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Optimizing High-Frequency Performance of Carbonyl Iron Powder-Based Soft Magnetic Composites via Magnesium Dihydrogen Phosphate Insulation Coating

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Abstract

Carbonyl iron powder (CIP)-based soft magnetic composites (SMCs) are promising for high-frequency power electronics due to their high saturation magnetization and cost-effectiveness. However, their high eddy current loss at elevated frequencies necessitates effective inter-particle insulation. This study systematically investigates the insulating coating validity of magnesium dihydrogen phosphate $\text{Mg}(\text{H}_2\text{PO}_4)_2$ for CIP. The results demonstrate that $\text{Mg}(\text{H}_2\text{PO}_4)_2$ facilitates the formation of a uniform and dense composite insulating layer on the CIP surface without altering its body characteristics. The optimal performance was achieved with a coating content of 0.15 wt.% and an annealing temperature of 500 °C. Under these conditions, the composite exhibited a balanced combination of high initial permeability (44.1 at 1 MHz), high cut-off frequency (236.1 MHz), low power loss (552.4 kW/m³ at 1 MHz, 20 mT), and minimal coercivity (10.1 A/m). The insulation layer effectively suppressed eddy current losses, which were reduced to 30% of the total loss compared to 64.7% in the uncoated sample. This work provides a viable strategy for developing high-performance CIP-based SMCs suitable for high-frequency applications.

Keywords:

Soft magnetic composite; Carbonyl iron powder; Magnesium dihydrogen phosphate; Insulation coating; High frequency

1. Introduction

The relentless pursuit of miniaturization and higher power density in modern electronic devices, driven by advancements in 5G communications, electric vehicles, and high-frequency switching power supplies, imposes increasingly stringent demands on soft magnetic materials [1-6]. Ideal core materials for these applications must simultaneously exhibit high saturation magnetization, high permeability, low coercivity, and minimal losses at high operating frequencies [7-10]. Traditional options face inherent limitations: metallic soft magnets (e.g., silicon steel, FeSiAl, FeNi etc.,) suffer from excessive eddy current loss at high frequencies due to low resistivity, while soft ferrites, despite their high resistivity, are constrained by low saturation magnetization ($\sim 0.3\text{-}0.5\text{ T}$), hindering further device miniaturization [11-15].

Soft magnetic composites (SMCs) present a promising solution by combining insulated magnetic powder particles into a bulk material, thereby integrating the high saturation of metals with the high resistivity of ceramics [16-20]. Among various magnetic particles, carbonyl iron powder (CIP) is particularly attractive due to its high saturation magnetization ($\sim 2.1\text{ T}$), excellent sphericity, and narrow particle size distribution [21-24]. The performance of CIP-based SMCs at high frequencies critically depends on the quality of the inter-particle insulating layer, which is essential to block eddy current paths [25-28].

While various insulating coatings, including phosphates, oxides, and organic resins, have been explored [29-35], magnesium dihydrogen phosphate $\text{Mg}(\text{H}_2\text{PO}_4)_2$ stands out for its high thermal stability, excellent resistivity, strong adhesion to metals, and cost-effective processing [36-38]. However, the synergistic effects between coating content and post-annealing temperature on the microstructure and magnetic properties of $\text{Mg}(\text{H}_2\text{PO}_4)_2$ -coated SMCs is insufficiently understood [37, 39]. Therefore, this work aims to systematically investigate the fabrication and performance of CIP-based SMCs using $\text{Mg}(\text{H}_2\text{PO}_4)_2$ as the insulating agent and silicone resin as the binder. The effects of the $\text{Mg}(\text{H}_2\text{PO}_4)_2$ coating content (0-0.30 wt.%) and annealing temperature (400-600 °C) on the microstructure, phase composition, and high-frequency magnetic properties (complex permeability, core loss, and coercivity) are thoroughly examined.

The primary goal is to elucidate the underlying mechanisms governing property regulation and to identify the optimal processing window that balances permeability and loss for high-frequency applications, thereby providing valuable insights for the development of advanced SMCs.

2. Experimental

Materials preparation: The CIP was provided by BASF Corporation. $\text{Mg}(\text{H}_2\text{PO}_4)_2$ (98% purity) was obtained from Guangdong Yuanfeng Chemical Reagent Co., Ltd. Silicone resin (SH-9602) was purchased from Hubei LongSheng Sihai New Materials Co., Ltd., and zinc stearate (99.9% purity) was supplied by Shanghai Macklin Biochemical Co., Ltd. Fig. 1 shows the process diagram for synthesizing the CIP-based soft magnetic composite. A specific mass of CIP was mixed and stirred with $\text{Mg}(\text{H}_2\text{PO}_4)_2$ solutions at contents of 0-0.30 wt.%. The resulting phosphate powder was placed on a heating platform and dried at 80 °C to remove excess acetone solvent. The phosphate powder was uniformly mixed with 1 wt.% silicone resin-acetone solution and dried at 80 °C to ensure the evenly coating of silicone resin on powder particles[40]. Zinc stearate was mixed with the dried powder until thoroughly blended to reduce wear between powder and mold during pressing. The toroidal samples were prepared in the size of $\Phi 12.7 \text{ mm} \times 7.6 \text{ mm}$ and under the pressure of 1200 MPa. The green compacts were annealed in N_2 protective atmosphere at temperatures of 400-600 °C for 1 hour.

Characterization: X-ray diffraction (XRD, Rigaku SmartLab SE from Japan) was employed to obtain the crystal structure and phase composition. The surface morphology of iron powder was observed using scanning electron microscopy (SEM, ZEISS Sigma 360 from Germany). An X-ray energy dispersive spectrometer (EDS, ZEISS Sigma 360 from Germany) enabled qualitative and semi-quantitative elemental analysis by capturing characteristic X-rays emitted during interactions between the electron beam and the sample. The magnetic permeability of the toroidal samples was measured using an impedance analyzer (Agilent E4991B) with a 16454 fixture. The power loss and AC hysteresis loop were measured using a B-H analyzer (Iwatsu SY8218). This article uses the classic Bertotti loss separation model to separate power loss and explores the changes in hysteresis loss and eddy current loss [41].

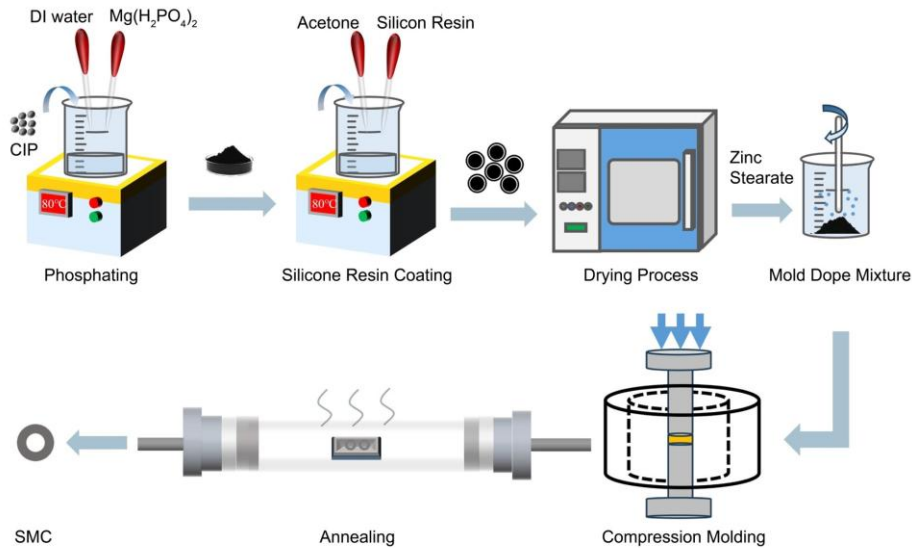


Fig. 1. Experimental procedure to prepare CIP-based SMC in this work.

3. Results and discussion

Fig. 2 presents the SEM images of CIP treated with varying contents of $\text{Mg}(\text{H}_2\text{PO}_4)_2$. The uncoated, raw CIP (Fig. 2a) displays a regular spherical morphology characterized by a smooth and clean surface without noticeable impurities; its excellent sphericity promotes close particle packing, which contributes to enhanced material density [10]. Following the $\text{Mg}(\text{H}_2\text{PO}_4)_2$ coating process (Fig. 2b–f), the surfaces of CIP powder become distinctly rough and are covered with granular deposits. As the coating content increases, the density of these surface deposits progressively rises. At a coating content of 0.10 wt.% (Fig. 2b), only sparse and fine particles are distributed across the powder surface, resulting in a discontinuous and incomplete insulating layer. At 0.15 wt.% (Fig. 2c), a uniform and densely packed coating forms, covering the powder surface thoroughly with no significant areas of exposure, thereby indicating good insulation integrity. When the content is further increased to 0.20 wt.% (Fig. 2d), 0.25 wt.% (Fig. 2e), and 0.30 wt.% (Fig. 2f), the surface deposits begin to aggregate into larger, lumpy protrusions, and slight inter-particle agglomeration becomes apparent. This phenomenon stems from the excessive accumulation of $\text{Mg}(\text{H}_2\text{PO}_4)_2$ on the powder surface, which leads to an uneven thickness of the insulating layer. Such agglomeration can adversely affect the flowability of the powder in subsequent forming stages and may introduce voids within the compacted material, ultimately reducing its

overall density. These observations underscore that the coating content must be carefully controlled and maintained within an optimal range to ensure the formation of a uniform insulating layer without compromising microstructural homogeneity.

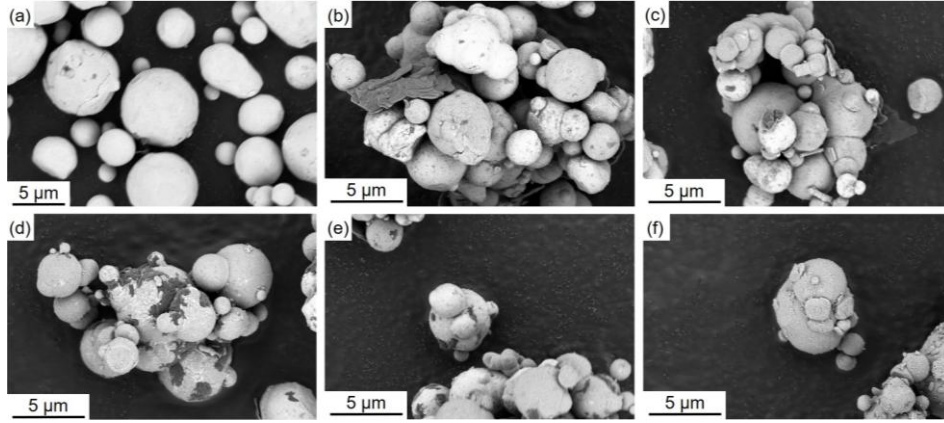


Fig. 2. SEM images of (a) raw CIP and CIPs coated with different contents of $\text{Mg}(\text{H}_2\text{PO}_4)_2$: (b) 0.10 wt.%, (c) 0.15 wt.%, (d) 0.20 wt.%, (e) 0.25 wt.%, (f) 0.30 wt.%.

Fig. 3 shows the XRD patterns of SMCs prepared with different coating contents and annealing temperatures. As shown in Fig. 3a, all tested samples exhibit distinct characteristic diffraction peaks at 44.7° , 65.0° , and 82.3° . Comparison with the standard PDF card (PDF#06-0696) confirms that these peaks correspond to the (110), (200), and (211) crystal planes of body-centered cubic (bcc) iron, with a lattice constant of $2.8664 \text{ \AA}$. The XRD patterns of samples with different coating contents showed no diffraction peaks corresponding to $\text{Mg}(\text{H}_2\text{PO}_4)_2$ or other impurity phases. This indicates that the $\text{Mg}(\text{H}_2\text{PO}_4)_2$ coating forms only a thin insulating layer on the iron powder surface without undergoing chemical reactions to form new phases or altering the original crystal structure of the iron powder [42]. Fig. 3b shows the XRD patterns of the samples with a 0.15 wt.% coating content after annealing at different temperatures. All annealed samples retained the bcc structure of elemental Fe, with no significant shift in diffraction peak positions and no appearance of diffraction peaks from oxide phases such as FeO or Fe_2O_3 . This indicates that the nitrogen atmosphere effectively suppressed oxidation of the iron powder during annealing. As the annealing temperature increased, the diffraction peak intensities slightly enhanced, indicating that the annealing treatment promoted grain refinement and lattice defect repair in the iron

powder. This facilitates the reduction of internal stresses within the material and improves its magnetic properties.

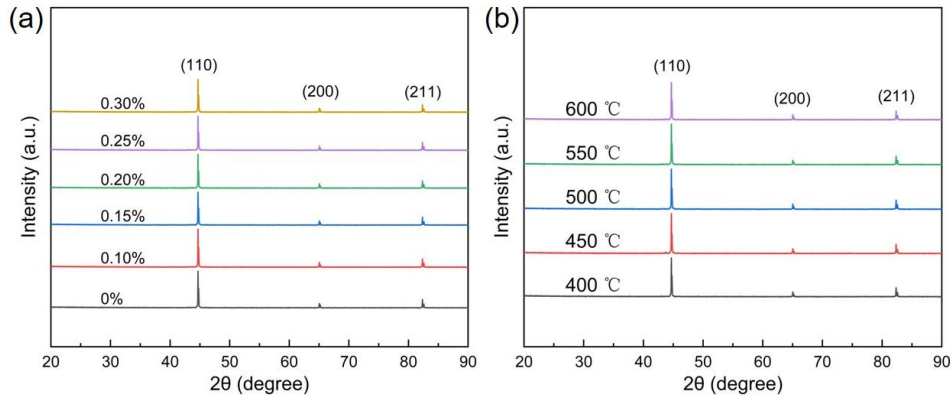


Fig. 3. XRD of CIPs with different (a) coating contents, and (b) annealing temperatures.

Fig. 4 shows the SEM morphology and corresponding EDS elemental distribution maps of a polished surface of the SMCs coated with 0.15 wt.% $\text{Mg}(\text{H}_2\text{PO}_4)_2$ and silicone resin following annealing at 500 °C. As observed in the figure, iron (Fe), serving as the matrix element, is uniformly distributed within the core region of the particles. In contrast, oxygen (O), silicon (Si), phosphorus (P), and magnesium (Mg) are all homogeneously dispersed across the particle surfaces, collectively forming a continuous, element-enriched layer. This spatial distribution provides direct evidence for the successful formation of a composite insulating layer on the iron powder surface through the combined application of $\text{Mg}(\text{H}_2\text{PO}_4)_2$ and silicone resin. More specifically, the signals of P and Mg originate from $\text{Mg}(\text{H}_2\text{PO}_4)_2$ coating, Si is derived from the silicone resin binder, while O is contributed by both the phosphate compound and the cured resin. The observed uniformity in the distribution of these key elements further indicates that the preparation process employed for fabricating the insulating layer is both stable and reliable, ensuring consistent coverage and compositional homogeneity across the coated powder particles.

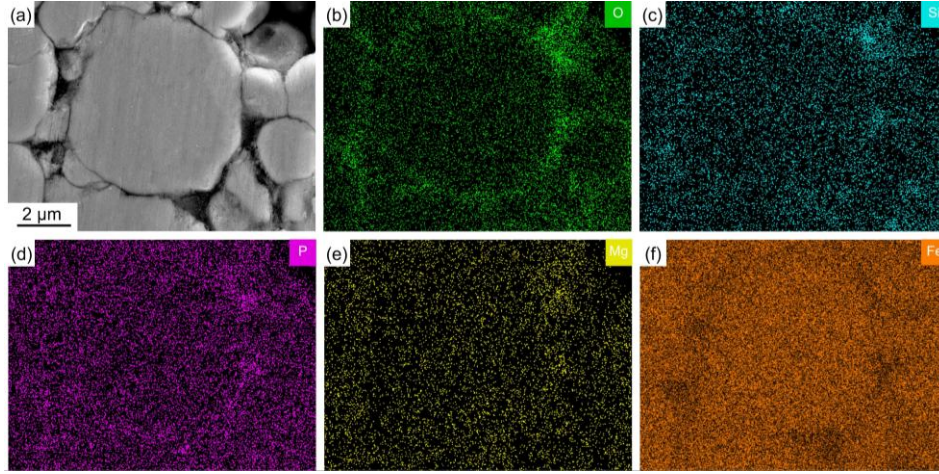


Fig. 4. SEM and EDS images of the polished surface of SMC-coated $\text{Mg}(\text{H}_2\text{PO}_4)_2$ (taking 0.15% annealing at 500 °C as an example): (a) secondary electron (SE) image, (b) O, (c) Si, (d) P, (e) Mg, (f) Fe.

To further verify the distribution of Fe, O, Si, P, and Mg elements across the cross-section, EDS elemental mapping was performed on a cross-section of the $\text{Mg}(\text{H}_2\text{PO}_4)_2$ -coated SMCs. As shown in Fig. 5, Fe is concentrated in the core region of the particles, while O, Si, P, and Mg form a continuous insulating layer covering the particle surfaces and inter-particle regions. This insulating layer effectively disrupts the conductive pathways between particles, increasing the overall resistivity of the material and thereby suppressing eddy current losses at high frequencies. Furthermore, the inter-particle insulating layer reduces magnetic domain coupling, enhancing the stability of the material's high-frequency magnetic properties [43].

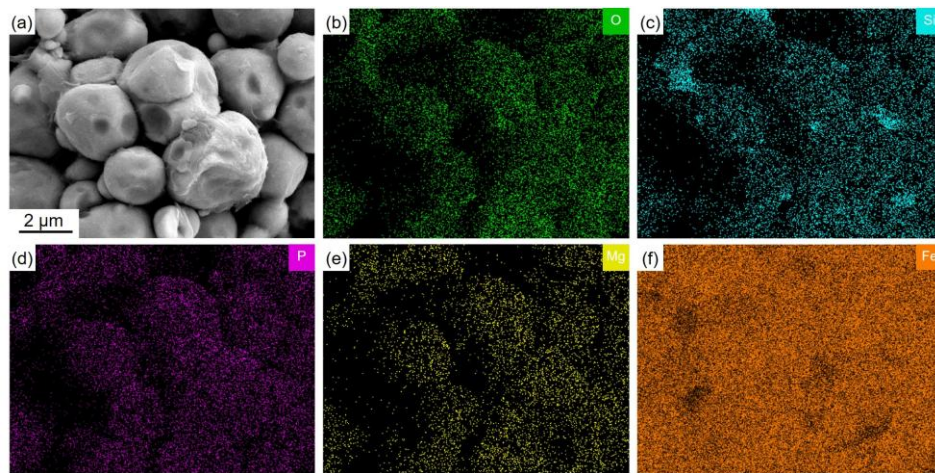


Fig. 5. SEM and EDS images of the cross-section of SMC-coated $\text{Mg}(\text{H}_2\text{PO}_4)_2$ (taking 0.15% annealing at 500 °C as an example): (a) secondary electron (SE) image, (b) O, (c) Si, (d) P, (e)

Mg, (f) Fe.

Fig. 6 shows the permeability spectra of SMCs with different $\text{Mg}(\text{H}_2\text{PO}_4)_2$ contents. As seen in Fig. 6a, the low-frequency μ' decreases with frequency for all samples, reflecting typical high-frequency behavior dominated by domain wall resonance and eddy current loss[44, 45]. Initial permeability (Fig. 6c) declines monotonically with coating content: from 54.3 (0 wt.%) to 47.7 (0.10 wt.%), 44.1 (0.15 wt.%), and 32.1 (0.30 wt.%). This reduction results from magnetic dilution by the non-magnetic coating and increased inter-particle magnetic resistance. The cut-off frequency (Fig. 6d), determined from the frequency where μ' decreasing to half its initial value and the maximum value of μ'' (Fig. 6b), increases markedly with coating content: from 59.3 MHz (0 wt.%) to 236.1 MHz (0.15 wt.%) and 381.7 MHz (0.30 wt.%). This improvement is attributed to the insulating layer enhancing resistivity, suppressing eddy currents, and extending high-frequency performance. Overall, the 0.15 wt.% sample achieves a favorable balance between initial permeability and cut-off frequency, offering both moderate permeability and good high-frequency stability.

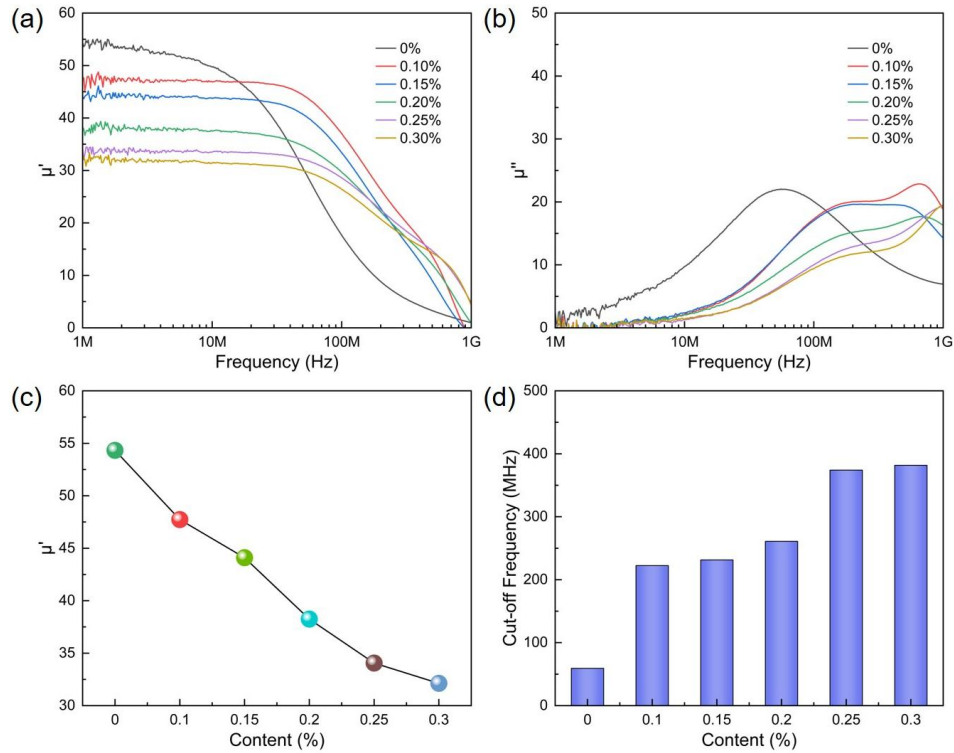


Fig. 6. Permeability characteristics of SMCs coated with different contents of $\text{Mg}(\text{H}_2\text{PO}_4)_2$: (a) real part (μ'), (b) imaginary part (μ''), (c) initial permeability, (d) cut-off frequency.

Fig. 7 shows the power loss curves for SMCs coated with different contents of $\text{Mg}(\text{H}_2\text{PO}_4)_2$. As shown in Fig. 7a, the power loss of all samples increases with frequency. This is because eddy current losses are approximately proportional to the square of the frequency, while hysteresis losses are proportional to frequency itself. The uncoated sample showed the highest power loss across all frequencies (1055.3 kW/m^3 at 1 MHz). As coating content increased, loss first decreased then increased, with the 0.15 wt.% sample achieving the lowest loss (552.4 kW/m^3 , a 47.7% reduction). Below 0.15 wt.%, the discontinuous insulating layer allowed conductive pathways and high eddy current loss; above 0.15 wt.%, excessive thickness or agglomeration reduced density, increased porosity, and raised hysteresis loss. Loss separation at 1 MHz and 20 mT (Fig. 7b) shows that eddy current loss accounted for 64.7% of total loss in the uncoated sample, but only 30% in the 0.15 wt.% sample (hysteresis loss 70%). This confirms that the $\text{Mg}(\text{H}_2\text{PO}_4)_2$ insulating layer effectively suppresses eddy current loss, which is key to reducing total power loss.

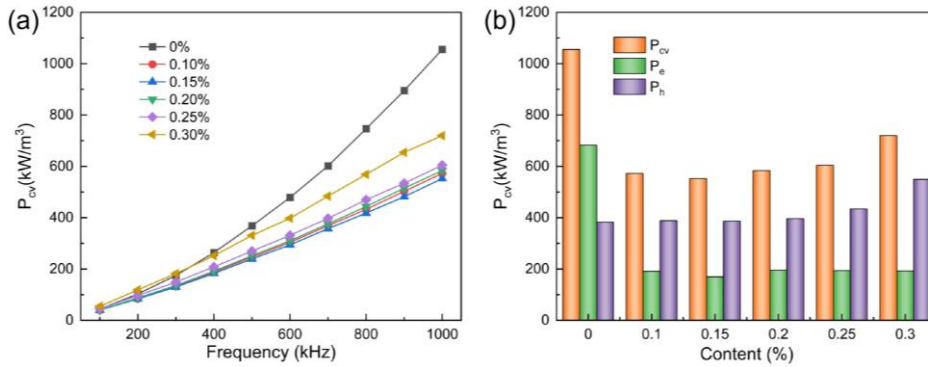


Fig. 7. Loss characteristics of SMCs coated with different contents of $\text{Mg}(\text{H}_2\text{PO}_4)_2$: (a) loss diagram at 20 mT, (b) loss and loss separation at 1 MHz and 20 mT.

Fig. 8 shows the magnetic properties of SMCs coated with different contents of $\text{Mg}(\text{H}_2\text{PO}_4)_2$. The AC hysteresis loops in Fig. 8a reveal that the sample with a 0.15 wt.% coating content exhibits the narrowest loop, indicating the lowest hysteresis loss. In contrast, the uncoated sample and the samples with high coating contents display wider hysteresis loops, indicating higher hysteresis losses. Coercivity (Fig. 8b) first decreases and then increases with increasing coating content: the 0 wt.% sample exhibits a coercivity of 16.5 A/m, the 0.15 wt.% sample drops to a minimum of 10.1 A/m, and the 0.30 wt.% sample rises to 12.9 A/m. This variation in coercivity is closely related to the

quality of the insulating layer and the internal stress within the material. An appropriate coating content (0.15 wt.%) forms a uniform and dense insulating layer, which reduces inter-particle friction and stress transfer, thereby lowering internal stress. Additionally, the insulating layer impedes domain wall movement and reduces magnetic domain coupling, contributing to the decrease in coercivity. Insufficient coating leads to direct particle contact and higher stress, while excess coating causes agglomeration, increased porosity, and greater resistance to domain wall motion, raising coercivity.

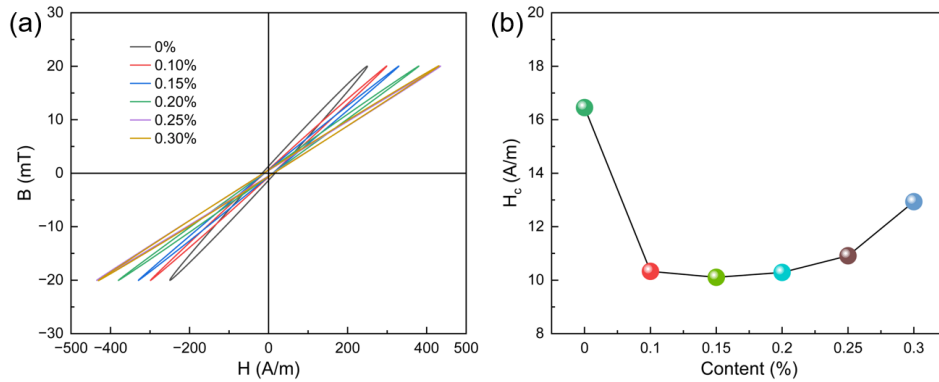


Fig. 8. Magnetic properties of SMCs coated with different contents of $\text{Mg}(\text{H}_2\text{PO}_4)_2$ at 1 MHz and 20 mT: (a) AC hysteresis loops, (b) coercivity.

Based on the above experimental results, the sample with a coating content of 0.15 wt.% was selected for further investigation into the effect of annealing temperature on magnetic properties. The results are shown in Fig. 9. The real permeability spectra in Fig. 9a reveal that as the annealing temperature increases, the μ' in the low-frequency range gradually rises, while its decay rate in the high-frequency range progressively accelerates. The low-frequency μ' of the sample annealed at 400 °C is 40.8, which increases to 44.1 for the 500 °C sample and further rises to 52.8 for the 600 °C sample. However, the cut-off frequency exhibits an opposite trend: the sample annealed at 400 °C has a cut-off frequency of 266.3 MHz, which decreases to 236.1 MHz for the 500 °C sample and drops further to 110.4 MHz for the 600 °C sample. The initial permeability data in Fig. 9c show a monotonically increasing trend with annealing temperature. This occurs because elevated annealing temperatures gradually release internal stresses within the material, repair lattice defects, reduce resistance to domain wall movement, and thereby enhance permeability. According to the cut-off frequency in Fig. 9, it can

be concluded that the cut-off frequency exhibits a monotonically decreasing trend with increasing annealing temperature. This is attributed to the potential slight decomposition of the insulating layer at high annealing temperatures, which lowers resistivity, increases eddy current losses, and accelerates the decay of permeability at high frequencies.

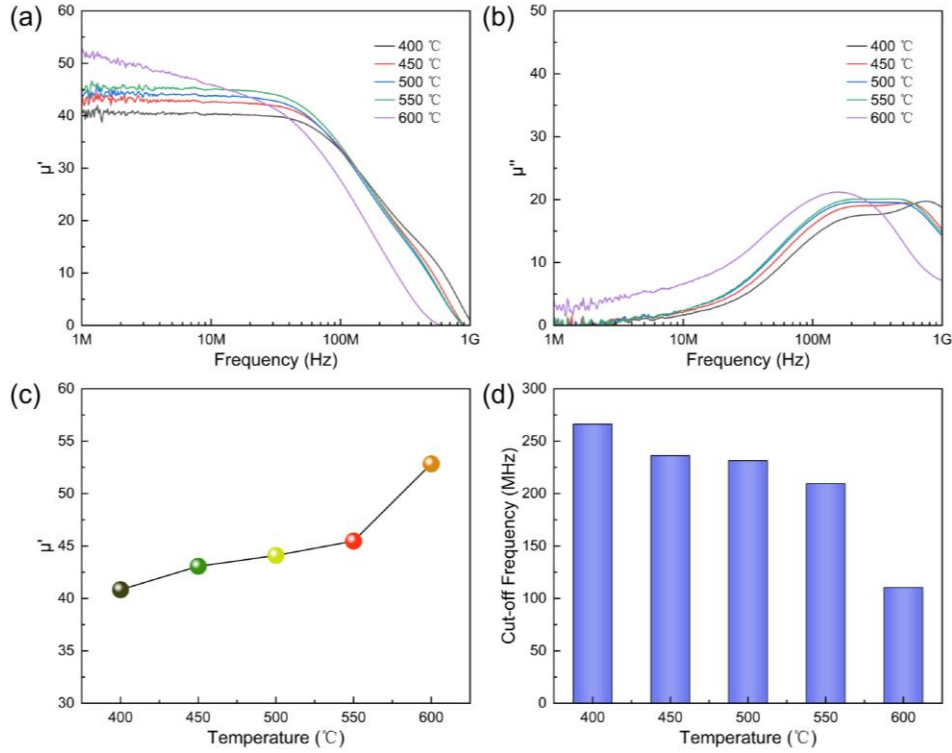


Fig. 9. Permeability characteristics of SMCs annealed at different temperatures: (a) real part (μ'), (b) imaginary part (μ''), (c) initial permeability, (d) cut-off frequency.

Fig. 10 shows the power loss curves of SMCs with 0.15 wt.% $\text{Mg}(\text{H}_2\text{PO}_4)_2$ under different annealing temperatures. As seen in Fig. 10a, power loss increases with frequency, and the annealing temperature significantly influences the loss magnitude. At 1 MHz, power loss first decreases and then increases with temperature: from 663.2 kW/m^3 (400 °C) to a minimum of 552.4 kW/m^3 (500 °C), followed by a sharp rise to 1163.7 kW/m^3 (600 °C). This non-monotonic trend stems from competing mechanisms. At 400 °C, insufficient stress relief results in high hysteresis loss. Optimal annealing at 500 °C balances stress relief with insulating layer integrity, minimizing total loss. Conversely, annealing at 600 °C degrades the insulating layer, reducing resistivity and triggering a significant increase in eddy current loss. Loss separation at 1 MHz and 20

mT (Fig. 10b) confirms this, showing that eddy current loss accounts for 57.5% of the total loss at 600 °C, compared to only 30.7% at 500 °C. These results confirm that high-temperature annealing deteriorates the insulating layer, making eddy current loss the dominant contributor to the increased power loss.

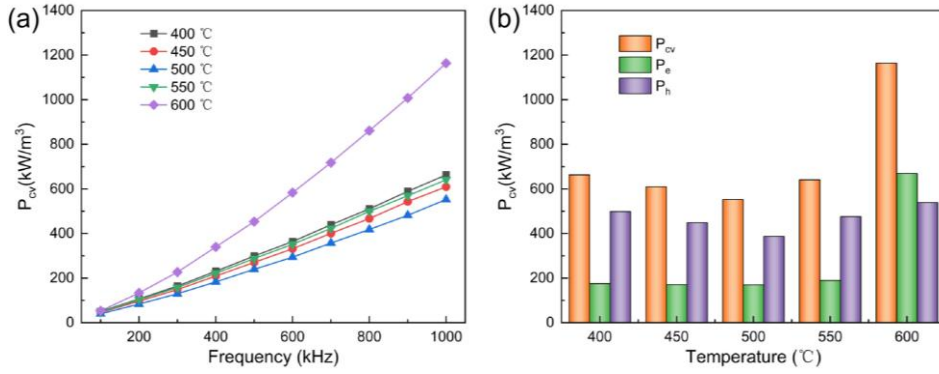


Fig. 10. Loss characteristics of SMCs annealed at different temperatures: (a) loss diagram at 20 mT, (b) loss and loss separation at 1 MHz and 20 mT.

The coercivity data in Fig. 11b reveal that coercivity first decreases and then increases with rising annealing temperature. This variation in coercivity is closely related to internal stress relief and the state of the insulating layer. At 500 °C, internal stresses are fully relieved, resulting in minimal resistance to domain wall movement and the lowest coercivity. At 600 °C, degradation of the insulating layer leads to direct interparticle contact, re-introducing internal stresses. At 600 °C, the phosphate coating may degrade or densify, which could impair its insulating properties and may be accompanied by slight surface oxidation, thereby leading to a sharp increase in coercivity. These results further confirm that 500 °C is the optimal annealing temperature for this sample. At this temperature, internal stresses are fully relieved, the insulating layer remains intact, coercivity is minimized, and the magnetic properties are optimized.

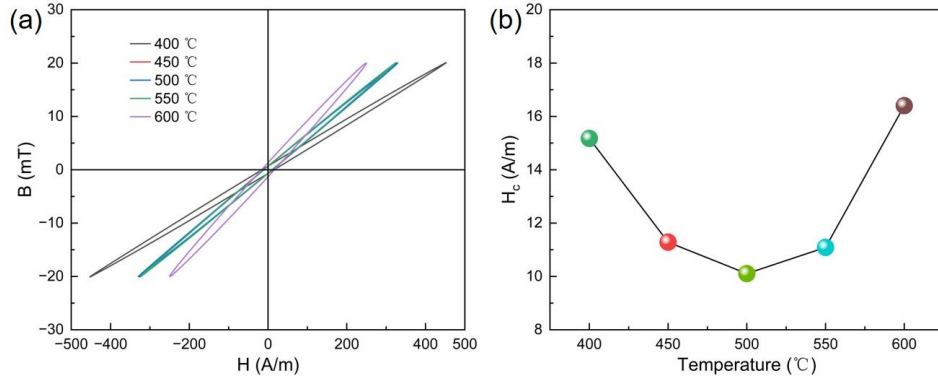


Fig. 11. Magnetic properties of SMCs annealed at different temperatures at 1 MHz and 20 mT: (a) AC hysteresis loops, (b) coercivity.

In summary, optimal magnetic properties of CIP-based SMCs are achieved with 0.15 wt.% $\text{Mg}(\text{H}_2\text{PO}_4)_2$ coating and annealing at 500 °C. The coating content governs performance via magnetic dilution and insulating layer integrity. Suboptimal coatings (<0.15 wt.%) are discontinuous, leaving conductive pathways that elevate eddy current loss. Excessive coatings (>0.15 wt.%) aggravate magnetic dilution and reduce density through agglomeration, increasing hysteresis loss. The 0.15 wt.% coating strikes a balance, forming a uniform layer that ensures high permeability and high-frequency stability. Annealing temperature modulates internal stress and coating stability. Temperatures below 500 °C provide insufficient stress relief, raising hysteresis loss, while temperatures above 500 °C degrade the insulating layer, reducing resistivity and triggering a surge in eddy current loss. Furthermore, high-temperature oxidation of iron particles may disrupt domain structures. Thus, 500 °C annealing optimally relieves stress and preserves coating functionality, yielding minimal core loss and superior overall magnetic performance.

4. Conclusion

$\text{Mg}(\text{H}_2\text{PO}_4)_2$ forms a uniform, dense insulating layer on the surface of SMCs, which increases the resistivity and suppresses eddy current losses without altering its bcc structure. As the coating content increases, the initial magnetic permeability decreases monotonically whilst the cut-off frequency increases monotonically; conversely, power loss and coercivity first decrease and then increase. As the annealing temperature rises, the initial magnetic permeability increases and the cut-off frequency

decreases, whilst power loss and coercivity similarly decrease initially and then increase. Optimal comprehensive magnetic properties are achieved under conditions of 0.15 wt.% coating and 500 °C annealing: initial magnetic permeability of 44.1 (1 MHz and 20 mT), cut-off frequency of 236.1 MHz, power loss of 552.4 kW/m³, and coercive force of 10.1 A/m, meeting the requirements for high-frequency power electronic devices.

Author's contribution

Shuang Guo: Conceptualization, Yanbing Ren: Methodology. Zhe Yue: Disposal data. Wei Zhou: Investigation. Chang Jiang: Validation. Xiuyuan Fan: Supervision. Yuchen Mao: supervision; Guohua Bai: funding acquisition and editing.

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Availability of data and materials

The corresponding author will provide data and materials supporting the present results upon reasonable request.

Declarations

Conflict of interest The authors declare no competing financial interest.

Ethical Approval There are no ethical implications in this study.

References

1. R Bures, M Strecková, M Fáberová, P Kollár, J Füszer, Advances in powder metallurgy soft magnetic composite materials, Arch. Metall. Mater. **62**(2),1149 (2017).<https://doi.org/10.1515/amm-2017-0168>
2. BR Rodriguez-Vargas, G Stornelli, P Folgarait, MR Ridolfi, AFM Pérez, A Di Schino, Recent advances in additive manufacturing of soft magnetic materials: a review, Materials **16**(16),33 (2023).<https://doi.org/10.3390/ma16165610>
3. S Wu, CM Hamel, QJ Ze, FY Yang, HJ Qi, RK Zhao, Evolutionary algorithm-guided voxel-encoding printing of functional hard-magnetic soft active materials, Adv. Intell. Syst. **2**(8),10 (2020).<https://doi.org/10.1002/aisy.202000060>

4. ZY Xiang, XL Xia, B Ducharne, YJ Ye, J Shang, RW Li, Magneto-X effects in magnetic soft materials and their applications, *Adv. Sci.*,29 (2026).<https://doi.org/10.1002/advs.202523234>
5. Z Bircáková, J Füzér, P Kollár, et al., Preparation and characterization of iron-based soft magnetic composites with resin bonded nano-ferrite insulation, *J. Alloy. Compd.* **828**,8 (2020).<https://doi.org/10.1016/j.jallcom.2020.154416>
6. YF Cai, L Xie, GJ Lu, et al., Multi-scale structural heterogeneity driving magnetic softness in relaxed Fe₈₂Si₂B₁₆ amorphous alloys: Pathways to enhanced AC permeability, *J. Alloy. Compd.* **1050**,11 (2026).<https://doi.org/10.1016/j.jallcom.2025.185585>
7. QY Deng, HG Li, HJ Zhu, et al., Spatiotemporal modulation of magnetization in magnetic soft materials, *Adv. Mater.* **37**(48),29 (2025).<https://doi.org/10.1002/adma.202506342>
8. S Elfgen, S Steentjes, S Böhmer, D Franck, K Hameyer, Continuous local material model for cut edge effects in soft magnetic materials, *Ieee Transactions on Magnetism* **52**(5),4 (2016).<https://doi.org/10.1109/tmag.2015.2511451>
9. D Garcia-Gonzalez, Magneto-visco-hyperelasticity for hard-magnetic soft materials: theory and numerical applications, *Smart Mater. Struct.* **28**(8),14 (2019).<https://doi.org/10.1088/1361-665X/ab2b05>
10. X Liu, P Wu, GW Wang, L Qiao, T Wang, F Li, High permeability and low loss flaky carbonyl iron soft magnetic composite for 5G applications, *J. Appl. Phys.* **128**(24),9 (2020).<https://doi.org/10.1063/5.0033692>
11. H Shokrollahi, K Janghorban, Soft magnetic composite materials (SMCs), *J. Mater. Process. Technol.* **189**(1-3),1 (2007).<https://doi.org/10.1016/j.jmatprotec.2007.02.034>
12. G Weir, J Leveneur, NC Long, Magnetic susceptibility of soft magnetic composite materials, *J. Magn. Magn. Mater.* **551**,8 (2022).<https://doi.org/10.1016/j.jmmm.2022.169103>
13. N Yabu, K Sugimura, M Sonohara, T Sato, Fabrication and evaluation of composite magnetic core using iron-based amorphous alloy powder with different particle size distributions, *IEEE Transactions on Magnetism* **54**(11),1 (2018).<https://doi.org/10.1109/tmag.2018.2832662>
14. TF Marinca, BV Neamtu, F Popa, AZ Mesaros, I Ciascai, I Chicinas, Novel supermalloy/alumina type soft magnetic composite obtained by reaction spark plasma sintering of Al-Supermalloy (Ni_{70.5}Fe_{18.8}Mo_{4.7}Al₆) surface oxidized particles, *J. Alloy. Compd.* **940**,12 (2023).<https://doi.org/10.1016/j.jallcom.2023.168899>
15. A Kolano-Burian, M Kowalczyk, R Kolano, R Szymczak, H Szymczak, M Polak, Magnetocaloric effect in Fe-Cr-Cu-Nb-Si-B amorphous materials, *J. Alloy. Compd.* **479**(1-2),71 (2009).<https://doi.org/10.1016/j.jallcom.2009.01.058>
16. H Tsukahara, HD Huang, K Suzuki, K Ono, A Kato, S Okamoto, General formulation of core loss in soft magnetic materials including effects of eddy current and magnetostriction, *J. Magn. Magn. Mater.* **635**,7 (2025).<https://doi.org/10.1016/j.jmmm.2025.173597>

17. SJM van Vilsteren, H Yarmand, S Ghodrat, Review of magnetic shape memory polymers and magnetic soft materials, *Magnetochemistry* **7**(9),24 (2021).<https://doi.org/10.3390/magnetochemistry7090123>
18. M Nabialek, Soft magnetic and microstructural investigation in Fe-based amorphous alloy, *J. Alloy. Compd.* **642**,98 (2015).<https://doi.org/10.1016/j.jallcom.2015.03.250>
19. LL Pang, A Inoue, EN Zanaeva, et al., Nanocrystallization, good soft magnetic properties and ultrahigh mechanical strength for Fe₈₂₋₈₅B₁₃₋₁₆SiCu₁ amorphous alloys, *J. Alloy. Compd.* **785**,25 (2019).<https://doi.org/10.1016/j.jallcom.2019.01.150>
20. ZB Zhu, L Jiang, HH Deng, et al., A thermally stable FeCoNiAlSi multi-principal element alloy with excellent soft magnetic and mechanical properties, *J. Alloy. Compd.* **1037**,12 (2025).<https://doi.org/10.1016/j.jallcom.2025.182273>
21. SY Deng, K Zhu, Y Zhang, Y Zhu, F Hu, XC Kan, Research on the soft magnetic properties of iron-nickel magnetic powder core composite with carbonyl iron powder, *J. Mater. Sci.-Mater. Electron.* **35**(4),8 (2024).<https://doi.org/10.1007/s10854-024-12061-1>
22. HI Hsiang, LF Fan, Magnetic properties of the soft magnetic composites prepared using mixtures of carbonyl iron, FeSiCr, and FeSiAl alloy powders, *Materials* **16**(17),10 (2023).<https://doi.org/10.3390/ma16176033>
23. HI Hsiang, LF Fan, JJ Hung, Phosphoric acid addition effect on the microstructure and magnetic properties of iron-based soft magnetic composites, *J. Magn. Magn. Mater.* **447**,1 (2018).<https://doi.org/10.1016/j.jmmm.2017.08.096>
24. XL Xie, CY Chen, YC Xie, et al., A novel approach for fabricating Ni-coated FeSiAl soft magnetic composite via cold spraying, *J. Alloy. Compd.* **749**,523 (2018).<https://doi.org/10.1016/j.jallcom.2018.03.306>
25. R König, S Müller, RE Dinnebier, et al., The crystal structures of carbonyl iron powders - revised using in situ synchrotron XRPD, *Z. Krist.-Cryst. Mater.* **232**(12),835 (2017).<https://doi.org/10.1515/zkri-2017-2067>
26. J Li, JL Ni, SJ Zhu, SJ Feng, Evolution of magnetic loss with annealing temperature in FeSiAl/carbonyl iron soft magnetic composite, *Mater. Technol.* **37**(12),2313 (2022).<https://doi.org/10.1080/10667857.2022.2029291>
27. SG Li, RT Liu, X Xiong, Preparation and characterization of carbonyl iron soft magnetic composites with magnesioferrite insulating coating layer, *Trans. Nonferrous Met. Soc. China* **30**(11),3067 (2020).[https://doi.org/10.1016/s1003-6326\(20\)65443-7](https://doi.org/10.1016/s1003-6326(20)65443-7)
28. JQ Liu, YN Dong, P Wang, et al., Improved high-frequency magnetic properties of FeSiBCCr amorphous soft magnetic composites by adding carbonyl iron powders, *J. Non-Cryst. Solids* **605**,9 (2023).<https://doi.org/10.1016/j.jnoncrsol.2023.122166>
29. HH Sim, SH Kwon, HJ Choi, Xanthan gum-coated soft magnetic carbonyl iron composite particles and their magnetorheology, *Colloid Polym. Sci.* **291**(4),963 (2013).<https://doi.org/10.1007/s00396-012-2816-6>
30. ZR Zheng, SG Li, K Peng, Magnetic properties regulation and loss contribution

- analysis of FeSi soft magnetic composites doped by carbonyl iron powders, *J. Magn. Magn. Mater.* **568**,7 (2023).<https://doi.org/10.1016/j.jmmm.2023.170423>
31. Y Zhu, C Zhang, XS Liu, et al., Study on the magnetic property of Fe-Si-B amorphous magnetic powder core mixed with carbonyl Iron, *J. Mater. Eng. Perform.* **34**(2),1169 (2025).<https://doi.org/10.1007/s11665-024-09165-4>
 32. ZQ Zhu, P Wang, JQ Liu, P Lan, J Pang, JQ Zhang, Magnetic property regulation and mechanism analysis of FeSiBC soft magnetic composites by mixing with FeSiCr or carbonyl iron powder, *J. Magn. Magn. Mater.* **588**,11 (2023).<https://doi.org/10.1016/j.jmmm.2023.171413>
 33. LL Evangelista, G Tontini, A Ramos, et al., Developments on soft magnetic composites with double layer insulating coating: Synergy between ZnO and B₂O₃, *J. Magn. Magn. Mater.* **497**,9 (2020).<https://doi.org/10.1016/j.jmmm.2019.166023>
 34. WJ Li, WC Li, JK Wu, et al., Particles size-dependent magnetic properties of a FeSiAl soft magnetic composite with hybrid insulating coating for MHz applications, *Mater. Sci. Eng. B-Adv. Funct. Solid-State Mater.* **291**,9 (2023).<https://doi.org/10.1016/j.mseb.2023.116387>
 35. ZG Luo, XA Fan, WT Hu, et al., High performance Fe-Si soft magnetic composites coated with novel insulating-magnetic-insulating (IMI) layer, *J. Magn. Magn. Mater.* **496**,7 (2020).<https://doi.org/10.1016/j.jmmm.2019.165937>
 36. X Fu, Z Lai, X Lai, Z Lu, S Lv, Preparation and characteristics of magnesium phosphate cement based porous materials, *Constr. Build. Mater.* **127**,712 (2016).<https://doi.org/10.1016/j.conbuildmat.2016.10.041>
 37. Y Li, N Wang, SR Long, H Lin, XF Liu, Fire resistance and corrosion performance of brucite-based magnesium phosphate fireproof coating for steel structure, *J. Build. Eng.* **118**,18 (2026).<https://doi.org/10.1016/j.jobbe.2025.114943>
 38. Y Li, N Wang, SR Long, ZG Wang, H Lin, JL Mu, Research on the properties of brucite-based magnesium phosphate cement fire resistive coating for steel structures, *Constr. Build. Mater.* **449**,16 (2024).<https://doi.org/10.1016/j.conbuildmat.2024.138481>
 39. JQ Zhou, PP Liu, CY Wu, et al., Properties of foam concrete prepared from magnesium oxychloride cement, *Ceram.-Silik.* **64**(2),200 (2020).<https://doi.org/10.13168/cs.2020.0009>
 40. ZC He, HZ Li, WS Cai, et al., Improved soft magnetic properties of Fe-6.5 %Si composites by regulating the thermal characteristics of insulation resin, *J. Alloy. Compd.* **1022**,9 (2025).<https://doi.org/10.1016/j.jallcom.2025.179757>
 41. G Bertotti, V Basso, M Pasquale, Application of the preisach model to the calculation of magnetization curves and power losses in ferromagnetic materials, *IEEE Transactions on Magnetism* **30**(2),1052 (1994).<https://doi.org/10.1109/20.312492>
 42. C Mei, JJ Li, BW Zhang, et al., Synthesis of FeNi@kaolin soft magnetic composites with adjustable magnetic properties under different DC bias fields, *J. Magn. Magn. Mater.* **587**,11 (2023).<https://doi.org/10.1016/j.jmmm.2023.171350>
 43. Y Gao, D Shindo, T Bitoh, A Makino, Mediated exchange interaction in Fe-Nb-B nanocrystalline soft magnetic materials - art. no. 172409, *Phys. Rev. B* **67**(17),4

- (2003).<https://doi.org/10.1103/PhysRevB.67.172409>
44. WC Li, X Zhou, Y Kang, et al., Microstructure and magnetic properties of the FeSiAl soft magnetic composite with a NiFe₂O₄-doped phosphate insulation coating, J. Alloy. Compd. **960**,13 (2023).<https://doi.org/10.1016/j.jallcom.2023.171010>
 45. H Zhang, K Wang, YD Huang, CH Zhang, Y Wang, T Wang, The excess loss analysis of an easy-plane FeSiAl@SiO₂ soft magnetic composite with high permeability, J. Magn. Magn. Mater. **588**,7 (2023).<https://doi.org/10.1016/j.jmmm.2023.171471>

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