Domain observation technique for Nd–Fe–B magnet in high magnetic field by image processing using liquid crystal modulator

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A different domain observation technique by modulation of a polarizing plane has been developed for Nd–Fe–B sintered magnets. A liquid crystal element inserted in a longitudinal Kerr microscope is used as an optical modulator to acquire a reference image needed to enhance Kerr contrast by image processing. Domain images of the Nd–Fe–B magnet can be clearly observed by this technique in a high magnetic field up to 4.4 kOe. It was found that polishing of the sintered magnet reduced its coercive force. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2712961]

I. INTRODUCTION

Recently, Nd–Fe–B sintered magnets have been widely used for motor applications because of the large energy product.[1] It is well known that microfabrication of such magnets by polishing decreases the coercive force and influences the driving characteristics of micromotors.[2] Since the important role of Nd-rich phase in grain boundaries for high coercive force has been reported,[3] domain observation around grain boundaries is required to solve the durability problems involved in microfabrication.

However, little has been reported about the domain observation of Nd–Fe–B sintered magnets in a high magnetic field by Kerr microscopy.[4] In general, digital image processing of Kerr-effect signals is used for domain observation to enhance the contrast of the domain image. The image processing requires a digitized video image of a magnetically saturated state as a reference image, and this reference is then subtracted from an image containing magnetic domain information.[5–7] However, it is not easy to prepare a reference image of hard magnetic materials, since a large applied field, typically over a few teslas, is needed to saturate the samples. In this work, a different image processing technique using a liquid crystal element, which can rotate the polarization plane of light by applying an electric field,[8,9] has been demonstrated. This paper reports the domain observation of Nd–Fe–B sintered magnets in a high field using a different image processing method with the liquid crystal element.

II. EXPERIMENT

Figure 1 shows the principle of a different reference image acquisition method. A commercially available nematic liquid crystal element was used. The liquid crystal element can rotate the polarization plane of incident light by applying an electric field. In short, the element operates as a controllable wave plate. When the polarization plane of the incident light was rotated back and forth within a range of several degrees, alternating bright and dark domain images inverted with respect to each other were continually observed, as shown in Fig. 1(c). Then by averaging the images while changing the contrast continually, a reference image containing only surface information of a sample and a gray tone of uniform contrast could be acquired, as shown Fig. 1(d).

The liquid crystal element was inserted into a longitudinal Kerr microscope to control the polarization plane, as shown in Fig. 2. The liquid crystal element was placed after a polarizer for the incident light.

By applying a peak-to-peak voltage of 100 $mV_{p\text{-}p}$ at 12 Hz to the liquid crystal element, the polarization plane of the incident light traveling to the sample was rotated within a range of $\pm 2° - 3°$. Figure 3 shows the wave form applied to the liquid crystal element. The modulated signal of 2.9 $V_{p\text{-}p}$ at 2 kHz in this figure was to prevent deterioration of the liquid crystal.

As a sample, a Nd–Fe–B sintered magnet for a voice coil motor was observed using a different domain observation technique with the liquid crystal element. The coercive force of the sample used in this study was about 15 kOe, which could be sufficiently saturated by the electromagnet of the Kerr microscope. The sample was cut to 1.0 mm thick, 11.0 mm long, and 7.0 mm wide and was set on the stage of the microscope. The easy axis of the sample magnet was along the longitudinal direction of the sample in plane. In

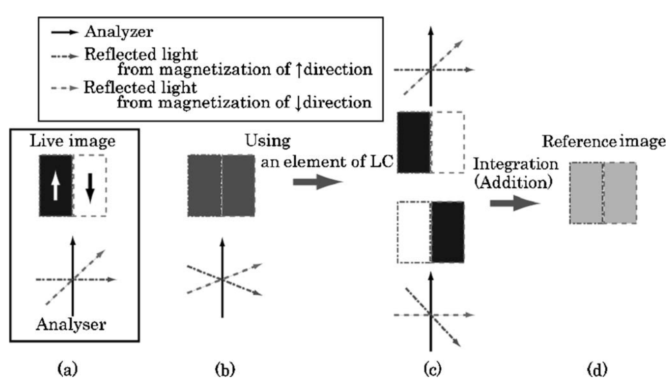

FIG. 1. Principle of reference image acquisition: (a) live image, (b) initial state, (c) modulated image, and (d) reference image.

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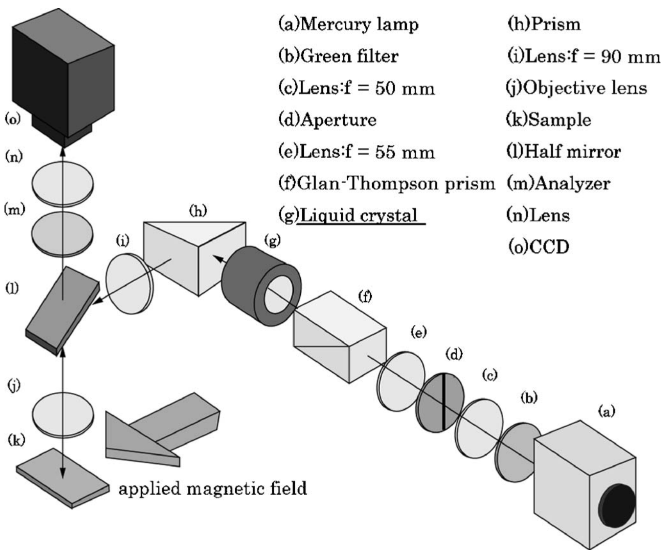

FIG. 2. A schematic diagram of the Kerr-effect microscope with liquid crystal element.

addition, a SiO thin film was deposited on the surfaces of the magnet by vacuum evaporation as an oxidation resistant coating, and the film thickness at the observation side was controlled to $3\lambda/4$ to serve as an antireflection coating. The wavelength of the light used for observation was $\lambda = 546$ nm. The magnetization process was observed by applying a dc field along the easy axis.

III. RESULTS AND DISCUSSION

Figure 4 shows the domain image obtained by the alternative domain observation technique in a demagnetization state. The live image without image processing showed some stripe domain patterns at the center, as shown in Fig. 4(a). However, the Kerr contrast was not high enough to analyze the domain structure. Figure 4(b) shows the reference image obtained by modulating the polarization plane with the liquid crystal element. It is noted that the information about only the specimen surface could be obtained, and no domain contrast was observed in the reference image. The reference image was subtracted from the live image, as shown in Fig. 4(c), and then 200 frames of subtracted images were integrated to enhance the domain contrast, as shown in Fig. 4(d). Stripe domain patterns along the easy axis were clearly observed in the processed image.

Figure 5 shows the magnetization process of the Nd–

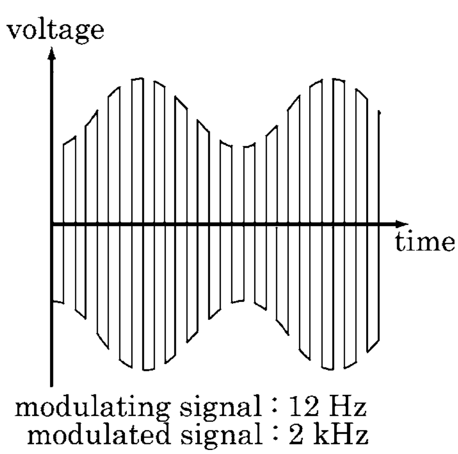

FIG. 3. Wave form of driving voltage for liquid crystal element.

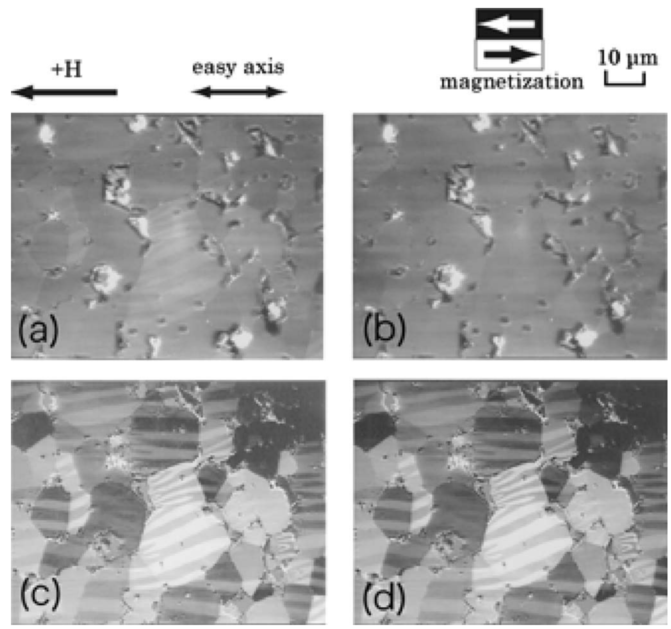

FIG. 4. Domain images by a different image processing technique with a liquid crystal element: (a) live image, (b) reference image, (c) subtracted image, and (d) integrated image.

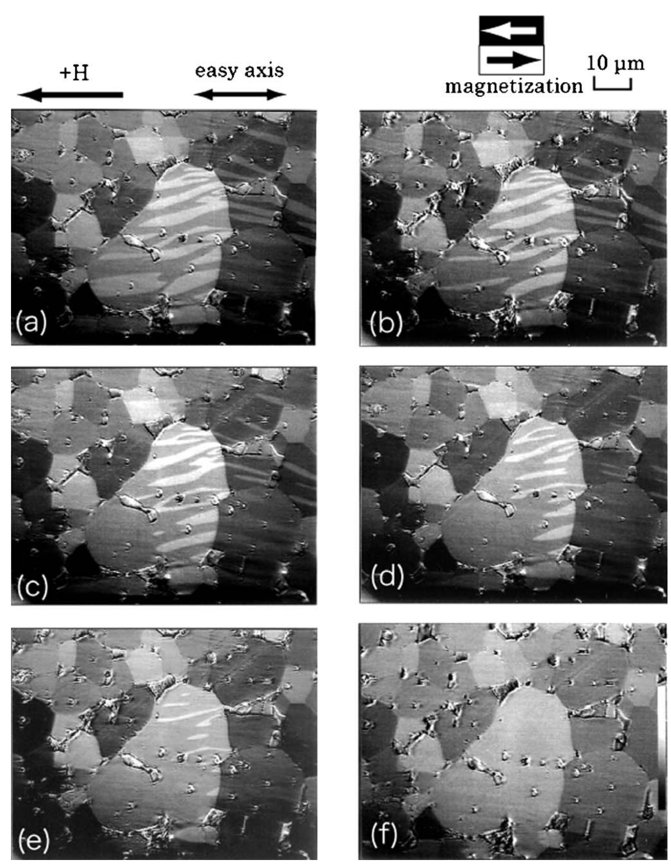

FIG. 5. Magnetization process of Nd–Fe–B sintered magnet: (a) $H=0$ kOe, (b) $H=0.3$ kOe, (c) $H=0.7$ kOe, (d) $H=1.3$ kOe, (e) $H=2.0$ kOe, and (f) $H=4.4$ kOe.

Fe–B sintered magnet when a dc field of up to 4.4 kOe was applied along the easy axis. In the images, the bright and dark domains have magnetizations pointing in rightward and leftward, respectively. The images show that the grain size of the magnet was a few tens of micrometers. Stripe domain patterns along the easy axis were clearly observed, and the stripe patterns crossed a few grains in the demagnetization state shown in Fig. 5(a). When the dc field was increased up to 4.4 kOe, wall displacement occurred and area of the dark domains increased, as shown in Figs. 5(b)–5(f).

It is difficult to acquire clear domain images in a high field with the conventional image processing technique by using a domain image in the saturation state as a reference image because of fluctuations of the specimen due to a large electromagnetic force during the subtracting process. In contrast, with this different technique, clear domain images of the Nd–Fe–B sintered magnet could be obtained in a high magnetic field up to 4.4 kOe by modulating the polarization plane using the liquid crystal modulator.

The saturation state was produced at a dc field of 4.4 kOe, as shown in Fig. 5(f). This field was smaller than the value measured by a vibrating sample magnetometer (VSM) before cutting and polishing the specimen.

IV. CONCLUSION

In the present work, magnetic domains of Nd–Fe–B sintered magnets were clearly observed by modulating the polarization plane with a liquid crystal element installed in a longitudinal Kerr microscope. Results indicated that the reference image could be easily acquired by the alternative image processing technique, and clear domain images with high Kerr contrast could be observed in a high magnetic field up to 4.4 kOe. Moreover, it was found that polishing of the sintered magnet reduced the field required to induce saturation. In our future work, it will be necessary to further investigate the reasons for the reduction of the saturation field. Nonetheless, this different domain observation technique will facilitate microscopic investigation of the magnetization process of Nd–Fe–B sintered magnets with large energy products in a high magnetic field.

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