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Continuous Visualization of Magnetic Domain Dynamics by Image Helmholtz Equation

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Abstract: All of the movies or animations are composed of sequential distinct static images called as the frames even though analogue or digital processing constructs each of the frames. On the other side, all of the physical phenomena are continuously described by the differential or integral equations. In order to extract the physical characteristics from the observed physical phenomenon as an animation, it is essentially required to searching for the state transition parameters connecting the 1st, 2nd and 3rd,…, frames. An innovative image processing methodology has been proposed to convert the distinct animation frames into continuous ones. It is called "Image Helmholtz equation method". In this paper, we apply this method to a series of distinct scanning electron microscope images of a soft magnetic material when being magnetized. In magnetic domain dynamics, the image Helmholtz equation method has two distinguished features. One is that the contrast of a magnetic domain image is regarded as an average of magnetic flux density. Another one is that several magnetic domain images are converted into the continuous ones, i.e., the solution of the image Helmholtz equation visualizes any magnetized states of the magnetic domains. Moreover, the contrast of an arbitrary point on the image gives the magnetization characteristics at this point on the target specimen. Thus, our methodology makes it possible to extract the macroscopic as well as microscopic magnetization characteristics of the magnetic materials.

Keywords: Visualization, Magnetic Domain Dynamics, Image Helmholtz Equation

1. Introduction

All of the ferromagnetic materials have the magnetization on atomic level. A set of magnetization constructs the magnetic domains. Observation of these magnetic domains in any magnetized ferromagnetic materials becomes a key technology to evaluate the quality of magnetic materials so that several methodologies, e.g., Bitter, magneto-optical and scanning electron microscope (SEM) methods, have been exploited and practically utilized for the evaluation of ferromagnetic materials (Endo et al, 2000).

Although Bitter method needs not expensive devices, this is capable of visualizing only the magnetic domain walls. Using magneto-optical method is difficult to visualize a global magnetic domain image, however, is easy to provide the direct magnetization characteristics at a particular point on ferromagnetic materials with elaborate preconditioning. A SEM approach makes it possible to visualize the magnetic domain images not only the surface but also interior regions of ferromagnetic materials when changing its acceleration voltages. Moreover, SEM observation can be carried out without material preconditioning(Alex et al, 2000).Thereby, we employ the SEM magnetic domain images while an external magnetic field is exciting to magnetize a grain-oriented electrical steel in the present paper.

Evaluation of the magnetic domain image whether good or bad quality requires a lot of experiences, i.e., experts who have been trained for a long time. To make breakthrough such a human oriented technology, one of the ways is to exploit an expert system fully utilizing the digital computer's logical and correct memorizing capability. A serious difficulty exploiting such expert system is that the magnetic domain movement is not linearly related with the external exciting field so that each of the animation frames is essentially captured in an irregular timing. On the other side, an innovative image processing methodology has been proposed to convert the distinct animation frames into continuous ones assuming piecewise linear relationship. This is called "Image Helmholtz equation method"(Endo et al, 2000).

In this paper, we apply the image Helmholtz equation method to a series of distinct SEM images of a soft magnetic material in order to clarify the dynamics of magnetic domain. Employed sample magnetic material is a grain-oriented electrical steel. In magnetic domain dynamics, the image Helmholtz equation method has two distinguished features. One is that the contrast of a magnetic domain image is regarded as an average of magnetic flux density. Another one is that several magnetic domain images are converted into the continuous ones. Namely, the solution of the image Helmholtz equation visualizes any magnetized states of the magnetic domains. Moreover, the contrast of an arbitrary point on the image gives the magnetization characteristics of the target point on the specimen. Thus, it is revealed that the macroscopic as well as microscopic magnetization characteristics can be evaluated by our image Helmholtz equation approach.

2. Image Helmholtz Equation in Magnetic Domain Images

2.1 Image Helmholtz Equation

As it is well known, the Helmholtz types of equations govern most of the physical dynamic systems. Let a domain image be a set of scalar potentials *U*, then the dynamics of magnetic domains is represented by the image Helmholtz equation as well. In magnetizing state, the domain motion are caused by external magnetic field *H*, so that our image Helmholtz equation is reduced into:

$$\nabla^2 U + \varepsilon \frac{\partial}{\partial H} U = -\sigma \tag{1}$$

where ε and σ denote a moving speed parameter and an image source density, respectively. The first and second terms on the left in (1) mean the spatial expanse and transition of image to the variable *H*, respectively. The first term on the left in (1) represents a static image. The image source density σ is given by the Laplacian of a final image. So that the final image U_{Final} is obtained as a solution of

$$\nabla^2 U_{Final} = -\sigma\ . \tag{2}$$

This means that the governing equation of static images is the Poisson equation.

2.2 Solution of the Image Helmholtz Equation

The modal analysis of (1) gives a general solution:

$$U(H) = \exp(-\Lambda H)\left(U_{Start} - U_{Final}\right) + U_{Final} \tag{3}$$

where U_{Start} and $\exp(-\Lambda H)$ are an initial image and a state transition matrix, respectively. The image presented by (3) becomes the initial image U_{Start} if H=0, and the final image U_{Final} when the variable H reaches to infinity. However, H never reaches infinity so that it is necessary to determine an optimal state transition matrix from the given domain images.

2.3 Determination of the State Transition Matrix

Let us define the domain image $U_{\Delta H}$ between the initial U_{Start} and final U_{Final} domain images, and then it is possible to determine the elements in matrix Λ by modifying (3).

$$\Lambda = -\frac{1}{\Delta H}\ln\left(\frac{U_{\Delta H} - U_{Final}}{U_{Start} - U_{Final}}\right) \tag{4}$$

Thereby, the elements in the number i matrix Λ_i are determined from a series of three distinct domain images by means of (5).

$$\Lambda_i = -\frac{1}{\Delta H}\ln\left(\frac{U_{i+1} - U_{i+2}}{U_i - U_{i+2}}\right),\ i = 1,2,\ldots,n-2 \tag{5}$$

The subscript i of U in (5) refer to a sequential number of given domain images; n denotes the number of domain images. The domain images U_i and U_{i+2} correspond to U_{Start} and U_{Final} in (3), respectively. Therefore, it is possible analytically to generate a domain image by substituting Λ_i into (3).

2.4 Physical Meaning of the Matrix Λ

According to well-known Preisach magnetization model, the relationship between the magnetic field H and flux density B can be represented by following constitutive equation (Saito, 1987, 1988)

$$\frac{1}{\mu}B + \frac{1}{\Psi}\frac{\partial B}{\partial(H_{eff} - H_c)} = H_{eff} - H_c \tag{6}$$

where H_{eff} and H_c represent the effective and coercive fields, respectively. Moreover, Ψ denotes a Preisach density function. Comparing ε in (1) and Ψ in (6), the matrix Λ_i obtained by (5) are just corresponding to the Preisach density function. The Preisach density function is a rate of change of permeability to the external field H. Thereby, our methodology fully takes the magnetic hysteresis into account.

2.5. SEM Domain Images

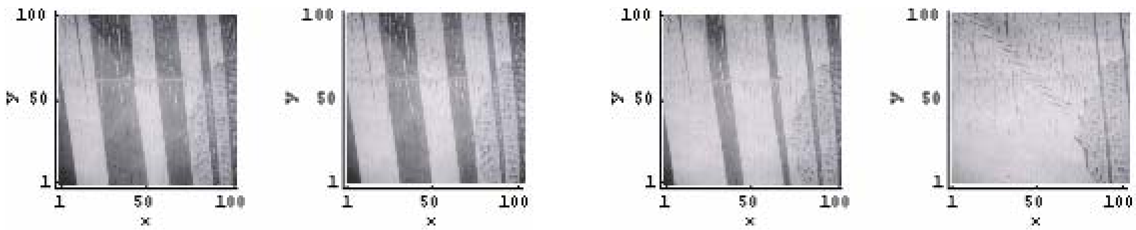
Table 1 lists the capturing conditions of magnetic domain images. Figure 1 shows the typical examples of domain images of a grain-oriented electrical steel sheet under the distinct magnetized states. Changing the given domain images sequentially by the field excitation, it is easy to visualize the dynamics of magnetic domains.

Figure 2 illustrates the matrices Λ at each of the magnetized regions. In the low field intensity, the real parts represent magnetic boundary displacements and magnetic domain movements (Figures 2 (a) and (b)). On the other hand, there are some values of the imaginary part in Figure 2(b). This visualizes the force against the applied field at the grain boundary. In the high field intensity, the magnetization process is mainly carried out by rotation of magnetization and the iron loss is caused by lancet domain appearance. Thus, based on the matrixΛ, it has been shown that the magnetic domain motion dynamics, i.e., behaviors of magnetic domain and iron loss generating processes, can be visualized.

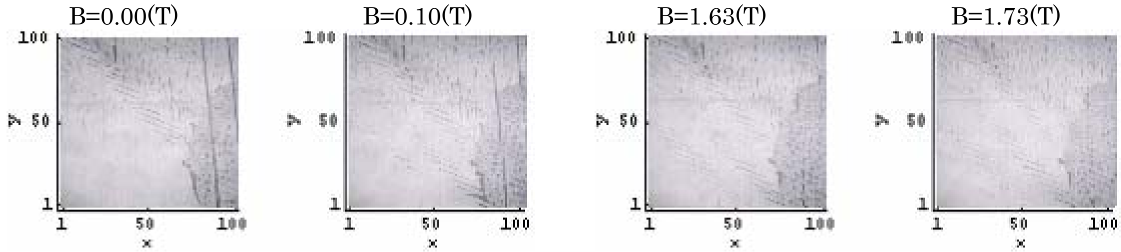
Substituting each of the state transition matrices obtained by means of (5) into (3) reproduces the SEM images and the magnetization curves. Especially, focusing on particular point on the SEM animation the local magnetization curves can be drawn. Figure 3 illustrates the selected points to draw the local magnetization curves shown in Figure 4. In this calculation, the magnetization curves have been reproduced after generating 111 frames from original 24 frame images by (3) substituting each of the corresponding state transition matrices by (5).

Table 1 Capturing Conditions of Domain Images
H : external magnetic field intensity, B : flux density

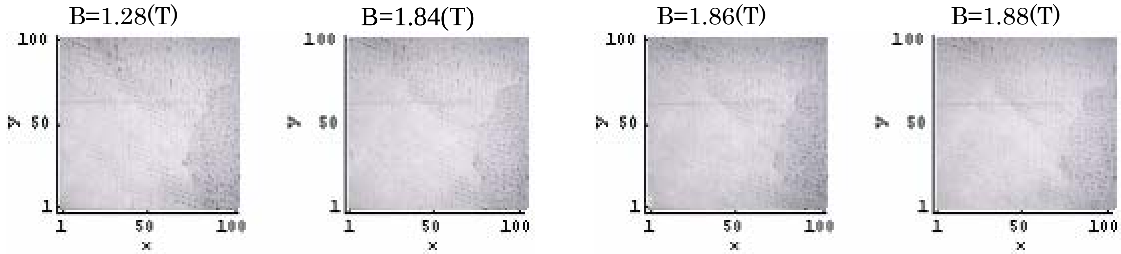
Image No.	H(A/m)	B(T)	Image No.	H(A/m)	B(T)
1	0.00	0.00	13	214.13	1.93
2	2.85	0.10	14	160.37	1.92
3	9.26	1.63	15	98.68	1.91
4	24.16	1.73	16	54.66	1.84
5	30.23	1.78	17	28.53	1.83
6	54.59	1.84	18	3.73	1.77
7	84.92	1.86	19	0.00	1.73
8	115.39	1.88	20	-4.60	1.73
9	160.69	1.90	21	-5.95	-0.06
10	236.32	1.92	22	-7.45	-1.43
11	324.31	1.95	23	-9.07	-1.56
12	269.64	1.95	24	-11.50	-1.62



(a)H=0.00(A/m), B=0.00(T) (b)H=2.85(A/m), B=0.10(T) (c)H=9.26(A/m), B=1.63(T) (d)H=24.16(A/m), B=1.73(T)



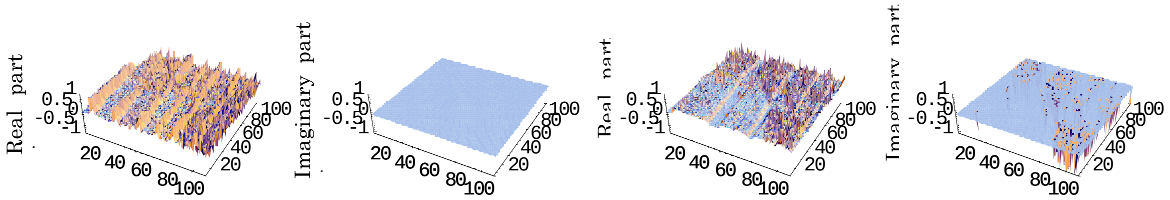
(e) H=30.23(A/m), B=1.28(T) (f) H=54.59(A/m), B=1.84(T) (g)H=84.92(A/m), B=1.86(T) (h)H=115.39(A/m), B=1.88(T)



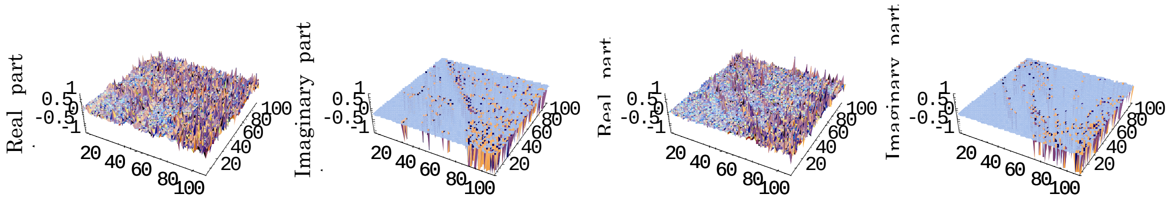
(i)H=160.69(A/m), B=1.90(T) (j)H=236.32(A/m), B=1.92(T) (k)H=324.31(A/m), B=1.95(T) (l)H=269.64(A/m), B=1.95(T)

Fig. 1 Examples of Magnetic Domain SEM Images (100x100 pixels, 0.1 mm/pixel)

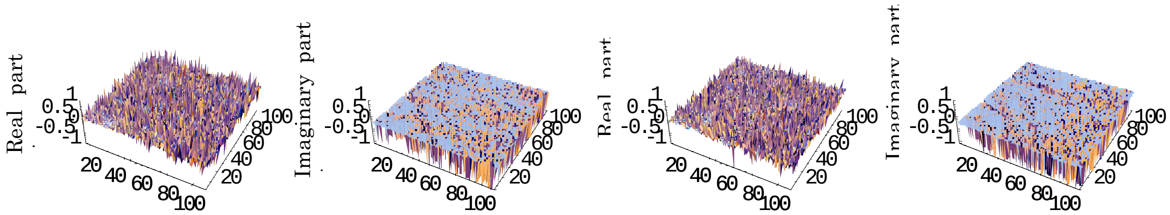
Let consider about the local magnetization curves reproduced by (3). In Figure 4 the magnetization curves at the 180° basic domains are from (a) to (g), the lancet domain are (h) and (i), and the strained parts are from (j) to (l). The residual inductions are higher than those at the lancet as well as strained domains. This means that the lancet and strained parts are hard to be magnetized. Second, because of the lancet domain generation, the discontinuous curves are observed at the beginning of rotating magnetization region. Finally, at the strained parts give the discontinuous magnetization curves reflecting on the physical stress to the specimen.



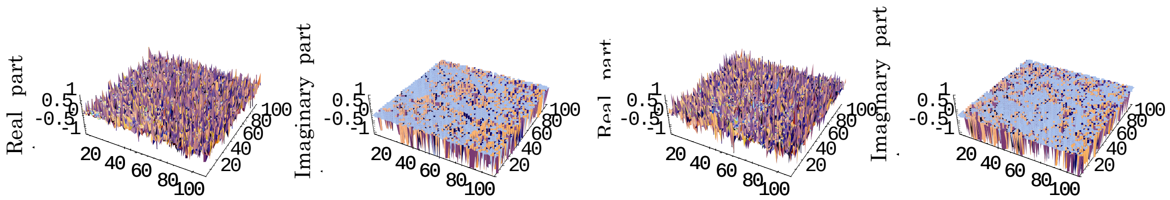
(a) 0.00 → H → 2.85(A/m)　　(b) 2.85 → H → 9.26(A/m)



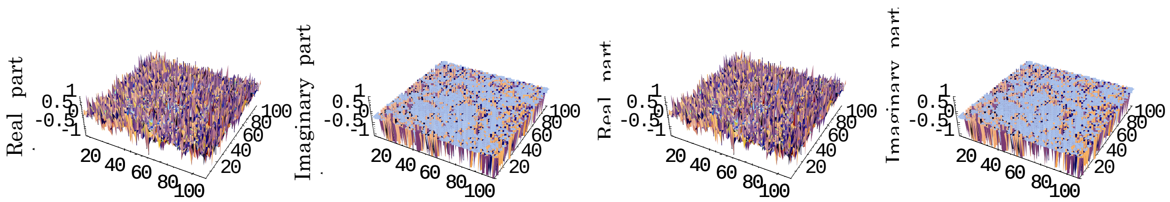
(c) 9.26 → H → 24.16(A/m)　　(d) 24.16 → H → 30.23(A/m)



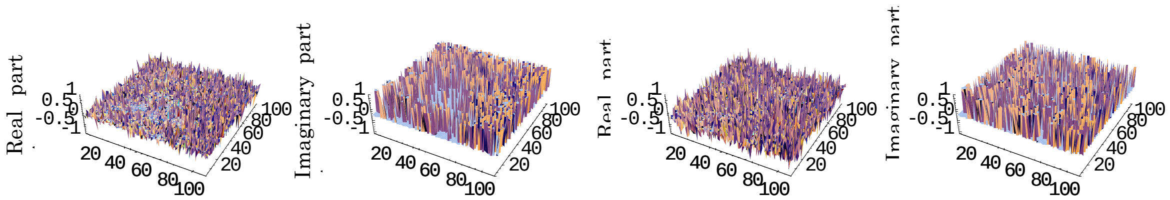
(e) 30.23 → H → 54.59(A/m)　　(f) 54.59 → H → 84.92(A/m)



(g) 84.92 → H → 115.39(A/m)　　(h) 115.39 → H → 160.69(A/m)



(i) 160.69 → H → 236.32(A/m)　　(j) 236.32 → H → 324.31(A/m)



(k) 324.31 → H → 269.64(A/m)　　(l) 269.64 → H → 214.13(A/m)

Fig. 2 Examples of the State Transition Matrices

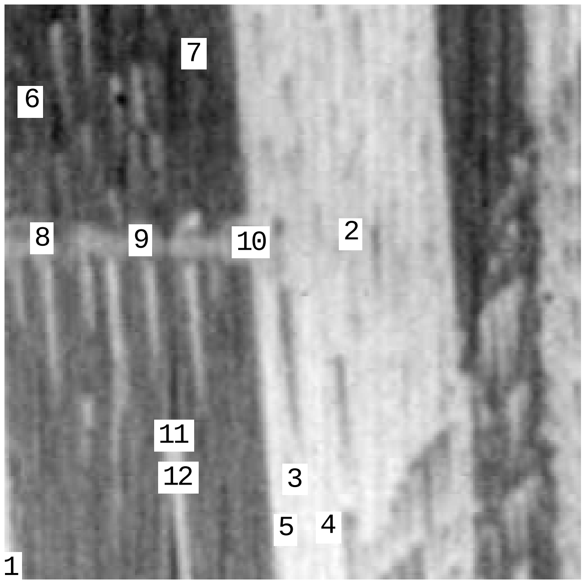
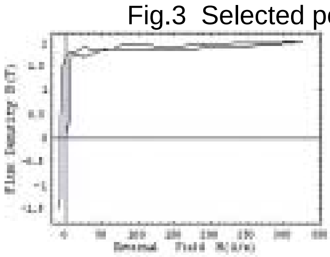
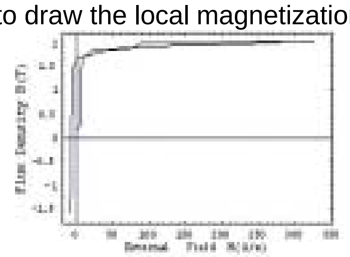


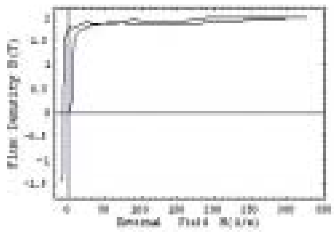
Fig.3 Selected points to draw the local magnetization curves



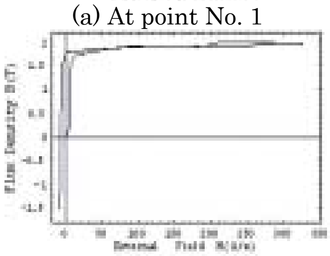
(a) At point No. 1



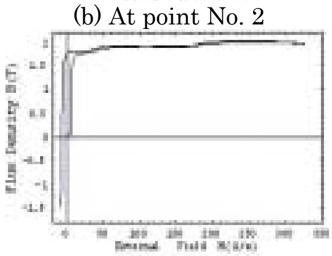
(b) At point No. 2



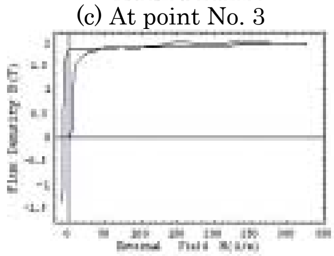
(c) At point No. 3



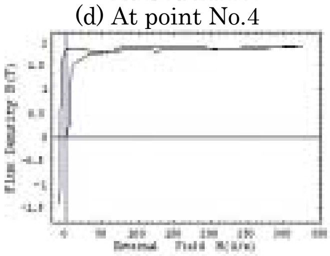
(d) At point No.4



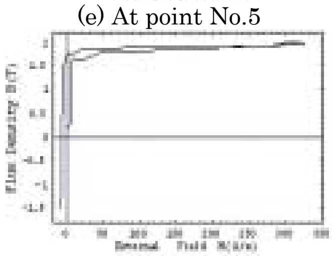
(e) At point No.5



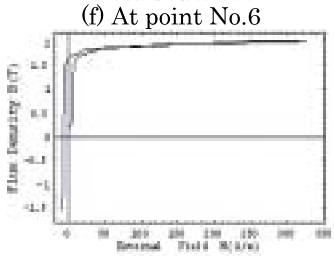
(f) At point No.6



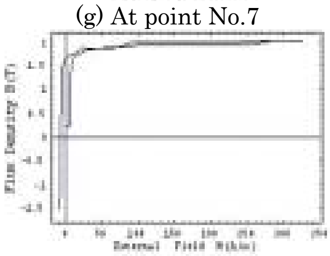
(g) At point No.7



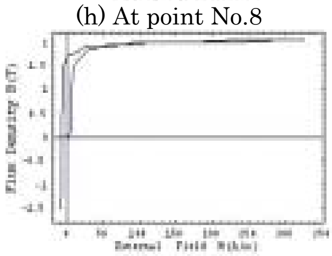
(h) At point No.8



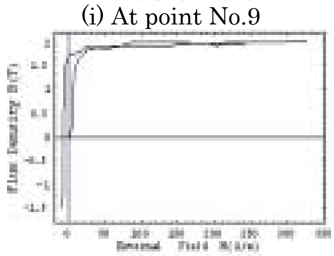
(i) At point No.9



(j) At point No.10



(k) At point No.11



(l) At point No.12

Fig. 4. Local Magnetization Curves Reproduced by (3)

To verify this visualization, we computed the magnetization curve of the entire generated domain images by (3). Figure 5 shows the computed magnetization curve together with experimental result. Fairly good agreement between the computed and experimented curves reveals the validity of our approach. Thus, we have succeeded in obtaining the magnetization characteristics in each of the domain image pixels on the ferromagnetic materials. This means that the magnetization characteristics can be extracted from the visualized domain images.

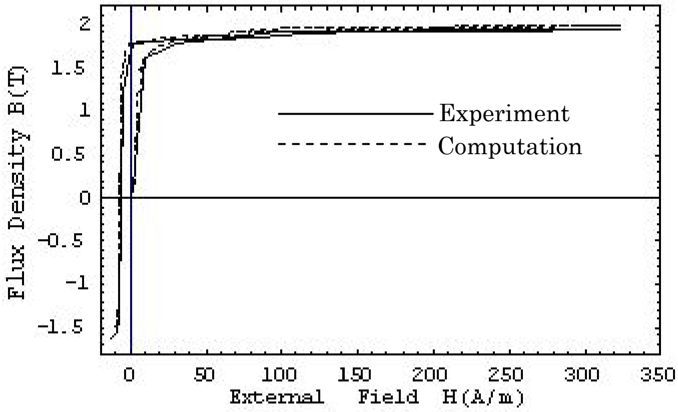


Fig. 5. Magnetization Curve Reconstruction Based on (3)

3. Summary

As shown above, we have succeeded in visualizing an arbitrary magnetized state from a series of SEM domain images. Applying the image Helmholtz equation method has made it possible to visualize any magnetized domain images from a sequential finite number of the animation frames. The state transition matrix derived from the series of images represents one of the most important key of magnetic domain dynamics, and is related to the Preisach density function, which is one of the popular models representing magnetic hysteresis properties. Thus, our approach in magnetism has potentials to evaluating the non-linearity, iron loss and so on.

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