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Influence of different kinds of rolling on the crystallographic texture and magnetic induction of a NOG 3 wt% Si steel

J.M. Silva [a], E.S. Baêta Júnior [a], N.R.D.C. Moraes [a], R.A. Botelho [a], R.A.C. Felix [b], L. Brandao [a,*]

[a] Department of Mechanical and Materials Engineering, Military Institute of Engineering (IME), Praça General Tibúrcio, 80,Urca, Rio de Janeiro/RJ, Brazil
[b] Scientific Instrumentation and Mechanical Technology Laboratory, Brazilian Center for Physics Research (CBPF), Rua Dr. Xavier Sigaud, 150-Urca, Rio de Janeiro-RJ, Brazil

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ABSTRACT

The purpose of this work was to study the influence of different kinds of rolling on the magnetic properties of NOG steel, an electric steel widely used in electrical motors. These properties are highly correlated with the crystallographic texture of the material, which can be changed by rolling. Three kinds of rolling were examined: conventional rolling, cross-rolling and asymmetrical rolling. The crystallographic texture was determined by X-ray diffraction and the magnetic properties were calculated from a theoretical model that related the magnetic induction to crystallographic texture through the anisotropy energy. The results show that cross-rolling yields higher values of magnetic induction than the other processes.

1. Introduction

Electrical steels are used in electrical motors, generators and transformers. Silicon is added to these steels with purpose of increasing the electrical resistivity and reducing the magnetic anisotropy in order to decrease power losses. The magnetic induction (B_{50}) depends on the energy required to change the magnetization direction, called anisotropy energy, which, in turn, depends on the crystallographic texture of the material [1,2] that can be changed by thermo-mechanical processes such as rolling and annealing.

Studies of the cross-rolling process [3–5] suggest that three rolling passes, in which the second pass occurs in a direction perpendicular to the first and the third passes, can optimize the magnetic induction of these steels by introducing a suitable crystallographic texture, dominated by cube (C) {100}<001> and Goss (G) {110}<001> components.

Asymmetric rolling involves the application of different stresses to the top and bottom surfaces of the sheet through different rotation speeds, friction coefficients [6–11] or diameters of the rolling cylinders [12]. This applies a large shear to the material [7–11,13], which results in a texture gradient through the material thickness with application of smaller forces and torques than in the conventional cold rolling process [14].

The magnetic anisotropy energy (AE) [1,2] has been theoretically estimated from the crystallographic texture, used to predict magnetic induction (B_{50}) [15–17] and compared with experimental B_{50} data for different electrical steels. It was found there was a good correlation [17] between the predicted B_{50} and the measured values.

The main purpose of this research was to evaluate the influence of different thermo-mechanical processes on the crystallographic texture and magnetic induction of a NOG electrical steel with 3 wt% Si. Cold reductions were made through three different types of rolling: conventional rolling, asymmetric rolling and cross-rolling, followed by conventional fast annealing. The anisotropy energy (AE) was used as global parameter for evaluation of texture and, as just reported above; it can be used to predict B_{50} with good accuracy.

2. Experimental procedure

This study was carried out on a ferritic silicon steel sheets with dimensions of 100 mm × 100 mm and 2.3 mm thickness received as hot-rolled and whose chemical composition is shown in Table 1.

As can be seen in the flow chart of Fig. 1, the samples were cold rolled using conventional, cross and asymmetrical rolling, the last one with cylinder ratios of 1.3 and 1.5, and annealed at 1000 °C for 120 s. The cold rolling was performed in a FENN MFG. Co mill, Model D-51710 with back-up roll of 133.70 mm diameter, in 6 passes of reduction, leading to a total accumulated reduction in thickness of 70%.

* Corresponding author.
E-mail address: brandao@ime.eb.br (L. Brandao).

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Table 1
Chemical composition of the samples (wt%).

C	Si	Mn	Cr	Ni	Mo	Al	P	S	N
0.004	3.250	0.050	0.070	0.004	0.008	0.510	0.001	0.004	0.0015

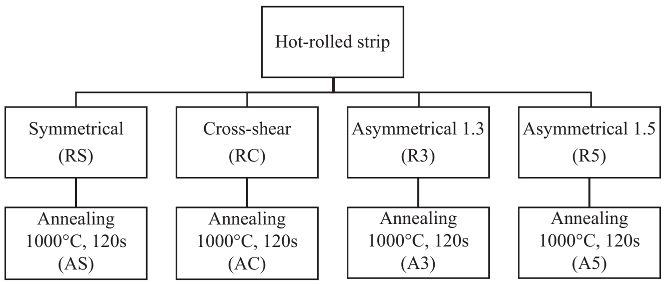

Fig. 1. Flow chart of the four rolling processes with thickness reduction of 70%.

In order to perform conventional and cross-rolling, work rolls with a diameter of 40 mm were used and the sample final thickness was 0.7 mm.

Asymmetric cold rolling was performed using work rolls with different diameters: for a 1.3 ratio, the top roll had a diameter of 52 mm and the bottom roll had a diameter of 40 mm; for a 1.5 ratio, the top roll had a diameter of 52 mm and the bottom roll had a diameter of 33 mm. In both cases, when the sheets remained bent after rolling, they were flattened using a press with a maximum load of 30 tons.

Annealing was performed in a tube furnace LENTON with electric heating chamber, in order to obtain a recrystallized microstructure in the samples and to avoid secondary recrystallization [18]. The samples were inserted in a quartz tube connected to a vacuum pump, providing a vacuum of 10^{-4} bar during annealing. The annealing time was 120 s at 1000 °C.

Crystallographic texture analyses were performed by X-ray in a PANalytical X'PERT PRO MRD diffractometer with cobalt anode and PIXcel detector with 255 channels, using 40 kV and 45 mA. Pole figures of (110), (200) and (211) were measured and the crystal orientation distribution function (ODF) was calculated using the popLA software (preferred orientation package - Los Alamos) in the Roe notation. For XRD measurements, the samples were previously cut into 20×20 mm sheets, mounted, grinded at 80, 220, 400, 600, and 1200 grit sizes with abrasive paper and chemically polished with a 95% solution of H_2O_2+5% HF. The textures were evaluated at mid-thickness to facilitate the comparison of samples produced by different processes.

The magnetic induction, B_{50}, was calculated from crystallographic texture with the aid of a software [19] that takes into account the coefficients of the harmonics obtained by the popLA software.

3. Results and discussion

The results of crystallographic texture analysis are shown in Figs. 2–6. The B_{50} values were calculated from the anisotropy energy [15–17], and it is important to remember that the model used in the calculation has a high correlation (0.995) with experimental data [17]. The samples were labeled using the following code: the first symbol is R for not annealed and A for annealed; the remaining symbols are S for symmetrical rolling, C for cross-rolling, A3 for 1.3 asymmetrical rolling and A5 for 1.5 asymmetrical rolling.

The texture components were similar for the three rolling types, with the typical behavior of a deformed BCC material.

In the Orientation Distribution Function (ODF) of the RS sample (Fig. 2a), it can be observed a rotated cube component with intensity 5. In the AS sample (Fig. 2b), there are a ζ-fiber with peaks 4 and 3 in Goss and rotated Goss components, respectively, and a γ-fiber. In order to facilitate the fibers interpretation, in Fig. 3 the ODF sections for Phi 0°and 45° are shown schematically where the fiber positions are indicated.

The ODF of the cross-rolled (RC) sample (Fig. 4a) shows the presence of the rotated cube component. The annealing of cross-rolled samples caused strengthening of γ-fiber, reaching intensity level 6 and the Goss component intensity level 4, as observed by Vanderschueren et al. [4]. The ζ-fiber remained weak, as shown in the AC sample ODF (Fig. 4b).

The cross rolling process showed high levels of embrittlement caused by stresses generated through the different rolling directions during the passes. As observed by Liu et al. [20], the cold cross-rolled sample, Fig. 4(a), exhibited crystallographic texture similar to the symmetrically-rolled specimen, Fig. 2(a).

Fig. 5(a) shows that the R3 sample has a rotated cube component with intensity 5. After annealing this sample, the ζ-fiber showed up, with peaks in Goss and rotated Goss reaching 3 and 2, respectively, and the γ-fiber increased to intensity 5, as shown in the A3 sample ODF (Fig. 5b).

Fig. 6(a) shows that the R5 sample has a rotated cube component with intensity 5 and γ-fiber with intensity 2. After annealing, the ζ-fibers and γ-fibers showed up with intensity 2 and 4, respectively, as shown in the A5 sample ODF (Fig. 6b).

Asymmetrically-rolled sheets tend to develop heterogeneous strains through the thickness, which can be explained by the different slip systems that come into operation to accommodate the active heterogeneous shear stresses [9], leading to buckling.

The anisotropy energy calculation [1] (AE) was carried out for ten different directions in the sheet plane (from 0° to 90° with respect to rolling direction). Fig. 7 shows the calculated anisotropy energy as function of rolling direction angles for the four rolling processes. The symmetrically-rolled and cross-rolled specimens presented similar AE behavior, showing lower AE values for most angles (from 0° to 65°) when compared with asymmetrically-rolled ones. For the rolling direction, one can note two sets of behavior: the asymmetrically-rolled samples with the higher AE and symmetrically-rolled and cross-rolled samples with the lower. At 90°, the AEs were similar, denoting, in this case, a smaller influence of the rolling processes.

Fig. 8 presents the anisotropy energy of the annealed samples calculated for each 10° on the sheet plane. For all specimens, one can see a large variation of the AE on the sheet plane. The lowest AE value, which should lead to a high magnetic induction [B_{50}], was found for the symmetrically-rolled sample (AS) in the rolling direction. It also can be noted that for all samples the lowest AE values were in the rolling direction and the highest one, which should lead to a low magnetic induction, were observed at 90°. The best results for B_{50} were observed at 10° and 40°, respectively for symmetrical-rolled and cross-rolled samples (see Fig. 9).

The magnetic induction B_{50} was calculated using Eq. (1), where AE is the anisotropy energy, which depends on the chemical composition and crystallographic texture of the material. C_1 and C_2 are constants that depend on chemical composition, as shown in more details by Bunge [21], Yonamine [15] and Botelho [17].

$$B_{50}(mT) = (C_1 - C_2\ X\ AE)\ X\ 1000 \tag{1}$$

Fig. 9 shows the angular dependence of the magnetic induction (B_{50}) for all annealed samples. As already mentioned, for all rolling processes the B_{50} reaches the highest values at the rolling direction and the lower values at 90°. The magnetic induction for the symmetrically-rolled and asymmetrically rolled with 1.3 ratio (A3