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Enhancement of Soft Magnetic Properties in FeCo-2V Steels via Optimization of Annealing Temperature

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Electric vehicles are a key component in carbon neutrality policies, and electrical steels used in EV motors must exhibit high magnetic flux density and low core loss. The Fe-Co alloy is known for its high saturation magnetization; however, its brittleness limits its practical applications. The Fe-Co alloy overcame brittleness by adding vanadium, which expands the two-phase coexistence region of the ordered body-centered cubic structure (α phase) and face-centered cubic structure (γ phase). As a result, the α phase with good soft magnetic properties has a stable structure at room temperature. In this study, steel with thicknesses of 0.2 mm and 0.15 mm were heat-treated based on the differential scanning calorimetry (DSC) results to form the α phase, and their structural and magnetic properties were subsequently analyzed. 0.2 mm steel heat-treated at 775 °C had low coercivity (50.58 A/m) and a high magnetic flux density of 5000 A/m (2.14 T). 0.15 mm steel heat-treated at 850 °C had low coercivity (60.18 A/m) and a high magnetic flux density of 5000 A/m (2.22 T). The increase of coercivity observed at 900 °C is attributed to V-rich phases formed at grain boundaries, which likely act as pinning sites. The hysteresis loss of 0.15 mm steels in a DC environment had the lowest value at 800 °C, while under an AC environment, it had a minimum of 750 to 850 °C.

Keywords : Soft magnetic materials, Annealing, FeCo alloy, Electrical steel, Core loss

1. Introduction

Electrification, which replaces internal combustion engines with electric motors, is a core technology essential for the widespread adoption of electric vehicles (EVs), a key element in carbon neutrality policies. Soft magnetic materials, such as electrical steels, play a critical role in determining motor performance in EVs. The required properties for these materials include compact size, high performance, and low energy loss. Currently, Si-steels are predominantly used due to their advantageous properties. Among the key performance indicators of electrical steels are core loss and magnetic flux density. Core loss can be divided into hysteresis loss and eddy current loss [1, 2]. Since electrical steels are typically operated under alternating current (AC) magnetic fields, eddy current loss becomes particularly significant in high-frequency applications [3]. Si-steel is a soft magnetic material well-suited for these applications, offering high permeability and low loss due to its increased electrical resistivity. Eddy current loss is inversely proportional to electrical resistivity, and Si is an effective alloying element for increasing the resistivity of Fe. In addition to enhancing resistivity, silicon also improves magnetic properties by reducing the magnetic anisotropy constant and magnetostriction [4]. Efforts have been made to increase the Si content in Fe-Si alloys to further reduce eddy current loss; however, higher Si content leads to increased brittleness, limiting the practical use to a maximum of approximately 3.5 wt.% [4, 5]. Continued research led to the development of the chemical vapor deposition (CVD) method by JFE Steel Corporation in Japan, which enabled the incorporation of 6.5 wt.% Si [6]. While other methods, such as diffusion annealing, avoiding conventional rolling, were explored [7], CVD remains the only successfully commercialized process for producing high-Si steels. Subsequently, the FeCo-V alloy, which has the higher saturation magnetization, emerged and began to be used in applications requiring such properties [2, 8].

FeCo alloys, discovered in 1929 [9], exhibit excellent magnetic properties; however, because of their inherent

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brittleness at room temperature, they limit their practical applications. In 1932, a U.S. patent revealed that adding V could overcome this brittleness [10], enabling the alloy's use in applications requiring high saturation magnetization. Since then, various approaches have been explored to improve the mechanical properties of FeCo-based alloys, including grain refinement heat treatments, precipitation hardening, and the addition of alloying elements. Minor additions such as B, C, and Nb can improve mechanical properties but often deteriorate magnetic properties due to precipitate formation. Similarly, various alloying elements (Mo, W, Ti, etc.) reduce saturation magnetization by 1–5 %, mainly because of paramagnetic precipitates [4, 11–15]. Therefore, to achieve a desirable balance between mechanical and magnetic properties in FeCo-based alloys, the appropriate selection of alloying elements and optimization of final heat treatment conditions are crucial.

Research on element addition to improve the mechanical properties of FeCo-based alloy has been conducted in various ways. Kawahara and Uehara investigated various alloying elements and identified several that could enhance strength without significantly degrading the soft magnetic properties. Comparative studies on Ta, Nb, and V have shown that while Ta or Nb can also improve ductility, V is more effective in simultaneously enhancing resistivity and reducing loss [14–18].

Final heat treatment conditions—such as cooling rate, temperature, and duration—are critical factors that significantly influence electrical steels' mechanical and magnetic properties. Ren et al. investigated the effects of temperature, particle size, and the degree of long-range ordering on the mechanical strength of FeCo-based alloys [19]. In their study, specimens were cooled from 820 °C at rates of 30 °C/hr, 60 °C/hr, and 90 °C/hr, as well as by air cooling and quenching. They found that slower cooling rates promoted atomic ordering, which led to reduced mechanical strength due to increased brittleness. Yu et al. studied the relationship between microstructure and magnetic properties by varying cooling rates [20]. After heat treatment of FeCo-2V-Nb alloy at 820 °C for 2 hours, they applied 3×10^4, 90, and 30 °C/hr cooling rates. Their results showed that slower cooling increased the ordering parameter and grain size. At the slowest rate (30 °C/hr), a secondary phase formed along grain boundaries, which introduced a domain wall pinning effect, ultimately degrading the magnetic properties. In this way, the cooling rate affects mechanical and magnetic properties, and the heat treatment temperature is the same. Different structures form at different temperature ranges, which in turn affect the material's properties. For example, heat treatment above the temperature associated with a face-centered cubic (FCC) structure, followed by rapid quenching, enhances cold workability [21, 22]. When heat treatment is performed at a temperature above the temperature with an ordered body-centered cubic (BCC) structure, good soft magnetic properties are obtained [23]. The magnetic properties depend heavily on the microstructural characteristics and are especially affected by the grain size among them [24].

Building on these insights, the present study focuses on FeCo-2V steels, which were selected for their improved cold workability and advantageous loss characteristics. Since mechanical processing routes that enhance formability often lead to deterioration of magnetic properties, this work concentrates primarily on evaluating the magnetic performance. To this end, final annealing processes were conducted to determine the optimal conditions for achieving an ordered BCC structure with excellent magnetic properties. The effects of annealing temperature were systematically examined for steels with thicknesses of 0.15 mm and 0.2 mm, and the influence of thickness on magnetic behavior was also assessed. Furthermore, microstructural analyses were conducted to explain the correlation between annealing conditions and magnetic properties, and core losses were directly measured to assess the steels' suitability for electric motor environments.

2. Experiment

The electrical steel alloy (Fe 49 at.%, Co 49 at.%, V 2 at.%) was prepared under high vacuum conditions, maintaining a pressure below 10^{-5} torr during the melting process. Following homogenization at 1200 °C for 4 hours, the alloy was hot-rolled to a thickness of 6 mm. Subsequent annealing was conducted at 950 °C for 1 hour to facilitate cold rolling, followed by rapid quenching. Cold rolling was then performed to achieve final thicknesses of 0.15 mm and 0.2 mm. Specimens were sectioned into 100×10 mm² dimensions for subsequent heat treatment.

All heat treatments were performed for 2 hours in an argon atmosphere, and the heat treatment temperatures were determined based on differential scanning calorimetry (DSC) measurements. The DSC analysis was performed at a 20 °C/min heating rate from 20 °C to 1100 °C. For the 0.2 mm thickness steel, heat treatments were carried out in a high vacuum of 10^{-5} torr at 25 °C intervals between 700 °C and 900 °C, followed by furnace cooling. After heat treatment, the structural properties of the steels were analyzed using X-ray diffraction (XRD) with Cu-Kα radiation. Magnetic properties such as coercivity and magnetic flux density at 5000 A/m were measured using a DC B-H loop tracer.

For 0.15 mm thickness steel, heat treatments were performed in a low vacuum of 10^{-3} torr at 50 °C intervals between 700 °C and 900 °C, also followed by furnace cooling. The magnetic properties after heat treatment were measured under the same conditions as those for the 0.2 mm steels, and the microstructure was observed using a scanning electron microscope (SEM). Additionally, to investigate the increase in coercivity at 900 °C, the energy-dispersive X-ray spectroscopy (EDS) was analyzed. The core loss of each heat-treated 0.15 mm steel sample was measured at frequencies of 10, 50, 60, 100, 400, and 1000 Hz under a magnetic flux density of 1 T using an AC B-H loop tracer. The eddy current loss was also analyzed to evaluate the applicability of the materials. AC B-H loops were constructed for the steel specimens heat-treated at temperatures exhibiting superior magnetic properties. Among them, the loop labeled as "DC" was measured using a DC B-H loop tracer at H = 1 T, while the remaining loops were obtained under alternating current conditions using an AC B-H loop tracer.

3. Result and Discussion

According to the Fe-Co binary phase diagram [25], when the Co content ranges from approximately 29 to 74 at.%, the alloy forms an ordered BCC (α' phase) structure. Upon heating, the material undergoes an order-disorder transformation (from ordered BCC structure, α′ phase to disordered BCC structure, α phase), followed by a polymorphic transformation (from BCC structure, α phase to FCC structure, γ phase). For the equiatomic FeCo alloy, the order-disorder transformation occurs at around 730 °C, and the polymorphic transformation occurs at around 985 °C. In comparison with these values, the differential scanning calorimetry (DSC) curve shown in Fig. 1 demonstrates that the addition of 2 at.% V shifts both transformation temperatures downward. Specifically, the order-disorder transformation is observed at 710 °C, while the polymorphic transformation is observed at 963 °C. The peaks in the DSC curve indicate the following transformations: at 710 °C, transformation from α′ to α phase; at 963 °C, the transformation from α to α + γ phase; and at 982 °C, transformation from α + γ to γ phase. The addition of vanadium broadens the two-phase α + γ region and allows the α and γ phases to have a stable state at room temperature [26]. Based on these results, the 0.2 mm steels were annealed at 25 °C intervals between 700 °C and 900 °C to obtain the ordered BCC structure.

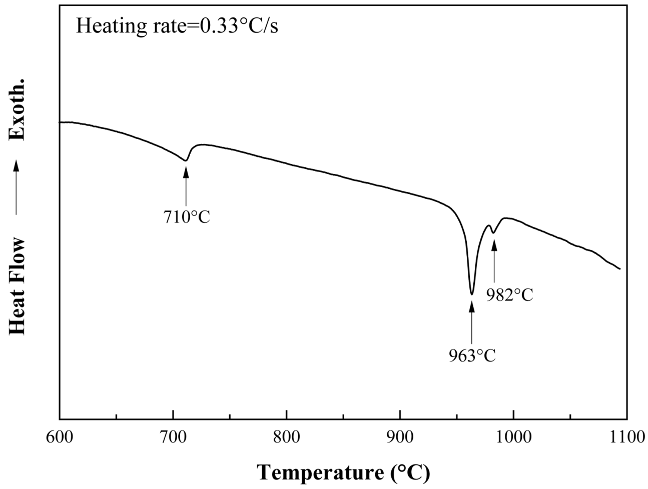

Fig. 1. DSC curve of as-rolled FeCo-2V steels (0.2 mm).

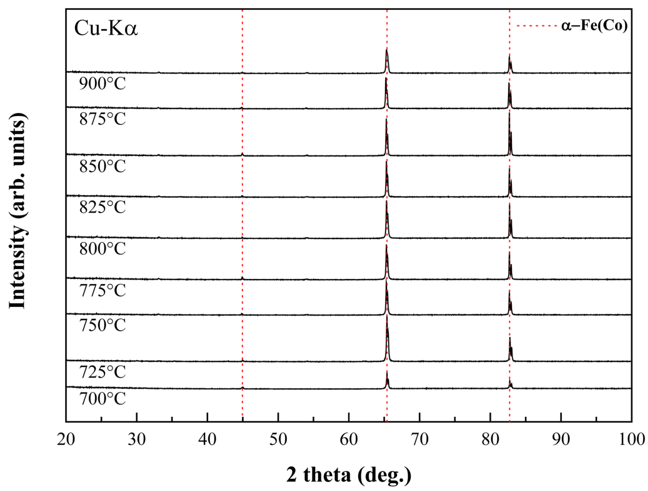

Fig. 2. (Color online) XRD graph of FeCo-2V steels (0.2 mm) after annealing.

To verify the formation of the desired phase in 0.2 mm steels after annealing, X-ray diffraction (XRD) analysis was conducted. As shown in Fig. 2, all annealed samples exhibited an ordered BCC structure (α′). As shown in the peak intensities at each annealing temperature in Fig. 2, it is estimated that the phase began to form at 700 °C, with significant grain growth occurring at 725 °C. The peak intensity remained at a high level compared to 700 °C, up to 850 °C, after which it decreased. In the XRD pattern of the BCC structure, three peaks are typically observed: the peak around 44° corresponding to the (110) plane, the peak around 65° corresponding to the (200) plane, and the peak around 82° corresponding to the (211) plane. In Fig. 2, the most intense peak after annealing appeared around 65°, followed by a secondary peak around 82°.

Table 1. Magnetic properties of FeCo-2V (0.2 mm steels) before and after annealing.

	B_{50} (T)	H_C (A/m)
as-rolled	0.53	2107
700 °C	2.09	106.1
725 °C	2.11	74.81
750 °C	2.03	53.23
775 °C	2.14	50.58
800 °C	2.10	61.69
825 °C	2.09	65.97
850 °C	2.04	59.33
875 °C	2.10	61.13
900 °C	1.94	115.7

As shown in Table 1, the samples exhibited a recovery of magnetic properties after annealing compared to as-rolled steel. B_{50}, which represents the magnetic flux density at an applied field of 5000 A/m, exceeded 2.0 T at all annealing temperatures except for 900 °C. This improvement in B_{50} is attributed to the formation of the α′ phase. A similar change can be observed in coercivity. Before annealing, the coercivity exceeded 2000 A/m, whereas after annealing, it significantly decreased, ranging from a maximum of 115 A/m to a minimum of 50.58 A/m. Since the coercivity of soft magnetic materials is generally considered to be below 100 A/m, it can be concluded that annealing at all temperatures except 700 °C and 900 °C effectively restores soft magnetic properties.

The tendency of coercivity and B_{50} according to temperature is shown in Fig. 3. A significant decrease in coercivity began at 725 °C, reaching a minimum at 750 °C. However, coercivity slightly increased at 800 °C,

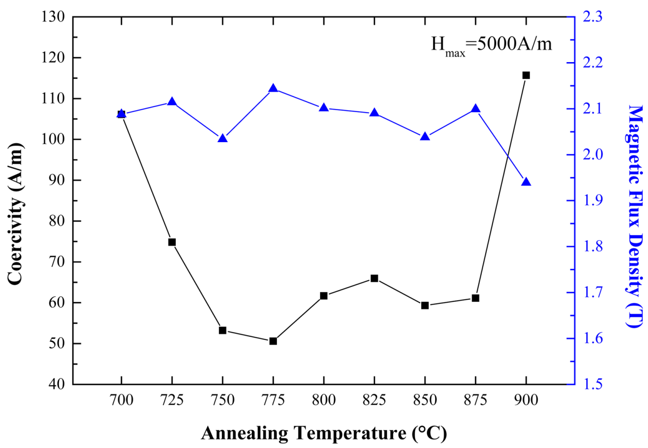

Fig. 3. (Color online) Tendency of coercivity and magnetic flux density at 5000 A/m (0.2 mm steels after annealing).

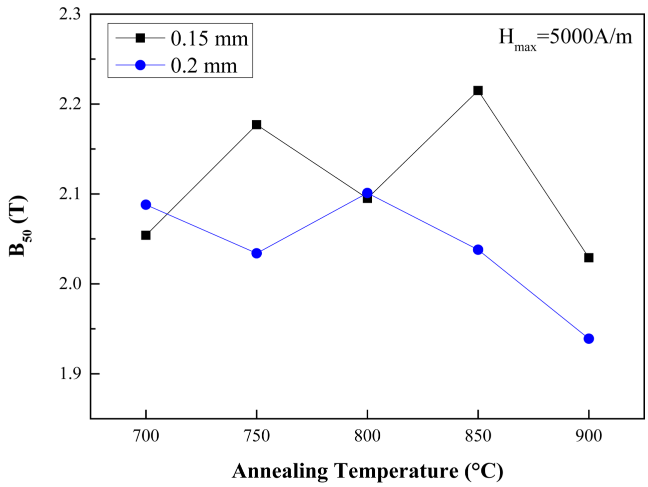

Fig. 4. (Color online) Comparison B_{50} between 0.2 mm and 0.15 mm steels.

decreased slightly again at 850 °C, and showed a sharp rise at 900 °C. This trend is attributed to stress relief, α′ phase formation, and grain growth during annealing. The optimal annealing temperature is 775 °C in 0.2 mm steels, which exhibited the highest B_{50} value of 2.14 T and the lowest coercivity of 50.58 A/m.

0.15 mm steels were annealed at 50 °C intervals between 700 °C and 900 °C. As shown in Table 2, the magnetic properties of the 0.15 mm steels were significantly improved after annealing, compared to as-rolled steels. Fig. 4 compares the B_{50} values of annealed 0.15 mm and 0.2 mm steels. The 0.15 mm steels generally exhibit higher B_{50} values than the 0.2 mm samples. The maximum B_{50} for 0.2 mm steel was 2.14 T, whereas the maximum for 0.15 mm steel reached 2.22 T. All annealed 0.15 mm samples showed B_{50} values exceeding 2.0 T. The high magnetic flux density at 5000 A/m indicates that the steels retain excellent magnetic performance under a high-current environment. Therefore, verification of these properties is essential for practical applications. Given the high B_{50} value, these steels are considered suitable for use in high-current environments.

Table 2. Magnetic properties 0f FeCo-2V steels (0.15 mm) before and after annealing.

	B_{50} (T)	H_C (A/m)	W_h (W/kg)@ DC
as-rolled	0.31	1671	0.36
700 °C	2.05	190	0.60
750 °C	2.18	80.59	0.49
800 °C	2.10	69.6	0.45
850 °C	2.22	60.18	0.46
900 °C	2.03	199	0.74

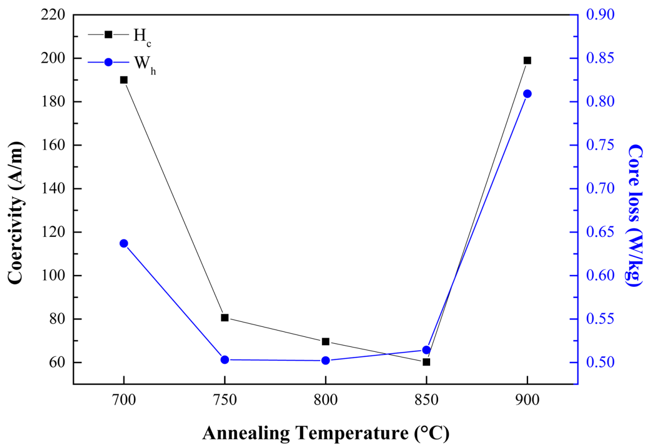

Fig. 5. (Color online) Tendency of coercivity and core loss (0.15 mm steels).

As shown in Fig. 5, the trends in coercivity and core loss at DC conditions for the annealed 0.15 mm steels follow a similar pattern. From 700 °C to 750 °C, both properties decreased sharply and remained at low values up to 850 °C. At 900 °C, however, both coercivity and core loss increased noticeably. The minimum core loss was 45 W/kg, observed at 800 °C, while the lowest coercivity was 60.18 A/m, measured at 850 °C.

Microstructural analysis was conducted using a scanning electron microscope (SEM) to investigate the origin of these changes in magnetic properties. As shown in Fig. 6, the annealed 0.15 mm samples underwent full recrystallization and grain growth. Recrystallization was observed at 700 °C, and grain growth began from 750 °C. Since grain size is inversely proportional to coercivity, an increase in grain size reduces coercivity on the micrometer scale [24]. The grain size of the samples annealed at 850 °C and 900 °C was the largest among all conditions and appeared similar. Therefore, coercivity reached its minimum at 850 °C, but increased again at 900 °C.

To investigate the cause of the increased coercivity observed at 900 °C, additional energy-dispersive X-ray spectroscopy (EDS) analysis was performed. As shown in Fig. 7, one point was selected from the matrix and

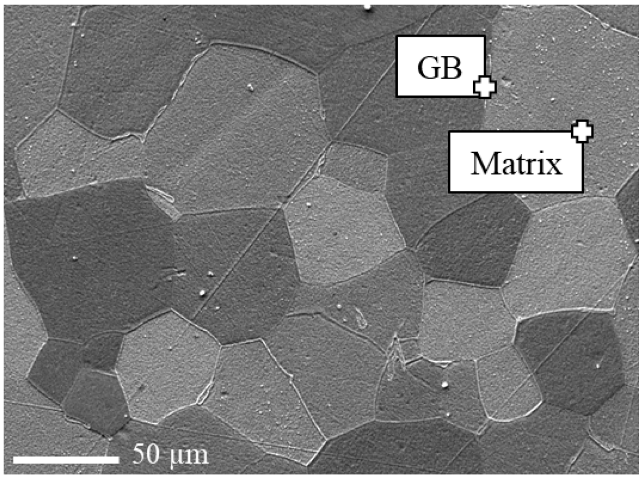

Fig. 7. The position of EDS analysis.

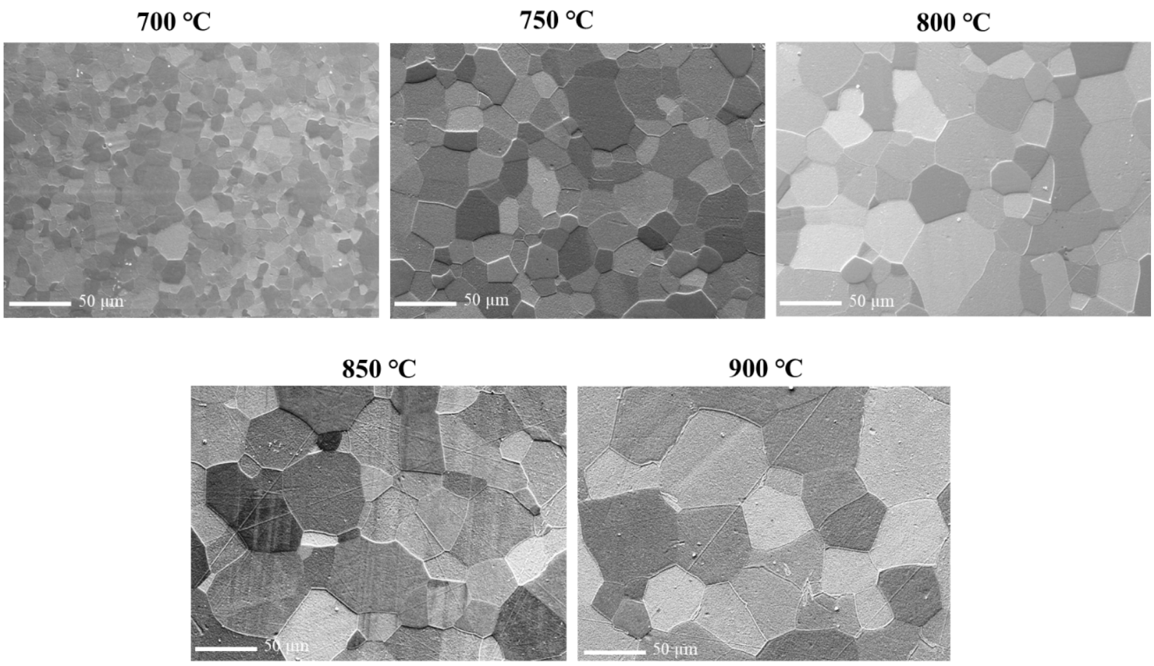

Fig. 6. Microstructure of FeCo-2V steels (0.15 mm) after annealing.

Table 3. Component of grain boundary and Matrix annealing at 850 °C and 900 °C through EDS analysis.

Atomic %	Grain Boundary (GB)		Matrix	
	850 °C	900 °C	850 °C	900 °C
Fe	50.39	46.36	51.71	49.95
Co	47.45	49.55	46.18	48.04
V	2.16	4.09	2.11	2.02

another from the grain boundary for composition analysis. The atomic percentages at each location are summarized in Table 3. The matrix at 850 °C contained 51.71 at.% Fe, 46.18 at.%, 2.11 at.% V and at 900 °C contained 49.9 at.% Fe, 48.04 at.% Co, and 2.02 at.% V, which is nearly identical to the prepared alloy composition. In contrast, the grain boundary at 900 °C exhibited a composition of 46.36 at.% Fe, 49.55 at.% Co, and 4.09 at.% V, suggesting partial substitution of Fe by V, while at 850 °C, exhibited a composition of 50.39 at.% Fe, 47.45 at.% Co, and 2.16 at.% V, which is similar to a matrix. This localized enrichment of V suggests the possible formation of a V-rich, non-magnetic phase at the grain boundaries, which likely acts as a domain wall pinning site [3, 12, 27, 28]. This microstructural analysis is estimated to contribute to the increased coercivity observed at 900 °C.

Fig. 8. presents the total core loss of annealed 0.15 mm steels measured at various frequencies using an AC B-H analyzer. Generally, steels annealed between 750 °C and 850 °C exhibited low core loss. The core loss increased with increasing frequency. At 50 Hz, the minimum core loss was 1.50 W/kg, observed in annealed steels at 750 °C. At 60 Hz, the lowest value was 1.76 W/kg at 850 °C. Similarly, at 100 Hz, 400 Hz, and 1 kHz, the minimum core loss values were 3.39 W/kg, 18.44 W/kg, and 69.14 W/kg, respectively, with all these minima corresponding to the steels annealed at 750 °C.

The total core loss (P_{total}) consists of hysteresis loss (P_h), eddy current loss (P_e), and anomalous loss (P_a). While all components of core loss increase with frequency, eddy current loss, in particular, is proportional

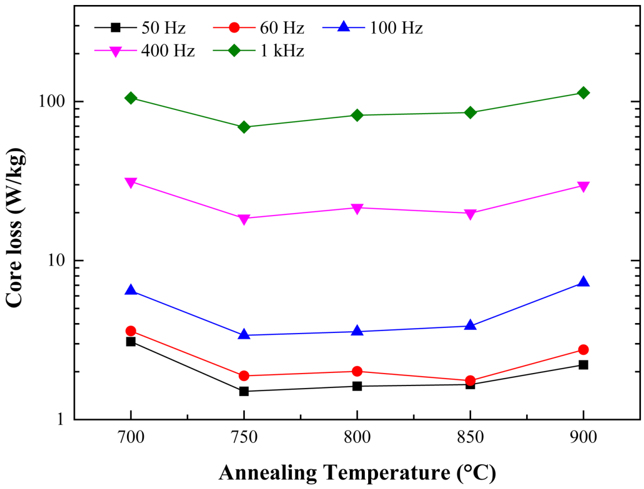

Fig. 8. (Color online) Core loss of FeCo-2V steels after annealing according to frequency.

to the square of the frequency and inversely proportional to the material's electrical resistivity.

$$P_h = W_h f \quad (1)$$

$$P_e \propto \frac{f^2 B_m^2 t^2}{\rho} \quad (2)$$

(B_m: amplitude of magnetic flux density, t: thickness, ρ: resistivity)

$$P_a = P_{total} - P_h - P_e \quad (3)$$

Using the above equation, the core loss of the annealed steel at 800 °C was analyzed, as this temperature exhibited the lowest hysteresis loss under DC conditions. Additionally, its behavior under AC conditions was examined to assess its applicability in practical magnetic applications. As frequency increased, the relative contribution of anomalous loss became higher compared to hysteresis loss, as summarized in Table 4. This trend is also shown in Fig. 9, which exhibits the B–H loops under both DC and AC conditions. At 50 Hz, hysteresis loss

Table 4. Decomposition of Core Loss Components by Frequency at 800 °C.

f	B_m	W_h		W_e		W_a		W_t
Hz	T	W/kg	%	W/kg	%	W/kg	%	W/kg
50	1	1.52	93.7	0.02	1.5	0.08	4.8	1.62
60	1	1.82	90.6	0.03	1.7	0.15	7.7	2.01
100	1	3.03	85.0	0.10	2.7	0.44	12.3	3.57
400	1	12.14	56.4	1.52	7.1	7.84	36.5	21.51
1000	1	30.34	37.0	9.53	11.6	42.11	51.4	81.97

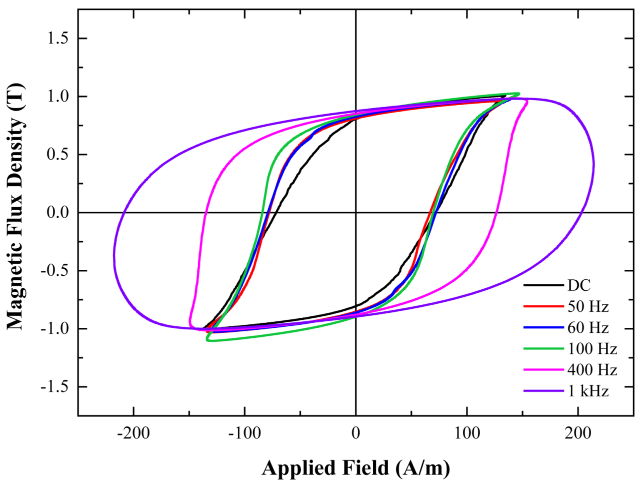

Fig. 9. (Color online) B-H loop of FeCo-2V annealed at 850 °C according to frequency.

dominated, accounting for 93.7% of the total core loss. However, at 1 kHz, its proportion dropped to 37.0%, while anomalous loss increased from 4.8% to 51.4%, becoming the dominant loss component. Eddy current loss contributed the least but showed a gradual increase with rising frequency.

4. Conclusion

Cold-rolled steels have a γ phase, which exhibits good ductility but poor magnetic properties. Therefore, the annealing process following cold rolling is essential for relieving stress and recovering magnetic properties. In this study, 0.2 mm and 0.15 mm steels were annealed at various temperatures, and the structure and magnetic properties of each steel were analyzed.

1. The annealing temperature was determined based on the DSC result, specifically near the peak's temperature (about ± 10 °C). Compared with the Fe-Co binary phase diagram, it was confirmed that the addition of V broadens the α + γ phase.

2. In the case of 0.2 mm steels, XRD analysis confirmed the formation of the α phase after annealing. As a result, the magnetic properties significantly improved compared to the as-rolled condition. Notably, at 775 °C, it exhibited the lowest coercivity of 50.58 A/m and the highest B_{50} of 2.14 T.

3. For the 0.15 mm steels, all annealed samples exhibited B_{50} exceeding 2.0 T, which is higher than that of annealed 0.2 mm steels. Those also are restored more than those of the steel before annealing. The coercivity and hysteresis loss at DC conditions showed similar trends. The lowest coercivity of 60.18 A/m was achieved at 850 °C, and the lowest hysteresis loss of 0.45 W/kg was observed at 800 °C.

4. To determine the increased coercivity at 900 °C, SEM and EDS analyses were performed. Through the SEM image, the full-annealing process can be observed, and through EDS analysis, the increase in coercivity at 900 °C is likely associated with domain wall pinning effects, possibly arising from the formation of a V-rich, non-magnetic phase at the grain boundary.

5. In AC magnetic conditions, the total core loss increased with frequency but remained relatively low between 750 °C and 850 °C. A detailed frequency-dependent decomposition of core loss at 800 °C, which exhibited the lowest hysteresis loss under DC conditions, showed a shift in the dominant loss mechanism from hysteresis to anomalous loss as the frequency increased.

The annealed FeCo-2V steels developed in this study exhibited superior magnetic properties—specifically, lower core loss under AC conditions and higher magnetic flux density (B_{50})—compared to commercially available Fe-Si steels. These results suggest that FeCo-2V steels are promising candidates for use in high-efficiency applications, particularly in electric vehicle motors.

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References

[1] D. Gautard, G. Couderchon, and L. Coutu, J. Magn. Magn. Mater. **160**, 359 (1996).
[2] G. Y. Chin and J. H. Wernick, in Handbook of Ferromagnetic Materials, Elsevier, Amsterdam (1980) pp. 55-188.
[3] R. S. Sundar, S. C. Deevi, and B. V. Reddy, J. Mater. Res. **20**, 1515 (2005).
[4] R. M. Bozorth, Ferromagnetism Wiley-IEEE Press, Hoboken (1993) pp. 67-101.
[5] M. A. Cunha and G. W. Johnson, J. Mater. Sci. **25**, 2481 (1990).
[6] Y. Takada, M. Abe, S. Masuda, and J. Inagaki, J. Appl. Phys. **64**, 5367 (1988).
[7] T. Ros-Yanez, Y. Houbaert, and V. Gómez Rodríguez, J. Appl. Phys. **91**, 7857 (2002).
[8] R. S. Sundar and S. C. Deevi, Intermetallics (Barking) 12, 1311 (2004).
[9] G. W. Elmen, US Patent No. 1,739,752 (1929).
[10] C. V. Wahl. J. H. White, US Patent No. 1,862,559 (1932).
[11] E. P. George, A. N. Gubbi, I. Baker, and L. Robertson, Materials Science and Engineering: A **329-331**, 325

(2002).
[12] R. H. Yu and J. Zhu, J. Appl. Phys. **97**, 053905 (2005).
[13] R. S. Sundar and S. C. Deevi, Intermetallics (Barking) **12**, 921 (2004).
[14] K. Kawahara and M. Uehara, J. Mater. Sci. **19**, 2575 (1984).
[15] A. I. C. Persiano and R. D. Rawlings, J. Mater. Sci. **26**, 4026 (1991).
[16] R. V. Major and C. M. Orrock, IEEE Trans. Magn. **24**, 1856 (1988).
[17] C.-W. Chen, Magnetism and Metallurgy of Soft Magnetic Materials (Dover Publications, Newyork (2013) pp. 239-367.
[18] R. V. Major and V. Samadian, Journal of Materials Engineering **11**, 27 (1989).
[19] L. Ren, S. Basu, R.-H. Yu, J. Q. Xiao, and A. Parvizi-Majidi, J. Mater. Sci. **36**, 1451 (2001).
[20] R. H. Yu, S. Basu, Y. Zhang, and J. Q. Xiao, J. Appl. Phys. **85**, 6034 (1999).
[21] K. Kawahara, J. Mater. Sci. **18**, 3427 (1983).
[22] A. A. Couto and P. I. Ferreira, Journal of Materials Engineering **11**, 31 (1989).
[23] E. Josso, IEEE Trans. Magn. **10**, 161 (1974).
[24] G. Herzer, IEEE Trans. Magn. **26**, 1397 (1990).
[25] T. Nishizawa and K. Ishida, Bulletin of Alloy Phase Diagrams **5**, 250 (1984).
[26] B. T. Hailer, Master's Theses, Effect of Heat Treatment on Magnetic and Mechanical Properties of an Iron-Cobalt-Vanadium-Niobium Alloy Virginia Tech, USA (2001).
[27] R. H. Yu, S. Basu, Y. Zhang, A. Parvizi-Majidi, and J. Q. Xiao, J. Appl. Phys. **85**, 6655 (1999).
[28] X. Zhang, D. Guoqiang, D. Jiao, and Z. Yuan, Journal of Magnetics **28**, 181 (2023).