Thermal Behavior of Iron-Nickel-Chromium Alloys and Correlation with Magnetic and Physical Properties- Part A: Static Effects Modeling

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Magnetic materials are required to perform in environmental conditions, which are becoming more and more stringent. Of the environments to be considered, temperature has the most deleterious effect on magnetic cores. For a better knowledge of the thermal behavior of ferromagnetic materials, it is expedient to resort to a temperature dependent behavioral model. In this paper, we propose a new temperature dependent model based on an extension of modified Weiss and Jiles-Atherton theories. The proposed model generates meaningful sets of J-A parameters versus temperature. Simulation results are compared to quasi-static measurements made on two iron-nickel-chromium soft magnetic alloys. Results are in good agreement.

***Index Terms*— Jiles-Atherton model, Hysteresis, Magnetic materials, Modeling, Modified Weiss theory Temperature.**

I. Introduction

Semi-empiric analytical laws of evolution of the Jiles-Atherton (J-A) model parameters versus temperature are proposed by the authors in [2], [3]. These laws need the knowledge of the five parameters at 0°K extrapolated from the measured data using suitable algorithms. The variation of the J-A parameters with temperature given by this method is monotonic but predicts more and more "inaccurate" hysteresis loops as the temperature increases [2].

In [4], we proposed another method based on optimization algorithms at each temperature value. We compared the two methods quantitatively and qualitatively and results showed that our method predicts more accurate hysteresis loops than the first one over the temperature range. However, the evolution of the J-A parameters becomes erratic above a certain temperature.

In this paper, we propose a new temperature dependent model based on an extension of modified Weiss and J-A theories. Simulation results are compared to quasi-static measurements made on two iron-nickel-chromium soft magnetic alloys; results shown here are those of Phytherm260.

II. Modified Weiss Theory

The Weiss theory of ferromagnetism is an extension of the classical theory of paramagnetism witch was developed by Langevin [5] (chapter 10, pp. 428):

$$\frac{M_s}{M_s(0°K)} = \tanh\left(\frac{\mu_A H}{K_B T}\right) \qquad (1)$$

where M_s is the saturation magnetization, M_s(0°K) is the saturation magnetization at 0°K, T represents temperature, H is the applied filed, K_B is the Boltzmann constant=1.38×10^{-23} J/°K and μ_A is the magnetic moment.

Weiss introduced a so-called "molecular field". The significance of the molecular field for ferromagnetism is apparent by introducing the molecular field parameter, α, representing the interaction between magnetic domains. The material behaves magnetically as if there were an additional field (proportional to magnetization) aiding the applied field H. If we replace the H by $H+\alpha M_s$(0°K) in the more general equation Eq.(1), the resulting equation is:

$$\frac{M_s}{M_s(0°K)} = \tanh\left(\frac{\mu_A (H + \alpha M_s(0°K))}{K_B T}\right) \qquad (2)$$

According to the modified Weiss theory, the law relating the saturation magnetization to the absolute temperature becomes:

$$\frac{M_s}{M_s(0°K)} = \tanh\left(\frac{M_s / M_s(0°K)}{T / T_c}\right) \qquad (3)$$

$$T_c = \mu_A \frac{\alpha M_s(0°K)}{K} \qquad (4)$$

III. Jiles–Atherton Theory

The J-A theory is exposed in more detail in [1]. The model equations are formulated into an explicit differential form $M(H)$ [4] describing the static hysteresis behavior with five parameters: molecular field parameter α, saturation magnetization M_s, domain density a, reversibility factor c, and pinning factor k to be determined.

IV. Experimental Procedure

Measurements are taken on toroid sample from the demagnetized state to saturation and from a temperature corresponding to equilibrium for the liquid nitrogen (≈ -196°C) until the Curie point Tc. Temperature of liquid nitrogen was not measured. It was assumed to be close to the normal boiling point of the liquid used in an adapted container.

V. Temperature Dependence in the Model

A. Temperature Dependence of Saturation Magnetization and Molecular Field Parameter

The measured saturation magnetization, M_s, as a function of temperature is used to estimate the saturation magnetization at 0°K, M_s(0°K) and the molecular field at 0°K, αM_s(0°K) by fitting to the analytical law in Eq.(3) using suitable optimization algorithms (see Fig.1). So, knowing the values of M_s(0°K) and molecular field at 0°K, αM_s(0°K), we can calculate the value of the molecular field coefficient α.

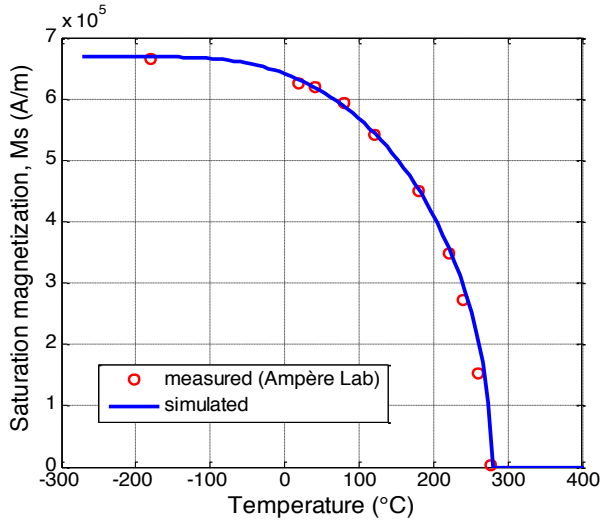

Fig.1. Saturation magnetization as a function of temperature in Phytherm 260

In Tab.I, we report the calculated value of the molecular field parameter, α for the investigated alloy.

TABLE I
MOLECULAR FIELD AT 0°K AND MOLECULAR FIELD PARAMETER α

Reference	$\alpha \times 10^7$(SI)
Phytherm 260	2991.99

The study made by P.Weiss in [6] on nickel showed that the coefficient of the molecular field, α is expected to have the same numerical value despite the change in the moment of the nickel atoms. He concluded that α has the same value for the magnetization at high temperatures and for saturation at absolute zero. In the following, we consider the implicit assumption that the molecular field coefficient is independent of temperature as pointed out by Wiess in [6].

B. Domain density, Pinning Factor, Reversibility and General Identification Procedure

Now, the temperature variation of saturation magnetization, M_s and molecular field parameter, α can be considered. The identification procedure for the proposed model consists in optimizing the three other parameters: domain density, *a,* pinning factor, *k* and reversibility, *c* from measured data. This procedure will identify all necessary parameters to describe hysteretic behavior at any temperature.

The model tested on the studied iron-nickel-chromium soft magnetic alloys generates meaningful sets of J-A parameters (Fig.2). This behavior is the result of the assumption that the molecular field coefficient is independent of temperature. For temperatures ranging from the temperature of liquid nitrogen (≈ -196°C) to the Curie point, all the J-A model parameters tend to decrease monotonically with temperature. Then, the model is validated against measurements at various temperatures. The results are in good agreement (see Fig.3).

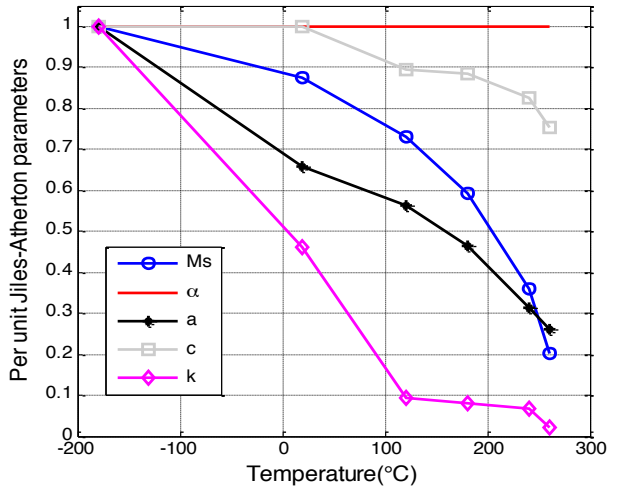

Fig.2. Normalized evolution of the J-A parameters versus temperature in the Phytherm 260 alloy

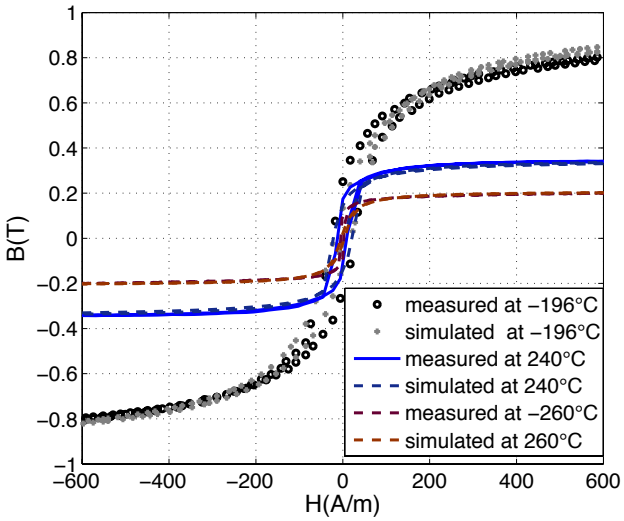

Fig.3. Measured and simulated hysteresis loops in the Phytherm 260 alloy for different temperatures

VI. CONCLUSION AND PROSPECTS

A new temperature dependent model based on modified Weiss and J-A theories is developed. It is used then to model the dynamic effects in the material in [7] where the dynamic model parameters will be correlated with the physical properties of the material. Further explanations and developments will be given in the extended paper.

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