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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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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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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

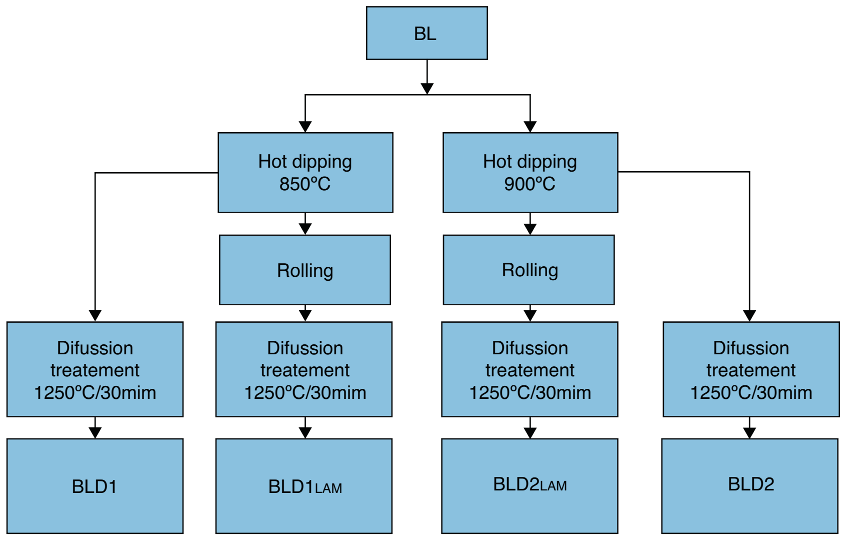

Fig. 1 – Flowchart of thermomechanical treatments performed on the BL sample.

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

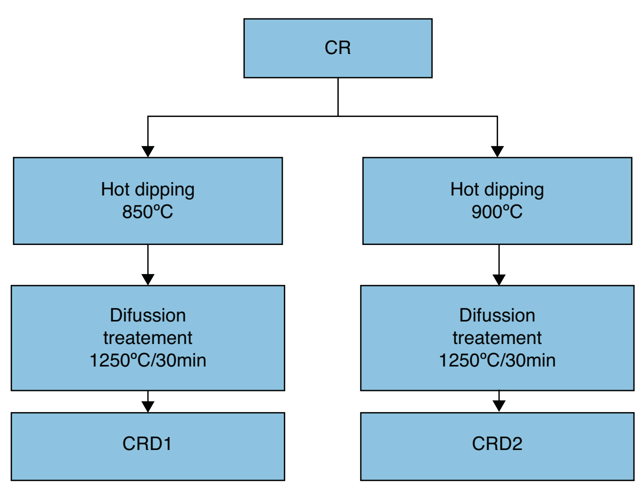

Fig. 2 – Flowchart of thermomechanical treatments performed on the CR sample.