Visualization of Magnetic Flux Distribution at Soft Magnetic Composite

Z. W. Lin[1], J. G. Zhu[1], Y. G. Guo[1], J. J. Zhong[1] and W. Y. Yu[2]
[1] Centre for Electrical Machines and Power Electronics, Faculty of Engineering,
University of Technology, Sydney, Australia
[2] Baosteel Group Shanghai Iron and Steel Research Institute, China

Soft magnetic composite (SMC), as one of soft magnetic materials, is being used increasingly in electromagnetic devices due to its magnetic isotropy, high electrical resistivity and easy formation. This paper presents the magnetic field distribution at the compressing surface of SMC by means of magneto-optical imaging technique. It is found that the flux density is non-uniform inside the sample, even within one particle region. Although there are interactions between neighbouring particles, the magnetized sample behaves as a collection of individual magnetized particles rather than as a uniform and continuous magnetic substance.

Key Words: Magneto-optical imaging, Soft magnetic composite, Magnetic field distribution.

1. Introduction

Soft Magnetic Composites (SMCs), made from iron powder coated with an organic coating, have been widely used in novel electromagnetic devices. The major advantages of these materials include magnetic isotropy, relatively high electrical resistivity, and easy compression into complicated and practical shapes required in various electromagnetic devices [1], [2]. The magnetic flux distribution in the sample interests many engineers when they design innovative electromagnetic component [3]. In addition, scientists are also interested in the distribution in order to understand magnetization process, as well as intrinsic and extrinsic magnetic properties [4]-[6]. Conventional magnetization methods only measure the properties over the whole volume of the sample [7], [8] and cannot provide local magnetization process in detail. This paper presents a method of magneto-optical imaging (MOI) to visualize the magnetic field distribution in SMC samples and intuitively observe the magnetization process. The study shows that the flux density is non-uniform at the sample surface, 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 line is intense in the particle and sparse at the interspace between the particles.

Correspondence: Zhi Wei (Jack) Lin, Centre for Electrical Machines and Power Electronics, Faculty of Engineering, University of Technology, Sydney, PO Box 123, Broadway, NSW 2007, Australia,
email: jacklin@eng.uts.edu.au

2. Experimental setup

The experimental setup was built based on the Faraday rotation [9], that is, a rotation of light polarization induced by magnetic field. As a result of rotation, an MO image is a grey scale picture. The brighter the area, the higher the flux density. For an opaque magnetic sample, the reflecting model of the Faraday rotation, illustrated in Fig. 1, can be employed to examine the flux distribution. In this study, a green filter was employed to improve the contrast of the image. The MOI technique can image

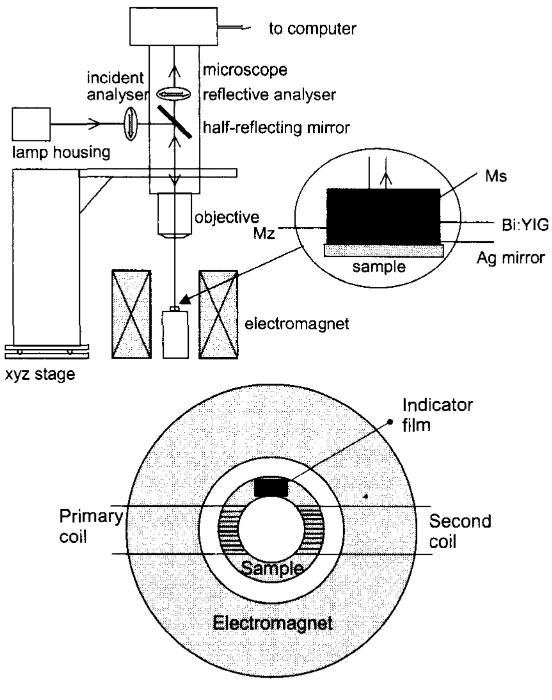
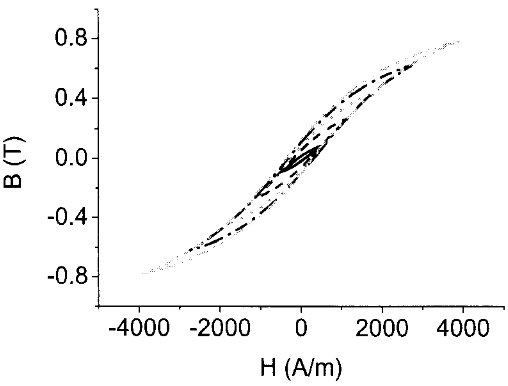


Fig. 1. Illustration of reflective model of MOI system (top) and arrangement of sample, indicator film and coils (bottom).

magnetic properties in real time/space with micrometer resolution. The major advantage of MOI technique is that the local detail of magnetic structures ranging from micrometer to centimetres can be directly visualized, rather than measuring the average magnetic properties over the whole volume of the sample. The MOI system is simple, effective, inexpensive, and requires less maintenance. Equipped with high speed, high sensitivity digital camera, it is capable to study the dynamic behaviour of magnetic structure. The system is easy to be built and operated comparing with high cost systems, for example, magnetic force microscope. Because the indicator film, which is a Bi substituted Yttrium Iron Garnet film [Y3Fe2(FeO4)3], is deposited on a gadolinium gallium garnet (GGG) substrate and protected by a hard thin film, it can be reused without any damage to the indicator film and the sample. The indicator film was immediately placed on the sample surface with slight mechanical pressure and the sample surface was carefully polished in order to improve spatial resolution. The magnetic field is generated by electromagnet located under the sample and used to magnetize the sample in the perpendicular direction. The magneto-optical image was captured by a CCD camera with movie function on the top of polarization microscope. At last, the image is transferred to a PC for analysis.

The toroidal-shape SMC sample involved in this study was compressed from commercially available iron powder Somaloy 500^{TM} + 0.6 % LB1 with 450 MPa, followed by a heat treatment in a steam/N2 atmosphere for 30 minutes. The density of the sample is 6.54 g/cm^3. The dimensions of the sample are inner diameter of 28.29 mm, outer diameter of 53.46 mm, and thickness of 5.05 mm. The conventional primary coil of 106 turns and second coil of 255 turns were wound around the sample to measure the hysteresis loops and the losses at different conditions. A control system was used to ensure that the flux densities in the sample were sinusoidal.



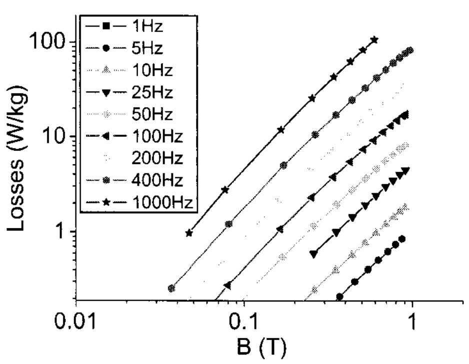


Fig. 2. Hysteresis loops at 1 Hz (top) and magnetic losses at different frequencies (bottom).

3. Results and Discussion

Fig. 2 shows hysteresis loops with different peak values of magnetic flux density at the frequency of 1 Hz and the loss chart at frequencies from 1 Hz to 1000 Hz when the flux densities were controlled to be a sinusoidal waveform. The data are consistent with that provided by manufacturer.

Fig. 3 shows the sample microstructure and morphology at the compressing surface taken by an optical microscope. It can be seen that the shape of particles is irregular and there are visible interstices between the particles. In addition, small intra-particle porosities and overlaps of the particles are found. However, the interstice decreases with increasing pressure [6], [10]. Comparing with the initial pre-pressed particle, the shape of the particle changes significantly. The particle size at the compressing surface is about 150 - 200 μm while the size of the initial particle is about 70 - 130 μm. It appears to be due to ductibility of the iron particle and occurs at compressing process. However, the oxide isolation layer cannot be perceived since the limitation of the optical microscope.

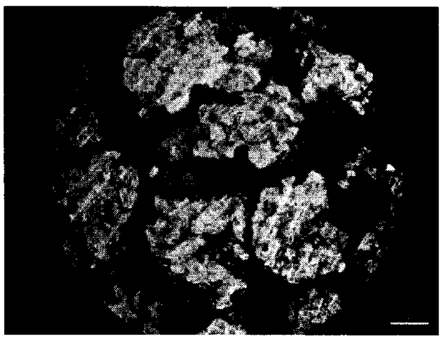


Fig. 3. Optical photograph of sample microstructure and morphology.

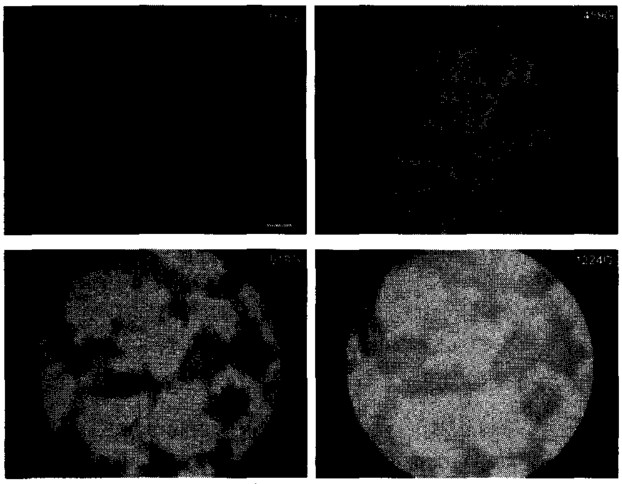


Fig. 4. Magneto-optical images when perpendicular external magnetic fields were applied to the sample up to 1224 G.

Fig. 4 shows the magneto-optical images in the indicator flim placed on the compressing surface immediately when external magnetic fields perpendicular to the examination surface were increased up to 1224 G. With increasing the fields, the brightness of the image increases, but it strongly depends on the position. Some regions are much brighter. Comparing with Fig. 3, it is noticed that the shape of brighter regions is well consistent with the shape of particles. It means that the flux density at the particle surface is much stronger than that at the porosity. In addition, the indicator film is so sensitive to the magnetic field that unexpected non-uniformity of flux density at the particle surface is visualized. It is believed that the non-uniformity is resulted from the porosities, overlaps of particles and contaminations in the intra-particle. It is also caused by the grain boundaries and crystal distortions, including thermal distortion and compressing distortion.

Fig. 5 shows a series of magneto-optical images taken when the sample was magnetized by toroidal fields generated by the primary magnetization coil around the sample. The field strengths in the sample were increased from zero to the maximum of 2596 A/m, and then reduced to zero. After changing the polarization of magnetization field (that is, changing the direction of magnetization current), the fields were increased to -2596 A/m, and then reduced to zero. Some scratches and defects in the indicator film can be observed. It is found that the normal component of stray field at the particle edges which are perpendicular to the magnetization field changes dramatically. The gradient of flux density alters sharply at the region where the particles are very

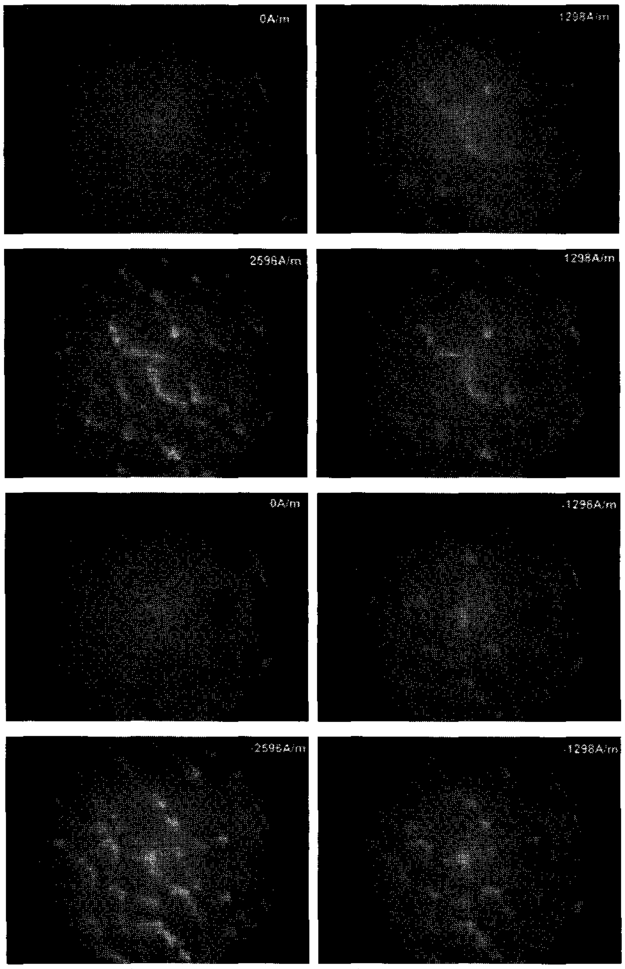


Fig. 5. The magneto-optical images taken when the sample was magnetized by the fields of the primary coil.

close. However, the alteration gradually becomes insignificant when the edge tends to be parallel to the magnetization field. At the parallel edge, the alteration is invisible. The alteration at the centre of particles is not observed. By rotating the reflective analyser, it is found that the field polarizations at the close edges of neighbouring particles are opposite. There is no doubt that flux lines start from one edge and end at the neighbouring edge.

Interestingly, the magnetization processes were recorded by the digital camera installed on the top of microscope when the sample was magnetized by the primary coil at 1 Hz. The frame rate is 15 frames per second. Fig. 6 shows some snapshots within one cycle. In this record, the reflective analyser is rotated to a specific angle so that the brightness at left edge of the particle is dark at the positive maximum field. Comparing the snapshots taken at 7/15 T and 8/15 T, it is noted that at the upper half period the left edge of particle is dark while the right edge is bright. At the lower half period the brightness is opposite, that

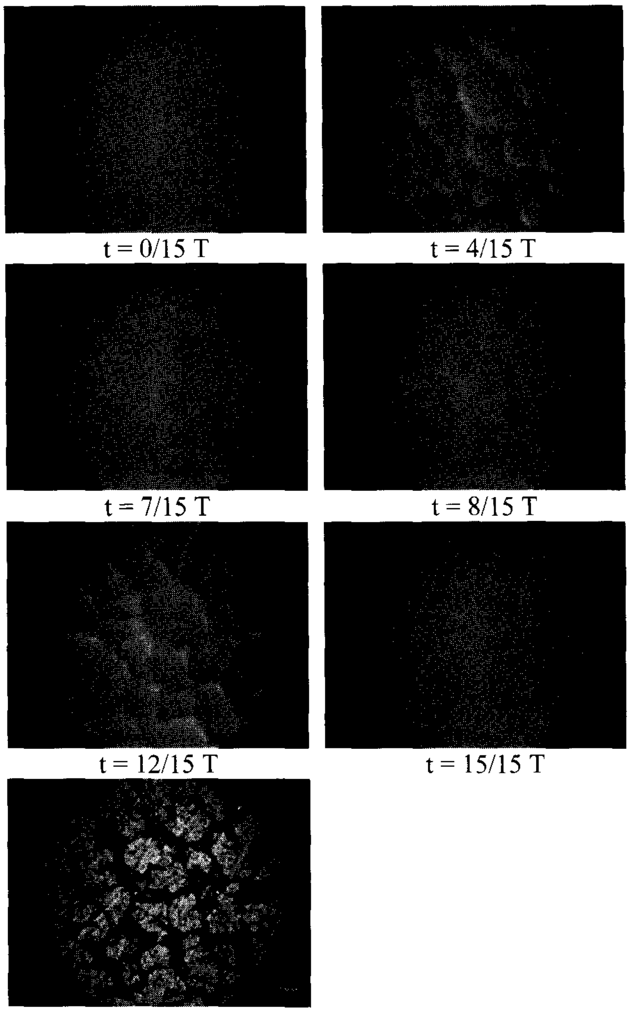


Fig. 6. Snapshot of magneto-optical images when sample was magnetized with 1 Hz field tangential to the sample surface. Morphology of studying region is referred.

is, the left edge becomes bright while the right edge becomes dark. It is evident that polarizations at the right and left edges of the particle are opposite. It means that particles of the sample are magnetized individually. The magnetic property of whole sample is contributed by each particle.

4. Conclusion

A magneto-optical imaging system has been used to visualize the magnetization processes of soft magnetic iron powder composite when it is magnetized by the fields perpendicular to the compressing surface and toroidal fields, respectively. It is found that flux density is concentrated inside the particle. The intra-particle porosity, contamination, overlaps grain boundary and crystal distortions lead to non-uniformity of flux density within one particle region. Although there are interactions between neighbouring particles, the magnetized sample behaves as a collection of individual magnetized particles rather than as a uniform and continuous magnetic substance.

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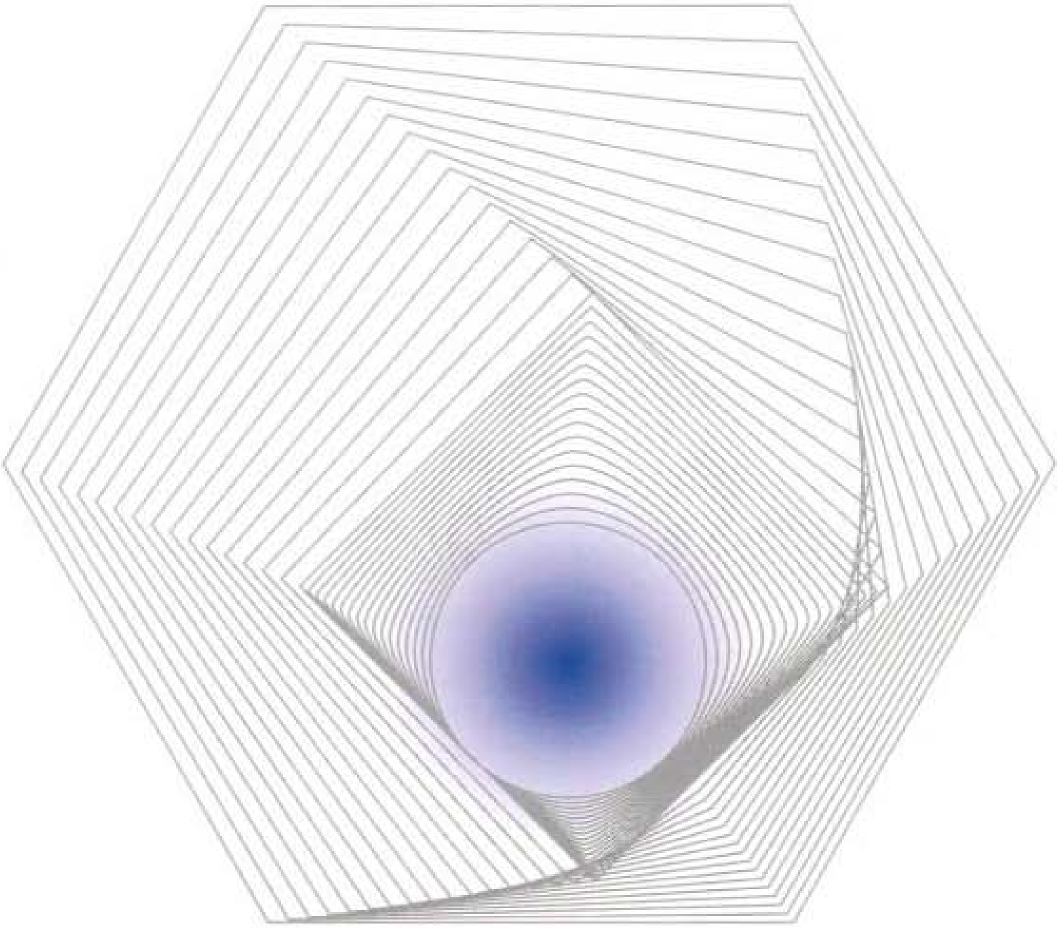

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