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MHz cut-off frequency and permeability mechanism of iron-based soft magnetic composites

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The lack of soft magnetic composites with high power density in MHz frequency range has become an obstacle in the efficient operation of the electrical and electronic equipments. Here, a promising method to increase the cut-off frequency of iron-based soft magnetic composites to hundreds of MHz is reported. The cut-off frequency is increased from 10 MHz to 1 GHz by modulating the height of the ring, the distribution of particles, and the particle size. The mechanism of cut-off frequency and permeability is the coherent rotation of domain modulated by inhomogeneous field due to the eddy current effect. An empirical formula for the cut-off frequency in a magnetic ring composed of iron-based particles is established from experimental data. This work provides an effective approach to fabricate soft magnetic composites with a cut-off frequency in hundreds of MHz.

Keywords: cut-off frequency, permeability, eddy current effect, soft magnetic composites

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1. Introduction

Soft magnetic composites (SMCs) with high power density are widely used in power electronic systems, such as energy conversion, filtering, resonance, and isolators.[1–6] With the development of electrification, increasing the cut-off frequency to improve the efficiency of power conversion has become essential.[7] However, no SMC is able to fully release the potential of wide bandgap semiconductors at MHz range.[8] Therefore, improving the cut-off frequency of SMCs from hundreds of kHz to hundreds of MHz has become an urgent issue.

As the most promising power soft magnetic materials, SMCs have been widely used at about 100 kHz since 1990.[9] Traditionally, by changing the metallic bulk to SMCs, cut-off frequency is improved from 1 kHz to hundreds of kHz range.[10,11] Experimentally, cut-off frequency can be increased further by decreasing the fill ratio of composites.[12–15] As an alternative approach, cut-off frequency is increased by adjusting the geometrical shapes of particles.[16,17] However, the mechanism to achieve SMCs with cut-off frequency in the hundreds of MHz is still lacking.

The cut-off frequency is defined as the frequency at which the value of permeability is half of its initial value. It is necessary to understand the mechanism of permeability first. It is known that particles with sizes on the order of micrometers (μm) have multi-domain structures.[18] Therefore, the displacement of domain wall is considered to be the main permeability mechanism in the MHz range.[19–23] Meanwhile, the results of cut-off frequency with different fill ratios indicate that the main mechanism of cut-off frequency and permeability cannot be the displacement of the domain wall.[24–27] Coherent rotation of domain is another possible mechanism of permeability in addition to the displacement of the domain wall. But the intrinsic natural resonance frequency of Fe particle occurs in the GHz range,[28,29] which is far from the cut-off frequency in MHz of its SMCs.[30] The mechanism of cut-off frequency and permeability of SMCs in the MHz range may be from the modulated displacement of domain wall and coherent rotation of domain.

With different thicknesses of Fe–Ni films,[31] we found that cut-off frequency and permeability come from the coherent rotation modulated by the eddy current effect. These results have shown clearly that the eddy current effect must be considered when we study the mechanism of cut-off frequency and permeability of SMCs. Meanwhile, because the distribution of field is simplified in theoretical models compared to the complex experiments, it is hard to describe cut-off frequency accurately.[32] Therefore, establishing an empirical formula from experiments is an effective way to understand the change of cut-off frequency in SMCs.

In this paper, the effects of eddy current on cut-off frequency and permeability of iron-based SMCs were studied by changing height of ring, fill ratio, and particle size. Cut-off frequency of SMCs is increased by decreasing height of ring, fill ratio, and particle size. Permeability of SMCs at 1 MHz is increased by increasing fill ratio. An empirical formula of cut-off frequency is established to optimize the structure and performance of SMCs in the MHz range. This work shows optimizing height and fill ratio is an effective way to increase cut-off frequency and permeability of composites.

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2. Materials and characterization

Carbonyl iron particles with size distribution of 1.0–10.0 μm were used. The particles with fill ratio 80%, 70%, 65%, 60%, 53%, and 45% were coated with epoxy, respectively. The coated particles were compacted into rings under 1000 MPa with heights of 6.5 mm, 5.5 mm, 2.0 mm, 1.0 mm, 0.5 mm, and 0.3 mm. The inner and outer diameters of all rings were 7 mm and 13 mm, respectively.

Microscopic morphology of the particles was examined by scanning electron microscope (SEM). Crystalline structure of iron particles was characterized by x-ray diffraction (XRD). Hysteresis loop and permeability spectrum were measured by a vibrating sample magnetometer (VSM) and an impedance analyzer (KEYSIGHT E4991B) at 1 MHz–1 GHz frequency range, respectively.

3. Results

Figure 1 shows the characterization of iron particles. An almost spherical morphology of iron particles with size 1.0–10.0 μm are observed by SEM as shown in Fig. 1(a). Figure 1(b) shows that iron particles have a bcc structure with lattice parameter 2.8664 Å. Hysteresis loop shows that iron particles have high saturation magnetic polarization $\mu_0 M_s$ of about 2 T and coercive field of about 10 Oe as shown by Fig. 1(c). By compacting the particles into rings with heights of 6.5 mm, 5.5 mm, 2.0 mm, 1.0 mm, 0.5 mm, and 0.3 mm, permeability spectra of SMCs (80 vol.%) are shown in Fig. 1(d). It is found that cut-off frequency increases from 10 MHz to 450 MHz by reducing the height of rings from 6.5 mm to 0.3 mm. Permeability of all rings is about 15 at 1 MHz.

To understand the origin of the cut-off frequency, Fig. 2 shows permeability spectra of composites μ_{eff}, aggregates μ_{agg}, and particles μ_{r} with different fill ratios. The heights of all rings are about 5.5 mm. The results show that cut-off frequency increases and permeability at 1 MHz decreases by decreasing fill ratio in SMCs. It is known that permeability can only come from the iron particles. Thus, by removing the effect of non-magnetic epoxy, the permeability of aggregate $\mu_{\text{agg}} = \mu_{\text{eff}}/v$ is shown in Fig. 2(b), where v is the fill ratio. It is found that the cut-off frequency increases and the permeability decreases slowly as the fill ratio decreases. Combining with the demagnetization field correction based on the distribution of particles, the permeability of particle can be expressed as follows:

$$\mu_{\text{r}} = \frac{2\mu_{\text{eff}}}{3v - 1}. \tag{1}$$

Figure 2(c) shows the permeability spectra of particle μ_{r}. The results show a normalized permeability at 1 MHz, which means there is almost no interaction between particles. Meanwhile, the cut-off frequency increases from 30 MHz to 700 MHz by decreasing the distribution ratio of particles from 80% to 60%. Ignoring the interaction between particles, the domain structure in particles cannot be changed with different distributions in SMCs. Generally, the intrinsic cut-off frequency of displacement of domain wall and coherent rotation is in the MHz and GHz range, respectively. Therefore, the cut-off frequency and permeability of SMCs come from modulated coherent rotation rather than the displacement of domain wall.

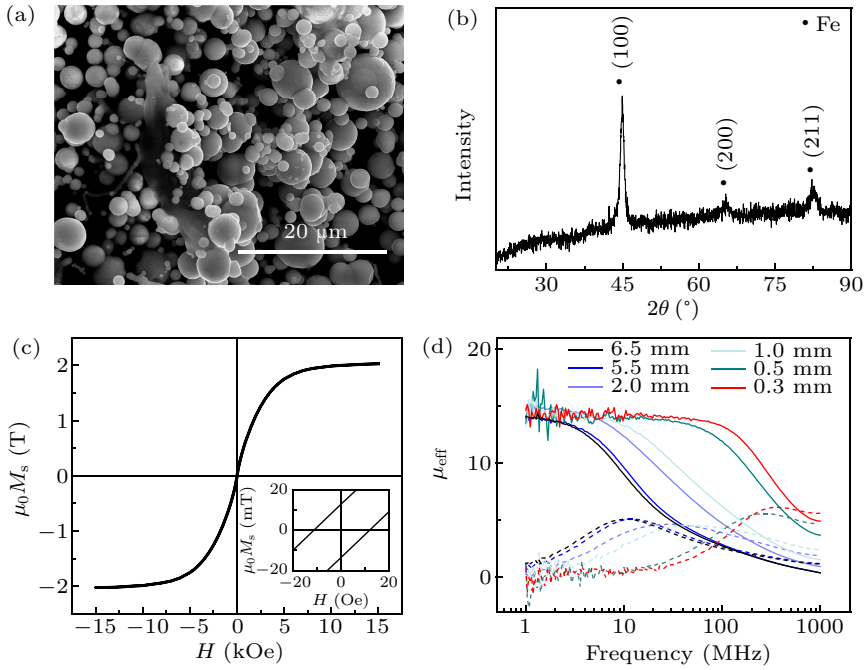


Fig. 1. Characterization of iron particles. (a) SEM picture, (b) XRD spectra, (c) hysteresis loop, (d) permeability spectra of ring with different heights.

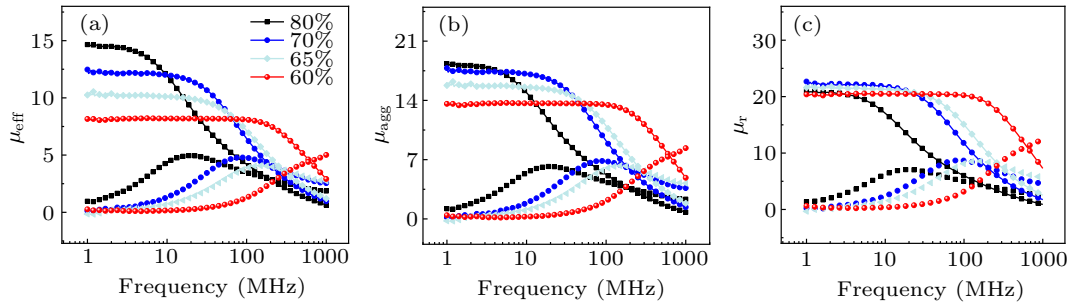


Fig. 2. Permeability spectra with different fill ratios. (a) Permeability spectra of composites. (b) Permeability spectra of aggregates. (c) Permeability spectra of particles.

It is known that the permeability of Fe–Ni film[31] can be expressed as

$$\mu = 1 + \frac{\tanh\left[(1+\mathrm{i})\,d/\delta\right]}{(1+\mathrm{i})\,d/\delta}\chi_{\rm in}, \tag{2}$$

where $\delta = \sqrt{2/\left[\sigma\omega\left(\chi_{\rm in}+1\right)\mu_0\right]}$ is skin depth, $2d$ is thickness of film, σ is conductivity, $\omega = 2\pi f$ is angular frequency, $\chi_{\rm in}$ is susceptibility of coherent rotation under a homogenous field, and μ_0 is vacuum permeability. This shows that the permeability of film decreases in the MHz range due to the inhomogeneous microwave field caused by eddy current effect. Increasing thickness and conductivity will further increase the inhomogeneous distribution of field. It is clear that inhomogeneous distribution of field will be more significant in metallic particles whose size is larger than the thickness of Fe–Ni films.[31] Therefore, the effect of inhomogeneous field on cut-off frequency and permeability of iron-based SMCs must be considered. Figure 3 shows the simulation results of microwave field amplitude in the magnetic ring depending on the height of ring and frequency. The heights of the magnetic ring are 0.5 mm, 2 mm, 5 mm, and 6 mm, and the frequencies are 10 MHz, 30 MHz, 100 MHz, and 300 MHz. The results show that the inhomogeneity of the magnetic field in the magnetic ring gradually increases with increasing height and frequency. The microwave magnetic field amplitude is highest on the surface of the magnetic ring and rapidly decays with transmission depth.

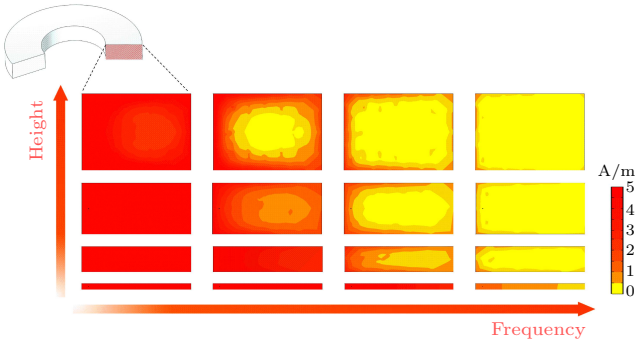


Fig. 3. Microwave field amplitude in magnetic ring depends on height and frequency.

Actually, the inhomogeneous distribution of field exists in both SMCs and particle. Assuming h_i is amplitude of applied microwave field on particles, permeability of SMCs can be derived as follows:

$$\mu_{\rm eff} = 1 + \frac{\sum_i V_i\left(\chi_i h_i\right)}{V_{\rm SMCs} h_0}, \tag{3}$$

where V_i is volume of particle, $V_{\rm SMCs}$ is volume of SMCs, h_0 is amplitude of applied microwave field on SMCs, and χ_i is susceptibility of particle,

$$\chi_i = \frac{\int_{V_i} h\left(r\right)\chi_{\rm in}\,\mathrm{d}\boldsymbol{r}}{V_i h_i}, \tag{4}$$

where $h\left(r\right)$ is amplitude of microwave field in particle. If the microwave field is homogenous in both SMCs and particles, then the permeability of SMCs is $\mu_{\rm eff} = 1 + v\chi_{\rm in}$. This shows that the cut-off frequency equals the resonance frequency of coherent rotation. Considering eddy current must exist in metallic particle in the MHz range, the inhomogeneous field caused by eddy current effect will lead to a decrease of permeability $\mu_{\rm eff} < 1 + v\chi_{\rm in}$. This indicates that the cut-off frequency of SMCs comes from the decrease of permeability of coherent rotation modulated by eddy current effect. Therefore, decreasing height and fill ratio will improve the homogeneity of h_i in SMCs and increase cut-off frequency of SMCs as shown in Figs. 1(d) and 2, respectively. If so, then by decreasing the particle size, the inhomogeneous distribution of $h\left(r\right)$ can be decreased and cut-off frequency of SMCs will be increased.

Figure 4 presents the permeability spectra of small particles with size of about 1.0–3.0 μm. The heights of both SMCs are about 1.0 mm and the fill ratios are about 80%, 65%, 53%, and 45%. It is found that cut-off frequency is removed from MHz range to GHz range except 80% fill ratio. Permeability at 1 MHz decreases gradually by decreasing the fill ratio. Figure 4(b) is permeability spectra of particle $\mu_{\rm r}$ obtained by the process similar to that described in Fig. 2(c). The normalized permeability of particle $\mu_{\rm r}$ in MHz range is exhibited except permeability with 80% fill ratio. These results show that cut-off frequency and permeability come from coherent rotation modulated by the inhomogeneous field in both of SMCs and particles.[19,33,34] Weakening the eddy current of particle to decrease the inhomogeneous distribution of field in SMCs and particles is an effective approach to realize SMCs with high cut-off frequency and high permeability above MHz.

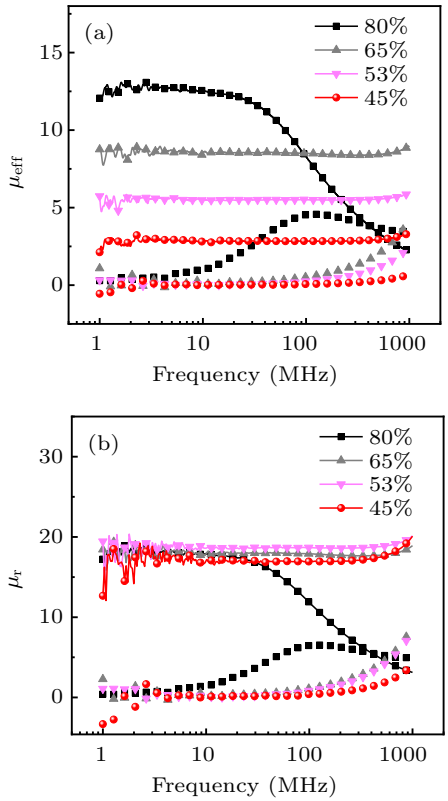


Fig. 4. Permeability spectra of 1.0–3.0 μm particles. (a) Permeability spectra of SMCs $\mu_{\rm eff}$. (b) Permeability spectra of particle $\mu_{\rm r}$ with different fill ratios.

4. Discussion

Establishing an empirical formula from experiments is helpful to understand and describe the change of cut-off frequency in SMCs. Figure 5 shows the cut-off frequency of SMCs with different fill ratios and heights. Particle size is 1.0–10.0 μm. The cut-off frequency of SMCs with fill ratios of 80%, 70%, 65%, and 60% increases as the height decreases. Considering the eddy current and effective conductivity model, the experimental data of cut-off frequency $f_{\rm c}$ can be well fitted by the following equation:

$$f_{\rm c} = \left\{ \frac{a}{d\,(3v-1)^{2.5}} \tanh\left[\frac{d\,(3v-1)^{2.5}}{a} \right] \right\} f_0, \tag{5}$$

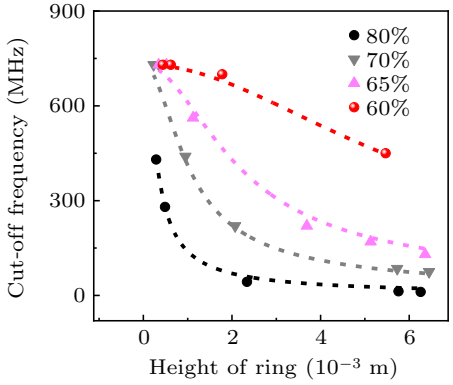


Fig. 5. Cut-off frequency of SMCs dependence on heights and fill ratios.

where $a = 0.1$ is a constant and $f_0 = 730$ MHz is the cut-off frequency which comes from the permeability modulated by the inhomogeneous field in particles. Therefore, decreasing the height and increasing the fill ratio of SMCs to weaken the inhomogeneous distribution field is an effective way to achieve high power density in the MHz range.

5. Conclusion

The cut-off frequency of iron-based SMCs was increased to over 100 MHz by reducing the ring height, fill ratio, and particle size. The mechanism of coherent rotation permeability modulated by the inhomogeneous field in both SMCs and particles is exhibited. An empirical formula is established from experimental data to understand and describe the cut-off frequency of SMCs. This work is helpful for fabricating SMCs with high cut-off frequency and high permeability in the MHz range.

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