Precipitation and magnetic models coupling for magnetic aging prediction

Fabien Dancoisne[a, b], Myriam Dumont[a], Stéphane Clénet[b], Abdelkader Benabou[b]

[a] *Arts & Métiers Institute of Technology. (MSMP-EA7350) Mechanics, Surfaces and Materials Processing, 8 bd Louis XIV, Lille Cedex, 59046, France*

[b] *Univ. Lille, Arts & Métiers Institute of Technology, Centrale Lille, HEI. (L2EP-EA2697) Laboratoire d'Électrotechnique et d'Électronique de Puissance, Bâtiment ESPRIT, Avenue Henri Poincaré, Villeneuve d'Ascq, 59655, France*

While in operation, widely-used electrical machines are not yet capable of converting all the input energy, thus resulting in a waste of energy. Within magnetic cores, the heat-dissipated iron losses pose a serious threat to energy efficiency. With Non-Oriented Electrical Steels (NOES) as the main material they are conceived with, it is of prime interest to understand and harness the irreversible consequences the operating temperature (between 160°C & 200°C) may have on magnetic performances. In fact, the losses increase over time is due to a precipitation mechanism at the microscopic scale: the magnetic aging. This paper proposes a multi-scale and multi-physics model that accounts for the effects of precipitation on iron losses and that is based on a combination of the JMAK and Jiles-Atherton's models.

Keywords: NOES; Magnetic Aging; Hysteresis; Precipitation

1. Introduction

Magnetic aging refers to an irreversible degradation of magnetic performances that appears when electrical steels are subjected to moderate temperatures during machine operation, usually between 160°C and 200°C. When specific material composition and microstructural conditions are met [1-2], this heat-dissipation phenomenon, in turn, causes carbon atoms present in the alloy lattice to precipitate, forming large particles hindering magnetization. In the literature, the effects of aging are well characterized [1], as well as their impacts on magnetic properties, such as coercive field [2] and iron losses [3]. In general, the more carbon there is, the higher the precipitate's volume fraction [4], the higher the drawbacks on performances. In this communication, a mutli-physics model accounting for precipitation in electrical steels is proposed. A first section will deal with the characterization method used on lab-cast samples, whose results will be explored in the next part so to build a multi-scale model coupling precipitation kinetics (JMAK model [3]) and static magnetic hysteresis (Jiles-Atherton's model [5]). For this study, several materials of known chemical composition will be considered. Lastly, the modeling suitability will be discussed and further developments mentioned.

2. Experimental methodology

Magnetic aging of Fe-Si alloy samples is characterized as follows: first, 200×30×0.25 mm samples are placed in an oven for a set amount of time (several hours) and undergo an isothermal heating at 160, 180 or 200°C. They are then taken out and their magnetic properties are measured at room temperature, at 5 and 50 Hz by means of a Single Strip Tester (SST) device. The chemical compositions of the studied samples feature different amounts of silicon and carbon.

3. Multi-scale model

The multi-scale model consists in applying the JMAK model to the evolution over time of the transformation rate $Y(t)$ linked to precipitation mechanisms. Since precipitates act as pinning sites for domain walls movements during magnetization, it can be represented by the pinning factor parameter k (1) of the Jiles-Atherton (J-A) model of magnetic hysteresis.

$$\frac{dM_{\mathrm{irr}}}{dH_e} = \frac{M_{\mathrm{an}} - M_{\mathrm{irr}}}{\pm k} \qquad (1)$$

Where M_{irr} is the irreversible part of magnetization, H_e the effective field and M_{an} the anhysteretic magnetization. The analysis of experimental data shows that the pinning factor evolution resembles that of the transformation rate, leading to its approximation of eq. (2).

$$k(t) = Y_k(t) \times \Delta k + k_{\mathrm{min}}, \qquad (2)$$

An application of the coupled approach is shown on fig. 1 and displays a satisfactory result between experimental and simulated B(H) loops after a 96-hour aging at 200°C.

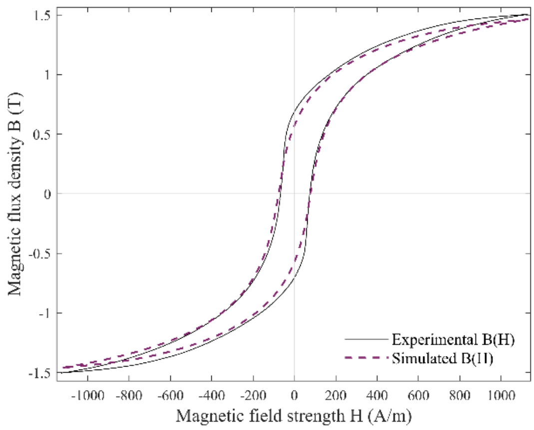

Figure 1: Hysteresis loop of a Fe-Si sample aged at 200°C for 96 hours. B_{max} = 1.5 T, f = 5 Hz

References

[1] S. Ray, "Magnetic ageing characteristics of low silicon electrical steels", Journal of Magnetism and Magnetic Materials, 28, 1982.
[2] L.J. Dijkstra, C. Wert, "Effect of inclusions on coercive force of iron", Phys. Rev. 79 (6), 1950.
[3] M. Jamil and al., "Application of the JMAK precipitation law in iron loss modelling to account for magnetic ageing effect" J.M.M.M., vol. 547, 2022.
[4] J.R. de Oliveira-Junior and al., "Kinetics of magnetic ageing of 2% Si non-oriented grain electrical steel", Mater. Res., 21 (1), 2018.
[5] D.C. Jiles and D.L. Atherton, "Theory of ferromagnetic hysteresis", J. Appl. Phys., 1984

Acknowledgements: ANR-PRC Mastermind2