Comprehensive Improvement of Temperature Dependent Jiles-Atherton Model Utilizing Variable Parameter Set

Dianhai Zhang[1], Mengfan Jia[1], Ziyan Ren[1], Yanli Zhang[1] and Chang-Seop Koh[2], *Senior, IEEE*

[1]School of Electrical Engineering, Shenyang University of Technology, Shenyang, Liaoning 110870, zdh700@126.com
[2]College of ECE, Chungbuk National University, Cheongju, Chungbuk 361-763, kohcs@chungbuk.ac.kr

The magnetic properties of ferromagnetic materials vary remarkably with temperature changing. If the magnetic field analysis of electromagnetic devices operating at high temperature is analyzed utilizing the magnetic properties obtained at normal temperature, the analysis results are quite different from the real ones. In order to understand and apply the real magnetic behaviour in ferromagnetic materials, a temperature dependent hysteresis model is necessary. In this article, a physical background based Jiles-Atherton model is improved to explain the temperature effects. Furthermore, the inaccuracy of the Jiles-Atherton model in the range of weak applied field is improved by introducing variable parameter set. Ultimately, a comprehensive improvement algorithm of temperature dependent Jiles-Atherton model is proposed and verified by experimental hysteresis data.

***Index Terms*—Ferromagnetic material, Jiles-Atherton model, Temperature dependent, Variable parameter set.**

I. INTRODUCTION

WHEN the magnetization data at room temperature is applied to analyze the magnetic field of electromagnetic device which is used at high temperature, the analysis results are quite different from the real one[1]. The reason is that the magnetic properties of magnetic material change dramatically with temperature varying. Therefore, it is necessary to investigate the magnetic behaviors of ferromagnetic material such as electrical steel sheets at high temperature. In this study, a physical background based model which is called Jiles-Atherton (J-A) model is adopted. As it is known, the original J-A model is not a temperature-dependent model[2]. In order to consider the effect of temperature, in the foregoing study, the work focused on expressing the micro-structural hysteresis parameters as a function of temperature[3],[4]. However, this method needs the value of Curie temperature and parameter set at absolute zero degree of temperature for a specific material. These parameters, usually, are hard to be obtained from conventional measurement. Furthermore, in general, the parameter set achieved from strong magnetization hysteresis data is not suitable for weak magnetization[5]. In this article, novel parameter set expressions are proposed to avoid introducing parameters which are difficult to measure meanwhile the inaccuracies of the J-A model in the weak magnetization region can be to a large degree removed. Besides, a miniature 1DSST is adopted to measure magnetic properties at different temperatures for silicon steel sheets.

II. PROBLEM DESCRIPTION

Fig. 1 shows the comparison of saturated major hysteresis loops (B=1.6T) at 25 ℃ and 270 ℃. The magnetic field intensity at hysteresis loop tip for 25 ℃ is obviously lower than the one at 270 ℃. However, the total iron loss value at B=1.6T is higher than that at 270 ℃. To analyze magnetic field for an electromagnetic equipment which operates at high temperature, if the magnetization curves and iron loss curves at room temperature for a specific material are applied into finite element magnetic field model, the results are quite different from the real results. Therefore, it is necessary to extend the origin J-A hysteresis model to describe the effect of temperature.

Fig. 2 compares the measured hysteresis loop and modelled one with same parameter set, which is identified from the saturated measured hysteresis loop. From the figure, it is obvious that two loops match very well at B=1.6T, however at B=1.2T, the simulated loop is far from the measured one. The constant parameter set is incapable for simulating the families of major (symmetric) hysteresis loops for the same material.

III. MEASUREMENT, MODELING AND THEIR RESULTS

A. Measurement Fixture and Process

In order to keep precise high temperature, an incubator is applied in our measurement. Due to space limitation, a miniature one dimensional single sheet tester (1DSST) is used to measure the magnetic properties. The fixture is improved so that it can

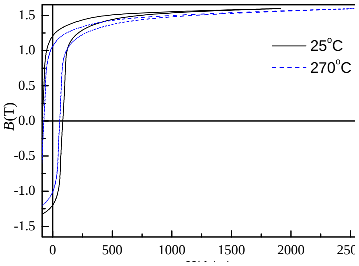
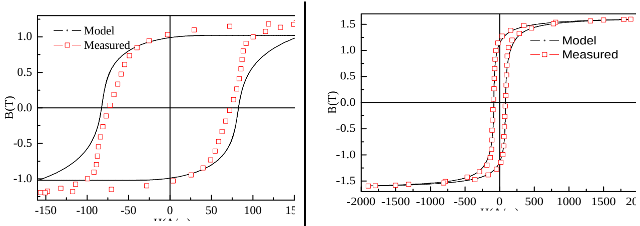


Fig. 1. The comparison of hysteresis loops at different temperatures.



(a).Comparison at H=160A/m (b).Comparison at H=1900A/m

Fig. 2. Comparison of measured and modeled hysteresis loops at different magnetic field intensities. (M_s=1.315MA/m, a=77.64, k=90.77, c=2.1×10^{-9}, α=1.92×10^{-5})

withstand high temperature. The dimension of prepared specimen is 150×150mm. In this article, the non-oriented silicon steel sheet 50AW600 is measured and applied to investigate the magnetic properties.

B. Comprehensive Improvement of Parameter Set

In original JA model, the five model parameters found from saturated major loop of silicon steel sheets is not suitable for unsaturated ones. Meanwhile, the original one cannot consider the effect of temperature. In order to settle these problems, this paper presents a group functions to describe the degree of saturation and effect of temperature.

From the description of original J-A model, it is known that the five JA model parameters are saturation magnetization M_s, hysteresis loss coefficient k, domain coupling α, reversibility factor c and domain density parameter a, respectively[2].

With a given parameter set, good matching can be obtained for saturated hysteresis loops. For unsaturated loops, the error between model and measurement becomes more and more obvious. According to our observation, for the model results, the following conclusions can be summarized:

a). The residual magnetization (M_r) is lower than measured value.

b). The coercive force (H_c) is higher than measured value.

c). The slope between point M_r and H_c is smaller than measured one.

Following the above rules, parameters k, c, and a may be modified. Here, we assume a simple linear relationship between parameters and magnitude of applied field. The expressions can be listed below:

$$\begin{cases} k(H_{tip}) = k + s_k(H_s - H_{tip}) \\ c(H_{tip}) = c + s_c(H_s - H_{tip}) \\ a(H_{tip}) = a + s_a(H_s - H_{tip}) \end{cases} \tag{1}$$

where s_k, s_c, and s_a are the slope of linear function of the three parameters, respectively. The slope can be identified from measured hysteresis loops with different H_{tip}. The detailed identification process will be given in the full paper.

In [4], five material related parameters are expressed as the function of temperature. In their expressions, the curie temperature (T_c) and parameter set at absolute zero degree of temperature (M_{s0}, a_0, k_0, c_0, α_0) are required. These parameters, actually, are difficult to get in experiment. Therefore, in our method, a novel temperature related parameter set expression is given to avoid introducing parameters which are hard to obtain.

$$\begin{cases} M_s(T) = M_{sT1} \cdot [1-(T-T_{\min})/T_{\max}]^{\lambda_1} \\ a(T) = a_{T1} e^{-\frac{1}{\lambda_3} \cdot \frac{(T-T_{\min})}{T_{\max}}} \\ k(T) = k_{T1} e^{-\frac{1}{\lambda_2} \cdot \frac{(T-T_{\min})}{T_{\max}}} \\ c(T) = c_{T1} e^{-\frac{2}{\lambda_1} \frac{T-T_{\min}}{T_{\max}}} \cdot [1-(T-T_{\min})/T_{\max}]^{-\lambda_1} \\ \alpha(T) = \alpha_{T1} e^{-\frac{2}{\lambda_1} \frac{T-T_{\min}}{T_{\max}}} \cdot [1-(T-T_{\min})/T_{\max}]^{-\lambda_1} \end{cases} \tag{2}$$

where parameters with subscript 'T1' represent the parameter set at lower boundary of temperature such as normal temperature. $T_{\min}$ and $T_{\max}$ represent lower and upper boundary of temperature in the experiment. The coefficients λ_1~λ_3 are additional parameters which can consider the effect of temperature.

In this article, a global optimization technique such as PSO algorithm is adopted to find the optimal J-A model parameter set by minimizing the error between experiment and modelled loops. Fig. 3 shows the comparison between model and measurement results when (2) is adopted to determine the specific parameter. Fig. 4 shows the comparison results for a family of major loops. The inaccuracies of the model in unsaturated region and high temperature condition may be to a large degree removed by introducing variable parameter set, respectively.

In the extended full paper, the comprehensive algorithm will be explained in detail and the analysis results will be compared with measured one to verify the validity of proposed method.

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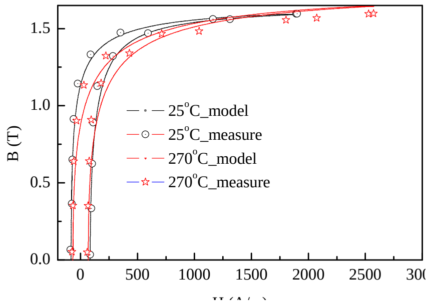

Fig. 3. Comparison of modelled and measured hysteresis loop @B=1.6T.

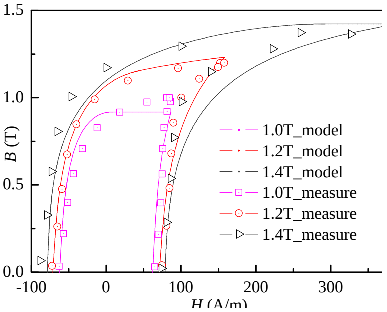

Fig. 4. Comparison of measured and modeled hysteresis loops @B=1.0T, 1.2T, and 1.4T.