jmr&t Journal of Materials Research and Technology
www.jmrt.com.br

Original article

Optimization of the magnetic losses of electrical steels through addition of Al and Si using a hot dipping process

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ARTICLE INFO

Article history:
Received 23 January 2013
Accepted 4 February 2013
Available online 4 August 2013

Keywords:
Electrical steel
Heat treatment
Diffusion

ABSTRACT

A major concern of society nowadays is the issue of sustainable development, which includes energy conservation. In order to induce a reduction of electrical energy consumption, governments across the world have pressured the appliance makers to increase in energy efficiency of electric engines. One of the ways to improve the performance of electric engines is to use steels with lower magnetic losses. The typical electrical steels are steels with about 3.5 wt.% Si. It is well known that an increase in Si content decreases magnetic losses. The purpose of this work was to evaluate the decrease of magnetic losses after increasing the Si and Al content in electrical steels by hot dipping, using an Al–Si alloy bath followed by a thermal treatment. A reduction of eddy current losses, for 60 Hz and 400 Hz, was observed in the steel after addition of Al and Si to about 4.5 wt.% Al and 4.8 wt.% Si.

1. Introduction

Steels used for electrical appliances, known as electrical steels, are of great importance for the industry. These are mainly used in electric engines and transformers, whose energy efficiency depend on magnetic permeability and on the "magnetic losses" associated the alternate current.

Electrical steels have, in general, high silicon content for better electric properties. Silicon increases the electrical resistance, decreases the magnetic anisotropy constant and the magnetostriction of the material, and makes the saturation magnetization and the iron losses much lower at high frequencies.

The grain size has a very strong effect on the magnetic losses. As the grain increases, the hysteresis losses decrease; however, anomalous losses increase and, therefore, there is an optimum grain size, between 100 and 150 μm [1].

Another important factor to be controlled in electrical steels is the crystallographic texture. The direction of easy magnetization in Fe-α crystals is $\langle 0\,0\,1 \rangle$ and the direction of hard magnetization is $\langle 1\,1\,1 \rangle$ [2].

In applications that require low magnetic losses, steels with high silicon content should be used since there is a considerable increase in the electrical resistivity of the Fe–Si sheet, ranging from 45–48 $\mu\Omega$ cm (3 wt.% Si) to 60–80 $\mu\Omega$ cm (6.5 wt.% Si). This increase in the electrical resistivity results in a reduction of eddy current losses [3].

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2238-7854/$ – see front matter
http://dx.doi.org/10.1016/j.jmrt.2013.02.014

Table 1 – Chemical compositions of electrical steels (wt.%).

Identification	C	Si	Mn	Cr	Ni	Mo	Al	P	S	N
B	0.003	3.02	0.58	0.04	0.01	0.01	0.003	0.03	0.001	–
C	0.003	0.6	0.6	–	–	–	0.27	<0.01	0.003	0.002

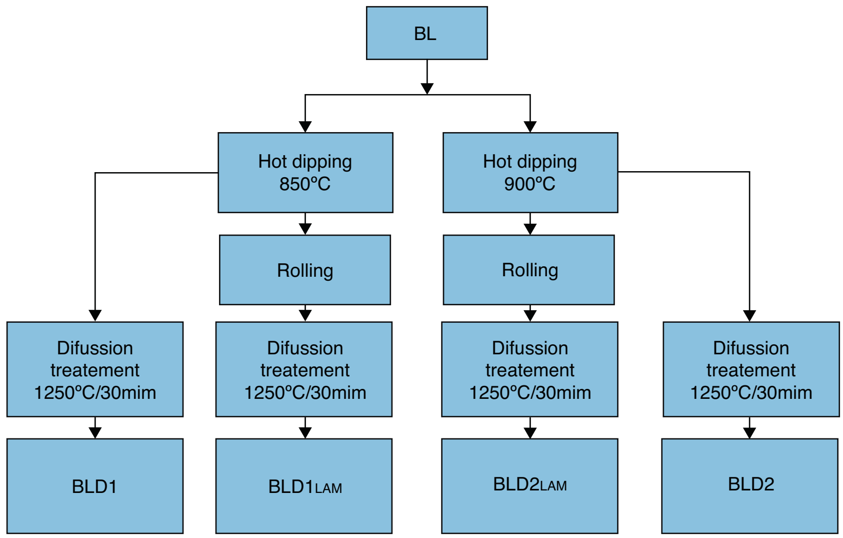

Fig. 1 – Flowchart of thermomechanical treatments performed on the BL sample.

This work aims to reduce magnetic losses by increasing the silicon and aluminum content in two types of electrical steel sheets, one with 3.2 wt.% Si and the other with 0.6 wt.% Si. They were processed by hot dipping in an Al alloy bath with 25 wt.% Si followed by a heat treatment.

2. Materials and methods

Two low carbon steels were used: one with 3 wt.% Si approximately and another with about 0.6 wt.%. The first was received as cold rolled with a thickness of 0.5 mm (type "B") and the second as annealed with thickness of 0.6 mm. Table 1 shows the chemical composition of these materials.

The materials as received were cut in 30 mm × 150 mm strips and cleaned in a 5% HF, 20% HCl, and 75% H_2O (distilled water) solution for 15 min in order to remove the oxide and also a coating layer which was present in the annealed strips. After cleaning, the strips were dried with alcohol and with a thermal blower.

2.1. *Hot dipping*

The strips were dipped in a molten binary alloy with hypereutectic chemical composition of Al with 25 wt.% Si at 850 °C (nomenclature 1) and 900 °C (nomenclature 2) for 10–30 s.

2.2. *Diffusion annealing*

After dipping, the strips were submitted to a heat treatment for Si and Al diffusion in an argon atmosphere. The pressure was about 1/3 of the atmospheric pressure and the heating ramp was 10 °C/min to 1250 °C and a dwell of 30 min.

The flowcharts of the thermomechanical treatments performed on the samples of types BL and CR are shown in Figs. 1 and 2, respectively.

2.3. *Intermediate cold rolling*

Some samples 0.5 mm thick, after the hot dipping process, were cold rolled up to 0.35 mm of thickness as shown in Fig. 1. This cold rolling is performed in order to control the final thickness and homogenize the coating. These cold rolled samples

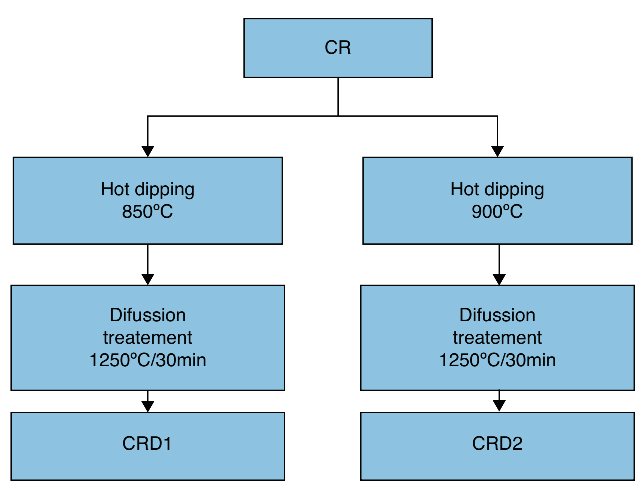

Fig. 2 – Flowchart of thermomechanical treatments performed on the CR sample.

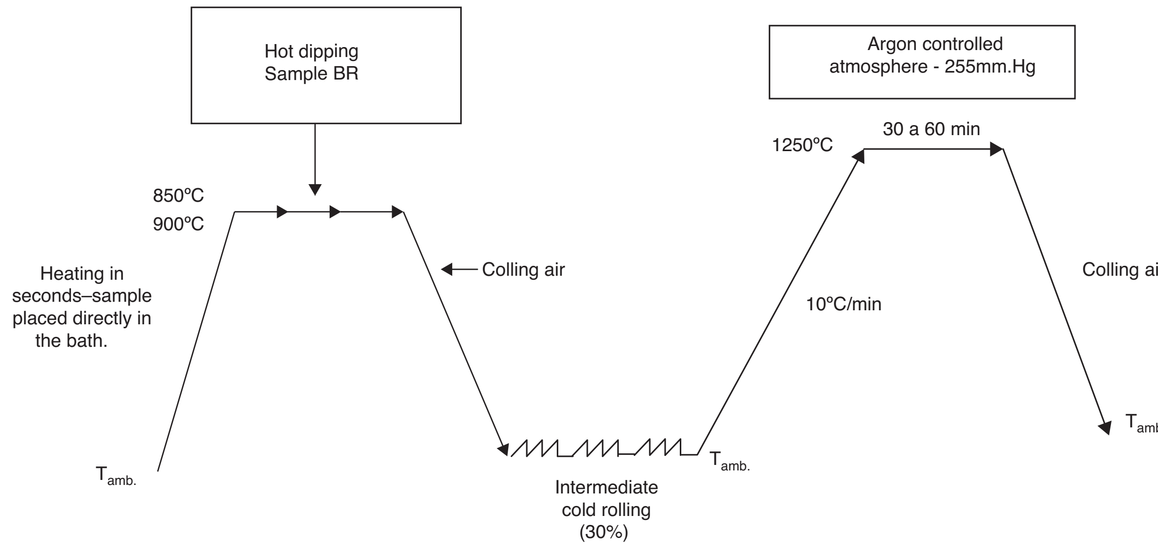

Fig. 3 – Flowchart of materials as received submitted to hot dipping and diffusion annealing with intermediate cold rolling.

were called "Lam". Fig. 3 illustrates this intermediate cold rolling process.

2.4. *Preparation of the samples for magnetic testing*

Both as received and treated samples were subjected to magnetic testing. The samples were cut to the dimensions of 100 mm × 30 mm with thicknesses of 0.6 mm, 0.5 mm and 0.35 mm. Prior to testing, the samples were chemically etched to remove the oxide layer resulting from the final annealing, first with a solution of 5% HF, 20% HCl, and 75% H_2O (distilled) for 10 min and then with a solution of 5% HF and 95% H_2O_2 for 10 s.

2.4.1. *Measurement of magnetic losses*

For the measurement of magnetic losses, we used the "Brokhauss" equipment and the MPG X'Pert software for Windows version 1.9 from the ArcelorMittal Research Center in Brazil.

The measurements were performed in strips of 100 mm × 30 mm with thicknesses of 0.35 mm, 0.5 mm, and 0.6 mm. The magnetic field was applied in the rolling direction in a single strip frame device where the following magnetic losses were extracted: total magnetic losses (P10/60) and (P10/400) that corresponded to a magnetic field of 1000 A/m at 60 Hz and at 400 Hz, respectively.

3. Results and discussion

3.1. *Hot dipping process*

Two samples after hot dipping, one with an immersion at 850 °C and the other at 900 °C, are shown in Fig. 4. It can be seen that the samples had almost the same appearance, although they were treated at different temperatures.

Table 2 presents the dipping time and temperature and the coating thickness of each treated sample. The coating thickness was obtained by subtracting the strip thickness before and after dipping and dividing the result by two. It can be seen that the temperature of 850 °C provided greater coating thickness.

The largest coating thickness obtained (45.3 μm) was close to the limit reported by Barros et al. [4] which showed that the typical coating thickness by hot dipping in a bath of Al/Si is up to 50 μm. It was observed that the dipping time had little effect on the coating thickness.

Regarding aluminum and silicon contents, the highest levels were obtained for 900 °C with the "B" samples. However,

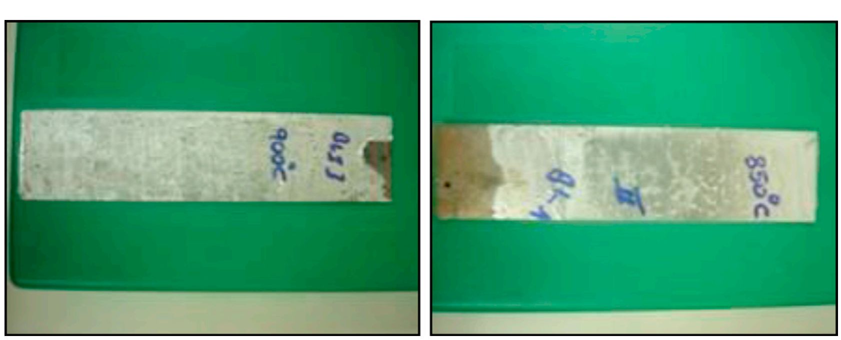

Fig. 4 – Samples coated with the aluminum and silicon alloy.

Table 2 – Parameters of hot dipping and coating thickness resulting.

Sample	Dipping temperature (°C)	Dipping time (s)	Coating thickness (μm)	Si + Al (wt.%)	Silicon (wt.%)	Aluminum (wt.%)
BLI1	850	20	45.3	7.04	4.08	2.96
BLI2	900	22	26	9.11	4.65	4.46
$BLI2_{LAM}$	900	25	30.25	8.83	4.83	4
CRI2	900	25	27.25	5.32	2.54	2.79

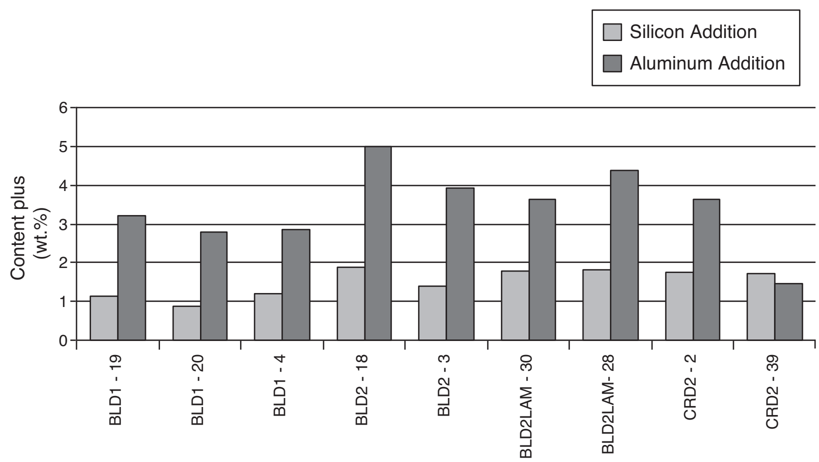

Fig. 5 – Graph relates each treated sample to the Al and Si added content after the diffusion treatment.

no relation was found between the coating thickness and the amount of Al and Si diffused into the strip. According to Barros et al. [5] during hot dipping, the molten alloy produces a coating made up from different intermetallic compounds distributed in layers as a result of the interaction between Fe and the molten Al–Si alloy. The additions of Si and Al do not occur in proportion to the coating thickness because the formation of these intermetallic layers creates a concentration gradient that lowers the diffusion rate. Moreover, Barros et al. [6] observed that the interdiffusion of Fe–Si is highly dependent on the Si concentration, so it is necessary to take into account the dependence of the diffusion coefficient on Si concentration.

3.2. *Diffusion of Al and Si in treated samples*

Fig. 5 shows a plot of the quantity of Si and Al added in each sample through the diffusion treatment. This added content is the result of the difference between the Si and Al contents in the as received materials and after diffusion.

The increase of Al and Si content through diffusion can be defined as a non-steady state. There was also interdiffusion of the atoms from the coating layer to the sheet and the atoms of the sheet to the layer. The graph of Fig. 5 shows that the addition of Al was higher than the addition of Si for all samples. This happens because the higher Al concentration gradient between the coating and the steel, in comparison to Si, resulted in a higher diffusion rate.

Regarding the Si addition, the result obtained was similar to that reported by Ros-Yanez et al. [7] who obtained a final silicon content up to 5 wt.% after the diffusion treatment, what is an equivalent total addition about 1.68 wt.%.

3.3. *Relation between the resistivity and Si and Al contents*

The graph of Fig. 6 shows the relation between the resistivity of the treated samples and the Si and Al contents. It is observed that a higher amount of silicon and aluminum in the samples provided in general higher resistivity values.

3.4. *Reduction of the magnetic losses with the increase of silicon and aluminum*

According to Bozorth [8] the electrical resistivity of iron, which is an intrinsic property of the material, increases with addition of Si and Al. In the graph of Fig. 6, it can be seen that the increase of aluminum and silicon contents through the diffusion yielded a higher electrical resistivity which decreases

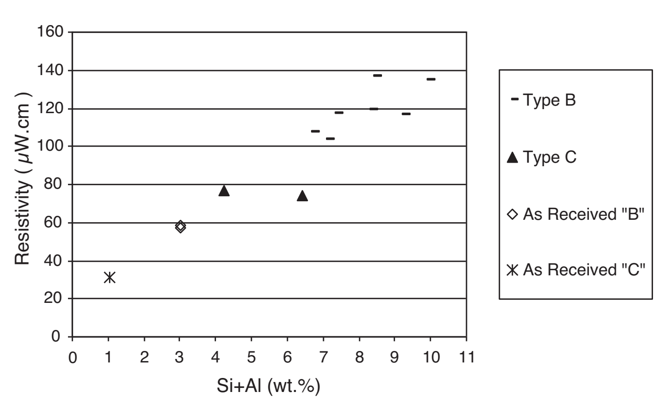

Fig. 6 – Graph relates the electrical resistivity to Si + Al contents of the treated samples and as received.

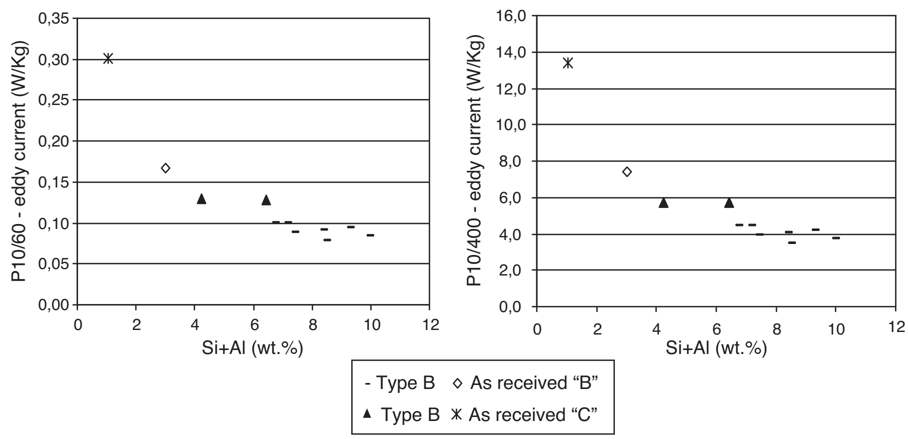

Fig. 7 – Relation between (Si + Al) content and the eddy current losses in a magnetic field of 1 T at 60 Hz (left) and 400 Hz (right).

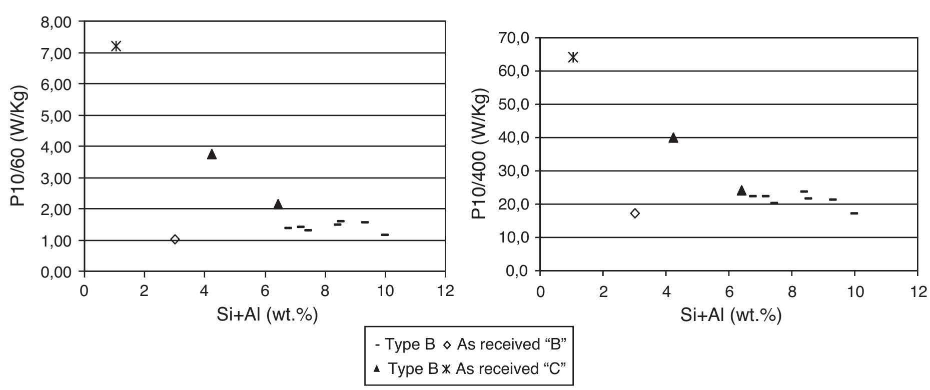

Fig. 8 – Relation between the Si + Al content and the total losses in a field of 1 T at 60 Hz (left) and 400 Hz (right).

magnetic losses. It occurs because the eddy current losses are inversely proportional to the electrical resistivity [8].

Fig. 7 presents two graphs that show the relation between the Si + Al content and eddy current losses at the frequencies of 60 Hz and 400 Hz in a magnetic field of 1 T.

It can be observed in Fig. 7 that the eddy current losses decreased with increasing of Si + Al content, for 60 Hz and 400 Hz, which can be related to an increase of the electrical resistivity.

Fig. 8 shows relation between the Si + Al content and the total losses at 60 Hz and 400 Hz in a magnetic field of 1 T.

It can be seen in Fig. 8 that type C samples showed a decrease in total losses with the addition of silicon and aluminum for both frequencies. In the case of type B samples, only at 400 Hz the losses were smaller in the treated samples than in the samples as received.

4. Conclusions

The addition of 4.5 wt.% and 4.8 wt.% of Al and Si, respectively, to a standard electric steel through a hot dipping process, followed by diffusion annealing, reduced of eddy current losses at the frequencies of 60 Hz and 400 Hz. These additions also reduced of total losses in the low silicon content samples (type C) at the frequencies of 60 Hz and 400 Hz, but for the steel which initially had 3.2 wt.% Si (type B), a decrease in the total losses was observed only at the frequency of 400 Hz.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgments

The authors thank CNPq for financial support through a PhD scholarship, and Centro de Pesquisas Arcelor Mittal, Instituto Militar de Engenharia and Centro Brasileiro de Pesquisas Físicas for the use of their facilities.

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