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Hysteresis loss reduction in self-bias FeSi/$SrFe_{12}O_{19}$ soft magnetic composites

Shuangjiu Feng(冯双久)[1,†], Jiangli Ni(倪江利)[1], Feng Hu(胡锋)[2], Xucai Kan(阚绪材)[1], Qingrong Lv(吕庆荣)[1], and Xiansong Liu(刘先松)[1]

[1] *Engineering Technology Research Center of Magnetic Materials of Anhui Province, School of Physics and Materials Science, Anhui University, Hefei* 230601, *China*

[2] *Engineering Technology Research Center of Preparation and Application of Industrial Ceramics of Anhui Province, School of Chemistry and Material Engineering, Chaohu University, Hefei* 238000, *China*

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The magnetic field provided by magnetized $SrFe_{12}O_{19}$ particles in FeSi/$SrFe_{12}O_{19}$ composites is used to replace the applied transverse magnetic field, which successfully reduces the magnetic loss of the composites with minor reduction of permeability. This magnetic loss reduction mainly comes from the decrease in hysteresis loss, while the eddy current loss is basically unaffected. The hysteresis loss reduction in magnetized composites is believed to be due to the decrease in domain wall displacement caused by the increase in the average magnetic domain size in a DC magnetic field. This is an effective method for reducing the magnetic loss of soft magnetic composites with wide application potential, and there is no problem of increasing the cost and the volume of the magnetic cores.

Keywords: soft magnetic composites, FeSi, $SrFe_{12}O_{19}$, magnetic loss

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1. Introduction

Soft magnetic composites (SMCs) have wide applications in power electronics at kHz frequency band due to their relatively higher resistivity as ferrites and high saturation magnetization as metallic soft magnetic materials.[1–3] In power electronics, wide band gap (WBG) semiconductors enable the reduction of soft magnetic components, but none of the magnetic materials available today can fully unlock the potential of WBG devices.[4] In the problems of soft magnetic materials, too much core loss of SMCs at high frequencies is a key issue.

In order to mitigate magnetic loss in SMCs cores, two approaches are often used in practice. One is to reduce the eddy current loss of SMCs by increasing the insulation between different soft metallic particles, including the surface oxidation,[5–7] insulating coating,[8–15] and the addition of various insulating agents,[16–24] which is proved to be an effective method to reduce magnetic loss in SMCs. The other is to reduce the hysteresis loss by increasing the permeability of SMCs[25,26] at the expense of deteriorating high frequency performance. There is a certain conflict between the two ways. For example, increasing the amount of insulating agent in SMCs is beneficial to reducing eddy current loss, but it will reduce the ratio of magnetic ingredient and increase the air gap in SMCs, which will cause a decrease in permeability and is not conducive to reducing hysteresis loss. It was reported that the hysteresis loss of SMCs can be reduced obviously by applying a transverse magnetic field in the cores.[27] This is an effective way independent of other methods of reducing losses of SMCs, however, the permanent magnets that provide the transverse field will increase the volume and cost of inductive components which use the SMCs cores. In order to overcome this shortcoming, it is proposed that introducing an internal magnetic field source in SMCs to replace external magnets is a possible approach to solve this problem. The high resistivity of $SrFe_{12}O_{19}$ can be used as an insulating agent for SMCs, and its magnetic properties can also be beneficial to relatively increase the saturation magnetization of SMCs, but its permanent magnetic characteristics are not conducive to improving the permeability and reducing the hysteresis loss of SMCs.[28] At the same time, $SrFe_{12}O_{19}$ ferrite particles can also be used as a magnetic field provider after magnetization. The advantage of FeSi soft magnetic composite is high saturation magnetization and low price, but the magnetic loss is relatively high. In this paper, experimental results of FeSi/$SrFe_{12}O_{19}$ composites in self-bias magnetic field provided by magnetized $SrFe_{12}O_{19}$ particles are reported.

2. Experimental details

Commercial FeSi powder and laboratory-prepared $SrFe_{12}O_{19}$ (SrM) ferrite are used as raw materials. Microsphere FeSi with about 35-μm average particle sizes is mixed with a certain proportion of SrM ferrite with about 3-μm particle sizes and the mixtures are compacted into toroidal shape cores (outer/inner diameter: 26 mm/14 mm and height about 8 mm) at 1.2-GPa pressure. The details of the manufacture

[†]Corresponding author. E-mail: fengsj@ahu.edu.cn

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process, the microstructure and the basic magnetic properties of FeSi/SrM composite are reported in Ref. [28]. After annealed at 500 °C for 2 hours in a vacuum, magnetic properties of the FeSi/SrM composite cores are measured by a BH/μ Analyzer (Iwatsu SY-8258) with the highest frequency 1-MHz and 1% tolerance. The same toroids are magnetized in a 1.2-MA/m magnetic field provided by an electromagnet, so that the permanent SrM particles in the FeSi/SrM composite can be magnetized to provide a magnetic field for the composite. Then magnetic properties of magnetized FeSi/SrM composites are measured again at the same measurement conditions.

3. Results and discussion

X-ray diffraction patterns of FeSi and SrM powder are shown in Fig. 1, it can be found in Fig. 1 that FeSi has a single-phase body-centered cubic structure, while SrM has a single-phase magnetoplumbite structure. Magnetic permeability of FeSi/SrM composites is measured to investigate the impact of magnetization on it. The AC field dependence of the permeability of FeSi/5.3 wt%SrM and FeSi/8.1 wt%SrM composite samples before and after magnetization measured at 50 kHz are shown in Fig. 2. It can be found in Fig. 2 that compared with the data before magnetization, the magnetic permeability after magnetization decreases by about 8% for two samples, which is similar to the results of applying a transverse magnetic field in SMCs.[27] Although the permeability of the FeSi/8.1 wt%SrM composite is about 30% lower than that of FeSi/5.3 wt%SrM sample, the experimental results of the two composites are very similar, and the relative reduction of permeability is also very close at the same magnetic field.

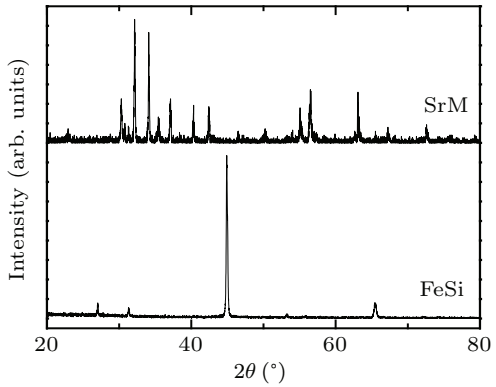


Fig. 1. XRD patterns of FeSi and $SrFe_{12}O_{19}$ powders.

Magnetic induction dependence of magnetic loss of FeSi/5.3 wt%SrM and FeSi/8.1 wt%SrM composites before and after magnetization measured at 50 kHz are displayed in Fig. 3. It can be found that the magnetic loss of both composites decreases after magnetization, which indicated that the magnetization process can effectively reduce the magnetic loss of FeSi/SrM composites except for minor reducing magnetic permeability. This result is similar to the result of applying a transverse magnetic field to the SMCs,[27] indicating that the magnetic field provided by magnetized SrM particles in the composites has the same effect as the applied transverse field. Compared with the magnetic loss before magnetization, the relative loss reduction of FeSi/8.1 wt%SrM composite after magnetization is greater than that of FeSi/5.3 wt%SrM, which implied that SrM content increase in the composite is conducive to reduction of magnetic loss after magnetization. Considering that the increase of SrM ferrite content in FeSi/SrM composites will significantly reduce the magnetic permeability, as showed in Fig. 2, low permeability implies that more magnetic field energy is stored in the composite under the same magnetic induction, which will lead to an increase in the magnetic loss before magnetization. So there is optimal SrM content in FeSi/SrM composites that can achieve the lowest magnetic loss in the composites after magnetization.

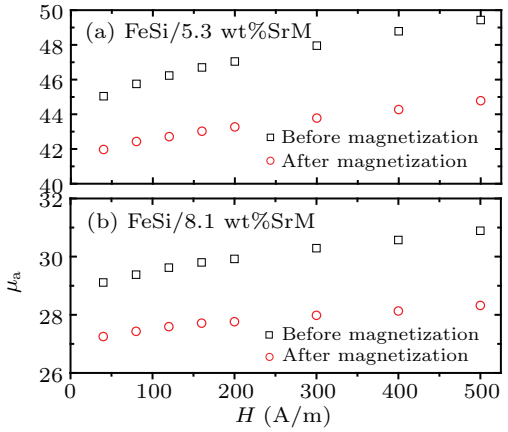


Fig. 2. Variation of permeability *versus* magnetic field of FeSi/5.3 wt%SrM (a) and FeSi/8.1 wt%SrM (b) composites measured at 50 kHz before and after magnetization.

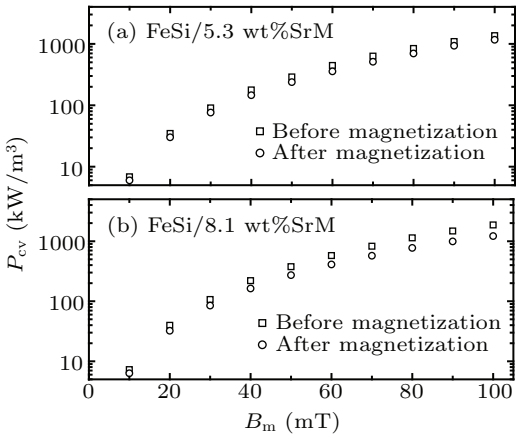


Fig. 3. Variation of magnetic loss *versus* magnetic induction of FeSi/5.3 wt%SrM (a) and FeSi/8.1 wt%SrM (b) composites measured at 50 kHz before and after magnetization.

In order to clarify the influence of the magnetization process on different kinds of magnetic losses, the frequency dependence of magnetic loss of FeSi/SrM composites before and after magnetization is also measured at $B_m = 50$ mT. Based on the different frequency dependence of hysteresis loss and eddy

current loss, these two kinds of losses can be separated from the measured total magnetic loss[29,30]

$$P_{\rm cv} = P_{\rm h} + P_{\rm e} = K_{\rm H} B_{\rm m}^3 f + \frac{C B_{\rm m}^2 f^2 d^2}{\rho}. \quad (1)$$

Here $K_{\rm H}$ and C are proportionality constants, f the frequency, $B_{\rm m}$ the magnetic induction magnitude, d the average size of eddy current loop and ρ the electrical resistivity of the FeSi alloy. In $P_{\rm cv}/f$ plotted *versus* frequency figure, $P_{\rm h}$ and $P_{\rm e}$ are given by the zero frequency intercept and the linear part, respectively.[29] The measured $P_{\rm cv}/f$ data plotted *versus* frequency of two FeSi/SrM composites before and after magnetization are shown in Fig. 4, and two conclusions can be clearly drawn from the data in the figure. One is that compared with before magnetization, magnetic loss of the FeSi/SrM composites after magnetization has been significantly reduced, and as added SrM content increases, the relative decrease of magnetic loss becomes more obvious, which is consistent with the results in Fig. 3. The other is that the data in Fig. 4 fit well with linearity, which is consistent with Eq. (1). The fitting parameters are listed in Table 1. From the fitting parameters, it can be found that the linearity slope basically did not change before and after magnetization for the same composite, indicating that the magnetization process does not change the eddy current loss characteristics of FeSi/SrM composites. However, zero frequency intercept of FeSi/SrM composite after magnetization is less than that of before magnetization for the same composite, which implied that the hysteresis loss decreases after magnetization process. Comparing the change in the hysteresis loss of FeSi/SrM composite with different SrM ferrite contents after magnetization, the reduction ratio of FeSi/5.3 wt%SrM composite is about 24.5%, and the reduction ratio of FeSi/8.1 wt%Sr M is about 30%. These results in Fig. 4 are also quite similar to the experimental results of SMCs in transverse magnetic field,[27] which indicates that the magnetic field provided by the magnetized permanent ferrite particles in SMCs plays the same role as the transverse magnetic field. From the point view of application, it has obvious advantages to replace the applied transverse magnetic field with the self-biased magnetic field provided by the magnetized permanent ferrite particles in SMCs, at least the cost and volume of the SMCs cores have been effectively controlled. From the fitting parameters of the data in Fig. 4, it should be pointed out that the eddy current loss coefficient decreases obviously with the increase of the SrM content in SMCs, which is inconsistent with the result in Ref. [28] that gives very similar eddy current loss coefficient for FeSi/5.3 wt%SrM and FeSi/8.1 wt%SrM composites. Of course, the annealing temperature of SMCs in this paper (500 °C) is higher than that in Ref. [28] (220 °C), which leads to a slight increase in permeability and an obvious decrease in magnetic loss, accompanied by differences in eddy current loss coefficients for SMCs with different SrM content. This result implies that it is important to improve the magnetic properties of SMCs with a proper annealing process.

Table 1. Linear fitting parameters of FeSi /SrM composites.

		Intercept (J/m^3)	Slope (μJ·s/m^3)
FeSi/5.3 wt%SrM	Before magnetization	5.00±0.03	16.2±0.4
	After magnetization	3.91±0.02	16.2±0.3
FeSi/8.1 wt%SrM	Before magnetization	6.97±0.02	9.8±0.3
	After magnetization	4.88±0.04	9.7±0.5

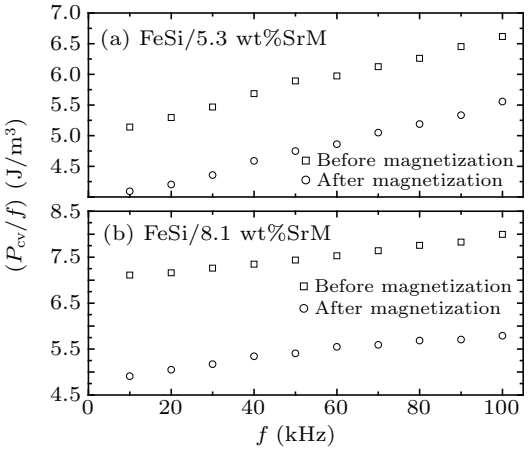


Fig. 4. Variation of magnetic loss per cycle *versus* frequency of FeSi/5.3 wt%SrM (a) and FeSi/8.1 wt%SrM (b) composites measured at 50 mT before and after magnetization.

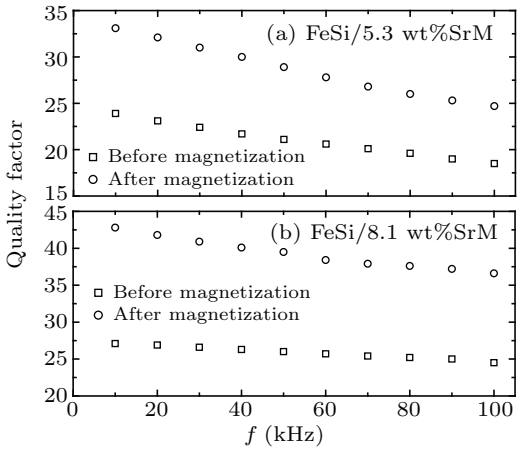


Fig. 5. Variation of quality factor *versus* frequency of FeSi/5.3 wt%SrM (a) and FeSi/8.1 wt%SrM (b) composites measured at 50 mT before and after magnetization.

In the magnetic loss measurement, a fixed magnetic induction magnitude is used. After magnetization, magnetic permeability of the FeSi/SrM cores decreases, resulting in more magnetic field energy stored in the cores under the same magnetic induction, and the measured power loss is overestimated. In this circumstance, it may be more reasonable to compare relative losses. The frequency dependence of quality factor Q of FeSi/SrM composites before and after magnetization measured at the same conditions as given in Fig. 4 is shown in Fig. 5. It can be found in Fig. 5 that Q value of FeSi/SrM composites has been significantly improved after magnetization. At the same time, it can also be found that the increase of

SrM content in FeSi/SrM composites is conducive to improving the quality factor of the composites. The relative quality factor increment of two FeSi/SrM composites after magnetization is displayed in Fig. 6, it can be found that the quality factor increment of FeSi/8.1 wt%SrM composite is about 1.5 times of FeSi/5.3 wt%SrM. The quality factor increment shows a decreasing trend with increasing frequency, because the ratio of hysteresis loss in the total loss decreases with increasing frequency, and the magnetization process only reduces the hysteresis loss of the composite.

It should be emphasized that the total power loss of FeSi/8.1 wt%SrM composite is bigger than that of FeSi/5.3 wt%SrM core at the same measurement condition before magnetization, just as shown in Figs. 3 and 4. But the quality factor of the former is also bigger than that of the latter at the same condition, as shown in Fig. 5. The evaluation of SMCs under different parameters is different because of the difference in permeability. Therefore, the composite properties are sometimes difficult to distinguish the pros and cons, but more suitable for application circumstance. FeSi/5.3 wt%SrM core with relatively low hysteresis loss and high eddy current loss, is more suitable for low frequency and high magnetic induction circumstance, and FeSi/8.1 wt%SrM composite with relatively high hysteresis loss and low eddy current loss, is more advantageous applied at high frequency and low magnetic induction condition. After magnetization, both permeability and magnetic loss of the composite are reduced, which may be closer to meeting the requirements of WBG devices for magnetic cores.

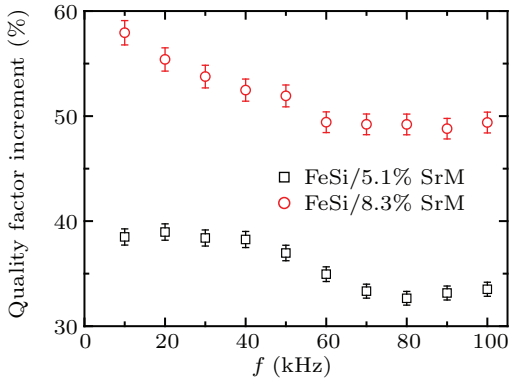


Fig. 6. Comparison of quality factor increment *versus* frequency of FeSi/5.3 wt%SrM and FeSi/8.1 wt%SrM composites measured at 50 mT after magnetization.

The direction of the applied transverse magnetic field in SMCs is determined, and it can be considered that the domain wall displacement and the spin rotation in the direction of the transverse field are completely locked, resulting in a reduction in permeability and hysteresis loss.[27] However, this locking requires SMCs to be magnetized to saturation in the direction of the transverse magnetic field. The magnetic field provided by magnetized SrM particles in the FeSi/SrM composites obviously no longer has a definite direction and cannot magnetize FeSi/SrM composite to saturation in any direction, so the original explanation is not suitable for FeSi/SrM composite. Considering that the application of a DC magnetic field to soft magnetic material would change the magnetic domain structure of the magnetic materials, the volume of the magnetic domain parallel to the direction of DC field increases, while the anti-parallel magnetic domain decreases or even disappears. As a result, the average volume of the magnetic domains in soft magnetic material increases and the number of magnetic domain walls decreases. In this way, permeability caused by the domain walls displacement and the hysteresis loss caused by the irreversible domain walls displacement will decrease. As for the inconsistency of the relative reduction ratio of permeability and magnetic loss after magnetization, it can be attributed to the distributed air gaps in the composites.[27] On the other hand, due to the volume reduction of the anti-parallel magnetic domain, the increases in the ratio of domain wall energy to magnetic domain energy will cause spin rotation to occur more easily, and the permeability contributed by the spin rotation and the hysteresis loss caused by the irreversible spin rotation increase. The domain wall displacement dominates the contribution of permeability and hysteresis loss at low magnetic induction, it was also observed in the experiment that the permeability and magnetic loss of FeSi/SrM composites at $B_{\rm m} = 50$ mT decreased significantly after magnetization, which is qualitatively consistent with the above analysis. As the magnetic induction increases, the contribution of spin rotation will gradually increase, it is possible that under a very high magnetic induction, the loss characteristic has a crossover behavior and magnetic loss changes from decreasing to an increase after magnetization.

4. Conclusions

Magnetic properties of FeSi/SrM composites before and after magnetization are investigated in this paper. Experimental results found that the magnetic field provided by SrM ferrite particles in the magnetized composite instead of the transverse magnetic field provided by the external magnets can also effectively reduce the power loss of the composites at the expense of minor reduction of permeability. The power loss reduction of FeSi/SrM composites after magnetization is due primarily to the reduction of hysteresis loss, and the eddy current loss is basically not affected by the magnetization process. The relative reduction of power loss after magnetization increases with increase of SrM ferrite content in the composite, however, increasing SrM ferrite content in the composite will also increase the power loss of the composite before magnetization, there is an optimal SrM ferrite content in the composite which has lowest power loss after magnetization. The possible mechanism of the hysteresis loss reduction in FeSi/SrM

composites after magnetization is discussed, and it is believed that the existence of the DC magnetic field caused the increase of the average magnetic domain size in the composites, which leads to a decrease in the number of domain walls and a weakening of domain wall displacement.

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