

Article

A Study on an Easy-Plane FeSi_{3.5} Composite with High Permeability and Ultra-Low Loss at the MHz Frequency Band

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Abstract: An easy-plane FeSi_{3.5} composite with excellent magnetic properties and loss properties at MHz were proposed. The easy-plane FeSi_{3.5} composite has ultra-low loss at 10 MHz and 4 mT, about 372.88 kW/m³. In order to explore the reason that the P_{cv} of easy-plane FeSi_{3.5} composite is ultra-low, a none easy-plane FeSi_{3.5} composite, without easy-plane processing as a control group, measured the microstructure, and the magnetic and loss properties. We first found that the real reason why magnetic materials do not work properly at MHz due to overheat is dramatical increase of the excess loss and the easy-plane composite can greatly re-duce the excess loss by loss measurement and separation. The total loss of none easy-plane FeSi_{3.5} composite is much higher than that of easy-plane FeSi_{3.5} composite, where the excess loss is a major part in the total loss and even over 80% in the none easy-plane FeSi_{3.5} composite. The easy-plane FeSi_{3.5} composite can greatly reduce the total loss compared to the none easy-plane FeSi_{3.5} composite, from 2785.8 kW/m³ to 500.42 kW/m³ (3 MHz, 8 mT), with the main reduction being the excess loss, from 2435.2 kW/m³ to 204.93 kW/m³ (3 MHz, 8 mT), reduced by 91.58%. Furthermore, the easy-plane FeSi_{3.5} composite also has excellent magnetic properties, high permeability and ferromagnetic resonance frequencies. This makes the easy-plane FeSi_{3.5} composite become an excellent soft magnetic composite and it is possible for magnetic devices to operate properly at higher frequencies, especially at the MHz band and above.

Keywords: easy-plane soft magnetic composites; MHz frequency band; ultra-low power loss; excess loss



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1. Introduction

With the development of electrical and electronic technology, soft magnetic materials are used as core components in daily life. Their magnetic properties and loss properties directly affect the power density and conversion efficiency [1]. In the further development of electrical and electronic devices, magnetic devices (inductor, power converters, etc.) are required to develop in the direction of miniaturization and high efficiency [2–5]. In the past, soft magnetic materials do not need to operate at higher frequencies due to the low operating frequency of power semiconductors. But now, the appearance of the third-generation wide bandgap semiconductors (WBG) has provided a high-frequency scenario to soft magnetic materials [6]. The conversion efficiency P_{th} and size of soft magnetic materials in power devices (for example inductance, transformer, etc.) can be optimized because WBG increases the operating frequency, which can be described:

$$P_{th} = C f B_m A_e W_d \quad (1)$$

where C is the conversion efficiency coefficient, f is the operating frequency, B_m is the maximum magnetic flux density, A_e is the effective sectional area, and W_d is the number of turns. However, soft magnetic materials have developed a problem, which makes them unable to work properly due to overheating at higher frequencies when WBG increases

the operating frequency above MHz. Especially with the commercialization of SiC and GaN, the problem that soft magnetic materials cannot work properly at higher frequencies becomes more serious. A review, published in 2018 in *Science*, noted that none of the soft magnetic materials available today can cope with this daunting challenge. However, it also pointed out that soft magnetic composites (SMCs) have the potential to solve this problem [6].

Traditional SMCs are often used in electric motors, transformers, inductors and sensors due to high permeability, high-saturation magnetization and high-ferromagnetic resonance frequency [7–10]. When the devices try to work at higher frequencies, SMCs also have the same problem, which makes them unable to work properly due to overheating, resulting in a huge loss [6,11]. This overheating was thought to be caused by the eddy current loss at higher frequencies in the previous research [11–14]. Addressing the sharp increase in the loss at higher frequencies will provide a means of dealing with WBG and making soft magnetic materials work effectively.

The easy-plane soft magnetic materials are materials with a special magnetic configuration, where easy magnetization axes distributed in parallel planes with the same type enables the formation of the easy magnetization plane. According to the physical origins for the formation of the easy magnetization plane, easy-plane soft magnetic materials are divided into the magnetocrystalline-easy-plane soft magnetic materials (the easy magnetization axes are determined by the minimal of the magnetocrystalline anisotropy energy) and the magnetostatic-easy-plane soft magnetic materials (the easy magnetization axes are determined by the minimal of the magnetostatic energy). In the easy magnetization plane, the magnetization of easy-plane soft magnetic material is more easily saturated, remanence and coercivity of easy-plane soft magnetic materials are lower and the easy-plane soft magnetic materials has higher permeability and ferromagnetic resonance frequencies. When prepared as composites, the easy-plane soft magnetic composites maintain the excellent properties of the easy-plane soft magnetic materials, and also have the advantages of the composites. In the field of wave absorption, excellent results have been achieved due to the excellent performance of easy-plane soft magnetic composites [15–18]. Therefore, the easy-plane soft magnetic composites have the potential to address challenges posed by energy problem and WBG.

In the up-to-date published SMCs, measurement frequency of most studies are 1 MHz and below, such as FeSiCr ($\mu = 37, 560 \text{ kW/m}^3$ at 1 MHz, 20 mT and $\mu = 47.5, 7086 \text{ kW/m}^3$ at 1 MHz, 50 mT) [19,20], $\text{Fe}_{73}\text{Si}_6\text{B}_{10}\text{P}_5\text{C}_3\text{Mo}_3$ ($\mu = 34.63, \sim 500 \text{ kW/m}^3$ at 1 MHz, 20 mT) [21], flake pure iron ($\mu = 67, 306.6 \text{ kW/m}^3$ at 1 MHz, 3 mT and $\mu = 10, 3.285 \text{ kW/m}^3$ at 3.5 MHz, 0.1 mT) [22], etc. There are almost no studies with high frequency and high maximum magnetic flux density. However, in this paper, we measured for the total loss P_{cv} of the easy-plane $\text{FeSi}_{3.5}$ composite at 10 MHz and 4 mT, and we found that the easy-plane $\text{FeSi}_{3.5}$ composite has an ultra-low loss. The P_{cv} of the easy-plane $\text{FeSi}_{3.5}$ composite and none easy-plane $\text{FeSi}_{3.5}$ composite was measured and analyzed at 3 MHz and 8 mT for this study; the reason for their ultra-low loss. We first found that the real reason why magnetic materials do not work properly at higher frequencies is due to overheating, which shows a dramatical increase in the excess loss of P_{exc} , and the easy-plane $\text{FeSi}_{3.5}$ composite can greatly reduce the total loss of P_{cv} , and the main part of the reduction is the P_{exc} . The easy-plane $\text{FeSi}_{3.5}$ composite has high permeability, high-ferromagnetic resonance frequencies and a lower loss compared with the none easy-plane $\text{FeSi}_{3.5}$ composite by measurement and separation of loss. It is found that the sharp increase in the excess loss combined with frequency far exceeded the eddy current loss, and the excess loss becomes the most main part of total loss. The easy-plane $\text{FeSi}_{3.5}$ composite not only has higher permeability and higher ferromagnetic resonance frequencies, but can also effectively reduce the excess loss. Thus, the easy-plane $\text{FeSi}_{3.5}$ composite has the potential to deal with the overheating of soft magnetic materials due to excessive loss at higher frequencies, and is effectively utilized for devices at higher frequencies, especially at MHz and above.

2. Experiment

FeSi_{3.5} are the tradition spherical particles, obtained by purchasing. The tradition spherical FeSi_{3.5} particles are easy-plane processed to obtain the easy-plane FeSi_{3.5} particles, and the tradition spherical FeSi_{3.5} particles are named the none easy-plane FeSi_{3.5} particles. The easy-plane FeSi_{3.5} particles were compounded with polyurethane (PU) to prepare a polyurethane-based composite with 60 vol% (optimal volume fraction obtained after extensive experiments), and oriented in a rotating magnetic field (1 T) for 10 min. After the composite was heated to 90 °C, it was pressed into a ring-shaped composite with an outer diameter of 7 mm, an inner diameter of 3.04 mm and a thickness of 1 mm. And the none easy-plane FeSi_{3.5} composite was prepared using the same method.

The morphology of both particles and the composites were characterized by SEM (Apreo S, Thermo Fisher Scientific, Waltham, MA, USA). The vibrating sample magnetometer (VSM) (Microsense EV9, MicroSense, Lowell, MA, USA) was used to measure the hysteresis loop, and the degree of the plane orientation of two composites were also obtained by VSM data. The complex permeability of the composite was measured by a precision impedance analyzer (Agilent E4991B, Agilent, Santa Clara, CA, USA) and vector network analyzer (Agilent E8363B, Agilent, Santa Clara, CA, USA) at 1 MHz~18 GHz. The power loss was measured by a B-H analyzer (SY-8218, Iwatsu, Tokyo, Japan).

3. Result

The P_{cv} of the easy-plane FeSi_{3.5} composite was measured at 10 MHz and 4 mT. It is found that the easy-plane FeSi_{3.5} composite has an ultra-low loss of about 372.88 kW/m³. The result is rare in SMC. In order to explore the reason that the P_{cv} of the easy-plane FeSi_{3.5} composite is ultra-low, the none easy-plane FeSi_{3.5} composite, without easy-plane processing as a control group, measured the microstructure, magnetic properties and loss properties.

3.1. Morphology and Microstructure

Figure 1 shows the morphology and microstructures of the none easy-plane FeSi_{3.5} particles (a,b) and the easy-plane FeSi_{3.5} particles (d,e), cross sections of the none easy-plane FeSi_{3.5} (c) and easy-plane FeSi_{3.5} composite (f), respectively. The thickness of the none easy-plane FeSi_{3.5} particles is 44.35 µm, and the thickness of the easy-plane FeSi_{3.5} particles is 1.14 µm, thus the latter is much smaller than the former. The microstructures of the none easy-plane FeSi_{3.5} composite are a homogenous mixture of none easy-plane FeSi_{3.5} particles and PU; the microstructure of the easy-plane composite is an ordered laminar structure because of the orientation process.

3.2. Static Magnetic Performance and Degree of the Plane Orientation

Figure 2 shows the static magnetic properties of FeSi_{3.5} particles (a), hysteresis loops and the degree of plane orientation (DPO) of the none easy-plane FeSi_{3.5} composite (b) and easy-plane FeSi_{3.5} composite (c). The saturation magnetization (M_s) and the coercivity (H_c) of original FeSi_{3.5} is 184 emu/g and 3.32 Oe. The degree of plane orientation was characterized by measuring hysteresis loops of the in-plane and out-of-plane direction. The DPO can be expressed by Equation (2) [23]:

$$DPO(\%) = \frac{M_s - M_{r, z-axis}}{M_s} \times 100\% \quad (2)$$

where M_s is the saturation magnetization, and $M_{r, z-axis}$ is the remanent magnetism in the z-axis direction. For the none easy-plane FeSi_{3.5} composite, the hysteresis loops of the in-plane and out-of-plane direction coincide. Neither the in-plane direction or out-of-plane direction was magnetized to saturation (about 154 emu/g). For the easy-plane FeSi_{3.5} composite, the hysteresis loops of the in-plane and out-of-plane direction are different. The in-plane direction is more easily magnetized to saturation (about 173.5 emu/g) than the out-of-plane direction (Table 1).

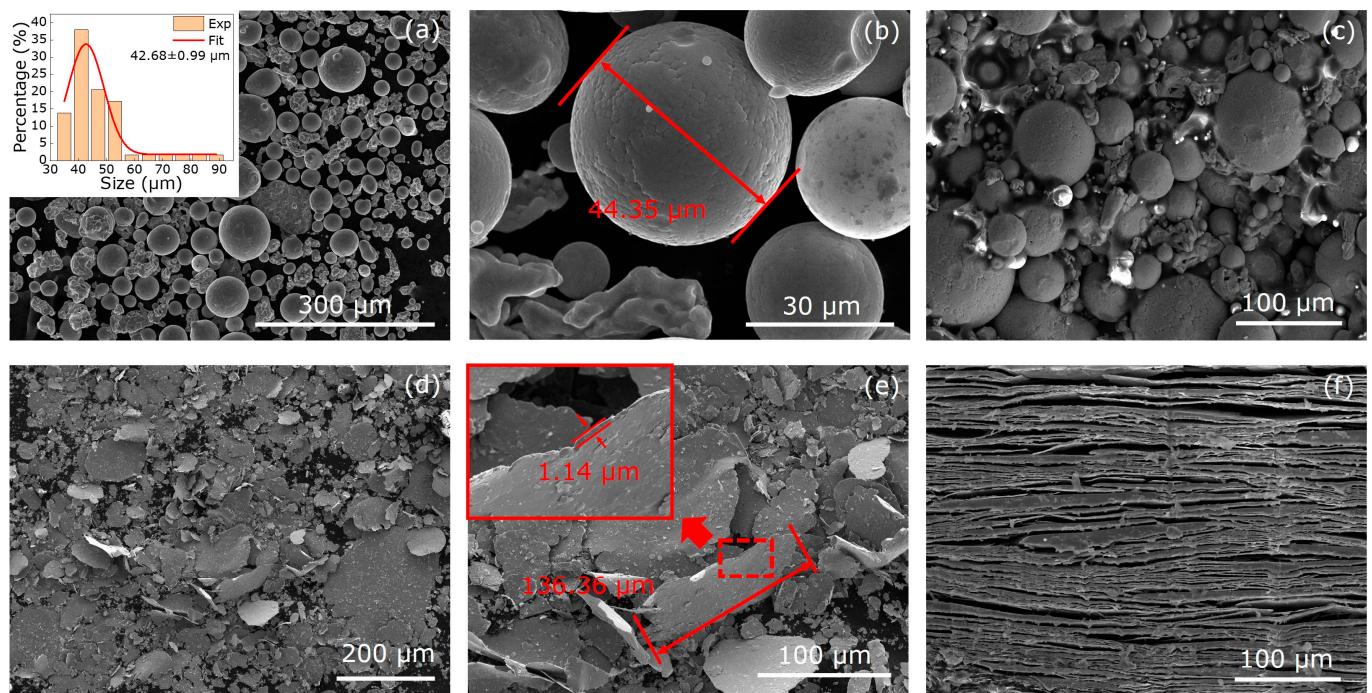


Figure 1. The SEM of the none easy-plane $\text{FeSi}_{3.5}$ particles (a,b) and the cross sections of the composite (c), the SEM of the easy-plane $\text{FeSi}_{3.5}$ particles (d,e) and the cross sections of the composite (f).

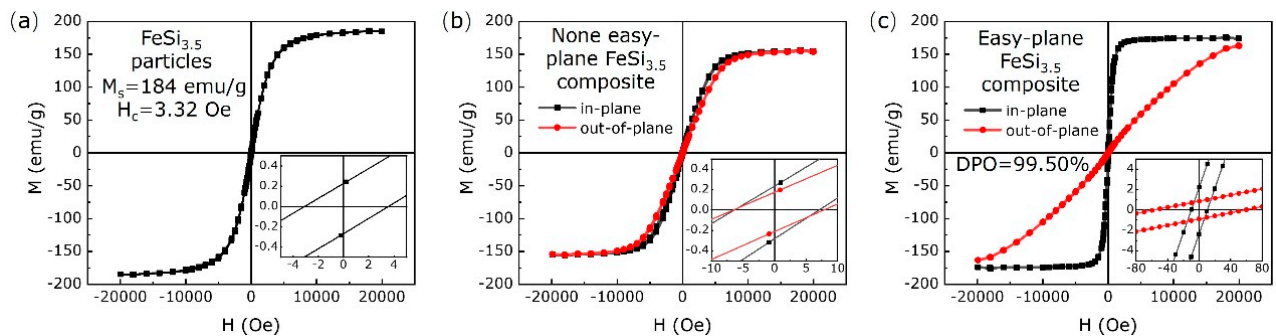


Figure 2. The hysteresis loop of $\text{FeSi}_{3.5}$ particles (a), hysteresis loops and DPO of the none easy-plane $\text{FeSi}_{3.5}$ composite (b) and easy-plane $\text{FeSi}_{3.5}$ composite (c).

Table 1. The M_s , M_r and H_c of the in-plane and out-of-plane direction and DPO of the none easy-plane $\text{FeSi}_{3.5}$ composite and easy-plane $\text{FeSi}_{3.5}$ composite.

	In-Plane			Out-of-Plane			DPO
	M_s	M_r	H_c	M_s	M_r	H_c	
None easy-plane $\text{FeSi}_{3.5}$	154.45	0.24	6.71	153.78	0.18	7.18	
Easy-Plane $\text{FeSi}_{3.5}$	173.53	2.28	10.19	163.00	0.87	57.79	99.50%

3.3. Complex Permeability and Magnetic Spectra Simulation

Figure 3 shows the magnetic spectra and spectra simulation of the none easy-plane $\text{FeSi}_{3.5}$ and the easy-plane $\text{FeSi}_{3.5}$ composite with 60 vol%. For the none easy-plane $\text{FeSi}_{3.5}$ composite, the real part of permeability is 30. It has a resonance peak at 20 MHz in the imaginary part of permeability. For the easy-plane $\text{FeSi}_{3.5}$ composite, the real part of permeability is 62. Two resonance peaks appear in the imaginary part of the permeability. The domain wall resonance peak is observed in a lower frequency (100 MHz), and the natural resonance is observed in a higher frequency (1.5 GHz). According to the domain

wall motion mechanism and spin rotation mechanism, magnetic spectra can be simulated by Equations (3) and (4) [24–28]:

$$\begin{aligned}\mu' &= \mu'_{dw} + \mu'_{spin} \\ &= \frac{\omega_{dw}^2 \chi_{dw} (\omega_{dw}^2 - \omega^2)}{(\omega_{dw}^2 - \omega^2)^2 + \omega^2 \beta^2} + \frac{\chi_{spin} \omega_{spin}^2 [(\omega_{spin}^2 - \omega^2) + \omega^2 \alpha^2]}{[\omega_{spin}^2 - \omega^2 (1 + \alpha^2)]^2 + 4\omega^2 \omega_{spin}^2 \alpha^2} + 1\end{aligned}\quad (3)$$

$$\begin{aligned}\mu'' &= \mu''_{dw} + \mu''_{spin} \\ &= \frac{\omega_{dw}^2 \chi_{dw} \omega \beta}{(\omega_{dw}^2 - \omega^2)^2 + \omega^2 \beta^2} + \frac{\chi_{spin} \omega_{spin}^2 \omega \alpha [\omega_{spin}^2 + \omega^2 (1 + \alpha^2)]}{[\omega_{spin}^2 - \omega^2 (1 + \alpha^2)]^2 + 4\omega^2 \omega_{spin}^2 \alpha^2}\end{aligned}\quad (4)$$

where μ'_{dw} and μ'_{spin} are the real part of permeability for the domain wall motion mechanism and spin rotation mechanism, and μ''_{dw} and μ''_{spin} are the imaginary part of permeability for the domain wall motion mechanism and spin rotation mechanism, respectively. ω_{dw} , χ_{dw} and β are the domain wall resonance frequency, static susceptibility and damping factor for the domain wall component. ω_{spin} , χ_{spin} and α is the resonance frequency, static susceptibility and damping factor for the spin rotation component. ω is the frequency of the applied field ($\omega = 2\pi f$). According to Equations (3) and (4), the magnetic spectra are simulated and six parameters (ω_{dw} , χ_{dw} , β , ω_{spin} , χ_{spin} , α) are obtained (Figure 3b,c and Table 2).

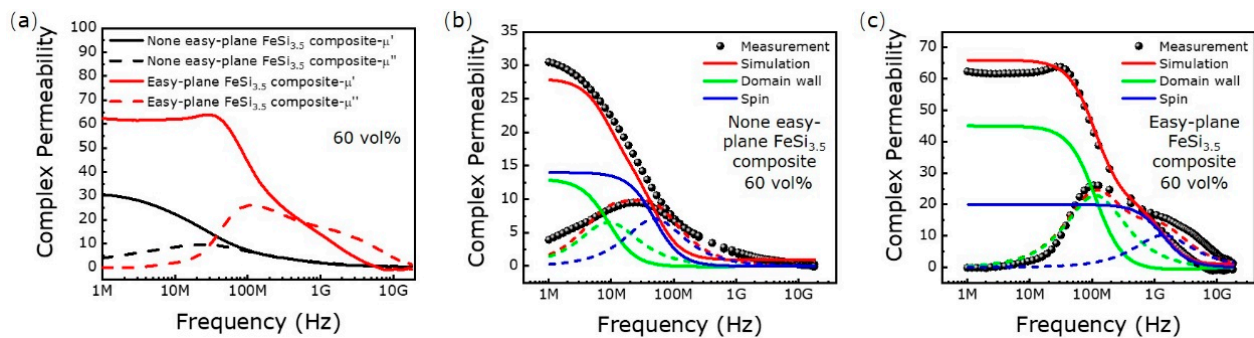


Figure 3. The complex permeability (a) and the spectra simulation of the none easy-plane FeSi_{3.5} composite (b) and the easy-plane FeSi_{3.5} composite (c) with 60 vol%.

Table 2. The six parameters in the magnetic spectra of the none easy-plane FeSi_{3.5} composite and easy-plane FeSi_{3.5} composite.

μ_i	Domain Wall Motion					Spin Rotation			
	χ_{dw}	f_{dw} (MHz)	$f_{dw}^{\mu''(\max)}$ (MHz)	β	χ_{spin}	f_{spin} (GHz)	$f_{spin}^{\mu''(\max)}$ (GHz)	α	
None easy-plane FeSi _{3.5}	28	13	120	9	1×10^{10}	14	0.35	0.05	7
Easy-Plane FeSi _{3.5}	66	45	840	100	4×10^{10}	20	7	1.5	5

The theoretical domain wall resonance frequency and natural resonance frequency of the none easy-plane FeSi_{3.5} composite are 120 MHz and 350 MHz. The real part of permeability for the domain wall component and spin rotation are 13 and 14. The theoretical domain wall resonance peak and natural resonance peak of the easy-plane FeSi_{3.5} composite are 840 MHz and 7 GHz. The real part of permeability for the domain wall component and spin rotation are 45 and 20.

3.4. Power Loss and Loss Separation

Figure 4 shows the power loss and loss separation of the none easy-plane FeSi_{3.5} composite and the easy-plane FeSi_{3.5} composite. The easy-plane FeSi_{3.5} composite exhibits a desired total loss P_{cv} of 500.42 kW/m³ under the test conditions of 8 mT and 3 MHz.

In general, the P_{cv} rapidly increases with increasing frequency, and the maximum P_{cv} of the easy-plane $\text{FeSi}_{3.5}$ composite (500.42 kW/m^3) is much lower than that of the none easy-plane $\text{FeSi}_{3.5}$ composite (2785.8 kW/m^3).

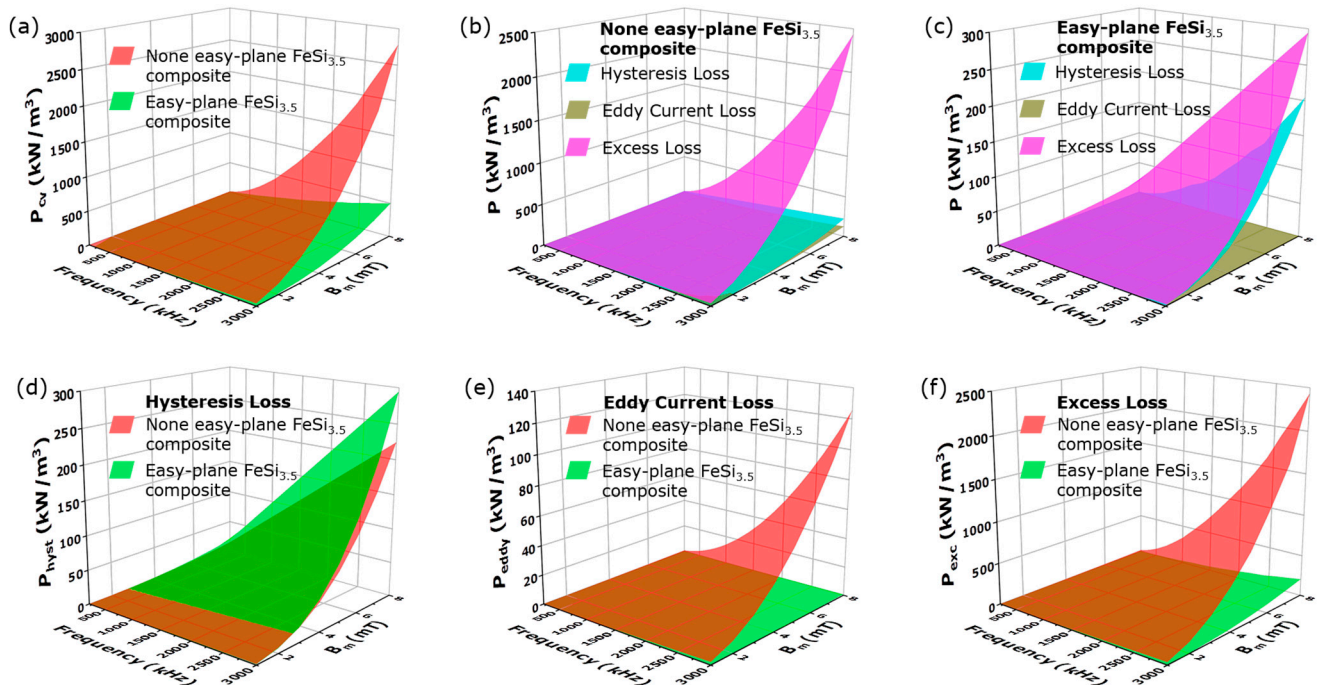


Figure 4. The total loss (a), loss separation (b,c), hysteresis loss (d), eddy current loss (e) and excess loss (f) of the none easy-plane $\text{FeSi}_{3.5}$ composite and easy-plane $\text{FeSi}_{3.5}$ composite.

According to classic Bertotti's loss separation theory, the total loss of P_{cv} can be separated into three different parts: hysteresis loss P_{hyst} , eddy current loss P_{eddy} and excess loss P_{exc} . The expression can be described [29]:

$$P_{cv} = c_{hyst} B_m^\alpha f + c_{eddy} B_m^2 f^2 + c_{exc} B_m^x f^y \quad (5)$$

where c_{hyst} and α are the coefficients of hysteresis loss, c_{eddy} is the coefficient of current eddy loss, and c_{exc} , x and y are the coefficients of excess loss. The coefficients in each term are shown in Table 3.

Table 3. Simulated parameters for loss separation of the none easy-plane $\text{FeSi}_{3.5}$ composite and easy-plane $\text{FeSi}_{3.5}$ composite.

	P_{hyst}		c_{eddy}^{inter}	P_{eddy}		P_{exc}	
	c_{hyst}	α		c_{eddy}^{intra}	c_{exc}	x	y
None easy-plane $\text{FeSi}_{3.5}$ composite	9.2463	2.43	5.14×10^{-12}	2.18×10^{-4}	4.02×10^{-4}	2.21	1.76
Easy-Plane $\text{FeSi}_{3.5}$ composite	42.897	2.69	8.18×10^{-7}	3.78×10^{-7}	4.16×10^{-6}	2.43	1.97

For the none easy-plane $\text{FeSi}_{3.5}$ composite, P_{exc} is the largest proportion of the total loss, about 2435.2 kW/m^3 (8 mT and 3 MHz), and P_{hyst} and P_{eddy} are small percentages of the total loss, about 224.79 kW/m^3 and 125.77 kW/m^3 . For the easy-plane $\text{FeSi}_{3.5}$ composite, P_{eddy} is the smallest proportion of the total loss, about 0.689 kW/m^3 , and P_{hyst} and P_{exc} are main part of total loss, about 294.8 kW/m^3 and 204.93 kW/m^3 . Although the P_{hyst} of the none easy-plane $\text{FeSi}_{3.5}$ composite is less than that of easy-plane $\text{FeSi}_{3.5}$ composite, the difference between them is only 70 kW/m^3 under the test conditions of 8 mT and 3 MHz. For the P_{eddy} and P_{exc} , the advantages of the easy-plane $\text{FeSi}_{3.5}$ composite are

shown. The P_{eddy} of the easy-plane $\text{FeSi}_{3.5}$ composite is $\frac{1}{200}$ for that of the none easy-plane $\text{FeSi}_{3.5}$ composite. The P_{exc} of the easy-plane $\text{FeSi}_{3.5}$ composite is $\frac{1}{20}$ for that of the none easy-plane $\text{FeSi}_{3.5}$ composite.

4. Discussion

The easy-plane $\text{FeSi}_{3.5}$ composite has excellent magnetic properties and loss properties at higher frequencies compared with the none easy-plane $\text{FeSi}_{3.5}$ composite. The easy-plane $\text{FeSi}_{3.5}$ composite has higher permeability and higher ferromagnetic resonance frequencies than the none easy-plane $\text{FeSi}_{3.5}$ composite, which is beneficial for reducing the excitation current, turns and achieving device miniaturization. And the P_{cv} of the easy-plane $\text{FeSi}_{3.5}$ composite (500.42 kW/m^3) is lower and about $\frac{1}{5}$ for than that of the none easy-plane $\text{FeSi}_{3.5}$ composite (2785.8 kW/m^3). It is emphasized that the easy-plane $\text{FeSi}_{3.5}$ composite has lower P_{cv} compared with the none easy-plane $\text{FeSi}_{3.5}$ composite because of the significant reduction in P_{exc} rather than the decrease of P_{eddy} . The P_{eddy} of the none easy-plane $\text{FeSi}_{3.5}$ composite and easy-plane $\text{FeSi}_{3.5}$ composite is only a small proportion of total loss (as shown in Figure 4b,c). The P_{eddy} of the none easy-plane $\text{FeSi}_{3.5}$ composite and easy-plane $\text{FeSi}_{3.5}$ composite, respectively, only accounts for 4.5% and 0.14% of the total loss at 8 mT and 3 MHz (as shown in Figure 5b,e). Both the none easy-plane $\text{FeSi}_{3.5}$ composite and easy-plane $\text{FeSi}_{3.5}$ composite have a particle size of microns, and are composite materials (high resistivity). Therefore, they have a low intra-particle eddy current loss P_{eddy}^{intra} and inter-particle eddy current loss P_{eddy}^{inter} . And the easy-plane $\text{FeSi}_{3.5}$ composite with smaller particle thickness can have a lower P_{eddy} (as shown in Figure 4e) compared with the none the easy-plane $\text{FeSi}_{3.5}$ composite. Therefore, the P_{eddy} will not become a relatively large part of the loss and a major issue at higher frequencies of SMCs.

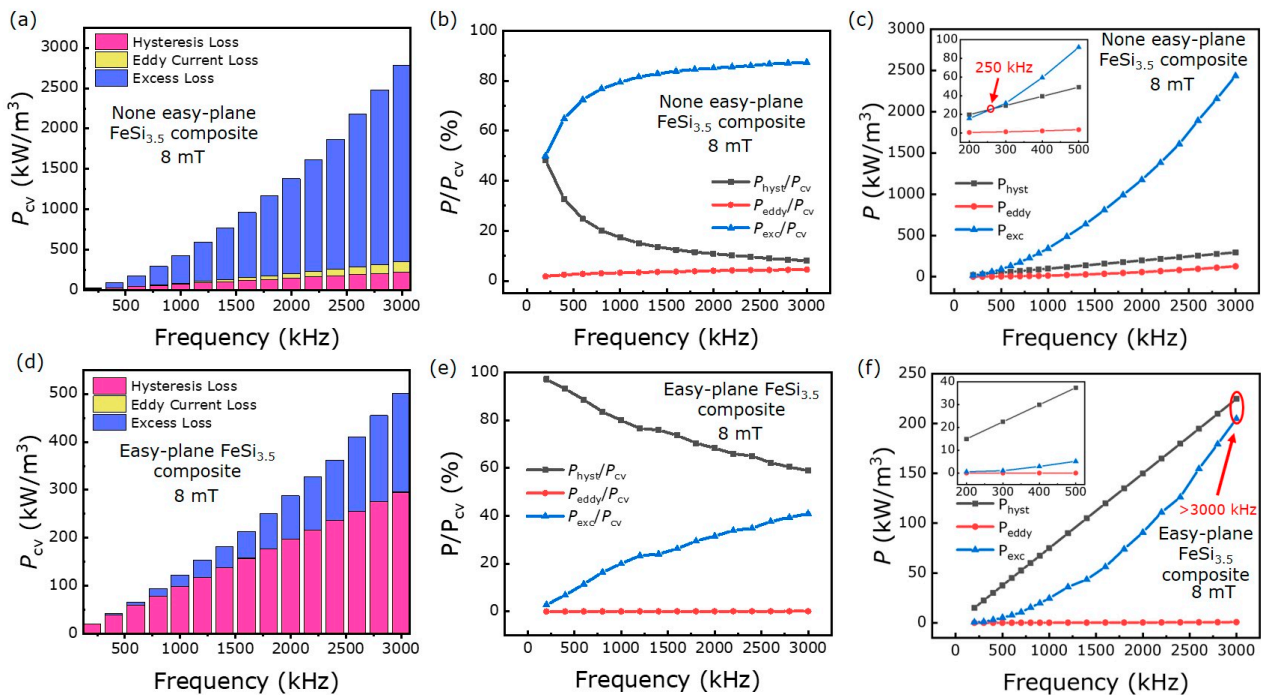


Figure 5. The percentage of loss of each part and loss separation of the none easy-plane $\text{FeSi}_{3.5}$ composite (a–c) and easy-plane $\text{FeSi}_{3.5}$ composite (d–f).

It is found that P_{exc} becomes the main loss when increasing the frequency, according to the experimental results (as shown in Figure 4b,c). The P_{exc} of none the easy-plane $\text{FeSi}_{3.5}$ composite and easy-plane composite both occupies the larger portion of the total loss, which accounts for 87.4% (2435.2 kW/m^3 : 2785.8 kW/m^3) and 40.9% (204.93 kW/m^3 : 500.42 kW/m^3) of the total loss at 8 mT and 3 MHz, respectively (as shown in Figure 5b,e).

Whether the none easy-plane FeSi_{3.5} composite or easy-plane FeSi_{3.5} composite, the P_{exc} both dramatically increases with frequency. For the none easy-plane FeSi_{3.5} composite, the P_{exc} sharply increases and becomes the main part of the total loss in the range of 200 kHz to 1200 kHz, accounting for about 80% of the total loss. For the easy-plane FeSi_{3.5} composite, the main loss is P_{hyst} at a low frequency. As the frequency increases, the P_{exc} of the easy-plane FeSi_{3.5} composite rapidly increases and becomes one of the main losses. Therefore, as the frequency increases, the dramatical increase of P_{exc} becomes a serious problem to soft magnetic materials in higher frequency applications, especially after reaching the MHz band.

Both of the none easy-plane FeSi_{3.5} composite and easy-plane FeSi_{3.5} composite can maintain a low loss at a lower frequency, but the easy-plane FeSi_{3.5} composite has an obvious advantage in the high-frequency band. For the none easy-plane FeSi_{3.5} composite, the dramatical increase in P_{exc} alongside frequency leads to a rapid increase in total loss, the P_{exc} is over P_{hyst} at 250 kHz, about 20 kW/m³; along with the rapid increase in frequency, the P_{exc} accounts for about 80% of the total loss at 1 MHz, about 342.8 kW/m³; the P_{exc} reaches about 2435.2 kW/m³ while the frequency continuously increases to 3 MHz (Figure 5c). For the easy-plane FeSi_{3.5} composite, the P_{exc} is about 0.75 kW/m³ at 250 kHz, 24.61 kW/m³ at 1 MHz and 204.93 kW/m³ at 3 MHz (Figure 5f). Compared with the none easy-plane FeSi_{3.5} composite, the P_{exc} in the easy-plane FeSi_{3.5} composite is lower. This phenomenon is possibly related to the domain wall resonance frequency, and we will continue to study this in the future. As shown in Figure 3, the domain wall resonance frequency of the easy-plane FeSi_{3.5} composite and none easy-plane FeSi_{3.5} composite is 100 MHz and 9 MHz, respectively. Due to the domain wall resonance frequency of the none easy-plane FeSi_{3.5} composite being low, the P_{exc} dramatically increases with frequency and the frequency is only 250 kHz when the P_{exc} exceeds the P_{hyst} (Figure 5c). For the easy-plane FeSi_{3.5} composite, P_{exc} still increases with frequency, but the rate of the increase of P_{exc} with frequency is lower, due to the high-domain-wall frequency, and P_{exc} exceeds the P_{hyst} only when the frequency is higher than 3 MHz (Figure 5f). The high-domain-wall resonance frequency can push the frequency point, where the excess loss dramatically increases to a higher frequency, thus the easy-plane material with a higher domain wall resonance frequency can well inhibit the increase in excess loss with frequency.

The performance factor (PF) is a parameter that describes the energy transformation efficiency and can be expressed as the product of B_m and f by Equation (1):

$$PF = B_m f \quad (6)$$

The PF is calculated by simulated parameters in Table 2. It is found that PF and total loss of the easy-plane FeSi_{3.5} composite is much more excellent than that of the none easy-plane FeSi_{3.5} composite. This indicates that the easy-plane FeSi_{3.5} composite has a higher transformation efficiency and lower loss compared with the none easy-plane FeSi_{3.5} composite, and that the easy-plane FeSi_{3.5} composite is more suitable for operating at higher frequencies. In addition, the currently published results of SMCs operating at higher frequencies are compared with those of the easy-plane FeSi_{3.5} composite. The easy-plane FeSi_{3.5} composite still has an advantage in permeability, operating frequency and transformation efficiency (as shown Figure 6b in Table 4).

Table 4. Magnetic properties and loss properties of various up-to-date published SMCs above 1 MHz.

SMCs	Initial Permeability	Power Loss	PF (under 500 kW/m ³)	
The easy-plane FeSi _{3.5} composite	62.5	500.42 kW/m ³ (3 MHz, 8 mT)	23.96	This work
Amorphous FeSiCr + carbonyl iron @ resin	37	560 kW/m ³ (1 MHz, 20 mT)	16	[19]

Table 4. Cont.

SMCs	Initial Permeability	Power Loss	PF (under 500 kW/m ³)	
Amorphous Fe ₇₃ Si ₆ B ₁₀ P ₅ C ₃ Mo ₃ @ epoxy resin	34.63	~500 kW/m ³ (1 MHz, 20 mT)	20	[21]
Amorphous FeSiCr/phosphating process and polyimide coating	47.5	7086 kW/m ³ (1 MHz, 50 mT)	5	[20]
Flake pure iron @ binder composite	67 (at 1 MHz)	306.6 kW/m ³ (1 MHz, 3 mT)	~5	[22]
	10 (at 3.5 MHz)	3.285 kW/m ³ (3.5 MHz, 0.1 mT)	~15	

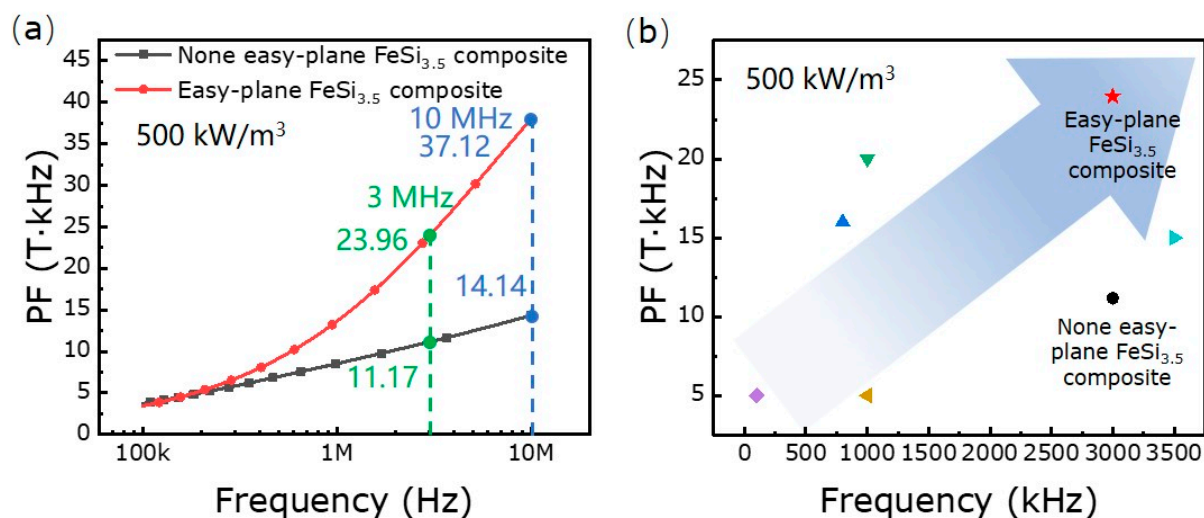


Figure 6. The PF calculate curve of the none easy-plane FeSi_{3.5} composite and the easy-plane FeSi_{3.5} composite at 500 kW/m³ (a). The PF of different SMCs at 500 kW/m³ (b) [19–22].

5. Conclusions

The easy-plane FeSi_{3.5} composite has an ultra-low loss at 10 MHz, 4mT (372.88 kW/m³). The reason for the ultra-low loss of the easy-plane FeSi_{3.5} composite at higher frequencies is because of setting up a control group (the none easy-plane FeSi_{3.5} composite). For the first time, we found that the root cause of the failure in soft magnetic composites to work properly at higher frequencies was due to the dramatic increase in the P_{exc} . The rate of increase and the percentage of the P_{exc} is much larger than that of the P_{hyst} and the P_{eddy} . The P_{exc} accounts for a large portion of the P_{cv} ; the portion continues to sharply increase with frequency, and conventional loss reduction methods have no effect on the P_{exc} . In addition, we also found that the easy-plane composite can effectively reduce the P_{exc} . Compared with the none easy-plane composite, the easy-plane composite can greatly reduce P_{exc} from 2435.2 kW/m³ to 204.93 kW/m³. This substantial reduction can greatly reduce the P_{cv} . And the easy-plane composite also has excellent magnetic properties, high permeability and ferromagnetic resonance frequencies. Thus, the easy-plane composite has strong potential to be applied for inductor and transformer cores at higher frequencies, especially at the MHz band and above.

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