ELSEVIER
Journal of Magnetism and Magnetic Materials 254–255 (2003) 364–366
Journal of magnetism and magnetic materials
www.elsevier.com/locate/jmmm

Magnetic properties of silicon steel with as-cast columnar structure

F.J.G. Landgraf[a,]*, T. Yonamine[a], R. Takanohashi[a], F.Q. Silva[a], J.P.V. Tosetti[a], F. Beneduce Neto[a], E. Albertin[a], V.N.G. Mazzarella[a], I.G.S. Falleiros[b], M. Emura[c]

[a] Instituto de Pesquisas Tecnológicas, Technological Research Institute, Av. Prof. Almeida Prado 532, 05508-901 São Paulo, Brazil
[b] Escola Politécnica, Universidade de São Paulo, 05508-901 São Paulo, SP, Brazil
[c] Globalmag, 05508-900 São Paulo, SP, Brazil

Abstract

The $(1\,0\,0)\langle 0\,v\,w\rangle$ texture, ideal for magnetic steels, can be obtained in a plane perpendicular to the solidification direction of Fe–3.5%Si. The strip casting process provides favourable conditions for obtaining this ideal texture. This paper compares magnetization curves of a directionally solidified 3.5%Si steel, strip-cast 3.5%Si steel and a commercial 2.2%Si non-oriented fully processed steel. The directionally solidified samples reached the best values of B_{50} and $H_{1.7}$.
© 2002 Published by Elsevier Science B.V.

Keywords: Electrical steel; Strip casting; Texture; Magnetic loss

The ideal crystallographic texture for use in electrical motors, $(1\,0\,0)[0\,v\,w]$, is found in the plane perpendicular to the axis of the columnar zone of ferritic steel solidification (with no δ–γ–α transformation). The conventional continuous casting process produces 250 mm thick steel plates that have to be hot rolled down to 2 mm, while in the strip-casting process the same thickness is obtained directly from the melt and, in general, with a columnar structure oriented almost perpendicular to the strip surface. Fig. 1 shows, in a schematic way, the formation of microstructure during the strip-casting process.

A figure-of-merit frequently used to evaluate indirectly the texture is the induction B_{50}. The value of B_{50} depends almost entirely on crystallographic texture and silicon content, if residual stresses are not present. Generally this property is not sensitive to thickness, grain size and volume fraction of inclusions. The theoretical model of Lawton and Stewart [1] has been used to calculate the magnetization curve above 1.4 T, as a function of the crystallographic direction, of the applied magnetic field, of the saturation magnetization value and of the magnetocrystalline anisotropy constant. It is possible to calculate average values of points in the magnetization curve, supposing a material with $(1\,0\,0)[0\,v\,w]$ texture and with magnetic field applied in all directions of the $(1\,0\,0)$ plane, as described by Campos et al. [2]. The B_{50} theoretical calculation resulted in 1.84 T for steel without silicon, 1.78 T for steel with 2.2%Si and 1.73 T for 3.5%Si. These values are valid for measurements that take into account all directions in the plane of the sheet, i.e., using samples with a ring shape. They cannot be compared with values obtained in an Epstein frame, which result from samples taken from the rolling and the transverse directions. It is known that the properties measured at 45° and 60° from the rolling direction are lower than that obtained along the transverse direction. Hence, ring-shaped samples were used in this paper. While the B_{50} value is used in many papers, $H_{1.7\,\mathrm{T}}$, the magnetic field necessary to reach 1.7 T, shows more clearly the difference between materials and it is closely related to the final

*Corresponding author. Tel.: +55-11-37674211; fax: +55-11-37674037.
E-mail address: landgraf@ipt.br (F.J.G. Landgraf).

0304-8853/03/$ - see front matter © 2002 Published by Elsevier Science B.V.
PII: S0304-8853(02)00869-7

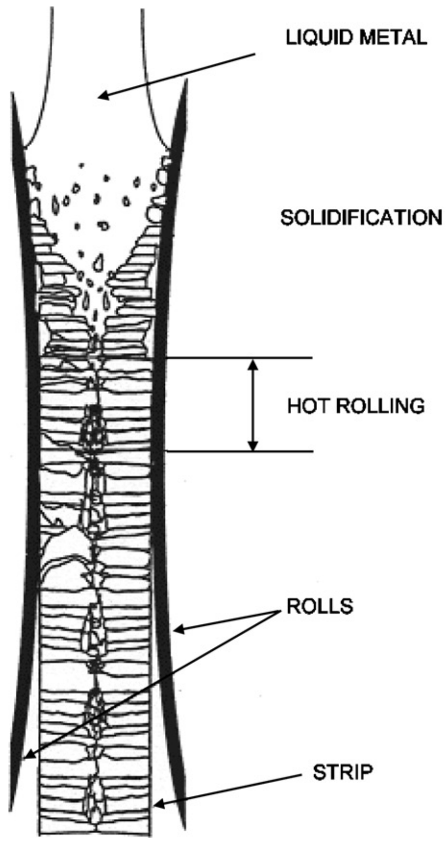

Fig. 1. Schematic representation of microstructure formation during the strip-casting process.

performance of the material. In the practical application, what does matter is the field required to magnetize the material, since its intensity will directly affect the "copper losses" of electrical machines.

The magnetic loss, related to the "iron losses" of electrical machines, is the most important property for the selection of these materials, but it lacks a model for a theoretical estimation of the texture dependence. As the total loss is very sensitive to the sample thickness and to the measuring frequency, an evaluation of the magnetic loss was obtained by measuring the hysteresis component obtained from the hysteresis area in the quasi-static condition, which does not depend on the sample thickness and is less sensitive to the chemical composition. The hysteresis area is a measurement of the dissipated energy, W_H, in J/m^3. From that, the hysteresis component of power losses at 60 Hz was calculated.

Directional solidification experiments were performed to obtain the $(1\,0\,0)[0\,v\,w]$ texture in the section transverse to the columnar growth direction. A 3.5%Si alloy was cast in a 57 mm diameter pre-heated ceramic mould with a water-cooled copper chill in the bottom. Pouring temperatures of 1650°C and 1700°C produced samples DS1 and DS2 with columnar grain lengths of 11 and 15 mm, respectively. In order to compare results, two other samples were obtained: an experimental strip-cast 3.5%Si steel supplied by an European laboratory (SC) and a 2.2%Si fully processed commercial steel (FP). The strip-cast sample was produced in a twin roll machine. The samples DS1, DS2 and SC were characterized by optical microscopy, including etch pit observation according to a method described elsewhere [3]. Rings 1.5 mm thick were machined from the samples and submitted to heat treatment at 760°C for 1 h, in an 88%N_2–9%H_2–3%H_2O atmosphere to decarburize and eliminate residual stresses. The B_{50} and $H_{1.7}$ values were determined from magnetization curves at 5 mHz.

The microstructures of DS1 and SC samples can be seen in Fig. 2. The DS1 sample presented columnar grains with a column diameter of 1–2 mm (Fig. 2a), very similar to what was seen in DS2 sample. By means of etch pit profile measurements at a surface perpendicular to the ring axis, it was possible to estimate that grain orientations were tilted about 11° from the cube-on-face position. The SC sample did not present a columnar zone (Fig. 2b), and the etch pit analysis did not confirm a strong $(1\,0\,0)\langle 0\,v\,w\rangle$ texture. This microstructure is very different from the ones presented in literature for strip-cast materials, which usually show much better developed columnar structures [4]. This difference may be associated with the type of machine that produced the present sample, without roll cooling.

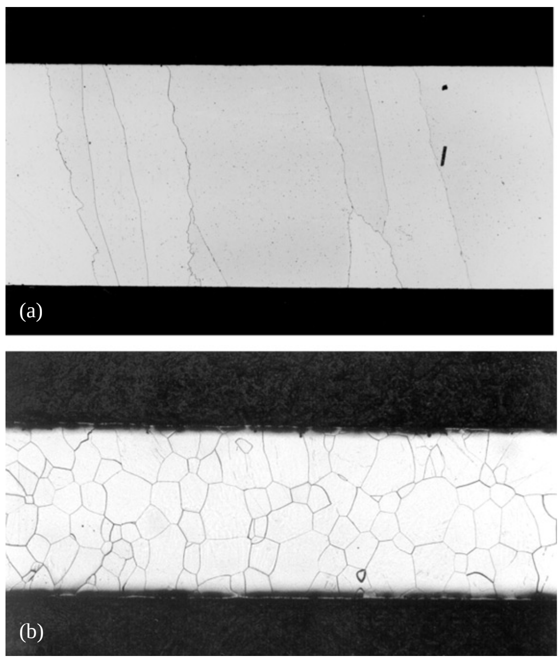

Fig. 2. Longitudinal section of silicon steel produced by: (a) directional solidification (1.5 mm thick sample) and (b) strip-casting process (2.1 mm thick).

Table 1
B_{50}, $H_{1.7}$, dissipated energy per cycle (W_H) and hysteresis loss (P_H) at 60 Hz and 1.5 T, measured in annealed rings

	B_{50} (T)	$H_{1.7}$ (A/m)	W_H (J/m^3)	P_H (W/kg)
Ideal 3.5%Si	1.73	3800	—	—
SC	1.61	8524	311	2.4
DS1	1.71	4660	395	3.1
DS2	1.70	5050	340	2.7
Ideal 2.2%Si	1.78	1800	—	—
FP	1.69	5400	390	3.0

Applying the Lawton and Stewart model for calculating the $H_{1.7}$ average value in the (1 0 0) plane, the values obtained were 1800 A/m for a 2.2%Si steel and 3800A/m for a 3.5%Si steel. The values of B_{50}, $H_{1.7}$, W_H and hysteresis loss for all annealed rings are shown in Table 1. The $H_{1.7}$ values for the directionally solidified and for strip-cast samples were, respectively, 30% and 120% above the theoretical value of 3800 A/m for an ideally oriented texture. The result for the 2.2%Si fully processed sample was 200% larger than the theoretical value of 1800 A/m. Based on B_{50} and $H_{1.7}$ values, we can conclude that samples DS1 and DS2, directionally solidified, have a texture fairly close to the ideal one, even if many grains are tilted by up to 11°. The values of hysteresis losses, which are calculated from hysteresis areas (Fig. 3), are high compared to the typical Epstein frame measurement value of 300 J/m^3 by cycle for 1.5 T. This indicates that other variables are interfering more than texture.

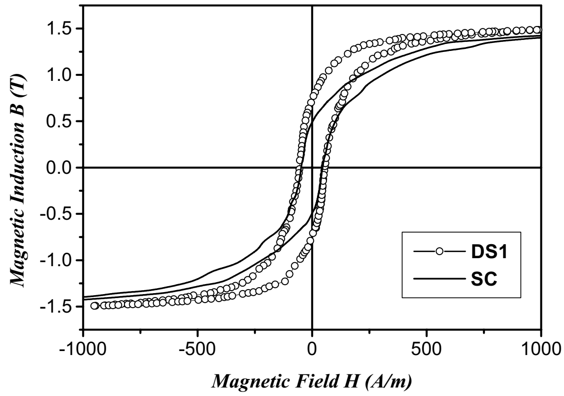

Fig. 3. Quasi-static hysteresis curves of DS1 and SC annealed ring samples.

This research was supported by grants from Brazilian agencies FAPESP and CNPq.

References

[1] H. Lawton, K.H. Stewart, Proc. R. Soc. (London) Ser. A 193 (1948) 72.
[2] M.F. De Campos, F.J.G. Landgraf, A.P. Tschipstchin, J. Magn. Magn. Mater. 226–230 (2001) 1536.
[3] E. Horn, U. Lotter, Pract. Met., Part 2 22 (1985) 439.
[4] R. Buchner, J.W. Schmitz, Steel Res. 63 (1992) 7.