

Article

Performance Enhancement of Amorphous Soft Magnetic Composites by Synergistic Warm Compaction and Fine FeNi Powders Addition

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Abstract

Molded inductors play a critical role in a wide range of power electronic devices, where soft magnetic composite materials serve as the key functional component. This study proposes a synergistic optimization strategy, which integrates warm compaction molding with FeSiBCCr/FeNi composite powder, to enhance the overall performance of FeSiBCCr-based amorphous soft magnetic composites (ASMCs) without requiring post-annealing treatment. The results demonstrated that the warm compaction process facilitates effective particle rearrangement, enabling fine FeNi particles to efficiently fill the voids among the large amorphous particles. Moreover, the plastic deformation of FeNi particles during compaction contributes to a significant increase in the density (ρ_c) of the composite, thereby reducing pore-induced magnetic domain wall pinning and substantially improving the soft magnetic properties. With an optimal FeNi content of 30 wt%, the FeSiBCCr/FeNi compound ASMCs exhibit excellent performance. Compared to cold-pressed soft magnetic composites without FeNi fine powder, the effective permeability (μ_e) increases by 55.4% to reach 20.6, with excellent frequency stability. Under the condition of 100 kHz and 50 mT, the total core loss (P_{cv}) is reduced by 21.8% to 285.6 kW/m³. The DC-bias performance ($\mu\%$ @ 100 Oe) achieves 94.5%. This study has successfully addressed the key technical challenges hindering the development of the compound ASMCs with high permeability and low core loss for molded inductors, thereby providing a practical and scalable material solution for advanced high-frequency and high-power electronic applications—particularly in emerging domains such as new energy vehicles and artificial intelligence systems.

Keywords: soft magnetic composites; warm compaction; amorphous alloy powder; FeNi alloy powder; high density; low core loss



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1. Introduction

Inductors are among the most essential passive electronic components and have been widely employed in various power electronic systems, including renewable energy, mobile communications, and robotics [1–3]. Driven by the rapid advancement of the power electronics industry, there is an increasing demand for the inductors with small size and enhanced performance including high-frequency operation, low core loss, high current handling capability, magnetic shielding, and high thermal stability. These properties are

important characteristics for the integrated molded inductors. Conventional inductors typically employ wire-wound magnetic core structures, and such design often suffers from inherent limitations such as bulky size and high leakage inductance [4]. In some critical application fields, including smartphones, computers, servers, and new energy vehicles, integrated molded inductors are progressively supplanting traditional wound counterparts and emerging as the dominant solution. These inductors consist of soft magnetic composites (SMCs) and embedded coils, with SMCs serving as the core functional material that governs the overall device performance. Generally, the SMCs are fabricated by compacting surface-insulated soft magnetic metal powders mixed with polymer binders [5,6]. Their distinctive interparticle insulation architecture [7–9] effectively reduces the high-frequency eddy current loss while maintaining superior DC-bias characteristics, thereby offering significant potential for both fundamental research and practical applications.

A wide range of magnetic powder materials are currently used for the SMCs, including iron, FeSiAl, FeSi, FeNiMo, FeNi, and amorphous–nanocrystalline alloys [10–15]. Among these, iron-based amorphous alloys demonstrate exceptional soft magnetic performances, such as low coercivity (H_c), high electrical resistivity, and minimized hysteresis loss, owing to their non-crystalline structure, which effectively diminishes the detrimental effects of crystalline defects like grain boundaries and dislocations [16,17]. FeSiBCCr alloy is a representative iron-based amorphous alloy, which is considered a promising candidate for fabricating high-performance integrated molded inductors. However, its application in such devices presents significant technical challenges stemming from intrinsic material characteristics. The ultrafast solidification process required for producing amorphous powders, typically involving cooling rates up to 10^6 °C/s, results in exceptionally high mechanical strength and limited ductility [18,19]. Consequently, substantial residual internal stress is generated during compaction, which severely degrades soft magnetic performance. Critically, the embedded coils in integrated inductors are commonly insulated with organic coatings (e.g., enameled wire), rendering them incompatible with high-temperature processing. As a result, the post-processing temperatures are strictly constrained, typically below 200 °C, thereby precluding the use of conventional high-temperature annealing treatment (>400 °C) for stress relief [20,21]. Under these combined limitations of low temperature and low compaction pressure, achieving high densification while effectively suppressing residual internal stress has emerged as the central technical barrier to the practical implementation of FeSiBCCr amorphous powders in molded inductor applications.

Reducing the forming pressure can effectively alleviate residual stresses in soft magnetic composite materials; however, it is generally associated with a reduction in density, which leads to the degradation of soft magnetic properties [22]. Warm compaction offers a promising route to enhance green density under low-pressure conditions and has been successfully applied in various metallic powder systems. Nevertheless, its systematic investigation in amorphous soft magnetic materials remains limited [23–26]. Moreover, the high hardness and strength of amorphous alloy powders originated from their ultrafast solidification history constrain plastic deformation during compaction, leading to incomplete interparticle void filling. Residual porosity not only compromises the structural integrity of the material but also introduces domain wall pinning sites, thereby increasing H_c and degrading soft magnetic performance. The incorporation of ultrafine FeNi soft magnetic alloy powder into the interparticle voids of amorphous alloy powder offers an effective technical strategy for enhancing the densification and overall performance of amorphous soft magnetic composites.

In this study, FeNi alloy powders with systematically varied mass fractions were incorporated into FeSiBCr amorphous powder matrices to simultaneously improve density and soft magnetic properties of the resulting amorphous soft magnetic composites. Subsequent

consolidation was performed via warm compaction. A systematic investigation was carried out to evaluate the influence of FeNi powder content on the microstructure, green density, and soft magnetic properties of the composites. The underlying mechanisms governing performance enhancement—and, particularly, the origins of core losses—were rigorously elucidated. The developed high-performance iron-based amorphous soft magnetic composites exhibit promising application potential in advanced technological fields such as wireless communication and artificial intelligence.

2. Materials and Methods

Water-atomized FeSiBCCr amorphous soft magnetic powders, with a median particle sizes (D_{50}) of 27.8 μm , were supplied by Zhongyan Magnetolectric Technology Co., Ltd. (Foshan, China) and used as the matrix material in this study. FeNi powders ($D_{50} = 6.0 \mu\text{m}$) were provided by Hunan Hualiu New Materials Co., Ltd. (Changsha, China), served as the secondary phase additive. Chemical reagents, including phosphoric acid, acetone, absolute ethanol, and paraffin, were sourced from Guangzhou Chemical Reagent Co., Ltd., (Guangzhou, China). The organic resin was supplied by Dongguan Mentech Optical & Magnetic Co., Ltd., (Dongguan, China). The compaction tooling includes an upper die, lower die, core rod, and heated female die with integrated temperature control. For warm compaction, the die is heated to the target temperature, powder is loaded and held for the set time, then compacted at the specified pressure. Cold compaction is performed at room temperature without heating. The preparation of FeSiBCCr amorphous soft magnetic composites (SMCs) was carried out as follows: (1) FeSiBCCr and FeNi powders were separately washed at least three times with anhydrous ethanol to remove surface contaminants and native oxides. (2) A phosphoric acid–ethanol passivation solution—containing 0.5 wt% H_3PO_4 relative to the total powder mass—was added to the washed powders, followed by magnetic stirring at 55 °C until complete ethanol evaporation. The resulting passivated powder was then dried at 80 °C for 30 min. (3) FeNi powders were blended into the FeSiBCCr amorphous powder at predetermined mass fractions (0, 10, 20, 30, 40, and 50 wt%) and homogenized via mechanical mixing under inert atmosphere to prevent oxidation. (4) A predetermined amount of resin (3.0 wt.%) was dissolved in 30 mL acetone, and the solution was subjected to ultrasonic treatment to ensure homogeneity before being added to the dried and passivated powders. The mixture was then continuously mechanically stirred until complete volatilization of the acetone solvent. (5) The coated composite powders were subsequently dried and granulated by passing through a 60-mesh stainless steel sieve to improve powder flowability and packing density during subsequent molding. After granulation, 0.3 wt.% paraffin was added as a lubricant and thoroughly mixed with the powders. (6) Green compacts were formed via warm compaction (140 °C, 300 MPa) and cold compaction (25 °C, 300 MPa), yielding toroidal specimens with dimensions of 20.00 mm (outer diameter) $\times$ 12.00 mm (inner diameter) $\times$ 5.50 mm (thickness). Finally, the toroids were thermally cured at 180 °C for 1 h in ambient air.

Microstructural and elemental characterization of raw powders, resin-coated powders, and polished cross-sections of the SMCs was performed using a scanning electron microscope (SEM; Phenom ProX, Thermo Fisher Scientific, Breda, The Netherlands) equipped with energy-dispersive X-ray spectroscopy (EDS). Phase composition and amorphous nature of the powders were assessed by X-ray diffraction (XRD; Empyrean, PANalytical, Almelo, The Netherlands) employing Cu $K\alpha$ radiation ($\lambda = 1.5406 \text{ \AA}$) over a 2θ range of 20–90° at a scan rate of 2°/min. Particle size distribution was determined via laser diffraction using a commercial particle size analyzer (Bettersize 9300-ST, Dandong Bettersize Instruments, Dandong, China). Thermal behavior of the phenolic resin binder was investigated by differential scanning calorimetry (DSC; DSC3, METTLER TOLEDO,

Greifensee, Switzerland) under a high-purity argon atmosphere (99.999%) at a heating rate of 10 °C/min (0.167 K/s). Compaction density (ρ_c) was measured in triplicate using the Archimedes method (ASTM B962-17), and the mean value was reported. Bulk electrical resistivity (ρ_b) was determined using the four-probe direct-current (DC) technique. Frequency-dependent effective permeability (μ_e) spectra (1 kHz–1 MHz) were acquired using an impedance analyzer (IM3536, Hioki, Nagano, Japan). DC-bias superposition characteristics were evaluated with a precision impedance analyzer (6632, MICROTTEST, Taipei, Taiwan). Total core loss (P_{cv}) was measured under sinusoidal excitation ($B_m = 25$ –100 mT, $f = 25$ –200 kHz) using a fully automated B – H loop tracer (MATS-3010SA, Linkjoin, Loudi, China).

3. Results and Discussion

3.1. Characterization of Alloy Powders

Figure 1 shows the morphology and particle size distribution of the as-received FeSiBCr amorphous powders and FeNi alloy powders. The median particle sizes (D_{50}) are 27.8 μm and 6.2 μm , respectively. Both powders exhibit uniform particle dispersion and a predominantly spherical morphology—features conducive to high flowability and favorable packing density during subsequent compaction.

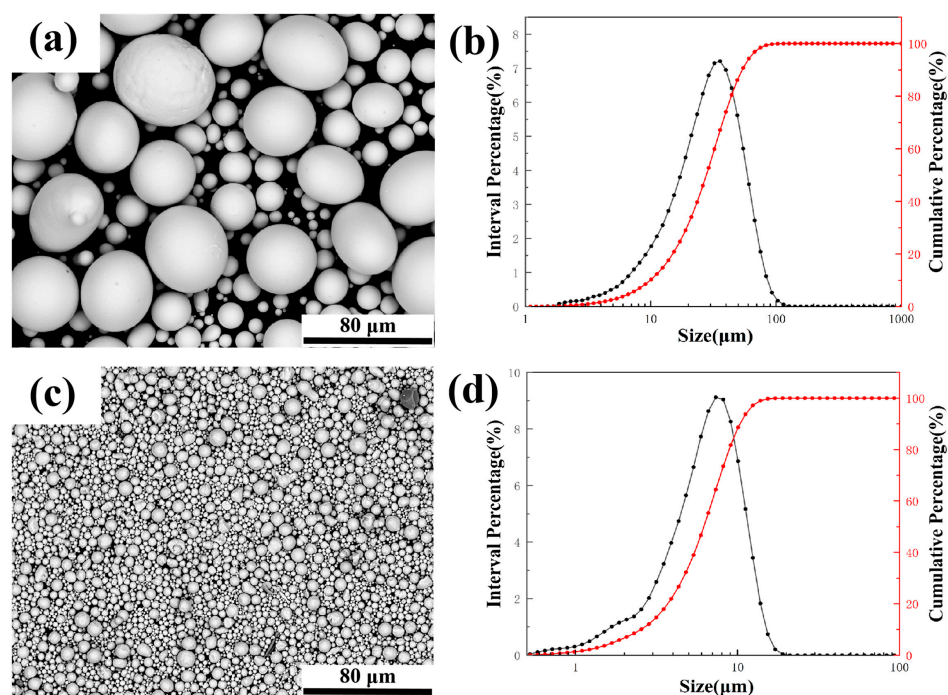


Figure 1. (a,c) Morphology, (b,d) particle size distribution of (a,b) FeSiBCCr powders and (c,d) FeNi powders.

Figure 2a presents the XRD patterns of the as-received FeSiBCCr powders and FeNi powders. The FeSiBCr powder exhibits a broad halo peak centered at $2\theta \sim 45^\circ$, confirming its fully amorphous structure; in contrast, the FeNi powder shows sharp crystalline diffraction peaks indexed to the face-centered cubic (FCC) phase, verifying its crystalline nature. Figure 2b presents the magnetic hysteresis loops of both powders, measured under zero-field-cooled conditions at room temperature. Saturation magnetization (M_s) values of 146.2 emu/g and 151.4 emu/g were obtained for the FeSiBCr and FeNi powders, respectively.

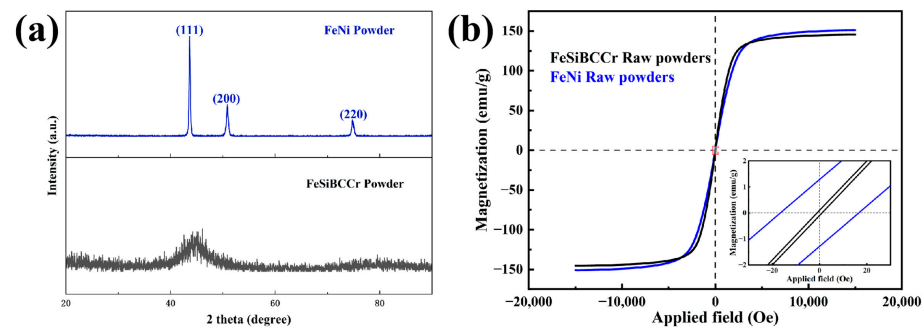


Figure 2. (a) XRD patterns, (b) hysteresis loops of the amorphous and FeNi alloy raw powders.

Figure 3 illustrates the SEM images (a,c) and EDS elemental maps (e,g) of the as-received FeSiBCr amorphous powders and FeNi alloy powders, alongside their post-passivation counterparts (b, d and f, h, respectively). Passivation successfully yielded a uniform, inorganic phosphate-based insulating layer on the surface of both powder types—as confirmed by EDS line scans and high-resolution SEM imaging—thereby enhancing electrical resistivity and suppressing eddy current losses in the resulting SMCs.

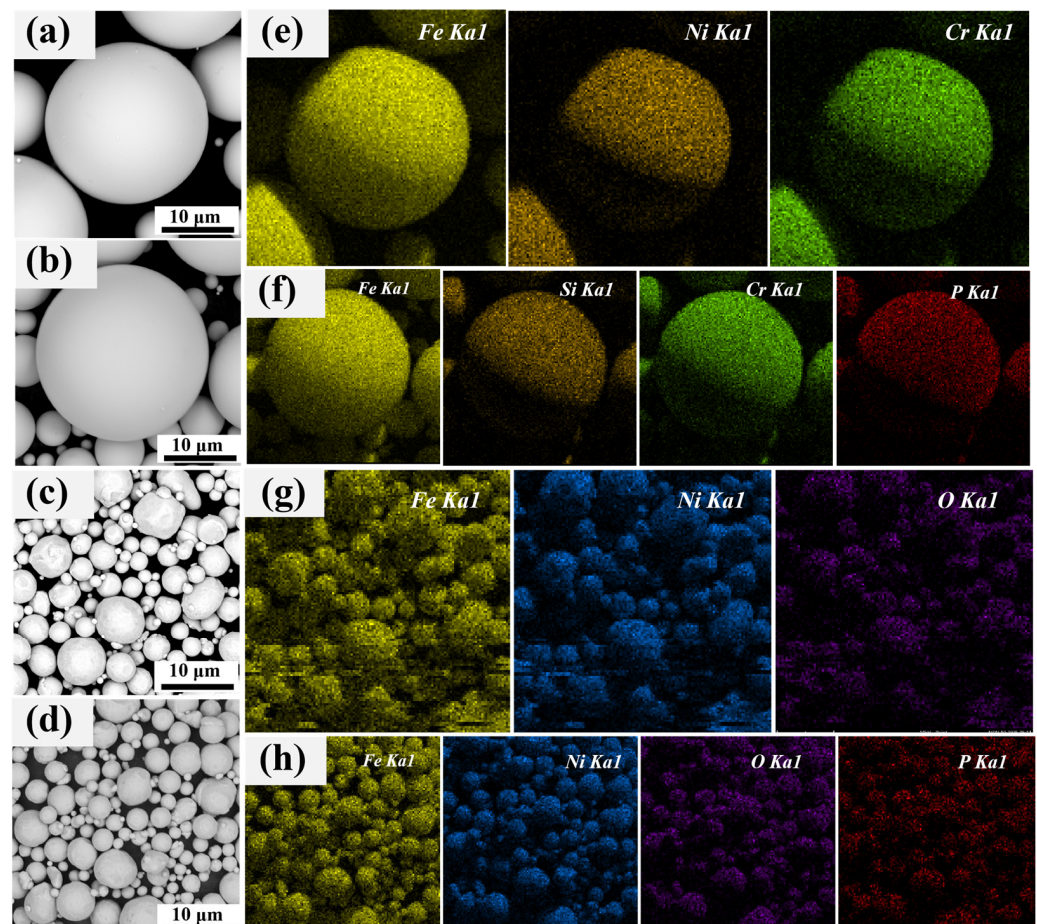


Figure 3. Morphology (a) and elemental distribution (e) of FeSiBCr powder before passivation; morphology (c) and elemental distribution (g) of FeNi powder before passivation; and morphologies (b,d) and elemental distribution (f,h) of the two powders after passivation.

3.2. Compaction Density of the FeSiBCr/FeNi Compound ASMCs

Figure 4 presents the green density and porosity evolution of the FeSiBCr/FeNi compound ASMCs as a function of FeNi powder content, comparing samples consolidated

via cold compaction at room temperature and warm compaction at 140 °C. At each FeNi content level, warm-compacted specimens exhibit significantly higher green density than their cold-compacted counterparts. A maximum density increase rate of 8.5% is observed at the FeNi content of 50 wt%. With increasing FeNi powder fraction, the density of both types of the compound ASMCs exhibit a monotonic increase, with the maximum values reaching 5.50 g/cm³ for cold-pressed samples and 5.97 g/cm³ for warm-pressed samples. Meanwhile, their porosities decrease monotonically, attaining minima of 26.8% and 20.5%, respectively. At 100 wt% FeNi, the porosity values are 31.3% for cold compaction and 25.7% for hot compaction samples. This demonstrates that warm compaction consistently enhances densification across the full FeNi compositional range, with concurrent peak density gain (8.5%) and peak porosity reduction (23.4%) observed exclusively at 50 wt% FeNi.

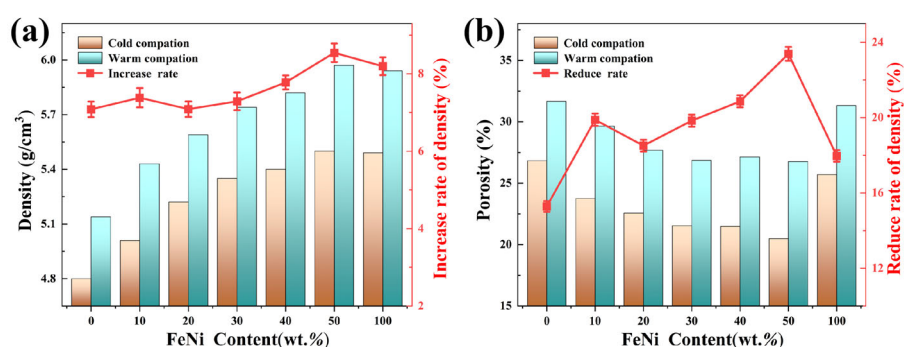


Figure 4. Compaction density (a) and porosity (b) variation of soft magnetic composites prepared by cold compaction and warm compaction as a function of FeNi powder content.

To elucidate the mechanism by which FeNi fine powder influences the densification behavior of the compound ASMCs, a sectional microstructural analysis was conducted. The results are presented in Figure 5. As shown therein, fine FeNi particles undergo plastic deformation under external pressure and infiltrate into the interstitial regions between large amorphous particles, thereby significantly enhancing the densification process.

To examine the distribution characteristics of FeNi within the compound ASMCs and its pore-filling efficacy, Figure 6 displays the SEM images of polished cross-sections from warm-pressed compound SMCs with various FeNi contents and elemental distribution (g–i) of SMC with 30 wt% FeNi contents. Figure 6a–c reveal that, at FeNi contents below 30 wt%, numerous interparticle pores persist within the FeSiBCr matrix—indicating insufficient pore-filling capacity of the fine FeNi particles. This observation is consistent with the steep density increase observed in Figure 3b as FeNi content rises from 0 to 30 wt%. Beyond 30 wt%, the densification effect becomes progressively more pronounced; at 30 wt% FeNi, the composite achieves a relatively high packing density (Figure 6d). However, at 40 and 50 wt% FeNi contents (Figure 6e,f), distinct FeNi particle agglomeration emerges, with agglomerates increasingly displacing the larger FeSiBCr particles and occupying regions previously filled by the amorphous matrix. The underlying mechanisms for the densification can be summarized as follows: (1) Moderate heating during compaction softens the resin, which can enhance the lubrication, reduce the interparticle and interfacial friction, and facilitate the particle rearrangement. (2) Warm compaction reduces the hardness of FeNi powder, promoting greater plastic deformation under pressure, thereby enabling effective filling of voids between hard FeSiBCCr particles and improving green density. (3) Fine FeNi particles infiltrate into the interstitial regions among coarse amorphous particles, further enhancing the packing efficiency [26]. In summary, when the FeNi powder content is 30 wt%, the compound ASMCs fabricated by warm compaction exhibits a more uniform microstructure and achieves a high density of 5.74 g/cm³.

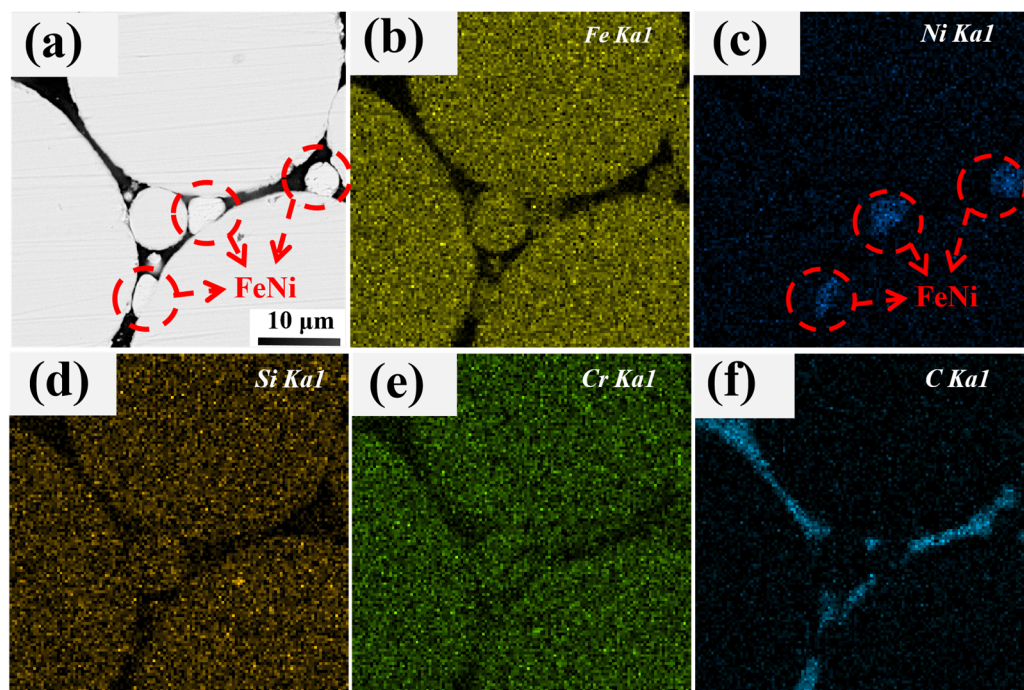


Figure 5. (a) Microstructural distribution of amorphous FeSiBCCr and crystalline FeNi powders in the soft magnetic composite; (b–f) Corresponding elemental distribution maps (EDS) for Fe, Ni, Si, Cr, and C.

3.3. Soft Magnetic Properties of the Compound ASMCs

Figure 7 shows the frequency-dependent effective permeability (μ_e) spectra of the compound ASMCs, comparing samples fabricated by cold compaction (room temperature) and warm compaction (140 °C) across FeNi powder contents of 0–50 wt%. Measurements were conducted from 1 kHz to 1 MHz under sinusoidal excitation ($B_m = 50$ mT). All specimens exhibit exceptional μ_e stability over the entire frequency range—defined as a relative variation of less than $\pm 3\%$ —indicating minimal dispersion and low magnetic loss. This stability arises primarily from two synergistic factors: (1) the intrinsically high electrical resistivity of the FeSiBCCr amorphous matrix, and (2) the uniform, phosphate-based interparticle insulation layer, which collectively elevate the magnetic relaxation frequency (f_r , Equation (1) [27]). As predicted by Visser’s coherent rotation model (Equation (2) [28]), a higher f_r directly suppresses the attenuation rate of μ_e with increasing f .

$$f_r = \frac{\rho_b}{2\pi\mu_0\mu_i d_p^2} \quad (1)$$

$$\mu' = u_i \frac{1}{1 + f^2/f_r^2} \quad (2)$$

where ρ_b denotes the bulk electrical resistivity of the compound ASMCs, μ_i represents the initial permeability of the magnetic powder phase, and d_p signifies the volume-weighted mean particle diameter of the magnetic powders.

At a fixed frequency, the effective permeability (μ_e) of both warm-pressed and cold-pressed compound ASMCs increases progressively with increasing FeNi powder content, consistent with the density (ρ_c) variation with FeNi content presented in Figure 4a. Specifically, for the cold-pressed samples, μ_e rises from 13.3 to 17.1, representing a 29.2% improvement. In contrast, warm-pressed samples exhibit an increase from 14.2 to 22.9, corresponding to a 61.0% enhancement. These observations can be attributed to the following factors: (1) FeNi possesses an exceptionally high initial permeability. When incorporated as

a high-performance magnetic phase into the composite matrix, it significantly enhances the overall magnetization capability of the material; (2) The increased density reduces internal porosity in the compound ASMCs, thereby decreasing the number of magnetic domain wall pinning sites. This reduction in pinning density lowers the energy barrier for both domain wall motion and coherent magnetization rotation, ultimately enhancing the μ_e ; (3) The warm compaction process facilitates the improved particle rearrangement, while thermal softening of the resin enhances the surface lubrication, effectively suppressing dislocation defect formation during compaction. This leads to reduced porosity and a weakened demagnetizing field effect. Through the synergistic integration of warm compaction and FeNi addition, the permeability of compound ASMCs is significantly improved, demonstrating that this strategy offers an effective approach for developing high-permeability soft magnetic composites.

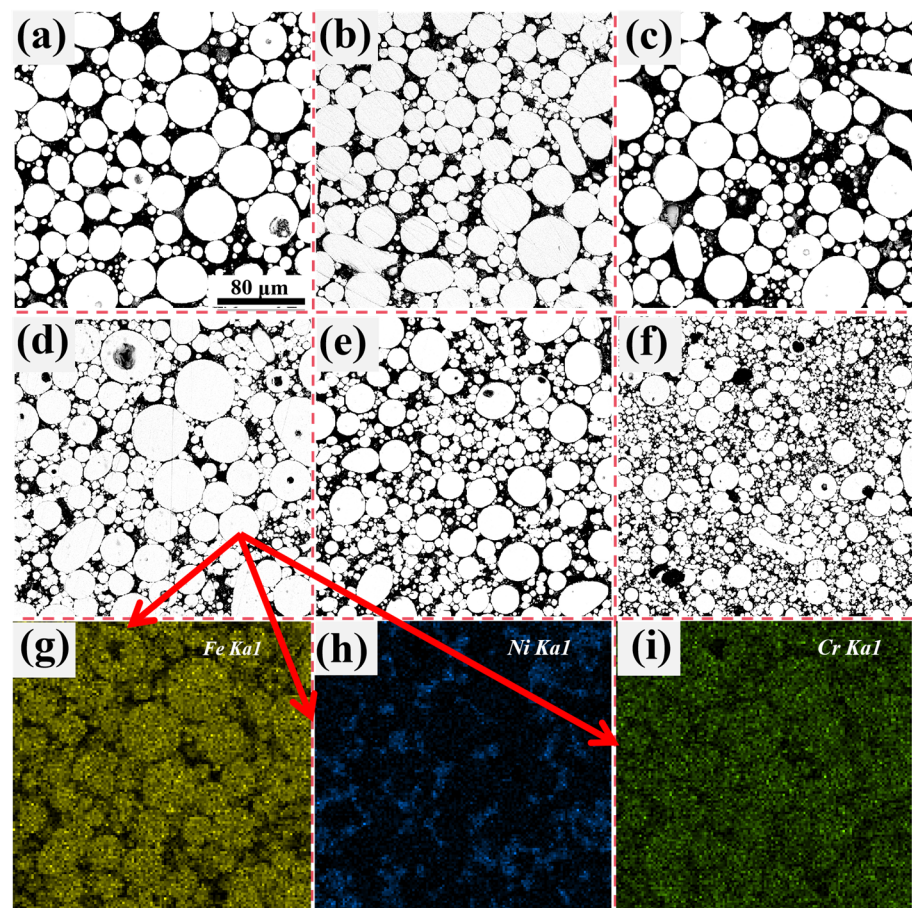


Figure 6. Cross-sectional SEM images of SMCs with varying FeNi contents (a): 0 wt% FeNi, (b): 10 wt% FeNi, (c): 20 wt% FeNi, (d): 30 wt% FeNi, (e): 40 wt% FeNi, (f): 50 wt% FeNi and elemental distribution (g–i) of SMC with 30 wt% FeNi contents.

Figure 8 shows the DC-bias superposition characteristics of the compound ASMCs as a function of FeNi powder content (0–50 wt%). The DC-bias capability ($\mu\%$), quantified as the percentage retention of μ_e at a specified DC-bias field strength of 100 Oe, is used to evaluate inductance stability under combined AC–DC excitation. As illustrated, the $\mu\%$ retention declines monotonically with increasing FeNi content—dropping from 92.4% at 0 wt% to 68.7% at 50 wt%—indicating a progressive degradation in DC-bias tolerance. When the FeNi concentration increases from 0 wt% to 50 wt%, the permeability retention of cold-pressed samples at 100 Oe decreases from 96.5% to 94.6%, while that of warm-pressed samples drops from 95.1% to 92.8%. Despite this trend, all samples maintain

excellent DC-bias characteristics. This behavior is attributed to the dependence of DC-bias resistance on the saturation magnetic flux density and magnetic permeability. The materials exhibiting lower saturation magnetization and higher permeability are more susceptible to magnetic saturation under DC bias fields [29]. Consequently, increasing FeNi content elevates the μ_e of the compound ASMCs but concurrently reduces their magnetic saturation resistance—resulting in accelerated permeability roll-off under DC bias. This trade-off directly accounts for the inferior DC-bias superposition performance observed in warm-compacted specimens relative to cold-compacted counterparts. Moreover, the saturation magnetization (M_s) of the FeNi alloy powder (151.4 emu/g) is inherently lower than that of the FeSiBCr amorphous powder (146.2 emu/g) [30], further rationalizing the progressive decline in DC-bias tolerance with higher FeNi incorporation.

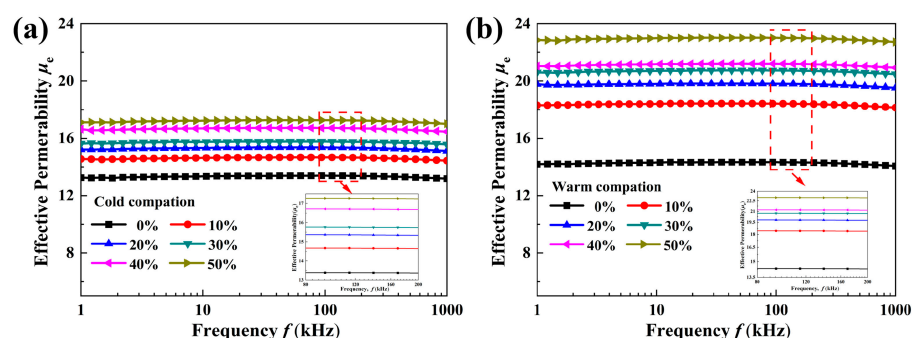


Figure 7. Frequency dependence of magnetic permeability for ASMCs with various FeNi powder contents: (a) cold compaction; (b) warm compaction.

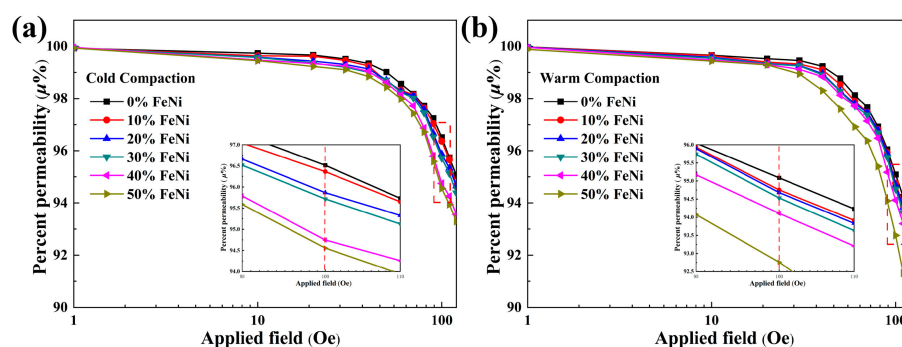


Figure 8. DC-bias capability of the compound ASMCs with various FeNi powder contents: (a) cold compaction; (b) warm compaction.

Figure 9a,b present the frequency-dependent core loss (P_{cv}) of the compound ASMCs with various FeNi powder contents. Figure 9c displays the core loss values and the relative reduction percentages of different SMCs samples compared to their cold-pressed counterparts under the test conditions of 100 kHz and 50 mT. Figure 9d shows the hysteresis loops of FeSiBCCr and FeNi powders after phosphating treatment. As illustrated in the figures, the P_{cv} of the compound ASMCs fabricated by both cold compaction and warm compaction increase with increasing frequency. For both types of samples, the core loss exhibits a non-monotonic dependence on FeNi content, initially decreasing and subsequently increasing at higher loadings, with the minimum core loss observed in samples containing 30 wt% FeNi powder. As the FeNi content increases from 0 to 30 wt%, the core loss of the cold-compacted compound SMCs decreases from 809.2 to 724.5 kW/m³—a reduction of 10.5%. For the warm-compacted specimens, core loss declines from 777.9 to 632.4 kW/m³, representing an 18.7% improvement. The synergistic effect of warm compaction (140 °C) and optimized FeNi incorporation (30 wt%)

thus reduces the total core loss from 809.2 kW/m³ (cold-compacted, 0 wt% FeNi) to 632.4 kW/m³ (warm-compacted, 30 wt% FeNi), yielding a net 21.8% enhancement in core loss performance. These results demonstrated that the combined strategy of warm compaction and fine magnetic particle incorporation effectively improves the magnetic loss characteristics of the SMCs.

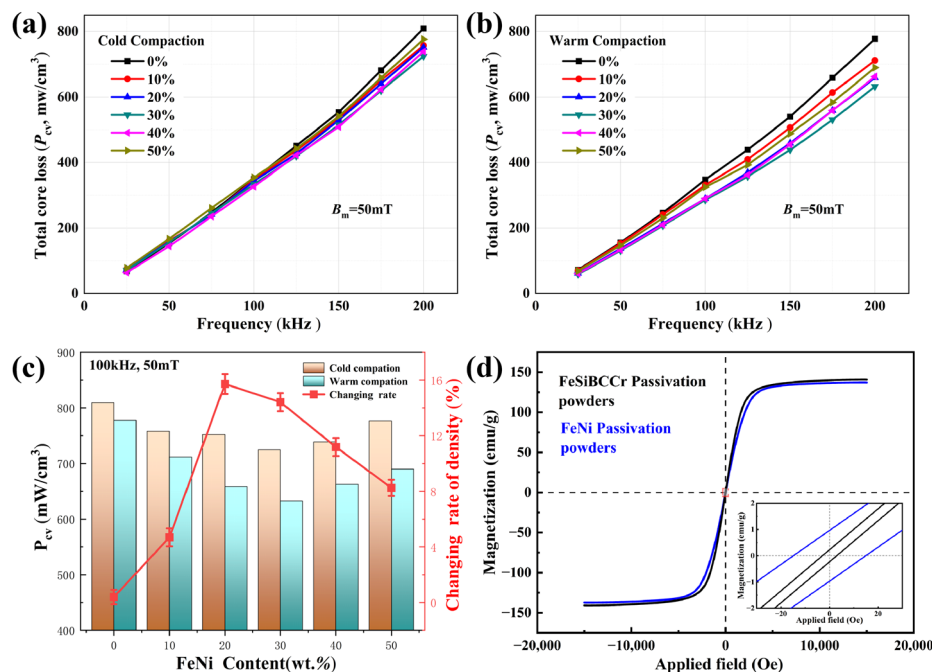


Figure 9. Core loss (P_{cv}) of SMCs with different FeNi powder contents as a function of frequency: (a) cold-pressed; (b) warm-pressed; (c) loss comparison at 200 kHz and 50 mT; (d) hysteresis loops of phosphated powder.

To elucidate the physical origins of core loss variation in the SMCs, a quantitative loss separation analysis was performed. Following the classical Bertotti loss separation model, the P_{cv} for a magnetic core can be decomposed into three physically distinct components: hysteresis loss (P_h), eddy current loss (P_e), and excess loss (P_{exc}) [31,32]. For the SMCs, P_h scales linearly with frequency (f), whereas P_e exhibits a quadratic dependence on f [33]. The excess loss component P_{exc} , which arises from non-uniform flux distribution and domain wall dynamics, is typically negligible under moderate frequency conditions [33,34]. Consequently, within the investigated frequency range, the total core loss can be expressed as:

$$P_{cv} = P_h + P_e = K_h f + K_e f^2 \quad (3)$$

where k_h and k_e are the fitting coefficients of P_h and P_e , respectively. By dividing both sides of Equation (3) by f , we can obtain Equation (4).

$$P_{cv}/f = P_h/f + P_e/f = K_h + K_e f \quad (4)$$

Consequently, in the linear regression of P_{cv}/f versus f , the intercept and slope correspond to the hysteresis loss coefficient (k_h) and the classical eddy current loss coefficient (k_e), respectively.

Figure 10a,b show the frequency-dependent P_h of the compound ASMCs fabricated by cold compaction (room temperature) and warm compaction (140 °C), respectively, across FeNi powder contents of 0–50 wt%. As shown, the P_h exhibits a non-monotonic dependence on FeNi content: it decreases progressively from 0 to 30 wt%, then increases thereafter. This

trend arises primarily from the pore-filling effect of fine FeNi particles within the interstitial void network of the FeSiBCr amorphous matrix—enhancing particle connectivity and reducing localized demagnetizing fields up to 30 wt% FeNi; beyond this threshold, FeNi agglomeration introduces new magnetic inhomogeneities that elevate domain wall pinning and irreversible magnetization losses. This leads to a significant reduction in porosity, which weakens the interparticle demagnetizing fields and facilitates domain wall motion, thereby suppressing hysteresis loss [35]. However, further increasing the FeNi content results in the increased P_h due to the intrinsically higher H_c of FeNi. Moreover, excessive fine particles introduce numerous micro-air gaps and additional particle interfaces, which enhance the demagnetizing field effect and impede domain wall displacement, ultimately increasing hysteresis loss [36].

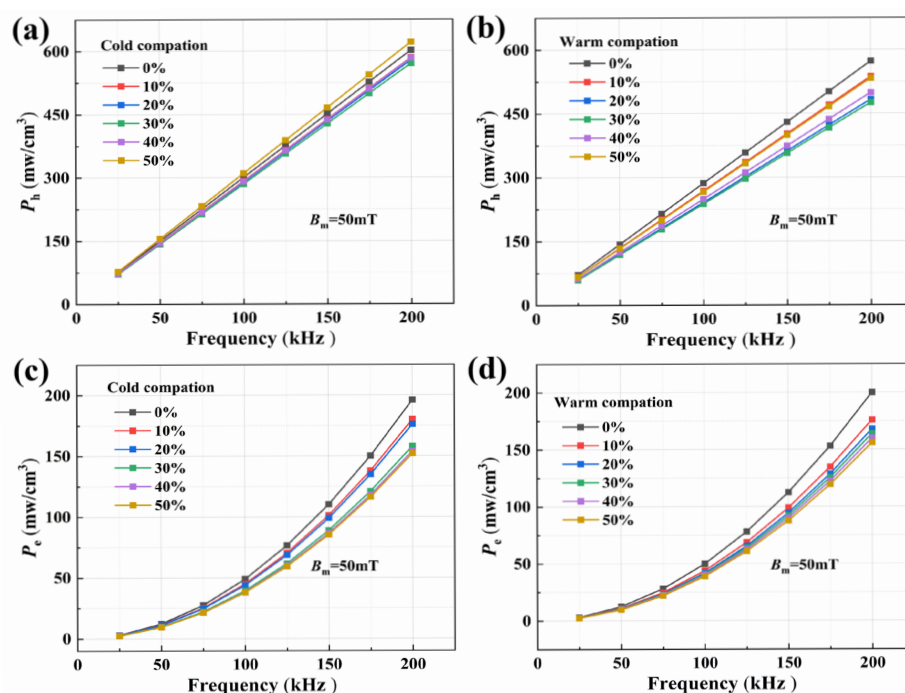


Figure 10. Frequency dependence of hysteresis loss (P_h) and classical eddy current loss (P_e) in the compound ASMCs with FeNi powder contents ranging from 0 to 50 wt%: (a,c) cold-compacted specimens; (b,d) warm-compacted specimens.

Figure 10c,d present the frequency-dependent classical P_e of the compound ASMCs fabricated by cold compaction (room temperature) and warm compaction (140 °C), respectively, across FeNi contents of 0–50 wt%. As shown, the P_e decreases monotonically with increasing FeNi content for both processing routes. According to Equation (3), $P_e \propto d^2 / \rho_b$, where d denotes the effective particle size. Thus, FeNi incorporation exerts a competing influence on P_e : while its lower intrinsic resistivity ($\rho_{\text{FeNi}} \approx 58 \text{ n}\Omega\cdot\text{m}$) relative to the FeSiBCr amorphous matrix ($\rho_{\text{FeSiBCr}} \approx 135 \text{ n}\Omega\cdot\text{m}$) tends to reduce overall ρ_b —and thereby elevate P_e —the concurrent reduction in the d , resulting from pore filling and enhanced interparticle connectivity, dominates the trend and strongly suppresses eddy current generation. When the grain refinement-induced loss reduction outweighs the adverse effect of reduced resistivity, the net P_e decreases.

Table 1 summarizes the soft magnetic properties of the FeSiBCr-based ASMCs fabricated by warm compaction (140 °C), benchmarked against representative SMCs reported in the literature. The present FeSiBCr/FeNi compound ASMCs achieves a balanced optimization of key performance metrics: it exhibits the lowest core loss (285.6 kW/m³ at 100 kHz/50 mT), highest DC-bias superposition capability (94.5% at 100 Oe), and rela-

tively high effective permeability ($\mu_e = 20.6$) within this comparative set—demonstrating superior overall performance. These findings not only highlight the effectiveness of the warm compaction process in tailoring the magnetic properties of ASMCs but also provide a solid foundation for their further optimization. This advancement is expected to meet the application demands of future high-frequency, miniaturized, and high-power density-molded inductors.

Table 1. Comparison of magnetic properties between the FeSiBCCr-ASMCs in this work and typical SMCs reported previously.

Samples	μ_e 100 kHz	DC-Bias (%) 100 Oe	P_{cv} (kW/m ³) 50 mT/100 kHz	Molding Method	P_m (MPa)	T_a (°C)	Ref
FeSiBCCr/FeNi	15.6	95.9	333.7	Cold	300	180	This work
FeSiBCCr/FeNi	20.6	94.5	285.6	Warm	300	180	This work
FeSiB	18.3	82	1489	Warm	80	250	[37]
FeSiBCCr	41	68	707	Hot	600	430	[38]
FeSiPC	81	/	321	Hot	400	420	[39]
FeSiCr	45.8	85.5	495.8	Warm	600	160	[22]
FeSiBCuNb/CIP	16.2	94.2	583.13	Cold	600	170	[40]
FeSiBCuNb/RIP	20.1	89.8	844.8	Cold	600	170	[40]
FeNi/CIP	26.7	/	486	Cold	670	180	[41]
FeSiAl/CIP	35.3	/	534	Cold	600	150	[42]
FeSiCr/CIP	26.76	90	466.5	Cold	600	200	[43]

4. Conclusions

This study systematically investigates the effect of FeNi powder incorporation on the microstructure and integrated soft magnetic performances of FeSiBCr-based ASMCs fabricated via cold compaction (25 °C) and warm compaction (140 °C). Relative to the base-line cold-compacted specimen (0 wt% FeNi), the warm-compacted composite with 30 wt% FeNi exhibits a 19.6% increase in green density ($\rho_c = 5.74$ g/cm³), a 55.4% enhancement in effective permeability ($\mu_e = 20.6$ at 100 kHz), and a 21.8% reduction in total core loss ($P_{cv} = 632.4$ kW/m³ at 100 kHz/200 mT). These improvements arise primarily from two synergistic mechanisms: (i) improved interparticle lubrication during warm compaction, which lowers yield stress and promotes particle rearrangement; and (ii) effective pore filling of the interstitial void network within the FeSiBCr amorphous matrix by fine FeNi particles—enhancing electrical insulation between conductive regions and reducing localized demagnetizing fields. Core loss separation analysis confirms that the P_h dominates P_{cv} across the full frequency range (74.1–89.3% contribution), with warm compaction alone reducing P_h by 12.7% and optimal FeNi addition (30 wt%) further suppressing both P_h and classical eddy current loss (P_e) by 18.4% and 26.9%, respectively. Collectively, the FeSiBCr/FeNi compound ASMCs demonstrate a balanced optimization of high μ_e , low P_{cv} , and robust DC-bias tolerance—making them highly suitable as core materials for high-frequency molded inductors in power electronics applications.

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References

1. Tseng, K.C.; Lin, J.T.; Huang, C.C. High Step-Up Converter With Three-Winding Coupled Inductor for Fuel Cell Energy Source Applications. *IEEE Trans. Power Electron.* **2015**, *30*, 574–581. [\[CrossRef\]](#)
2. Minami, M.; Hase, G. Analysis of Switching Frequency Characteristics of Single-switch High Step-up DC-DC Converter with Three-winding Coupled Inductor. *IEEJ J. Ind. Appl.* **2021**, *10*, 682–687. [\[CrossRef\]](#)
3. Basu, A.; Mukherjee, S. Analysis and Design of a Multiport Converter based Integrated On-board Charger for Electric Vehicle Powertrains. In Proceedings of the 2021 IEEE ENERGY Conversion Congress and Exposition (ECCE 2021), Vancouver, BC, Canada, 10–14 October 2021; pp. 1661–1668. [\[CrossRef\]](#)
4. Yuan, H.; Hu, J.W.; Yu, H.Y.; Luo, P.; Li, J.Z.; Liu, Z.W. Temperature resistance of soft magnetic composites based on carbonyl iron powder for molding inductor. *Mater. Chem. Phys.* **2024**, *314*, 128808. [\[CrossRef\]](#)
5. Park, J.Y.; Park, K.; Fadonougbo, J.O.; Jang, K.R.; Park, S.D.; Park, C.S.; Mo, C.B.; Hwang, N.M.; Park, H.K. Enhancement of the magnetic properties of Fe-Si-Cr soft magnetic composite by selective oxidation annealing. *J. Magn. Magn. Mater.* **2022**, *561*, 169697. [\[CrossRef\]](#)
6. Haibo, S.; Ce, W.; Changbao, Z.; Jinghui, W. High-frequency loss analysis and related magnetic properties of Fe-based amorphous soft magnetic composites with different granularity matches. *J. Appl. Phys.* **2022**, *131*, 193903. [\[CrossRef\]](#)
7. Sarfraz, M.S.; Hong, H.; Kim, S.S. Lightweight thermoplastic coated soft magnetic composites (SMC) and application for high-efficiency brushless DC motors. *Compos. Struct.* **2023**, *320*, 117195. [\[CrossRef\]](#)
8. Cheng, H.; Li, X.H.; Zhang, L.Y.; Shen, F.Y.; Liu, X.G.; Sun, Y.P. Ultra-low core loss FeSiAl soft magnetic composites with in-situ double oxidation layers of outer Fe₃O₄ layer and inner super-thin Al₂O₃/SiO₂ hybrid layer. *Ceram. Int.* **2023**, *49*, 26568–26577. [\[CrossRef\]](#)
9. Guo, Z.L.; Wang, J.H.; Chen, W.H.; Chen, D.C.; Sun, H.B.; Xue, Z.L.; Wang, C. Crystal-like microstructural Finemet/FeSi compound powder core with excellent soft magnetic properties and its loss separation analysis. *Mater. Des.* **2020**, *192*, 108769. [\[CrossRef\]](#)
10. Sunday, K.J.; Taheri, M.L. Soft magnetic composites: Recent advancements in the technology. *Met. Powder Rep.* **2017**, *72*, 425–429. [\[CrossRef\]](#)
11. Wang, J.H.; Guo, Z.L.; Zeng, Q.T.; Hang, G.H.; Xue, Z.L.; Chen, D.C.; Liang, Z.K.; Sun, H.B. Magnetic properties regulation and loss contribution analysis for Fe-based amorphous powder cores doped with micron-sized FeSi powders. *J. Magn. Magn. Mater.* **2020**, *510*, 166931. [\[CrossRef\]](#)
12. Zang, B.W.; Song, L.J.; Parsons, R.; Shen, J.; Gao, M.; Zhang, Y.; Huo, J.T.; Sun, Y.H.; Li, F.S.; Suzuki, K.; et al. Influence of thermal history on the crystallization behavior of high-Bs Fe-based amorphous alloys. *Sci. China-Phys. Mech. Astron.* **2023**, *66*, 256111. [\[CrossRef\]](#)
13. Gutfleisch, O.; Willard, M.A.; Brück, E.; Chen, C.H.; Sankar, S.G.; Liu, J.P. Magnetic Materials and Devices for the 21st Century: Stronger, Lighter, and More Energy Efficient. *Adv. Mater.* **2011**, *23*, 821–842. [\[CrossRef\]](#)
14. Shokrollahi, H.; Janghorban, K. Different annealing treatments for improvement of magnetic and electrical properties of soft magnetic composites. *J. Magn. Magn. Mater.* **2007**, *317*, 61–67. [\[CrossRef\]](#)
15. Yang, S.; Xu, J.; Tian, M.Y.; Wang, J.; Yang, T.S.; Li, G.B.; He, Y.H.; Zeng, M.Q.; Liu, X. Microstructure evolution and soft magnetic properties of Fe-based nanocrystalline soft magnetic composites coated with lubricant. *Adv. Powder Technol.* **2023**, *34*, 104024. [\[CrossRef\]](#)
16. Lu, S.H.; Wang, M.G.; Zhao, Z.K. Recent advances and future developments in Fe-based amorphous soft magnetic composites. *J. Non-Cryst. Solids* **2023**, *616*, 122440. [\[CrossRef\]](#)
17. Zhou, B.; Dong, Y.Q.; Chi, Q.; Zhang, Y.Q.; Chang, L.; Gong, M.J.; Huang, J.J.; Pan, Y.; Wang, X.M. Fe-based amorphous soft magnetic composites with SiO₂ insulation coatings: A study on coatings thickness, microstructure and magnetic properties. *Ceram. Int.* **2020**, *46*, 13449–13459. [\[CrossRef\]](#)

18. Shi, L.X.; Hu, X.Y.; Li, Y.H.; Yuan, G.T.; Yao, K.F. The complementary effects of Fe and metalloids on the saturation magnetization of Fe-based amorphous alloys. *Intermetallics* **2021**, *131*, 107116. [[CrossRef](#)]
19. Dong, Y.Q.; Man, Q.K.; Zhang, J.J.; Chang, C.T.; Li, R.W.; Wang, X.M. Fabrication of FePbNbCr Glassy Cores With Good Soft Magnetic Properties by Hot Pressing. *IEEE Trans. Magn.* **2015**, *51*, 2006704. [[CrossRef](#)]
20. He, J.Y.; Yuan, H.; Nie, M.; Guo, H.; Yu, H.Y.; Liu, Z.W.; Sun, R. Soft magnetic materials for power inductors: State of art and future development. *Mater. Today Electron.* **2023**, *6*, 100066. [[CrossRef](#)]
21. Kim, T.H.; Jee, K.K.; Kim, Y.B.; Byun, D.J.; Han, J.H. High-frequency magnetic properties of soft magnetic cores based on nanocrystalline alloy powder prepared by thermal oxidation. *J. Magn. Magn. Mater.* **2010**, *322*, 2423–2427. [[CrossRef](#)]
22. Huang, H.H.; Zhang, R.; Sun, H.B.; Zhang, J.C.; Wang, J.H. High density Fe-based soft magnetic composites with nice magnetic properties prepared by warm compaction. *J. Alloys Compd.* **2023**, *947*, 169460. [[CrossRef](#)]
23. Gün, T.; Simsir, M. Effects of Molybdenum and Boron Additions of Fe-Based Metal Matrix Composites by Warm Compaction Method. *ACTA Phys. Pol. A* **2019**, *135*, 819–824. [[CrossRef](#)]
24. Zhang, H.; Zhang, L.; Dong, G.; Liu, Z.; Qin, M.; Qu, X. Effects of warm die on high velocity compaction behaviour and mechanical properties of iron based PM alloy. *Powder Metall.* **2016**, *59*, 100–106. [[CrossRef](#)]
25. Wu, M.L.; Li, Y.P.; Wang, X.; Chen, L.Z.; Mu, Y.Z. Anisotropic NdFeB/SmCoCuFeZr composite bonded magnet prepared by warm compaction process. *J. Rare Earths* **2017**, *35*, 1221–1225. [[CrossRef](#)]
26. Lee, J.G.; Lim, C.H.; Kim, H.S.; Hong, S.J.; Kim, M.T.; Kang, B.C.; Park, D.K.; Lee, M.K.; Rhee, C.K. Highly dense steel components prepared by magnetic pulsed compaction of iron-based powders. *Powder Technol.* **2012**, *228*, 254–257. [[CrossRef](#)]
27. Gheiratmand, T.; Hosseini, H.R.M.; Reihani, S.M.S. Iron-borosilicate soft magnetic composites: The correlation between processing parameters and magnetic properties for high frequency applications. *J. Magn. Magn. Mater.* **2017**, *429*, 241–250. [[CrossRef](#)]
28. Johnson, M.T.; Visser, E.G. A coherent model for the complex permeability in polycrystalline ferrites. *IEEE Trans. Magn.* **1990**, *26*, 1987–1989. [[CrossRef](#)]
29. Kim, H.R.; Jang, M.S.; Nam, Y.G.; Kim, Y.S.; Yang, S.S.; Kim, Y.J.; Jeong, J.W. Enhanced Permeability of Fe-Based Amorphous Powder Cores Realized through Selective Incorporation of Carbonyl Iron Powders at Inter-Particle Voids. *Metals* **2021**, *11*, 1220. [[CrossRef](#)]
30. Liu, X.R.; Zhang, Z.; Guo, W.H.; Zhang, R.B.; Xu, F. Ultra-low core loss and high permeability Fe-based amorphous soft magnetic composites with ultra-fine FeNi additives. *J. Mater. Sci.-Mater. Electron.* **2024**, *35*, 1655. [[CrossRef](#)]
31. Bertotti, G. General properties of power losses in soft ferromagnetic materials. *IEEE Trans. Magn.* **1988**, *24*, 621–630. [[CrossRef](#)]
32. Flohrer, S.; Schäfer, R.; McCord, J.; Roth, S.; Schultz, L.; Herzer, G. Magnetization loss and domain refinement in nanocrystalline tape wound cores. *ACTA Mater.* **2006**, *54*, 3253–3259. [[CrossRef](#)]
33. Feng, T.; Cheng, M.; Li, Y.H.; Zhang, Y.B.; Jiang, L.; Yang, L.; Zhang, W. Enhancing high-frequency soft magnetic performance of Fe-Si-B-Cu-Nb nanocrystalline alloy powder cores via hybridizing with FeNi. *Sci. China-Phys. Mech. Astron.* **2025**, *68*, 296111. [[CrossRef](#)]
34. Li, X.B.; Dong, Y.Q.; Wu, S.D.; Zhao, R.L.; Ding, Q.; Jia, X.J.; He, A.A.; Li, J.W.; Liu, X.C. Evolution of magnetic domain structure and magnetic properties of Fe-based nanocrystalline powder cores during transverse magnetic field annealing. *Adv. Powder Technol.* **2022**, *33*, 103823. [[CrossRef](#)]
35. Wang, B.; Zhang, Z.S.; Shen, J.B.; Tian, Y.; Wang, B.X.; Cai, L.W.; Liu, L.D.; Yu, Y.D.; Wang, G.D. Mechanism of adding carbonyl iron powder to enhance the magnetic properties of Fe-Si-B-Cu-Nb nanocrystalline soft magnetic composites. *J. Alloys Compd.* **2024**, *972*, 172812. [[CrossRef](#)]
36. Xia, C.; Peng, Y.D.; Yi, X.W.; Yao, Z.X.; Zhu, Y.Y.; Hu, G. Improved magnetic properties of FeSiCr amorphous soft magnetic composites by adding carbonyl iron powder. *J. Non-Cryst. Solids* **2021**, *559*, 120673. [[CrossRef](#)]
37. Ma, R.; Yu, P. The influences of matrix materials on the magnetic and mechanical properties of Fe78Si9B13 soft magnetic composites fabricated by injection molding. *Mater. Res. Bull.* **2021**, *139*, 111256. [[CrossRef](#)]
38. Ma, R.; Chang, L.; Ye, S.L.; Xie, H.Z.; Xiao, Q.; Zhang, L.A.; Si, J.J.; Yu, P. Magnetic properties of soft magnetic composites fabricated from amorphous Fe₇₃Si₁₁B₁₁C₃Cr₂ powder by hot pressing under a low pressure. *Powder Technol.* **2023**, *426*, 118639. [[CrossRef](#)]
39. MA, Y.; Xie, L.; Sun, X.T.; Zhang, C.L.; Li, Q.; Chi, Q.; Zhang, G. Magnetic properties of soft magnetic composites fabricated from FeSiPC amorphous powder by hot pressing molding. *J. Mater. Sci. Mater. Electron.* **2025**, *36*, 1915. [[CrossRef](#)]
40. Shi, G.B.; Li, M.R.; Wang, H.L.; Zang, J.A.; Yin, G.C.; Wang, M.X.; Wang, L. Effect of the shape and content for added iron powder on properties of nanocrystalline soft magnetic composites. *Mater. Today Commun.* **2024**, *39*, 108888. [[CrossRef](#)]
41. He, S.; Huang, X.; Li, A.; Wang, J.; Chen, Y.; Li, Q.; Zhang, Y.; Fei, J.; Huang, H.; Zhang, X. Dynamic magnetization process of low loss Fe/submicron FeNi soft magnetic composites for inductor. *J. Magn. Magn. Mater.* **2025**, *629*, 173275. [[CrossRef](#)]

42. Hsiang, H.I.; Fan, L.F. Magnetic Properties of the Soft Magnetic Composites Prepared Using Mixtures of Carbonyl Iron, FeSiCr, and FeSiAl Alloy Powders. *Materials* **2023**, *16*, 6033. [[CrossRef](#)] [[PubMed](#)]
43. Wang, F.L.; Dong, Y.Q.; Chang, L.; Pan, Y.; Chi, Q.; Gong, M.J.; Li, J.W.; He, A.N.; Wang, X.M. High performance of Fe-based soft magnetic composites coated with novel nano-CaCO₃/epoxy nanocomposites insulating layer. *J. Solid State Chem.* **2021**, *304*, 122634. [[CrossRef](#)]

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