TWO-DIMENSIONAL PREISACH MODELS

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Preisach modeling, long known in the area of magnetic, has introduced mathematical abstraction to the modeling of the highly nonlinear and complex phenomenon of hysteresis. The 2D Preisach-type models presented here, departing slightly from the classical formulation, waive some of its limitations while maintaining the major advantages of simplicity and speed in calculations. The results presented in this work are based on ferromagnets but the 2D formulation, in the spirit of the classical one, is not restricted in applications to ferromagnets and can be applied to other systems with hysteresis as well.

1 INTRODUCTION

In the early thirties, Ferenc Preisach, an electrical engineer working for Siemens & Halske in Berlin, developed a model on hysteresis in ferromagnets [1]. It was a scalar model treating the magnetization response of a magnet exposed to an externally applied field as the superposition of responses of local hysteresis operators appropriately distributed. It was a novel idea for treating hysteresis departing from the classical thermodynamic treatment. After twenty years of successful application to ferromagnets, the Preisach model, as it became known, attracted the interest of the mathematicians Krasnoselskii and Pokrovskii [2] who were intrigued by the mathematical structure of the model and investigated its properties. Stripped of its ferromagnetic past, the Preisach formalism became available to the modeling of systems exhibiting hysteresis other than ferromagnets.

To this day the scalar model has been extensively studied, modified and applied. The rigorous mathematical treatment [3, 4] highlighted the advantages as well as the disadvantages of the model. The formalism is abstract, elegant and simple leading to fast algorithms and reliable results in spite of the complexity of the phenomenon it models.

Hysteresis is a non-linear phenomenon encountered in problems in magnetism, in biology, in plasticity, in economics even. The etymology of the word suggests that in a system exhibiting hysteresis (means *delay* in Greek) the output, y, lags the input, x. This is true but it is not all. The present output is a complicated non-linear function of the present input as well as of the past input values. From a stability point of view, there are many possible equilibrium states for one input value. The resulting state depends on the history of the system, on the previous equilibrium states. Therefore, a system with hysteresis is also a system with memory.

The *major loop* curve (Fig.1) is the trademark of hysteresis but it doesn't reveal the whole picture. The curve demonstrates a non-linear x-y relationship but it suggests bistability: for a given input there are only two possible output states. As mentioned already, things are much worse. Any given point on or inside the curve can be reached through several trajectories called *minor loops*. Fig. 5 shows the set of minor loops used to reach the state [0,0]. A major loop curve is indicative of the behavior of a system, holding a lot of useful information and delimiting the input/output space but it is just a trajectory obtained for a specific input sequence. Other input sequences yield different sets of ascending or descending curves all of them inside the major loop.

In order to obtain a major loop curve one needs to start at the positive ($+S$) or the negative ($-S$) saturation state. The positive (negative) saturation state is the state at which the output stops changing with an increasing (decreasing) input, *i.e.*:for

$$x \geq +X_s, y = +S$$

$$x \leq -X_s, y = -S$$

where $+X_s, -X_s$ are the input values leading to positive and negative saturation respectively.

Note that these two states are the only uniquely defined states of a system with hysteresis. Starting at the $+S$ - state and with a monotonically decreasing input x the $-S$ - state is reached tracing the left-hand side branch of the curve, called the *major descending* curve. The *ascending* branch on the right is the trajectory obtained when the input increases from $-X_s$ to $+X_s$.

Tracing the major loop this way, it is obvious that the output lags the input. It is important to remember that this is the only way to trace the major loop otherwise the second law of thermodynamics is violated. The shape and size of the major and minor curves depends on the physics of the system which in most cases are quite complicated taking into account the internal microstructure and interactions developed.

Another issue arising in the treatment of hysteresis is the rate of change of the input. There are problems where hysteresis can be treated *quasistatically*, as a rate-independent phenomenon, the underlying assumption being that the time elapsing between two consecutive inputs is long enough for the transients to reduce to zero.

Hysteresis is a complex and challenging to model phenomenon while in the same time common in systems in nature. The popularity of the Preisach formalism is due exactly to the fact that it is a fairly simple approach to a complicated problem. The original model is presented in section 2 in order to highlight its potential and limitations one of them being its inherently scalar nature. In modern magnets, for example, the one-dimensional treatment is no longer adequate. Vector models based on the formalism but also departing from it have been proposed [5-6].

A two-dimensional approach is discussed in section 4 for both homogeneous and inhomogeneous systems and the identification issue is raised. In section 5, results from applications in magnetism are used to illustrate the analysis of the model and the potential for future development.

2 THE ORIGINAL MODEL

2.1 The scalar operator

In the Preisach approach, hysteresis is the result of superposition of scalar local memory operators. Let's assume a bistable operator, $\gamma_{\alpha,\beta}$, like the one shown in Fig. 2b:

$$\gamma_{\alpha,\beta} = \begin{cases} +1, & x(t) > \alpha \\ -1, & x(t) < \beta \end{cases}$$

When the input becomes greater than α the operator $\gamma_{\alpha,\beta}$ assumes the value +1 which it retains until the input, $x(t)$, becomes smaller than β in which case it switches to −1. The function $\gamma_{\alpha,\beta}$ is discontinuous at the *switching points* α and β. The system being modeled can then be viewed as a collection of subcomponents each of which has a hysteresis characteristic $\gamma_{\alpha,\beta}$ with different switching points α and β. The displacement of the elementary loop from the origin corresponds to the effective interactions, x_{int}, experienced by the given component: $x_{\text{int}} = \dfrac{\alpha + \beta}{2}$.

If the subcomponents are isolated or the sum of interactions one of them experiences is zero the corresponding loop is centered at the origin and $\alpha = -\beta$.

Another quantity of interest is the loop halfwidth, $x_{hw} = \dfrac{\alpha - \beta}{2}$. When $\alpha = \beta$ the degenerate loop of zero halfwidth, $x_{hw} = 0$, is obtained.

2.2 The Preisach plane and the characteristic density

The system can then be modeled as a distribution of α and β, as a collection of elementary loops of various switching points, or equivalently, of various interactions and halfwidths. The distribution is obtained from the characteristic density of the system, $\rho(\alpha,\beta)=\rho(x_{hw},x_{\text{int}})$, which is defined over the Preisach plane (Fig. 2a) [7].

The plane is bounded by $x_{hw}=0$ (otherwise the lower switching point β is greater than the upper switching field α which violates the second law of thermodynamics), $x=+X_s$ and $x=-X_s$ where $+X_s$ and $-X_s$ are the input values leading to positive and negative saturation respectively: $\forall\alpha,\beta \quad \alpha\le +X_s, \beta\ge -X_s$.

The response of the system, $y(t)$, to an input, $x(t)$, is the sum of contributions of each elementary loop weighed by the probability density function $\rho(\alpha,\beta)$:

$$y(t)=\iint_{\alpha\ge\beta}\rho(\alpha,\beta)\gamma_{\alpha,\beta}\,x(t)\,d\alpha d\beta$$

The identification of such a model consists in the determination of the characteristic density $\rho(\alpha,\beta)$. It has been shown [4, 7] that the density in the scalar case can be measured. This method has also been used in non-linear control applications where one needs to invert the model and determine the input value *x(t)* needed to obtain an output *y(t)* [8]. The density can also be constructed as a product of two independent probability density functions when appropriate: $\rho(\alpha,\beta)=\rho(x_{hw},x_{\text{int}})=\rho(x_{hw})\rho(x_{\text{int}})$.

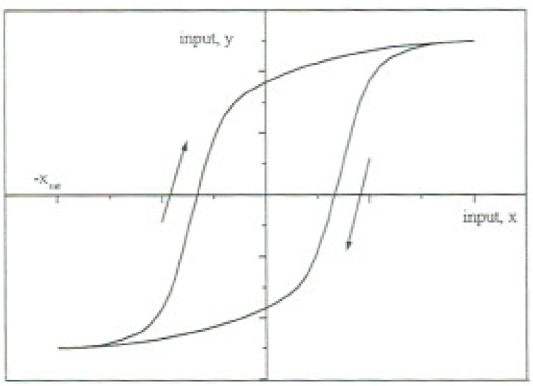

Figure 1: Hysteresis: major loop curve.

2.3 The boundary as memory

If an input $x(t) < -X_s$ is applied the system goes into the negative saturation state, $y(t) = -S$, where all the operators $\gamma_{\alpha,\beta}$ are in the -1-state:

$$y(t) = \int_{-X_s}^{+Xs} \int_{-Xs}^{\beta} \rho(\alpha,\beta)(-1)x(t)d\alpha d\beta = -S$$

Increasing the input to $x_1 > -X_s$ the operators with $-X_s < \alpha < -x_1$ will switch to +1. A horizontal boundary separating the regions of +1- and −1- states is established at $\alpha < -x_1$. Decreasing the input to $-X_s < x_2 < x_1$, all operators with $\beta > -x_2$ will revert to −1 and a perpendicular boundary segment appears (Fig. 2a). This way, at the end of an input sequence a staircase boundary is established between areas of positive and negative state. This boundary serves as a memory maintaining the history of the system.

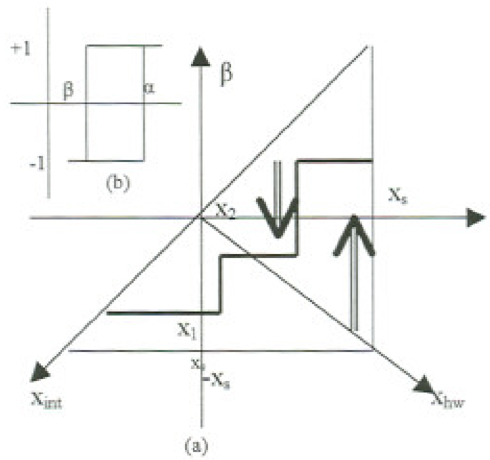

Figure 2: (a) The Preisach plane with the staircase boundary (b) the scalar operator

2.3.1 Wipe-out and congruency

It has been shown that wipe-out and congruency property are two properties of the original Preisach model which are necessary and sufficient in order for a system to be modeled by it [4].

According to the wipe-out property, the model remembers only the local extrema wiping out the effect of inputs smaller than the extremum values, e.g., for an input sequence $x_1 \to x_2 \to x_1$ the output will be $y_1 \to y_2 \to y_1$ regardless of the path followed due to intermediate inputs, $x_1 < x < x_2$. This property is, in general, a property of the actual systems, as well, unless dynamic phenomena cannot be ignored.

The congruency property is usually not obeyed by the systems but it is property of the original model. According to this property, for an input sequence $x_1 \rightarrow x_2 \rightarrow x_1$ the resulting minor loop will be qualitatively the same regardless of the previous history. An example of noncongruent minor loops is shown in Fig. ????.

2.4 The pros and cons of the Preisach formalism

Concluding this section, the Preisach formalism is a macroscopic, quasistatic approach to hysteresis modeling simple and easy to implement. The resulting fast algorithms are very convenient in cases where tedious calculations are needed like magnetic recording simulations [9] or control [8] applications. The simplifying assumptions underlying the model suggest its limitations as well.

The Preisach model can reproduce irreversible behavior only and this is due to the operator $\gamma_{\alpha,\beta}$ acting as a switch. When reversible processes are involved, rotation for example, they have to be added on. Another limitation directly related to the operator is the one-dimensional treatment of hysteresis. Both of the above are waived by substituting $\gamma_{\alpha,\beta}$ by a 2D functional (Fig. 3) as will be seen in Section 4.

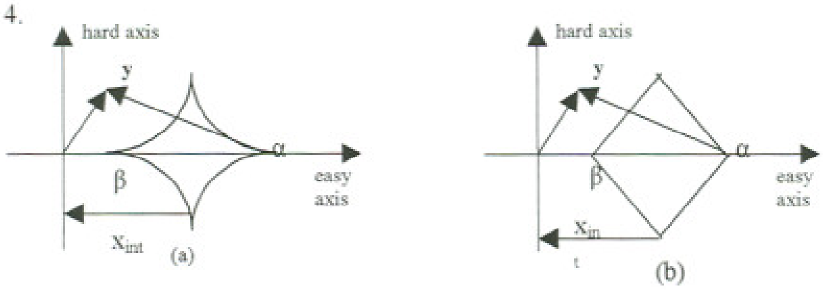

Figure 3: Vector operators: (a) the S-W astroid (b) the diamond.

Finally, another interesting and rather open question is the applicability of a modified dynamic Preisach model [10].

3 The two-dimensional approach

The properties of the original Preisach model are largely due to the properties of the elementary operator $\gamma_{\alpha,\beta}$. One way to add vector properties to the model is to substitute the scalar $\gamma_{\alpha,\beta}$ by a vector 2D operator $\Gamma_{\alpha,\beta}$.

In magnetics, there exists the well-known Stoner-Wohlfarth (S-W) model [11] of coherent rotation of the magnetization which can serve as a vector operator (Fig. 3a). This model assumes that the system is anisotropic with an easy and a hard axis. Let x_e and x_h be the components of the input x along the easy and hard axis respectively. Then the resulting y is a tangent to the astroid drawn from the tip of the input vector. Switching occurs when the output vector crosses the astroid from the inside out. Otherwise the output vector rotates reversibly. The locus of the astroid is given by: $x_e^{2/3} + x_h^{2/3} = 1$. Note that the astroid equation results from the minimization of the free (Gibbs) energy equation for an ellipsoidal magnetic particle with uniaxial anisotropy under the influence of an applied field. It is not an abstract mathematical structure like its scalar counterpart.

A modification of the above is the diamond-shaped operator of Fig. 3b given by the first-order approximation of the S-W astroid: $x_e + x_h = 1$.

The modified 2D Preisach model is then given by:

$$y(t) = \iint_{\alpha \geq \beta} \rho(\alpha, \beta) \boldsymbol{\Gamma}_{\alpha,\beta} \boldsymbol{x}(t) d\alpha d\beta$$

The operator $\Gamma_{\alpha,\beta}$ acts on the vector input $x(t)$, the result is weighed by the

$$y(t) = \int_{-\pi/2}^{+\pi/2} \iint_{\alpha \geq \beta} \rho(\phi) \rho(\alpha, \beta) \boldsymbol{\Gamma}_{\alpha,\beta} \boldsymbol{x}(t) d\alpha d\beta d\phi$$

density function $\rho(\alpha, \beta)$ and integrated over the Preisach plane yielding the output *y(t)*. The boundary on the Preisach plane no longer consists of horizontal and vertical segments allowing for more switching facilitated by the rotations.

The above formulation assumes a perfectly oriented system. Angular dispersion around the easy axis is included by superimposing the effect of several such models normally distributed around the preferred axis of orientation. To the limit, this becomes:

The identification problem is not as straightforward as in the scalar case. The density cannot be measured as before because of the reversible rotations predicted by the vector operator. One way to tackle this, is the factorization of the density on the assumption, valid in ferromagnets, that the halfwidths of the elementary operators, x_{hwt}, and the interactions, x_{int}, experienced by them are independent variables:

$$\rho(\alpha,\beta)=\rho(x_{hw},x_{\text{int}})=\rho\ (x_{hw})\rho\ (x_{\text{int}})$$

Then $\rho(x_{hw})$ and $\rho(x_{\text{int}})$ are modeled by Gaussians or other probability density functions and the identification problem consists of determining their parameters based on macroscopic experimental measurements.

3.1 Inhomogeneous systems

Inhomogeneous systems are systems consisting of different phases where each phase has different hysteresis properties. For a two-phase system, the density function of the halfwidths, $\rho_1(x_{hw})$, is substituted by the weighted average of two density functions, one for each phase [12]:

$$\rho_1(x_{hw})=w\times\rho(x_{hw,1})+(1-w)\times\rho(x_{hw,2})$$

where w is the % content of one phase in the system.

In this case, the identification consists of determining the parameters of four density functions: angular dispersion, $\rho\ (\phi)$, interactions, $\rho\ (x_{\text{int}})$, and halfwidths, $\rho(x_{hw,1})$ and $\rho(x_{hw,2})$ of the two phases.

4 Results and Discussion

In order to illustrate the use and applicability of the 2D Preisach models simulations of major and minor loop measurements of permanent magnets have been carried out. The major loops of ferromagnets are taken as in plane measurements of the magnetization, M, as a function of the applied field, H. The experimental data taken on samples of single-phase $Sm_2Fe_{14}Ga_3C_2$ and two-phase $Sm_2Fe_{14}Ga_3C_2/\alpha\text{-}Fe$ was found in the literature [13].

Normal distributions $N(\mu,\sigma^2)$ were used for the all three (four) probability density functions needed for the identification of the single-phase (two-phase) sample. The identification was based on four characteristics of the major loop curve: the saturation magnetization, M_s, and the remanent magnetization $M_r(H=0)$, the coercivity field $H_c(M=0)$, and the slope of the loop around the coercivity, $S^*=dM/dH\,|_{H_c}$ [12].

Fig. 4 shows major and minor loops for the two media. Even though the identification was based on four points of the major loop the major loop as well as minor loops were successfully reproduced. The modified 2D Preisach model justified the choice of a vector operator capturing both reversible and irreversible processes. The discrepancies between the experimental and simulated curves are

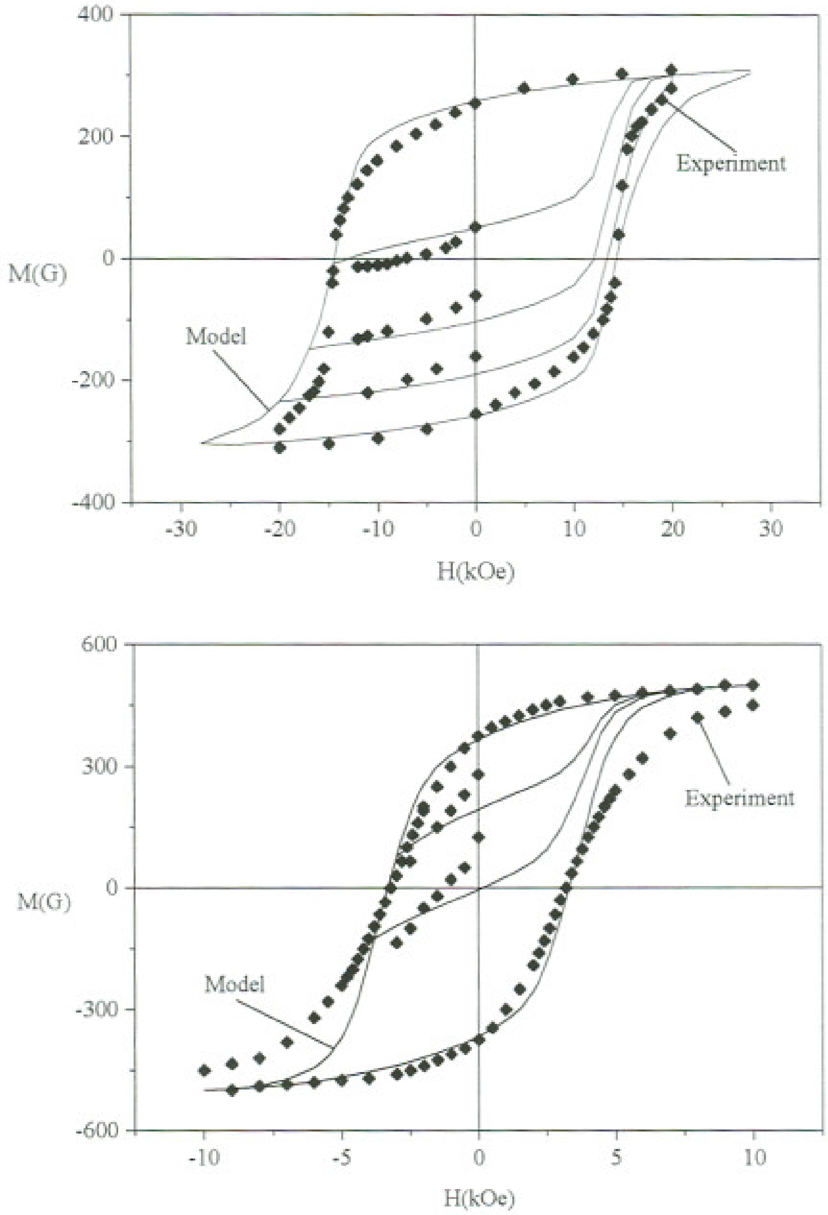

Figure 4: Major and minor loops (a) single-phase magnet (b) two-phase magnet.

due to the still coarse identification procedure and the limitations of the operator. For example, in the two-phase magnet, because of the exchange coupling between the two phases, the mode of coherent rotation employed by the operator is not accurate and the discrepancy is bigger. The use of such an operator incorporates physics into the mathematical abstraction of the model. Even though, it hasn't been tried, it is possible that the astroid will not perform as well in a non-magnetic system and different operators might need to be developed.

Fig. 5 shows the simulation of an ac demagnetization curve. Because of the highly non-linear nature of hysteresis, the output (M), starting from saturation, cannot be reduced to zero by reducing the input (H) to zero. Instead, a cycling input of decreasing magnitude needs to be applied. The model reproduces qualitatively this behavior.

The wipe-out and congruency properties of the 2D models were also tested (Fig. 6). As expected, the first applied, while the second did not which is a direct consequence of the use of a vector operator. Therefore, the 2D formulation is not a Preisach model in the strict sense of the term [4] but it is a more realistic model since actual systems with hysteresis, in general, possess the wipe-out but not the congruency property.

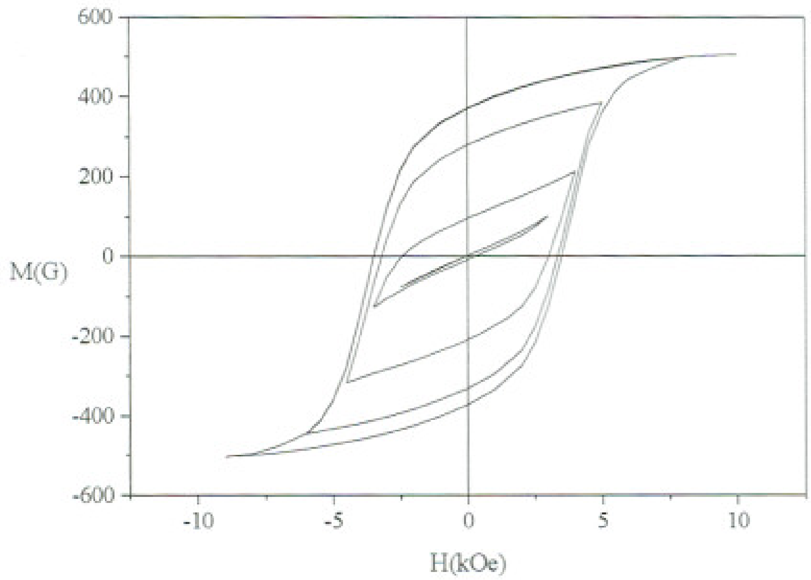

Figure 5: Ac demagnetization curve for the two-phase magnet.

Finally Fig. 7 shows a rotational hysteresis loss calculation, $W_r = \int_0^{2\pi} (\boldsymbol{M} \times \boldsymbol{H}) d\theta$, which shows the expected vector behavior of an anisotropic medium.

5 Conclusions

The 2D Preisach formulation has so far yielded satisfactory results. It maintains the major advantages while waiving some of the disadvantages of the classical model. It remains simple and abstract leading to fast algorithms. The substitution of the original operator by vector ones gives the model vector properties and allows it to reproduce both reversible and irreversible properties and raises the question of the development of such operators. The identification procedure is not as systematic yet which makes the model unfriendly to newcomers. However, it is a point of current research.

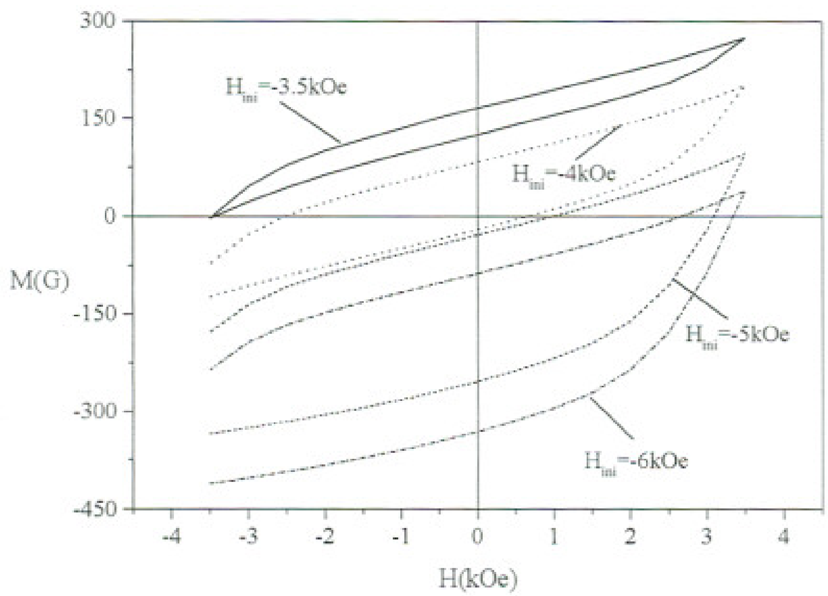

Figure 6: Non – Congruent Minor Loops for the Two – Phase Magnet.

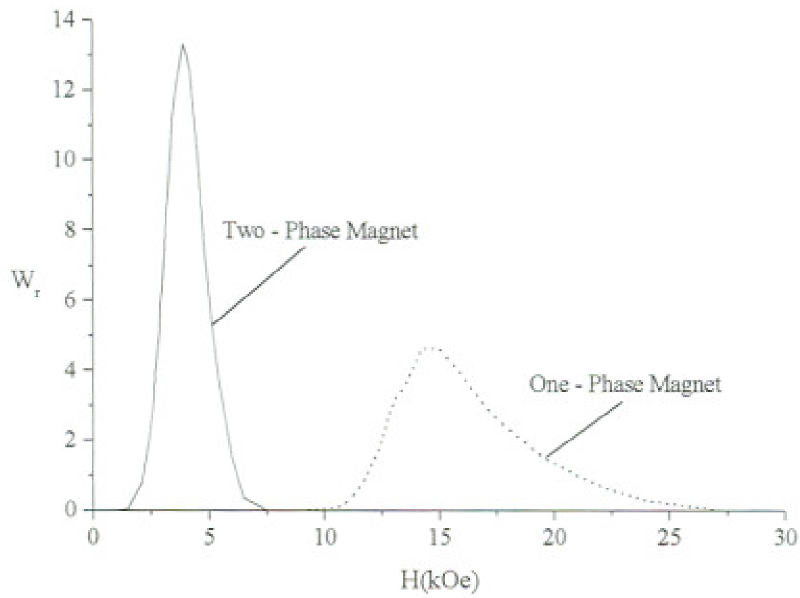

Figure 7: Rotational hysteresis loss.

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