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Magnetic aging anisotropy of a semi-processed non-oriented electrical steel

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Abstract

Electric motor cores are made of semi-processed non-oriented electrical steels. These steels are processed in such a way that the final heat treatment, which causes decarburization and improves magnetic properties, is made by the core producers. Depending on the effectiveness of this heat treatment, the core can heat during motor operation, causing carbide precipitation/coalescence in the metallic matrix, impairing the magnetic properties of the steel. This phenomenon is known as magnetic aging. The present study shows that magnetic aging takes places under anisotropic conditions. In a semi-processed steel, the largest magnetic loss variation occurs at 0°, around 40° and 90° in relation to the rolling direction. This anisotropy can be attributed to the crystallographic structure of this kind of material, in combination with the oriented precipitation of the carbides during aging.

Keywords: Magnetic aging; Magnetic loss; Electrical steel; Carbide precipitation

1. Introduction

During operation, the cores of alternating current motors are subjected to oscillating and rotating magnetic fields, which lead to expansion and contraction of the magnetic domains inside the steel strips. Fine second-phase particles present in the electrical steel matrix are deleterious to the magnetization, since they hinder domain movement, thus causing magnetic energy dissipation [1]. This dissipated energy, referred to as magnetic loss, has a hysteretic component that is quite sensitive to the presence of such particles. The remaining two portions of the magnetic loss in such systems, namely the anomalous loss and the Foucault current loss, are virtually free from this kind of influence [2]. Magnetic losses generate heat and this effect contributes to the heating of electric motor cores. When the temperature of the core material is increased, precipitation or coalescence of fine second-phase particles can take place, increasing the magnetic loss, impairing the magnetic characteristics of the steel. This phenomenon is referred to as magnetic aging.

In modern electrical steels, the aluminum content is higher than the stoichiometric value required for precipitating of AlN, thus keeping nitrogen innocuous to the magnetic aging phenomenon. This means that carbon atoms are responsible for the magnetic aging in this kind of steel, by precipitating as fine iron carbides inside the ferritic grains, during steel processing [3]. Morish [4] stated that iron carbides in steel are more effective in restraining magnetic domain movement when their diameter is close to the domain wall thickness. This behavior has been experimentally confirmed, since the highest magnetic losses in electrical steels occurred when cementite particles diameter was around 120 nm, which, according to the author, is of the same order of the domain walls thickness in this class of materials. It is generally accepted that the carbide particles are more harmful to the magnetic domain wall movement when their average diameter is in the range of 0.1–1.0 μm [5].

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Cementite and the ε-carbide are the two types of iron carbides that cause magnetic aging in electrical steels [6,7]. Aging above 250 °C, or long soaking below this temperature, can lead to precipitation of cementite particles, with the basic composition Fe_3C and orthorhombic crystal structure, having an {1 1 0} type habit plane. Cementite particles usually form as plates oriented along the ⟨1 1 1⟩ direction in ferrite. In the early stages of aging in temperatures ranging from 100 °C to 250 °C, ε-carbide forms, with the approximate composition $Fe_{2,4}C$ and hexagonal crystal structure. The ε-carbide particles usually have the form of disks and an habit plane of the type {1 0 0}. Below 100 °C, very fine carbides (20–40 nm) precipitate, in the form of coherent particles whose crystal structure has not yet been determined. These very fine and coherent precipitates, referred to in the literature as low temperature carbides (LTC), are innocuous as far as magnetic aging is concerned [8].

It is well known that semi-processed electric steels develop a certain crystallographic texture after the decarburization treatment [9]. Thus, it can be inferred that there are preferred directions for the precipitation of the aging-inducing particles in the steel sheet plane. As a consequence, the magnetic aging phenomenon should be anisotropic. This work has been carried out in an attempt to provide evidence of such anisotropy, as well as to correlate this behavior with the steel microstructure.

2. Experimental procedure

A semi-processed, ultra-low carbon steel, produced under industrial conditions was used for the assessment of the magnetic aging anisotropy. Its chemical composition (in wt.%) was Fe–0.0087C–0.52Mn–0.67Si–0.013P–0.005S–0.29Al–0.03Sb–0.0035N. The semi-processed steel was submitted to thermal decarburization treatment in a laboratory furnace, developed to reproduce the industrial conditions prevailing at the electric motor manufacturers. The heat treatment is schematically shown in Fig. 1. Rectangular steel strips 280 mm long, 30 mm wide and with 0.5 mm in thickness, were arranged in packages and soaked at 760 °C for 2 h under a 90% nitrogen–10% hydrogen atmosphere, with a dew point of 10 °C. After the decarburization treatment, the residual carbon content was 25 ppm in weight.

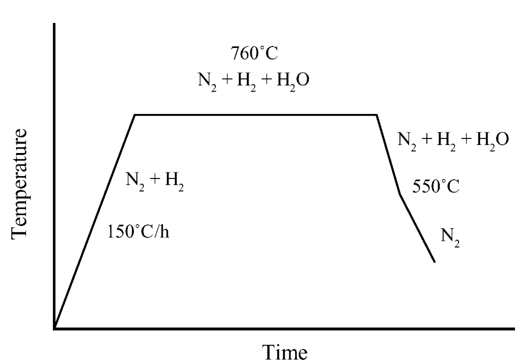

Fig. 1. Schematic representation of the decarburization heat treatment.

The heat-treated strips were subsequently submitted to accelerated aging treatments at 210 °C for 8, 24, 48, 100, 200, 400 and 600 h. In order to investigate the influence of the crystallographic orientation on the susceptibility to magnetic aging, samples were taken according to the following orientations in relation to the rolling direction: 0, 15, 30, 45, 55, 75 and 90°.

The steel susceptibility to magnetic aging was evaluated by measuring magnetic losses at 1.0 T and 60 Hz before and after the aging treatments, using a Brockhauss Single Strip Tester device model BDS280. The values of the magnetic loss employed in the analysis were the average of three measurements made on individual strips.

The measured magnetic losses enabled the calculation of the magnetic aging index (AI), according to the following equation:

$$\mathrm{AI} = \frac{P_{\mathrm{TA}} - P_{\mathrm{T}}}{P_{\mathrm{T}}} \times 100\% \quad (1)$$

where P_T is the magnetic loss of the heat-treated steel and P_{TA} the magnetic loss of the heat-treated and aged steel.

In order to investigate the evolution of the magnetic loss during the aging treatment, the measured values were split into their three components: the Foucault, the hysteretic and the anomalous portion, using the Bertoti method [10].

Transmission electron microscopy was used to investigate the steel microstructure before and after the aging treatments. A Philips model CM120, operating at 120 kV, was employed for this purpose. The steel specimens were prepared by electrolytic polishing in a solution of 15% perchloric acid in acetic acid at 15 °C.

The crystallographic texture of the steel was evaluated by the Schulz reflection method, using a Siemens D5000 X-ray diffractometer. Direct pole figures from the planes {1 1 0}, {2 0 0} and {2 2 2} were employed to determine orientation distribution functions (ODF), from which fiber figures were obtained.

3. Results and discussion

The change in the aging index (AI) with aging time at 210 °C, measured in the rolling direction, is shown in Fig. 2. It can be seen that AI reaches 40% within 24 h, showing little variation for longer treatment times. Fig. 3 shows the development of the three types of magnetic loss, evaluated as described before, with the aging time. It is remarkable that only the hysteretic portion changed during aging, reflecting its sensitivity to the precipitation/coalescence of the iron carbides.

The images obtained of the decarburized steel strips by transmission electron microscopy shown in Fig. 4 indicated that only the low-temperature carbides (LTC) are present in the steel. After accelerated aging at 210 °C for 24 h, instead of