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Texture and magnetic properties improvement of a 3% Si non-oriented electrical steel by Sb addition

Marcio Ferreira Rodrigues [a,*], Marco Antonio da Cunha [a], Sebastião da Costa Paolinelli [a], André Barros Cota [b]

[a] Aperam South America, Timóteo, MG, Brazil
[b] Physics Department—Universidade Federal de Ouro Preto, Redemat, Ouro Preto, MG, Brazil

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ABSTRACT

The influence of small antimony addition and thermomechanical processing on the magnetic properties of a 3% Si steel was investigated. The samples were processed in the laboratory with 930 °C hot rolling finishing temperature, three different hot band thicknesses, hot band annealing at 1030 °C, cold rolling with three different reductions to 0.35 mm thickness and final annealing at 1030 °C. The results have shown that the best combination of core loss and magnetic induction can be obtained by Sb content of 0.045% and 76% cold rolling reduction, and that Eta/Gamma ratio is higher and grain size larger at this Sb content.

1. Introduction

Electric motors manufacturers are looking for high magnetic induction and low core loss electrical steels to guarantee the high efficiency requirements of the high performance electrical machines. For non-oriented steels high values of magnetic induction has become a big challenge for steel producers. To achieve high values of magnetic induction, the manufacturers have worked on chemical composition, control of cold rolling reduction, recrystallization, presence of non-metallic inclusions and grain size to improve texture maximizing the incidence of Eta and {100}⟨0vw⟩ fibers and minimizing the incidence of Gamma fiber [1].

Among non-oriented cold rolled electrical steels, the highest grade is produced with about 3.3% Si. High Si content steels are brittle and present poor cold workability. Then, researchers are replacing the practice of silicon addition by other alternatives to improve magnetic properties and one of them being the Sb addition.

Magnetic properties in non-oriented electrical steels, mainly magnetic induction, can be improved by adding small quantities of Sb to non-oriented electrical steels with hot band annealing [2–6]. According to Takashima et al. [2], Sb addition to 1.85% Si non-oriented electrical steels, with 0.25% Mn and 0.3% Al, improved the magnetic properties due to an increase of (100) and (110) texture components and a decrease of (111) texture component. The initial annealing treatment promotes an increase in grain size and, additionally, Sb segregation in the grain boundaries. After cold rolling, during final annealing, the Sb prevents the nucleation of recrystallization near the original grain boundaries and decreases formation of (111) grains [2].

In order to improve the crystallographic texture of non-oriented electrical steels, Sb should be preferably between 0.015% and 0.15%. The effect of Sb on the crystallographic texture depends on the hot band annealing temperature, and its effectiveness is reduced when hot band annealing is not performed [3]. The effect of Sb and Sn to the magnetic properties of low-core losses electrical steels was evaluated by Chang and Huang [1] and Huang et al. [4]. They observed that Sb and Sn increase the volume fraction of Goss and cube components (that contain easy magnetization axis) and decrease the gamma fiber (hard magnetization).

These studies about the Sb influence on magnetic properties in non-oriented silicon steels were usually limited to silicon content below 2.5% [1–9].

The effects of cold rolling deformation (CRD) and hot rolling finishing temperature were evaluated by Dafé et al [10] in a 3% Si electrical steel. They observed that there is a specific relationship between these parameters to achieve the best magnetic properties results, where the best combination of B_{50} and $W_{15/60}$ could be obtained when the hot band 1.4 mm thickness was cold rolled to 0.50 mm, 64.3% of CRD.

Paolinelli et al [11,12] observed that improvement of magnetic properties in a 3% Si electrical steel is possible, obtaining the

* Corresponding author. Tel.: +55 31 3849 7449; fax: +55 31 3849 7448.
E-mail address: marciof.rodrigues@aperam.com (M.F. Rodrigues).

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magnetic favorable textures, controlling the grain size and the hot band texture.

The objective of this paper is to show the results of lab experiments verifying the influence of the antimony addition on the magnetic properties of a 3% Si non-oriented steel processed with 930 °C hot rolling temperature (HRT), under three different degrees of cold rolling reductions.

2. Experimental procedure

The chemical composition of three heats produced industrially is shown in Table 1. The chemical analyses were made by optical emission spectrometer (ARL 4460).

The 200 mm thick slabs obtained in a steel plant, according to the flow: MRPL Converter, Ladle Furnace, VOD and Continuous Casting Machine, were hot rolled to 28 mm thickness. The rough bar samples were prepared with 100 mm width and 70 mm long and processed in the lab.

The samples were reheated at 1140 °C for 60 s hot rolled at 930ºC in seven passes to 1.4, 1.8 and 2.3 mm thicknesses in a reversing pilot mill with interpass heating. After hot rolling the samples were cooled down using forced air and maintained at 450 °C in a muffle furnace to simulate coiling conditions. The hot band annealing was performed in a muffle furnace at 1030 °C for 60 s. The scale was removed by hydrochloric acid. The samples were cold rolled to 0.35 mm final thickness obtaining the different degrees of cold rolling reduction: 76%, 81% and 84%. Final annealing was performed in a continuous furnace at 1030 °C for 60 s in an atmosphere with 90%H_2–10%N_2 and dew point lower than −30 °C.

Core loss at 1.5 T/50 Hz ($W_{1.5/50}$) and magnetic induction at 5000 A/m (B_{50}) were measured in Brokhaus single sheet tester along the rolling direction.

The grain size was analyzed by optical metallography and volume fraction of the main fibers and texture components were determined by X-ray diffraction and electron backscatter diffraction—EBSD.

3. Results and discussion

3.1. Final grain size

The effect of Sb content and cold rolling deformation (CRD) on the final grain size is shown in Fig. 1. After final annealing, it is observed that the grain size increases when the Sb content rises up to 0.045% and it decreases when the Sb content achieves 0.098%. This effect was observed for the three CRD conditions. The mean grain size of steel varied from 129 to 141 µm for 0.045% Sb content and the larger grain size was observed for 0.045% Sb content and 76% cold strain.

The Sb content up to 0.045% does not restrict the grain growth during recrystallization. However, above this value, the Sb segregated on grain boundaries hinders the grain growth during recrystallization and reduces the final grain size [9].

Table 1
Chemical composition of heats.

Heat	C (%)	Mn (%)	Si (%)	Sb (%)
1	0.0021	0.5122	3.02	0.000
2	0.0023	0.5586	3.01	0.045
3	0.0024	0.5215	3.01	0.098

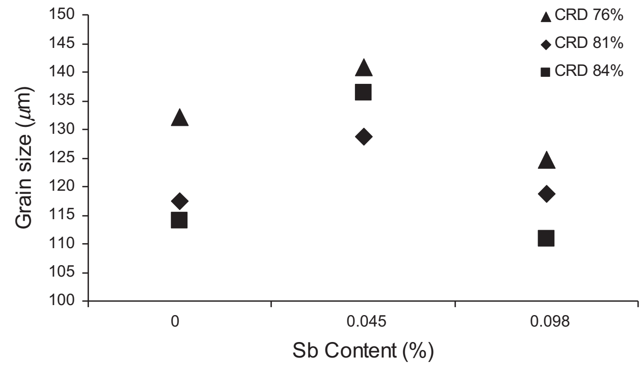

Fig. 1. Final grain size as a function of Sb content for CRD conditions.

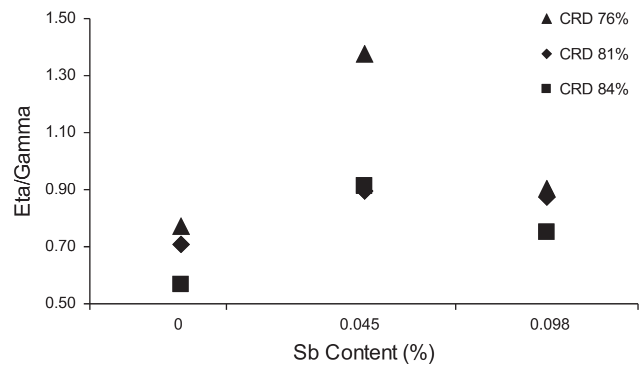

Fig. 2. Texture factor as a function of Sb content for different CRD conditions.

3.2. Texture factor

The texture factor is defined as the ratio of Eta fiber to Gamma fiber volume fractions and it is important to evaluate the texture effectiveness in improving magnetic properties.

Fig. 2 shows this factor after final annealing as a function of Sb content for different CRD conditions. A higher value of texture factor can be observed in general when Sb content is around 0.045%.

The results agree with the observations of Jenko et al. [5], where the density of grains with soft magnetic orientations near the (001) plane was higher in 2% Si steel doped with 0.05% Sb than in steel without Sb and with 0.1% Sb.

The texture factor increases with an increase of grain size for the samples with Sb content of 0.045%. It is suggested that grains with (111) orientation are nucleated in the vicinity of the original hot rolled band grain boundaries and antimony might be responsible for retarding the nucleation of grains with (111) orientation during the recrystallization [5].

The increase in Eta fiber volume fraction is due to the fact that samples with large grain sizes result in higher generation of shear bands on deformation where grains with orientations belonging to this fiber preferentially nucleate [11,12].

The orientation distribution functions (ODF) after final annealing for Sb contents of 0%, 0.045% and 0.098%, for CRD 76% are shown in Fig. 3. It can be observed that higher intensities of Eta fiber and Goss component, and lower intensities of Gamma fiber, occur when Sb content is around 0.045%.

3.3. Magnetic properties

The effects of Sb content and cold rolling reduction on the core loss at 1.5 T/50 Hz ($W_{15/50}$) and magnetic induction (B_{50}) are shown in Figs. 4 and 5. It can be observed that the best core loss

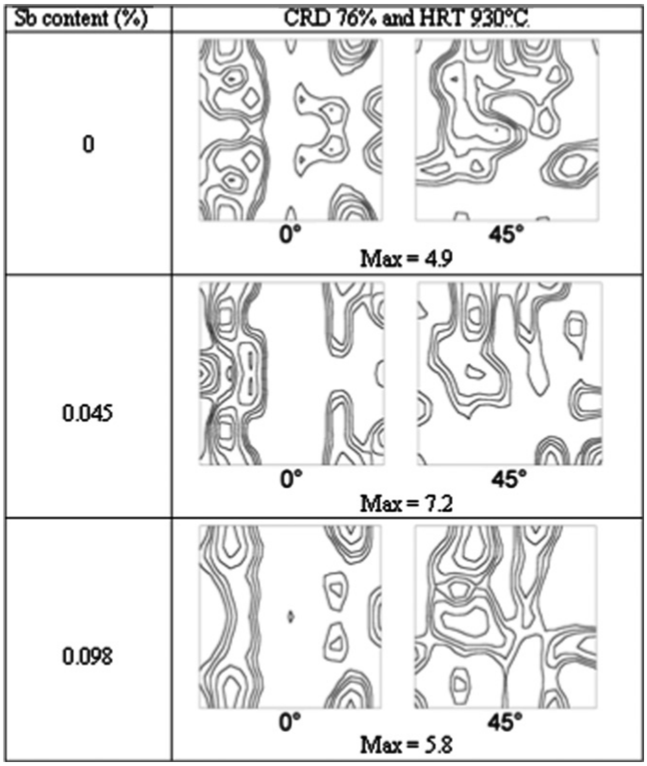

Fig. 3. ODF sections, Bunge notation ($\varphi_2=0^\circ$ and $\varphi_2=45^\circ$) for Sb content of 0%, 0.045% and 0.098% and CRD of 76%, after final annealing. Levels: 1,2,3,4,5,6,7.

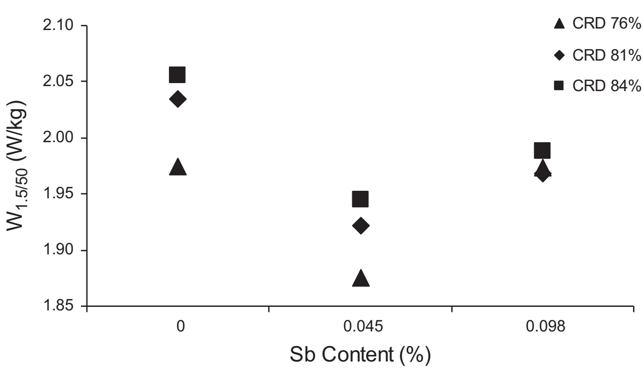

Fig. 4. Core loss at 1.5 T/50 Hz as a function of Sb content for different CRD conditions.

and magnetic induction values occur around 0.045% of Sb and 76% of CDR. These results can be predicted by structural analysis and it is due to the increase in texture factor after final annealing as can be seen in Fig. 6.

The tendency to decrease the core loss with increasing the final grain size and texture factor, for all cold rolling reductions is shown in Fig. 7.

It was demonstrated that Sb additions change the magnetic properties. Even applying the best cold reduction the magnetic properties still could be improved with 0.045% Sb. Based on these effects, processing conditions in Sb containing steels can be optimized.

The results presented in this work show higher B_{50} and lower $W_{15/50}$ for 0.045% Sb and cold rolling deformation of 76%. Based on the results of Dafe et al. [10] it can be estimated that the best magnetic properties could be obtained, for 0.35 mm final thickness, when hot band thickness is reduced to 0.95 mm.

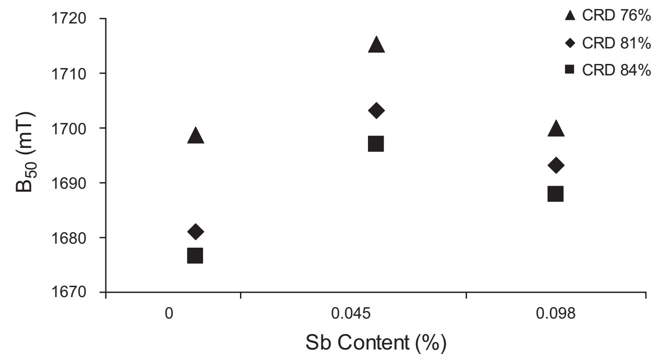

Fig. 5. Magnetic induction B_{50} as a function of Sb content for different CRD conditions.

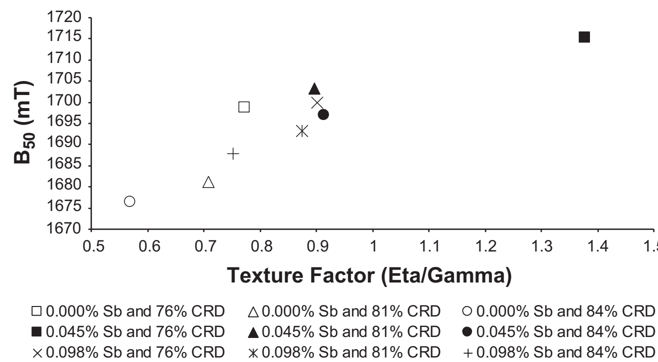

Fig. 6. Magnetic induction as a function of texture factor for all CRD conditions.

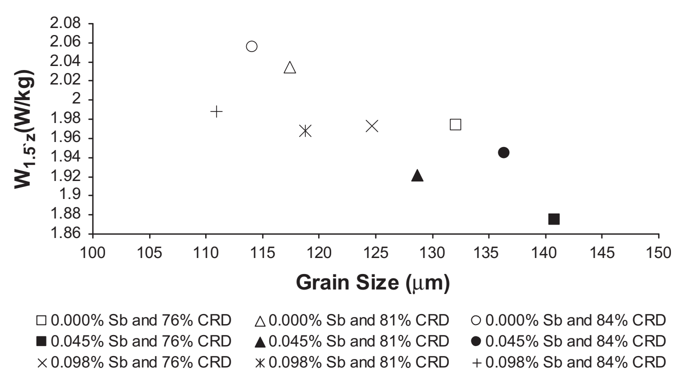

Fig. 7. Core loss as a function of final grain size for all cold rolling reduction conditions.

4. Conclusions

Addition of 0.045% Sb in a 3% Si steel improves core loss and magnetic induction. The largest final grain size was detected for the Sb content of 0.045% and cold rolling reduction of 76% and it was verified to have lowest core loss. For these conditions, it was observed to have highest texture factor and magnetic induction. However the 0.098% Sb addition shows a significant increase of core loss and decrease of magnetic induction and this result indicates that 0.098% Sb is fairly detrimental to magnetic properties. Taking into account the results presented for magnetic induction and core loss, it can suggest that the addition of 0.045% Sb and cold rolling reduction of 76% results in a combination of higher B_{50} and lower $W_{15/50}$ in this investigation.

Based on the previous work [10] it can be estimated that the best magnetic properties could be obtained, for 0.35 mm final strip thickness, when hot band thickness is reduced to 0.95 mm, CRD 64%.

The improvement of magnetic results was possible due a combination of optimum final grain size and a best texture factor, Eta/Gamma fiber.

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