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Dependence of Harmonics Profiles on Domain Dynamics in Current-Carrying Iron Whisker

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The first and second harmonics have been measured in the iron whisker with the axial current that produces a circular field. The observed harmonics profiles have been discussed in terms of theoretical analysis based on the nonlinear, asymmetric magnetization that are related to the nucleation, transformation and annihilation of domains. The change of second harmonics profile is more sensitive to the domain variation than that of first harmonics.

1. Introduction

The magnetic anisotropy is induced in amorphous materials by annealing under magnetic field, stress, or both of them. The second harmonics have been applied to measure the anisotropy field distribution in the amorphous having easy axis perpendicular to the field [1] and to investigate the dynamic interaction of a domain wall with a pinning plane in an amorphous having an induced helical anisotropy [2]. For the longitudinal easy axis sample, the harmonics profiles have been related to the domain nucleation and annihilation without the experimental variations because the nucleation field is a function of demagnetizing and anisotropy fields [3].

The harmonics spectrum for the B-H loop has been well analyzed for the application of fluxgate magnetometry [4, 5]. When the induced voltage in pick-up coil is symmetry without the bias field, the only odd harmonics of the fundamental frequency of the driving field are present even though the magnetization of core material is nonlinear. The external field causes the shift in a B-H loop and the induced voltage becomes asymmetrical, giving rise to the even harmonics. However, the analysis of harmonics profiles for small perturbing field along the magnetization curve is not available, relating the profiles with the microscopic magnetization processes.

In this paper, the harmonics profiles during a B-H loop have been measured in a current-carrying whisker, of which domain dynamics have been well known [6], and discussed with the nucleation, transformation and annihilation of domains related to the nonlinear, asymmetric magnetization.

2. Harmonics Profiles

It is difficult to correlate the microscopic domain variations with a macroscopic characteristics of the B-H loop. For an ideal magnetization curve depicted in the Fig. 1, it is generally accepted that the domain rotation takes place in the state of single domain with the magnetization aligned close to the applied field in region I, reverse domain nucleates at the lower knee, followed by the movements of domains in region Ⅱ, then the domain annihilates at positive knee [7]. Even though the magnetization in each regions is not linear in the actual materials, the slopes of the magnetization curve are different in each regions.

For the detection of the microscopic magnetization from the sequencial domain variations along a major B-H loop, it is better to make the magnetic processes repeat at the field. Hence, let's suppose the applied field H is superposition of a slow varying field H_o and a small ac perturbing field h as following where H_o, ω is amplitude and angular frequency of the ac field, respectively. The perturbing field induces minor loops along a major loop. It is hard to prove that the magnetic proceses on a minor loop are the same as those on the major loop. However, the nonlinear magnetization is repeated by the perturbing field with the central point of H_o, and is phenomenologically expressed in power series of h as [8]

$$H = H_o + h = H_o + h_o \sin(\omega t) \qquad (1)$$

$$m = x_1 h + x_2 h^2 + x_3 h^3 + \cdots \quad (2)$$

where m is the induced magnetization, x_1 is a linear magnetic component, x_2, x_3, ···, are nonlinear higer order components. The magnetizations for the minor loops are symmetrical in the each regions I, II, and III of major loop, but with the different magnitudes as drawn in the inset of Fig. 1. The symmetrical magnetization is expressed in odd power series. When H_o is equal to the nucleation and annihilation fields, H_n and H_a, the magnetization is affected by the slopes of both regions of I and II, II and III, respectively, and becomes asymmetrical, causing the even power series.

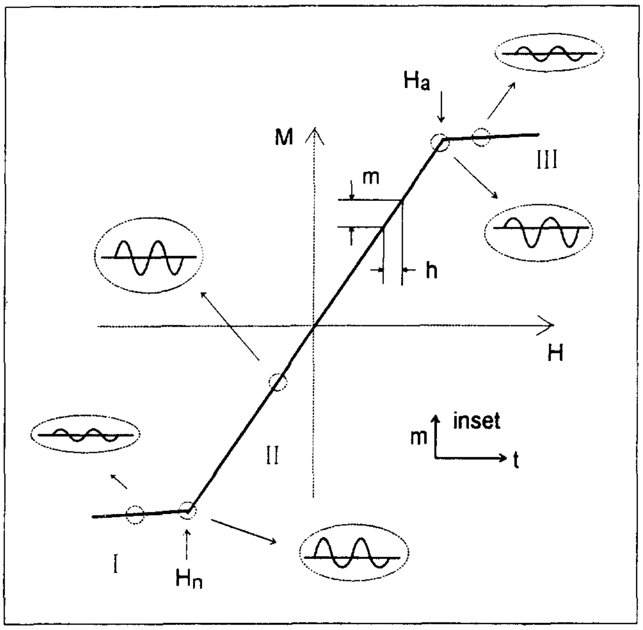

Fig. 1. Idalized magnetization curve (Inset ; symmetric and asymmetric magnetization induced by a small field in each regions).

The induced magnetization causes the voltage $E\,(H_o)$ in a sample pick-up coil. $E\,(H_o)$ is given by the time derivative of magnetic flux that is proportional to the magnetization in Eq. (2). After a little algebra, $E\,(H_o)$ is written as

$$E(H_o) \propto \frac{dm}{dt}$$

$$= \sum_{n=1,3,5\cdots} E_n \cos(n\omega t) + \sum_{n=2,4,6\cdots} E_n \sin(n\omega t) \quad (3)$$

with

$$E_1 = A\omega\left(x_1 h_0 + \frac{3}{4} x_3 h_0^3 + \cdots\right)$$

$$E_2 = A\omega\left(x_2 h_0^2 + x_4 h_0^4 + \cdots\right)$$

$$E_3 = -A\omega\left(\frac{3}{4} x_3 h_0^3 + \frac{15}{16} x_5 h_0^5 + \cdots\right), \cdots \quad (4)$$

where A is constant representing the geometry of pick-up coil. It is noted that the coefficients of odd harmonics, E_1, E_3, ···, are derived from the odd power in Eq. (2) and reflect nonlinear magnetization. Whereas even harmonics coefficients are derived from the even power and represent the asymmetry of minor magnetization loops, related to the transition of magnetization slope due to the nucleation, transformation, annihilation of domains. The asymmetrical magnetization can also be induced around the pinning points that cause the irreversible wall motions. The second harmonic is the first term among the even harmonics and its profiles signify the distributions of nucleation and annihilation fields along the B-H loop.

3. Experimentals

A block diagram for the harmonics measurement is shown in Fig. 2, where an iron whisker sample of 0.2 mm × 0.2 mm × 1.5 cm length has been used. The sample is surrounded by a pick-up coil with a coaxial primary coil for 80 Hz perturbing field. A pair of Helmholtz coils produce a slow varying magnetic field of 0.01 Hz, using a triangular waveform current. The silver paster was used to attach the current leads at the sample ends, where the induced stress could suppress the Landau domain configuration [6].

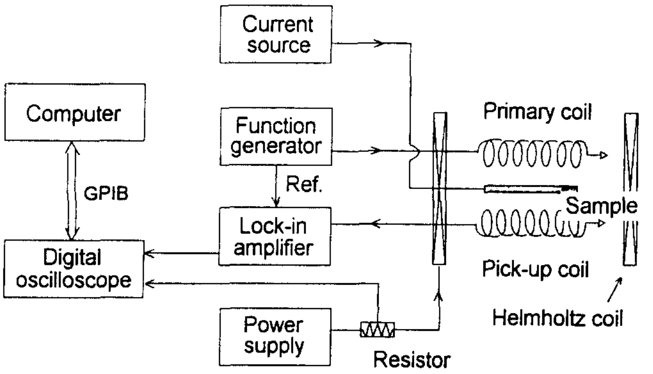

Fig. 2. Schematic diagram for the measurement of first and second harmonics profiles.

A lock-in amplifier measures the voltages incuced in pick-up coil with a reference as the perturbing field. The first and second harmonics were chosen by selecting the reference modes, single and double frequency. The slow varying magnetic field was measured by the current using the voltage across a shunt resistor of 1 Ω. The first and second harmonics were measured during a cycle of slow varying field as a function of the current along the sample axis using a computer with GPIB interface.

4. Results and Discussion

The major magnetization in whisker is accompanied by the dynamics of 180° domains in ±[001] without current [6]. When the current flows along long ±[001] axis, the circular field is induced inside the sample. With the current over a critical value, the domain configuration changes from a structure that is in ±[001] to one where the magnetization circulates the closure domains in ±[010], ±[100] in the plane of the square cross section, as depicted in Fig. 3. Hence, during a half cycle of magnetization with the current, distinctve domain dynamics could be the nucleation of 180° domains at negative knee, transformation of 180° into closure, closure into 180° according to the counterbalance of circular and parallel applied fields around the coercive force, and annihilation of 180° domains at positive knee.

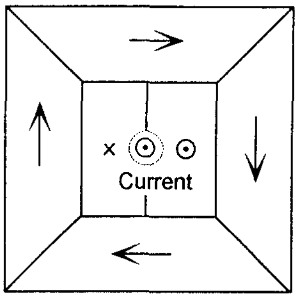

Fig. 3. Diagrams of induced domains in ±[010], ±[100] by the axial current. (Arrow : direction of magnetization for the induced domains)

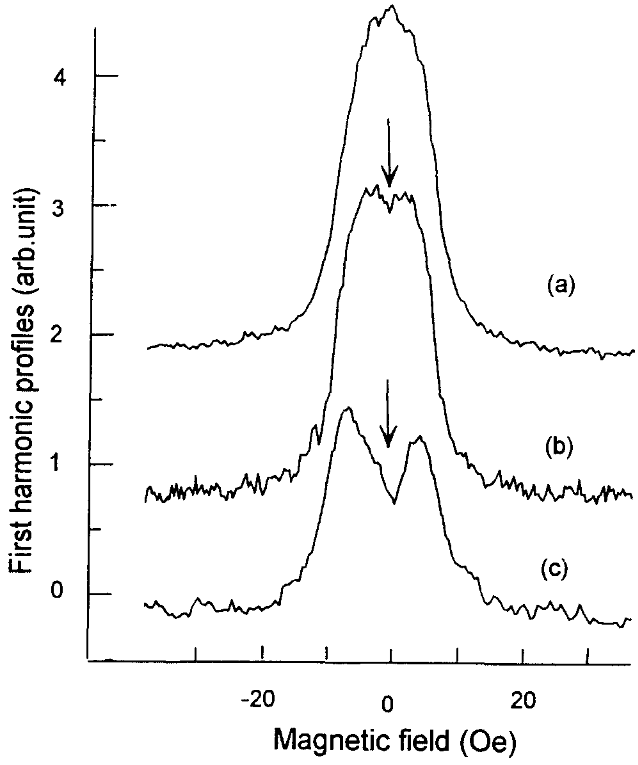

Fig. 4. First harmonic profiles during a half cycle of major B-H loop for the various axial currents, (a) $I = 0$, (b) 20 mA, (c) 100 mA.

Figure 4(a)-(c) show the first harmonic profiles for current $I = 0$, 20, and 100 mA, respectively, during a half cycle of B-H loop for increasing field. There is a broad peak in the profiles without current, different to the sharp shape in the good whisker [6]. The difference may be due to the stress at the sample ends, suppressing the Landau structure. A small dip appears for $I > 20$ mA and becomes distinctive for $I = 100$ mA as marked in Fig. 4(c). The appearance of the dip with current is qualitatively in agreement with the published results [6] and ascribed for by the involvement of closure domains ±[100], ±[010] during the magnetization.

The second harmonic profiles for $I = 0$, 20, 100 mA are shown in Fig. 5(a)-(c), respectively, during a half cycle of B-H loop for increasing field. The profile without current has two peaks S1 and S2 split around maximum of first harmonics in Fig. 4(a). This observation is in agreement with the reported results for the general magnetic materials [1-3]. Two peaks are due to the nucleation and annihilation of 180° domains, respectively, as expected from the asymmetry of minor loops based on

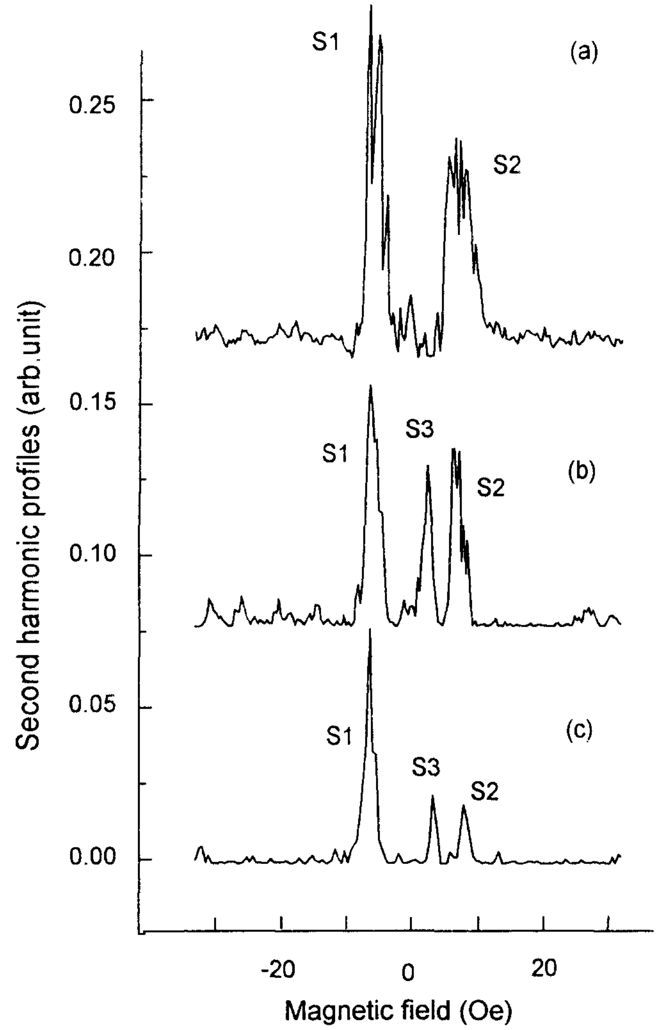

Fig. 5. Second harmonic profiles during a half cycle of major B-H loop for the various axial currents, (a) $I = 0$, (b) 20 mA, (c) 100 mA.

the ideal magnetization curve in section Ⅱ. The peak amplitude due to the domain nucleation was measured to be higher than that due to annihilation.

Another peak labeled S3 appears between the original peaks S1 and S2 for $I > 20$ mA, which is clearly signified by the transformation of 180° into closure, closure into 180° domains around the coercive field. The shift in S3 peak to the higher field may be due to the fact that the circular field by the axial current is more influential on the magnetic state at the zero magnetic induction, that is, coercive field strength, than the other magnetic induction. In contrast to the dip in the first harmonics, peak S3 for $I = 20$ mA is more profound than that for $I = 100$ mA, but it is not well described at present.

5. Conclusion

The harmonics profiles for a small ac perturbing field superimposed on the slow varying bias field have been analyzed in terms of the nonlinear, asymmetric magnetizations that are related to the nucleation, transformation and annihilation of domains. The first and second harmonics have been measured in the iron whisker of long [001] axis with the axial current that produce a circular field. Two peaks appeared in the profile of second harmonics during a half cycle of magnetization without the current, ascribed for by the nucleation and annihilation of 180° domains in ±[001] directions. Another peak appears between original two peaks for the current $I \geq 20$ mA, due to the involvement of the induced domains in ±[100], ±[010] by circular field. The change of second harmonics profile is more sensitive to the domain variation than that of first harmonics, suggesting that the second harmonics measurement is effective in the detection of microscopic magnetization.

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