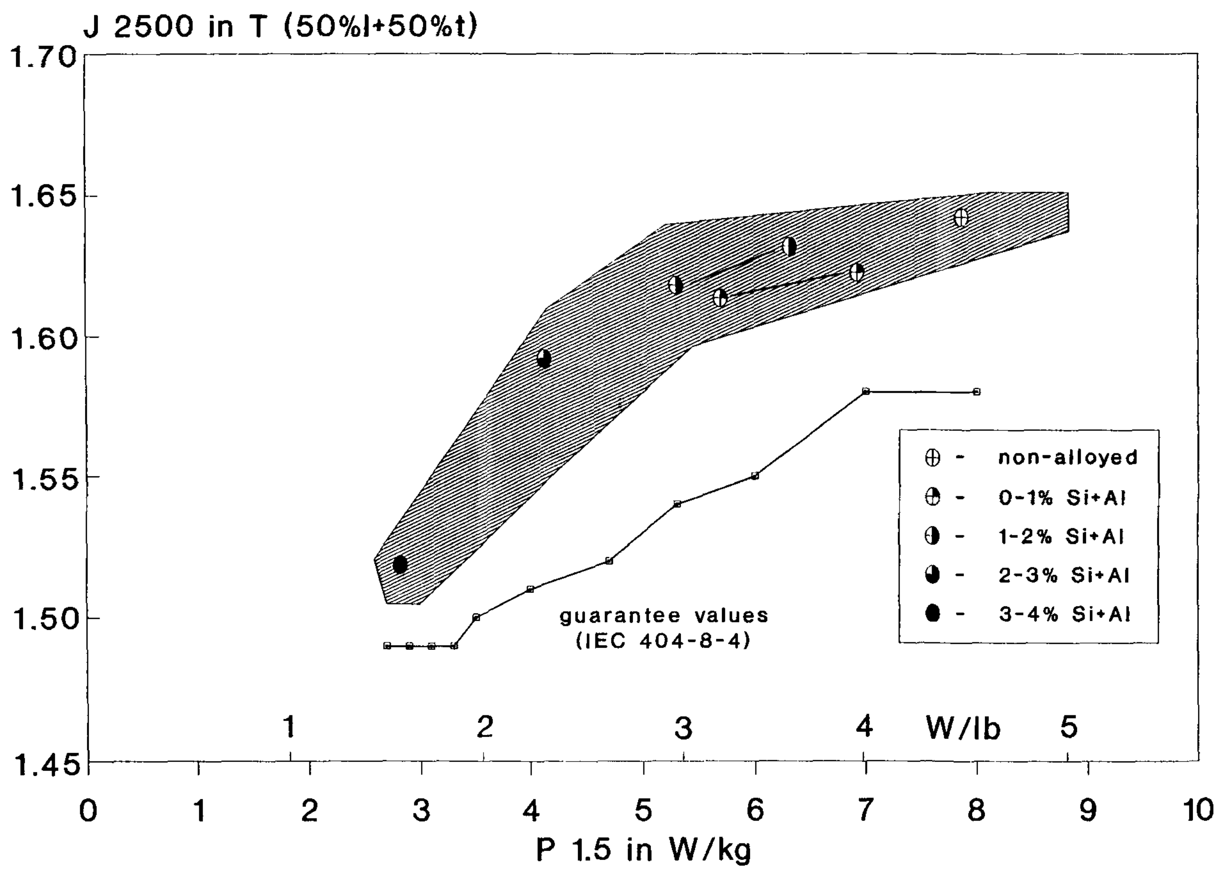

Fig. 1 Typical relation between total loss P 1.5 at $J = 1.5$ T and the magnetic polarization J 2500 at a magnetic field strength of $H = 2500$ A/m of fully processed grades in 0.5-mm thickness. The symbols indicate the alloy content of the material.

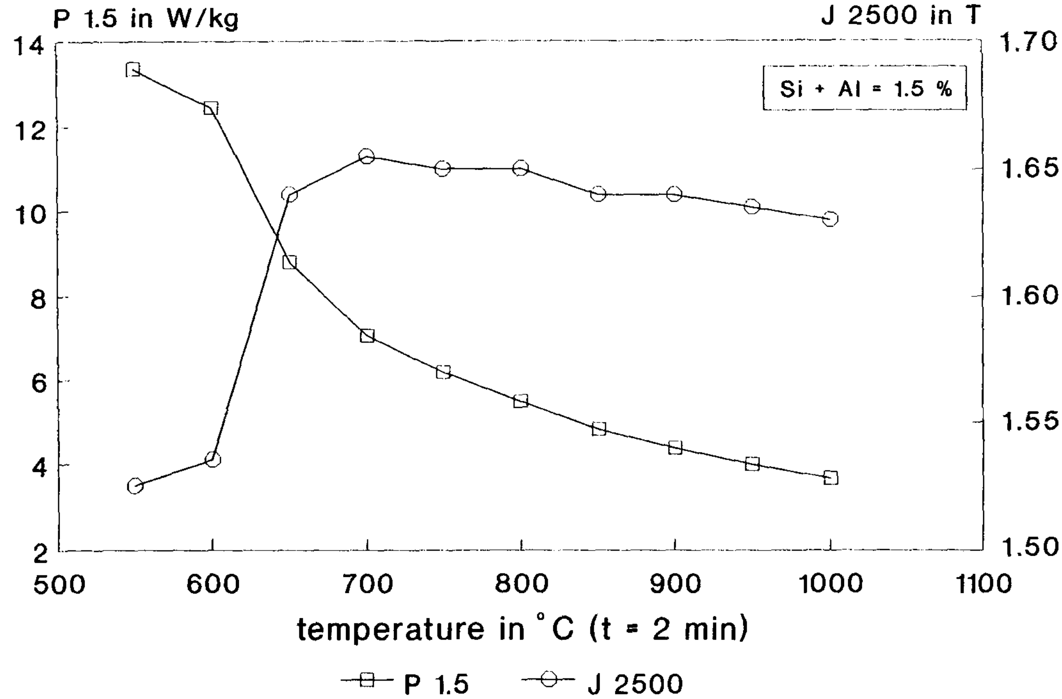

Fig. 2 Influence of final annealing temperature on core loss and polarization.

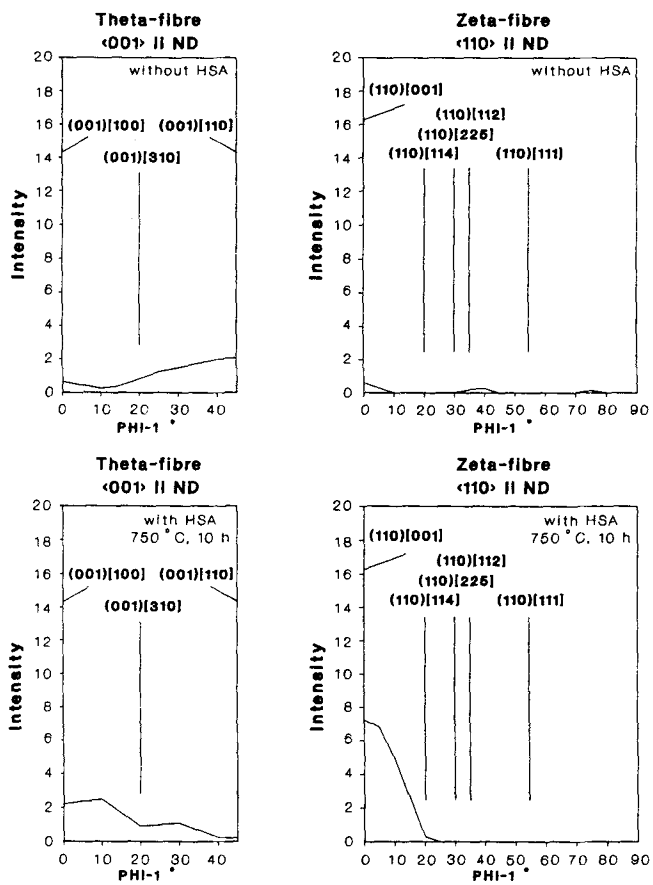

Fig. 3 Texture of low-alloyed (Si + Al < 1%) grade after final annealing at 950 °C for 1 min.

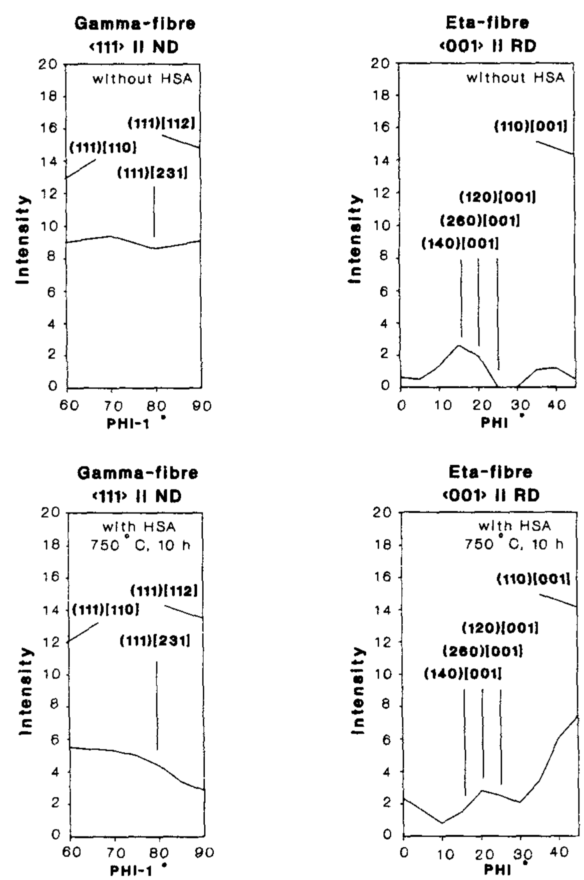

Fig. 4 Texture of low-alloyed (Si + Al < 1%) grade after final annealing at 950 °C for 1 min.

2.1 *Total Loss*

A low total loss is achieved by a low strip thickness, a high alloy concentration, an optimum grain size of about 100 μm,[6] a low level of impurities, and a good texture in that the lowest coercivity is found in the (100) crystallographic direction.

2.2 *Magnetic Polarization*

The magnetic polarization J is highest at a low alloy concentration, a small grain size—except for secondary recrystallized material—and a good texture. Two favorable textures are the (001)[*hk*0]-cube-on-face and the (001)[100]-cubic texture, bearing the highest in-sheet-plane polarization:

$$\langle J(\alpha)\rangle = \frac{1}{\pi}\int_0^{\pi} J2500(\alpha)d\alpha$$

where α is the angle to the rolling direction.

Table 1 Typical magnetic values for Staboperm® T1 at 0.5 mm thickness

	Longitudinal to RD	Transverse to RD	45° to RD
P1.5, W/kg	3.0	3.6	3.6
J2500, T	1.70	1.63	1.59

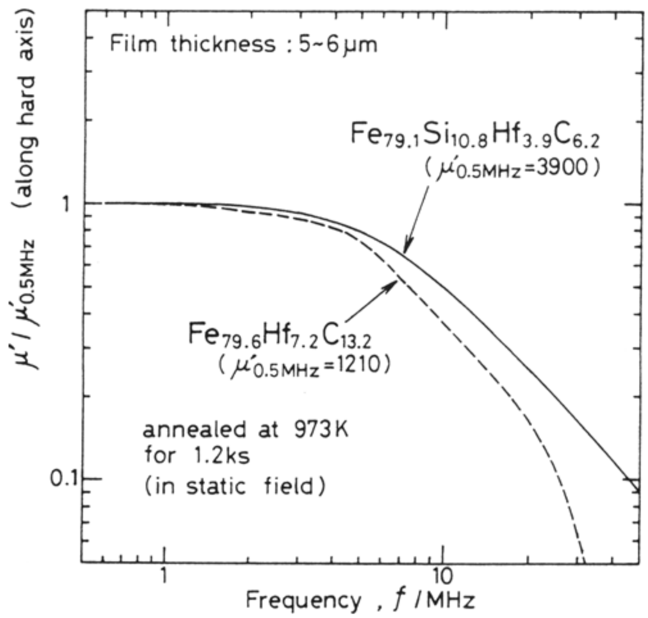

Fig. 6 Micrograph of the hot strip grain structure of Staboperm® T1.

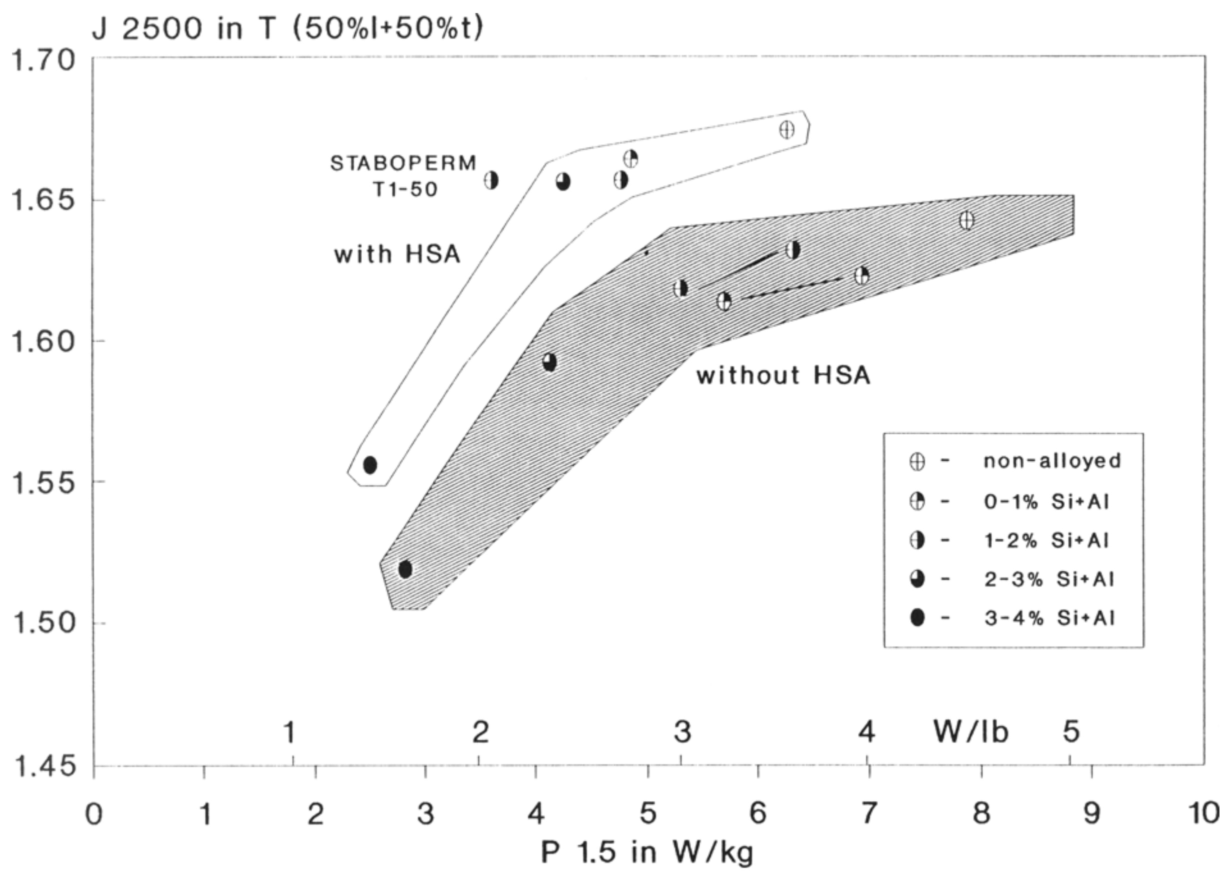

Fig. 5 Comparison of grades with and without hot strip annealing and Staboperm® T1.

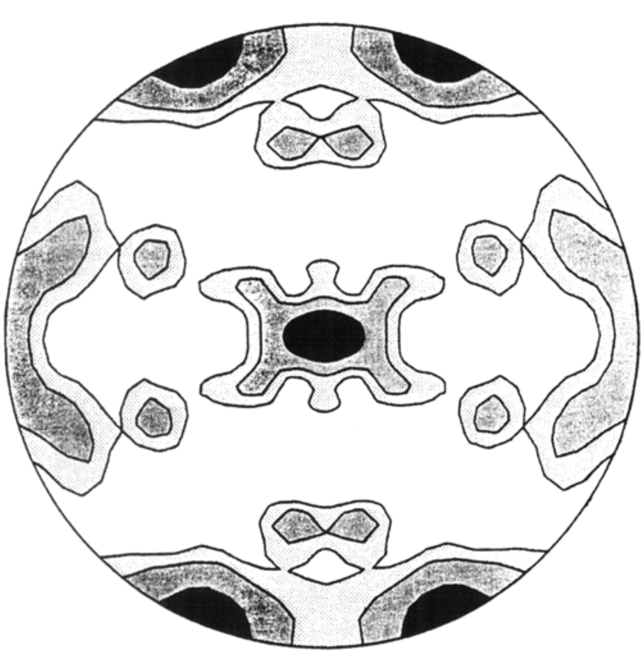

Fig. 7 (100) pole figure of Staboperm® T1.

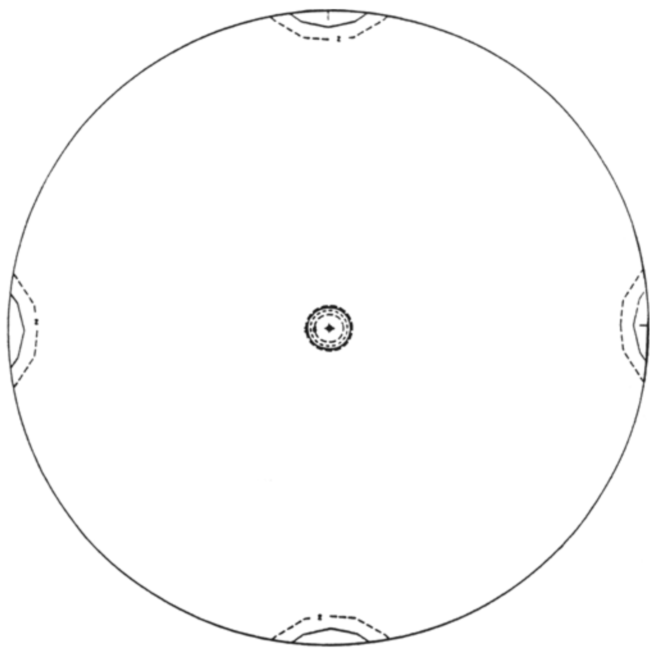

Fig. 8 (100) pole figure of 0.12-mm strip after direct casting, cold rolling, and final annealing.

At a field strength of $H = 2500$ A/m, for both textures this value amounts to $J\,2500 = 1.795$ T for a nonsilicon and 1.723 T for a 2% silicon material.[7]

The adverse effect of grain size on magnetic properties can be seen in Fig. 2. With increasing annealing temperature, the total loss decreases monotonically due to grain growth, whereas the polarization increases drastically during recrystallization and decreases immediately afterwards.

2.3 *Development of Grades with Improved Texture*

Measures influencing the texture of the final strip are the texture of the hot rolled strip, the degree of cold rolling, and grain growth control by segregating elements or by the surface. Hot strip annealing (HSA) in either a batch or a continuous annealing furnace is commonly used to improve the texture, primarily of high-silicon steels, where the increased costs can be justified.

The modifications of the crystallographic texture of a low-silicon grade due to HSA are shown in Fig. 3 and 4 by fiber representation after ODF measurement.

2.3.1 *Theta Fiber (Cube Edge Parallel to Normal Direction)*

The integral intensity of this fiber is not changed by HSA, but the intensity maximum is shifted from (001)[110] to the cube texture (001)[100]. This results in higher polarization values of the longitudinal and transverse directions, which are measured by the Epstein method, but has no positive effect for rotating machines.

2.3.2 *Zeta Fiber (⟨110⟩ Direction Parallel to Normal Direction)*

Without HSA, the intensities of this fiber are very low. Goss i.e. (110) [001] oriented grains are strongly promoted by HSA.

2.3.3 *Gamma Fiber (⟨111⟩ Parallel to Normal Direction)*

This magnetically disadvantageous fiber exhibits high intensities without HSA. The integral intensity is lowered by about 50% with HSA.

2.3.4 *Eta Fiber (⟨001⟩ Parallel to Rolling Direction)*

The integral intensity of this fiber is increased by cube and cube-on-edge oriented grains.

2.3.5 *Summary*

It thus appears that HSA lowers the ⟨111⟩ orientations and increases cube and cube-on-edge orientations. Application of HSA on non- and low-silicon steels results in lower loss and improved polarization J 2500 by about 0.06 T, as is shown in Fig. 5.

The HSA conditions may vary from $T = 750$ °C for several hours to 1 min, for example, at temperatures above 950 °C. Similar effects can be achieved if after hot rolling the strip is coiled at elevated temperatures.

Recently, a new process was established to manufacture the low-loss high-permeability material called Staboperm*, shown in Fig. 5. This medium alloyed α/γ transition-free material is

* Staboperm® is a registered trademark of EBG Gesellschaft für Elektromagnertische Werkstoffe mbH, 4630 Bochum 1, Kastroper Str. 228.

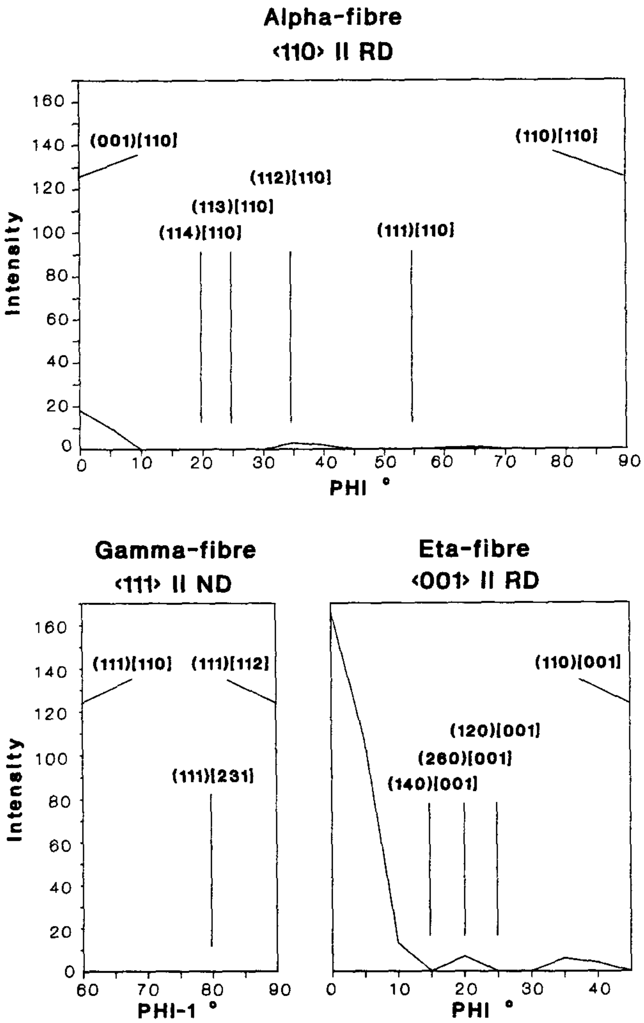

Fig. 9 Texture of 0.12-mm strip (3.4% Si) after direct casting, cold rolling, and final annealing.

hot rolled at elevated temperatures, cold rolled by more than 85%, and uses interface active elements like Sn or Sb.[8] During the hot rolling process, in the interior of the hot strip, large elongated grains of orientations near (113)[110] are created, as shown in Fig. 6. After cold rolling and annealing at 1050 °C for less than 2 min, the material has an imperfect (100)[001] texture, as shown in Fig. 7. The [001] plane is tilted transversely by about 5°, and the (100) direction has a misorientation of about 20°. In addition, a small number of grains have an orientation near the cube-on-edge orientation.

The magnetic properties of the Staboperm® T1 grade shown in Table 1 indicate its suitability for electromagnetic devices where the flux is in both the longitudinal and transverse directions, as in E-J, U-J, and E-E transformer cores, ballast chokes, linear motors, or the stator cores of large generators.

3. Future Developments

It has been long known that a nearly perfect cube texture can be achieved by surface energy-controlled grain growth in strip with thickness less than 0.1 mm. In recent years, near-net shape casting has made great progress, and it seems that in directly cast strip the as-cast texture facilitates the promotion of cube texture during annealing.

Figure 8 shows the (100) pole figure of a strip cast at a thickness of 0.3 mm, cold rolled to 0.12 mm, and annealed in pure hydrogen. The pole figure and the fiber representation in Fig. 9 indicate that this bidirectional material has a sharpness of texture comparable to unidirectional regular grain oriented material.

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