IRREVERSIBLE SUSCEPTIBILITY ALONG A MAJOR HYSTERESIS LOOP

G. GOEV¹, V. MASHEVA¹, J. GESHEV² and M. MIKHOV¹

¹Faculty of Physics, “St. Kl. Ohridski” University of Sofia, 1164-Sofia, Bulgaria,
E-mail: gogo@phys.uni-sofia.bg, vmash@phys.uni-sofia.bg, mikhov@phys.uni-sofia.bg
²Instituto de Física, UFRGS, 91501-970 Porto Alegre, RS, Brazil,
E-mail: julian@if.ufrgs.br

Received July 23, 2009

A method for experimental investigation of irreversible and reversible susceptibilities of a major hysteresis loop is presented. It is based on the energy consideration only, without considering the nature of the magnetization processes. Thus, it could be applied for a broad range of magnetic materials. The method consists of measuring a set of minor recoil loops of a technically saturated sample, plotted with progressively increasing value of the reversed field. The obtained irreversible magnetizations coincide precisely with those calculated by the DCD remanence curve method for a Stoner–Wohlfarth model system.

Key words: Reversible and irreversible magnetizations, hysteresis loops, magnetic losses.

1. INTRODUCTION

The magnetization of a ferro- and ferri-magnetic body is partly reversible and partly irreversible. The irreversible processes of magnetization play a key role of magnetic hysteresis phenomena. They predetermine the main parameters of hysteresis loop, such as coercivity, remanence, and magnetic energy losses, and thus, the applicability of given substance as magnetic material. The irreversibility itself is a fairly complex phenomenon. A number of factors, such as domain-wall motion, reverse domain nucleation, magnetization rotation, different types of magnetic anisotropy etc., are responsible for this complexity. Since they usually coexist, the detailed investigation of irreversible magnetization is a complicated problem. Additional complications come from the coexistence of reversible and irreversible processes. Even more, the predominance of one of these factors depends on the applied magnetic field as well as on the type of magnetization curve used, initial or hysteresis ones. A number of techniques for investigation of reversible and irreversible processes have been proposed [1–6]. Recently, a method for estimation of the field dependence of irreversible magnetic susceptibility along initial magnetization curve has been suggested [7]. The advantage of this method is that it deals with the energy necessary for magnetizing and demagnetizing the sample but neither with the nature of the magnetization processes nor with a specific type of anisotropy, so it could be applied for a wide variety of real materials.
However, a virgin or even DC demagnetized state is not always possible to achieve for some type of samples, e.g., magnetically very soft materials, or magnetron sputtered-deposited films. In order to overcome this restriction, in the present paper the energetic approach of Ref. 7 is extended for estimation of field dependence of irreversible susceptibility along a major hysteresis loop.

2. THE METHOD

The method presented here is similar to that developed for estimation of the field dependence of irreversible susceptibility along the initial magnetization curve, described in [7]. The physical background of the present method is as follows. Let the upper (descending) branch of a major hysteresis loop is considered. The starting point is the point $s$ of major hysteresis loop, corresponding to a technically saturated state with parameters $H_s$, $I_s$, as shown in Fig. 1. The magnetization in fields above $H_s$ is only reversible. With decreasing field from $H_s$ to 0 the magnetization changes, as a rule, reversibly from $I_s$ to $I_r$, and if then the field is changed back from 0 to $H_s$ the magnetization changes without any hysteresis from $I_r$ to $I_s$. The magnetic susceptibility along this part $I_s - I_r - I_s$ of major hysteresis loop is only reversible:

$$\chi_{rev}(H) = \frac{1}{H} \frac{\partial W_{rev}(H)}{\partial H},$$

(1)

where $W_{rev}(H)$ is the density of “reversible” energy, corresponding to the given $H$.

As a first step of the method, the measurement field is changed from $H_s$ to a certain negative field $H_1$ that incites some irreversible magnetization rotations, as demonstrated in Fig. 1. I.e., as the magnetization changes from $I_s$ to $I_1$ along the trajectory 1, the magnetization changes only reversible between $I_s$ and $I_r$ but between $I_r$ and $I_1$ irreversible processes appear apart to the reversibly ones. (If, due to some reasons, the irreversibility occurs in positive fields, the first step of the measurement should start from this field.)

![Fig. 1. Representative major hysteresis loop and arbitrary minor loops.](image)
As a result, when magnetic field is changed back from $H_1$ to $H_s$ the magnetization changes from $I_1$ to $I_s$ along a new, different trajectory $1^b$. The area $\Sigma_1$ between the branches $1^a$ and $1^b$ of this first minor (recoil) hysteresis loop is equal to the energy dissipated when magnetization has been changed along the closed trajectory $I_s \rightarrow I_1 \rightarrow I_s$:

$$\Sigma_1 = W_{\text{hyst}}(H_1)$$

(2)

The energy losses, $W_{\text{irr}}(H_1)$, conditioned by the irreversible changes of magnetization along the trajectory $1^a$ between $I_s$ and $I_1$, corresponding to the field $H_1$ are half of the above value:

$$W_{\text{irr}}(H_1) = \frac{1}{2} W_{\text{hyst}}(H_1) = \frac{1}{2} \Sigma_1.$$

(3)

The validity of this relation is demonstrated in details in [7]. The physical reason is that the values of irreversible magnetization variation $|\Delta I_{\text{irr}}(H_i)|$ along the trajectory $1^a$ and along the trajectory $1^b$ are equal, and that the values of field variation $|H_1 - H_s|$ along both trajectories are equal too.

The second step is to plot the minor hysteresis loop starting from the same saturated state with parameters $H_s, I_s$ and the point 2 on the major hysteresis loop with parameters $H_2$ (negative, $|H_2| > |H_1|$) and $I_2$. The point 2 should be close enough to point 1 so that $\Delta H = |H_2 - H_1|$ is sufficiently small so does $\Delta I = |I_2 - I_1|$ for $I_2 < I_1$. The energy losses, $W_{\text{irr}}(H_2)$, conditioned by the irreversible changes of magnetization along the trajectory $2^a$ between $I_s$ and $I_2$ corresponding to the field $H_2$, can be calculated as a half of the area between the branches $2^a$ and $2^b$ of this minor hysteresis loop.

Thus, step-by-step, the dense enough set of neighboring minor hysteresis loops is plotted until the sample is technically saturated in the opposite direction to a state with parameters $-H_s, -I_s$ and the field dependence of the irreversible energy $W_{\text{irr}}(H)$ can be obtained, as will be demonstrated later in Fig. 3a.

The total magnetic susceptibility along the trajectory $+I_s \rightarrow -I_s$ is a sum of reversible and irreversible parts:

$$\chi_{\text{tot}}(H) = \chi_{\text{rev}}(H) + \chi_{\text{irr}}(H).$$

(4)

For a field $H_i$, the above sum can be expressed as:

$$\chi_{\text{irr}}(H_i) = \frac{1}{H_i} \left. \frac{\partial W_{\text{irr}}(H)}{\partial H} \right|_{H_i}.$$

(5)
if the field increment is sufficiently small enough. This means that by differentiating the experimentally obtained \( W_{ir}(H) \), the field dependence of irreversible susceptibility can be obtained along the whole major hysteresis loop. The reversible susceptibility can be calculated as a difference between the total susceptibility and the irreversible part according to Eq. 4. Both irreversible, \( m_{ir}(h) \), and reversible, \( m_{re}(h) \), magnetizations can be obtained by the already known susceptibilities.

3. DISCUSSION

Due to the lack of real samples with well-known field dependencies of both reversible and irreversible susceptibilities of major hysteresis loops, the suggested method would not be proved experimentally at present. The correctness the method can be checked on an appropriate model system. Here, this is the system consisting of non-interacting disordered single-domain particles with uniaxial anisotropy, described by a well-known Stoner-Wohlfarth (S-W) model [8].

A S-W model system consisting of 6400 particles has been built. Major hysteresis loop and a set of minor loops, starting from a saturated state in positive direction and finishing to a saturated state in the negative direction has been calculated numerically as described in [9]. The normalized major hysteresis loop and some minor loops are shown in Fig. 2.

![Fig. 2. Major hysteresis loop (open circles) and set of minor (recoil) loops (triangles), calculated for a Stoner-Wohlfarth system. Some of the minor loops as well as some of the points on each curve are skipped for clarity. (It should be noted that the irreversibility appears for \( h \geq -0.5 \) for the S-W system.)](image-url)
Here, \( h \) and \( m \) are the magnetic field (normalized to the system’s anisotropy field) and the normalized to the saturation value magnetization, respectively. The field has been decreased from \( h = 1 \) to \( h = -1 \) with an increment of \( \Delta h = 0.02 \), and in the region of the more rapid changes of magnetization the increment has been reduced to \( \Delta h = 0.005 \).

The energy losses were calculated from the minor loops areas. One of the remanence curves – so called Direct Current Demagnetization (DCD) curve was also extracted from the above mentioned minor hysteresis loops. It consists of the sequence of remanences, obtained after applying on the magnetically saturated system the demagnetizing field with progressively increasing value. It is commonly accepted that the field dependence of DCD presents the irreversible magnetization during demagnetization of the system, starting from completely saturated state [5].

The field dependence of \( W_{irr}(h) \), obtained by the proposed here method for the above described S-W system is shown in Fig. 3a, and the field dependencies of the irreversible susceptibility, \( \chi_{irr}(h) \), calculated from (5), as well as the total susceptibility, \( \chi_{tot}(h) \), and the reversible susceptibility, \( \chi_{rev}(h) \), are shown in Fig. 3b. All the results obtained are in coincidence with the S-W model. The irreversible energy \( W_{irr}(h) \) starts to increase for a field of \( h \leq -0.5 \), where the irreversibility appears.

For comparison, the corresponding DCD curve is presented in the same figure. There exists a very good agreement between our results and those obtained by the remanence curves method. It can be also seen that the reversible magnetization goes through a minimum at the critical field, which is a direct consequence of the fact that \( M_{irr}(H) \) and \( M_{rev}(H) \) are mutually connected, as shown in [10].

The result of the above test is that the present method, just like that of the remanence curves one, works satisfactory for a model S-W system. This can be regarded as an unambiguous proves of its mathematical correctness. Since the method is based only on energy considerations, it is not restricted either with the nature of magnetization processes or with a specific anisotropy type, and thus can be used for a broad range of magnetic materials. In contrast with the DCD method, where the remanences are measured in a zero field, the present method offers possibility the field dependence of irreversible susceptibility to be obtained. The
method is very suitable for investigation of soft and nearly soft magnetic materials in ac magnetic fields with the broadly used AC magnetic curve tracers, hysteresiographs and similar experimental techniques.

Fig. 3. (a) Field dependence of energy losses $W_{irr}$. (b) Field dependencies of total magnetic susceptibility, $\chi_{tot}$ (crosses), irreversible susceptibility, $\chi_{irr}$ (up triangles) and reversible susceptibility, $\chi_{rev}$ (down triangles) of a major hysteresis loop of S-W system.

Fig. 4. Field dependencies of major hysteresis curve, $m$ (crosses), DCD remanence curve (solid circles), irreversible magnetization, $m_{irr}$ (up triangles), and reversible magnetization, $m_{rev}$ (down triangles) of a major hysteresis loop of a S-W system.
4. CONCLUSIONS

The proposed method for obtaining the irreversible susceptibility of major hysteresis loop deals with the energy losses only, but no specific magnetization mechanisms are taken into account. It permits the field dependence of both reversible and irreversible susceptibilities and magnetizations to be obtained. The method has been proved on a model Stoner-Wohlfarth system and a quite satisfactory coincidence has been obtained.

Acknowledgments. This work was supported by Scientific Foundation of the Sofia University under grant 163/2008, and partly by the Brazilian agency CNPq.

REFERENCES