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Attractive features of soft magnetic composites (SMCs) are high resistivity, isotropic three-dimensional flux behavior, and easy compression into the complicated shapes required in electromagnetic devices. Comprehensive understanding of the materials will help optimize design of electromagnetic devices. This paper presents the magnetization processes in a SMC sample in micron scale by means of the magneto-optical imaging technique. The sample was magnetized by magnetic fields tangential or perpendicular to the observation surface. It is observed that the flux density is higher at the particle region but lower at the interparticle space. When a tangential field is applied, the stray fields change polarization at the particle boundaries. Both results suggest that the magnetized sample behaves as a collection of individual magnetized particles rather than as a uniform and continuous magnetic substance such as soft iron although there are some interactions between neighboring particles. [DOI: 10.1063/1.2713706]

I. INTRODUCTION

The applications of soft magnetic composites (SMCs) to electromagnetic devices are increasing. The materials are made from iron powder coated with an insulating coating. The major advantages of these materials include magnetic isotropy, relatively high electrical resistivity, and easy compression into the complicated and practical shapes required in various electromagnetic devices.[1,2] The magnetic flux distribution in the sample interests many engineers when they design electromagnetic components.[3] In addition, scientists are also interested in the magnetic flux distribution in order to understand magnetization processes and to interpret intrinsic and extrinsic magnetic properties.[4–6] Conventional magnetization methods only measure the average properties over the whole volume of the sample[7,8] and cannot provide information of the local magnetization process in detail. This paper presents a method of magneto-optical imaging (MOI) technique to visualize the magnetic field distribution in the sample and to directly observe the magnetization process. The study shows that the flux density is nonuniform inside the sample, even within the particle region. Instead of the smooth flux line in solid and continuous soft magnetic materials, for example, soft iron metal, the flux density is intense inside the particles and sparse at the interspace between them.

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II. EXPERIMENTAL SETUP

The experimental setup was built based on the Faraday rotation,[9] that is, a rotation of light polarization in an indicator film induced by a magnetic field. For an opaque magnetic sample, the reflecting model of the Faraday rotation can be employed to examine the flux distribution at the sample surface.[10] As a result of rotation, a magneto-optical image obtained in a microscope with crossed polarizers is a gray scale image. The brighter the area (pixel), the higher is the local flux density. In this study, a green filter was employed to improve the contrast of the image. The MOI technique can image magnetic properties in real time/space with micrometer resolution. The major advantage of the MOI technique is that the local detail of magnetic structures ranging from micrometer to centimeter can be directly visualized, rather than measuring the average magnetic properties over the whole volume of the sample.

The toroidal-shape SMC sample studied in the work was compressed from commercially available iron powder Somaloy 500™+0.6% LB1 with 450 MPa, followed by a heat treatment in a steam/N_2 atmosphere for 30 min. The density of the sample was 6.54 g/cm^3. The dimensions of the sample were inner diameter of 28.29 mm, outer diameter of 53.46 mm, and thickness of 5.05 mm. A conventional primary winding of 106 turns and a secondary winding of 255 turns were wound around the sample to measure the hysteresis loops and the losses at different conditions. A control

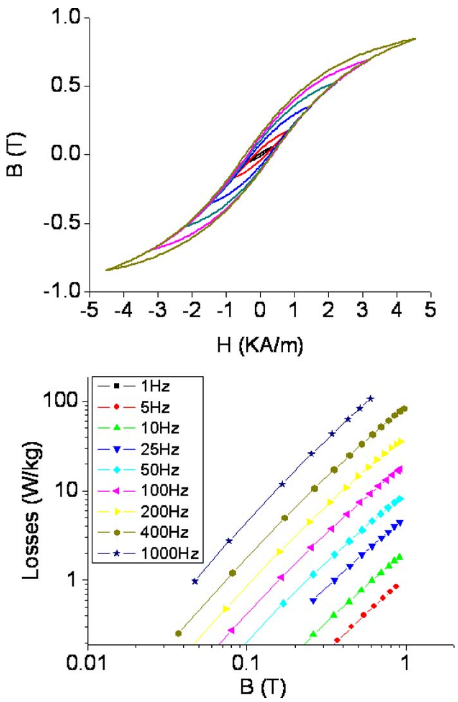

FIG. 1. Hysteresis loops at 50 Hz (top) and power losses at different frequencies (bottom).

system was used to ensure that the flux densities in the sample were sinusoidal. The sample surface was carefully polished using 1 μm lapping paper to improve the magneto-optical image quality. The magneto-optical indicator film, which was a Bi substituted yttrium iron garnet film [$Y_3Fe_2(FeO_4)_3$] deposited on a gadolinium gallium garnet (GGG) substrate, was placed directly on the sample surface with a slight mechanical pressure in order to improve spatial resolution.

III. RESULTS AND DISCUSSION

The hysteresis loops and power losses of the sample were measured at frequencies between 1 and 1000 Hz when the flux density was controlled to be a sinusoidal wave form. Figure 1 shows the loops measured at 50 Hz and the losses at different frequencies. The results are consistent with those provided by the manufacturer.

The perpendicular fields, generated by an electromagnet, were applied to the sample up to 1224 G. Figure 2 shows the magneto-optical image taken at an external field of 918 G and *in situ* optical microstructure at the compression surface. The scale bar applies to all images in the paper. It can be

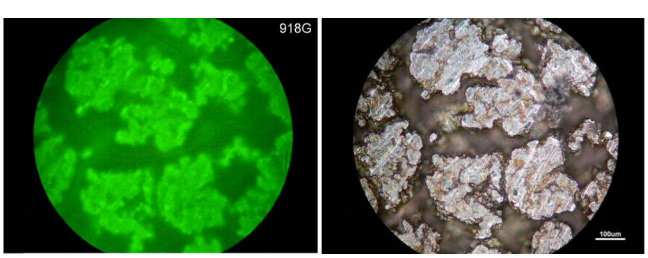

FIG. 2. Magneto-optical images at field of 918 G and *in situ* microstructure at the compression surface.

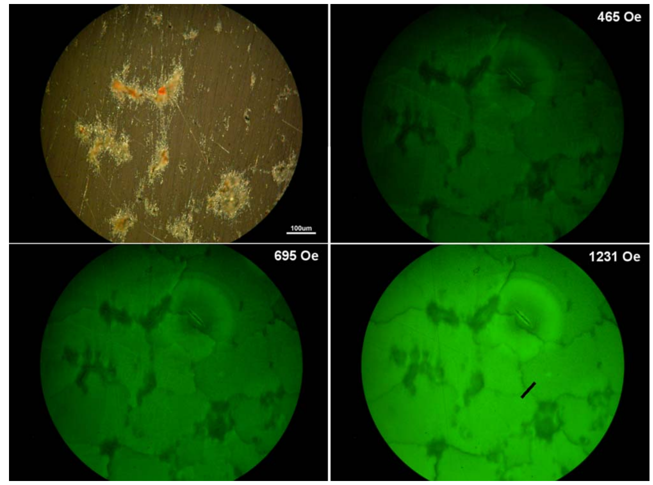

FIG. 3. Magneto-optical images taken at the ground surface and *in situ* microstructure.

seen that the particle shapes are irregular and there is visible interspace between the particles. In addition, small intraparticle pores and overlaps are found. The shape of the particle changes significantly in comparison with the initial prepressed particle. The particle size at the compressing surface is about 150–200 μm while the size of the initial particle is about 70–130 μm. This can be attributed to the ductility of the iron particles. However, the oxide isolation layer could not be perceived because of the limitation of the optical microscope.

When the field increases, the overall brightness of the image increases, but it strongly depends on the position of the sample; some regions are much brighter than others. In comparison with the microstructure, it was noticed that the shape of the brighter regions was consistent with the shape of particles. This means that the flux density at the particle surface is much stronger than that at the interstices, and the flux lines travel mainly inside the particles. In addition, the indicator film is so sensitive to the magnetic field that an unexpected nonuniformity of flux density at the particle surface was visualized. It is believed that the nonuniformity results from the pores, overlaps of particles, and contaminations in the intraparticle. It is also caused by the grain boundaries and crystal distortions, including thermal distortion and compressing distortion.

Since there are not enough particles at the compression surface to fill the space between the particles during the compression, the particle density at the compression surface will be looser than that inside the sample, and hence, the field distribution at the compression surface will be different from that inside the sample. The sample surface was then ground off and polished. Figure 3 shows the magneto-optical image at different fields and *in situ* microstructure at the ground surface. The boundaries of the neighboring particles cannot be identified from the morphology. However, the shiny regions are believed to be the isolated layer of the particle, which became exposed when the upper particle was ground off. The shape and position of the shiny regions are consistent with those of the dark regions in the magneto-optical images. It is also clearly seen that there are darker lines, i.e.,

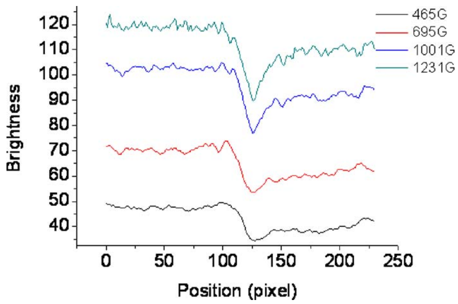

FIG. 4. The brightness along the black line shown in Fig. 4 at different field strengths.

weak field lines, in the magneto-optical images, which are believed to correspond to the particle boundaries. Figure 4 shows the profile of brightness along the black line shown in Fig. 3. The overall brightness, i.e., the field strength at the polished surface, increases when the applied fields are increased. The fields were weak at the interspace.

Figure 5 shows the images when the sample was magnetized by toroidal fields tangential to the observation surface. Figure 6 shows the brightness profile along the black line in Fig. 5. The profiles show that the normal component of the stray field changes dramatically at the particle interspace that is perpendicular to the applied field. There are one low peak in the middle and two high peaks aside. The observations found that the polarizations of the field at both sides were opposite by turning the reflective analyzer. However, the alteration gradually became insignificant when the boundary tended to be parallel to the magnetization field. At

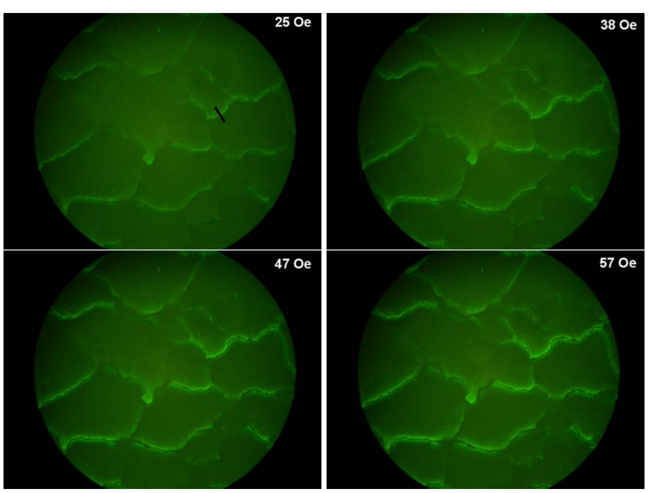

FIG. 5. Magneto-optical image while the sample was magnetized by magnetic fields tangential to the observation surface.

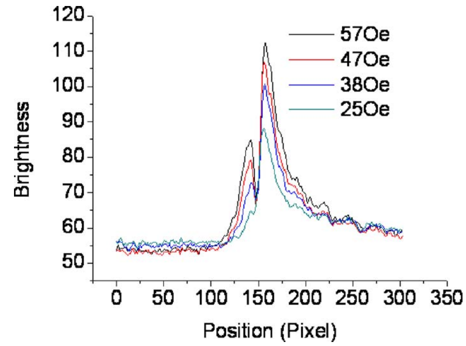

FIG. 6. Brightness profile along the black line shown in Fig. 6 in response to the application of different parallel fields.

the parallel boundary, the alteration was invisible. The field distribution suggested that the particles composing the whole sample were magnetized individually, and the magnetic behavior of the whole sample was a collection of that of each particle.

IV. CONCLUSION

A magneto-optical imaging system has been used to visualize the magnetization process of individual particles comprised of a soft magnetic composite material when they were magnetized by magnetic fields perpendicular and tangential to the compression surface. It was found that the flux density is concentrated inside the particle. The intraparticle pores, contamination, overlaps, grain boundary, and crystal distortions led to nonuniformity of flux density within one particle region. The particle was magnetized individually and the whole sample behaved as a collection of individually magnetized particles rather than as a uniform and continuous magnetic substance.

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