

Influence of non-ferromagnetic Al/Cr ratio on microstructure, magnetic and corrosion properties of medium-entropy alloys

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Research Article

Keywords: Magnetic Properties, Mechanical Properties, Corrosion Resistance, Medium-entropy Alloys

Posted Date: October 14th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10823378/v1>

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Additional Declarations: No competing interests reported.

Abstract

A series of $\text{Fe}_2\text{Co}_4\text{Al}_x\text{Cr}_y$ ($x + y = 3$, $x = 1.0\text{--}2.0$) medium-entropy alloys were fabricated by vacuum arc melting. The effects of the Al/Cr ratio on the microstructure, hardness, magnetic properties, and electrochemical corrosion behavior were systematically investigated using XRD, SEM, VSM, microhardness testing, and electrochemical measurements. The results show that increasing Al content drives the microstructure evolution from an FCC + BCC dual-phase structure to a BCC+B2 dual-phase structure, with an intermediate FCC + BCC+B2 three-phase region at $x = 1.2$. The formation of the ordered B2 phase significantly enhances hardness, and the highest hardness is obtained at $x = 1.2$. Magnetic measurements reveal that increasing the Al/Cr ratio suppresses the antiferromagnetic contribution of Cr and strengthens ferromagnetic interactions, leading to improved magnetic performance. The $\text{Fe}_2\text{Co}_4\text{Al}_{1.8}\text{Cr}_{1.2}$ alloy exhibits the best soft magnetic properties, with a saturation magnetization of $128 \text{ emu}\cdot\text{g}^{-1}$ and a low coercivity of 5.97 Oe . Electrochemical results indicate that the corrosion resistance is strongly dependent on phase constitution and follows a decreasing–increasing–decreasing trend with increasing Al content. $\text{Fe}_2\text{Co}_4\text{Al}_{1.0}\text{Cr}_{2.0}$ exhibits the most noble corrosion potential (-0.459 V) and a low corrosion current density ($2.492 \times 10^{-6} \text{ A}\cdot\text{cm}^{-2}$), whereas $\text{Fe}_2\text{Co}_4\text{Al}_{1.6}\text{Cr}_{1.4}$ shows the highest impedance value ($1.90 \times 10^5 \Omega\cdot\text{cm}^2$), indicating the best overall corrosion resistance. The enhanced corrosion performance is attributed to the synergistic effect of the BCC+B2 dual-phase structure and a compact passive film enriched in Al and Cr oxides. Owing to its excellent combination of high saturation magnetization, low coercivity, and good corrosion resistance, $\text{Fe}_2\text{Co}_4\text{Al}_{1.8}\text{Cr}_{1.2}$ is a promising candidate for soft magnetic applications.

1 Introduction

Alloys with medium entropy (MEAs) that have a configurational entropy between 1.0 R and 1.5 R are now gaining more interest as they are characterized by its high mechanical properties, great resistance against corrosion, and notable structural stability [1–4]. The presence of high entropy leads to the formation of single-phase solid solutions with FCC, BCC, or HCP structures [5, 6]. There exist many MEA systems which have been studied extensively and BCC-structured MEAs in particular have shown higher mechanical properties with decent soft magnetic features, thereby positioning themselves as potential alloys with all-around properties in high performance alloys [4, 7, 8]. Recently, Fe-Co-based medium-entropy alloys have attracted increasing attention as promising soft magnetic materials because they combine high saturation magnetization, low coercivity and relatively high electrical resistivity. The addition of non-ferromagnetic elements can effectively regulate phase constitution and lattice distortion, thereby tailoring the magnetic performance [9]. Recent studies have demonstrated that compositional optimization is an effective strategy to achieve a desirable balance between soft magnetic properties and structural stability, making Fe-Co-based MEAs promising candidates for high-frequency electromagnetic devices and microelectronic applications [7, 10, 11].

Medium-entropy alloys (MEAs), an important subgroup in the class of high-entropy alloy systems, usually have three to four main constituents in equal atomic or nearly equal atomic amounts [12, 13]. Due to

their strong lattice distortion impact as well as the cocktail-effect, MEAs generally show better mechanical and functional characteristics than regular alloys yet retain basic phase structures [14, 15]. Using vacuum arc melting technology, which can offer a highly pure melting atmosphere, prevent oxidation reactions and ensure compositional homogenization, one of the most important methods of producing high-performance MEAs has emerged. The underlying principle behind this technique is that under vacuum conditions, the partial pressure of impurities is lower, allowing the real melting point of the alloy melt to rise. Input thermal energy controlled via variations of the arc power alters the liquid pool temperature as well as the solidification process.

The corrosion resistance of MEAs is primarily governed by their phase constitution, elemental distribution and passive film characteristics. Cr promotes the formation of compact Cr-rich oxide films, effectively suppressing anodic dissolution, whereas Al contributes to the formation of Al-containing passive oxides and increases electrical resistivity [16]. Recent studies have further indicated that lattice distortion, chemical short-range order and grain boundary characteristics significantly influence passive film stability and corrosion kinetics [17–19]. Therefore, optimizing the Al/Cr ratio is expected to simultaneously regulate corrosion resistance and magnetic performance in FeCoAlCr MEAs.

Despite intensive investigations carried out on the microstructure and mechanical properties of MEAs, detailed investigations regarding how the ratio of non-ferromagnetic alloying elements (Al and Cr) affects both their magnetic behavior and corrosion resistance have limited availability. This current study centers on the FeCoAlCr MEA system, with attention being paid to the control effect of varying ratios of Al/Cr, on the microstructure of the alloy, its electrochemical corrosion performance and magnetic properties. The objective is to provide the theoretical basis and hands-on advice on creating high-performance MEAs appropriate for magnetic components and micro electronic devices.

2 Materials and methods

$\text{Fe}_2\text{Co}_4\text{Al}_x\text{Cr}_y$ alloys with $x = 1.0, 1.2, 1.4, 1.6, 1.8$, and 2.0 (where $x + y = 3$) were made through vacuum arc melting of high-purity (99.95 wt.%) Fe, Co, Al, and Cr as starting materials. The ingots were re-melted and turned over at least 5 times so that they had uniformized chemistry. Once melted, the alloys were cooled down within the furnace to achieve a cast state. Further analysis samples were obtained by cutting the as-cast ingots with a wire electrical discharge machine and named them Sample 1–6 based on their x -value respectively.

Phase identification was performed using a D8A-A25 X-ray diffractometer (XRD). The surface morphology of the alloys was observed with an EVO 18 scanning electron microscope (SEM). Microhardness was measured using an HV-1000TPA micro-Vickers hardness tester. The magnetic properties were characterized using a vibrating sample magnetometer (VSM) to obtain hysteresis loops, from which the saturation magnetization and coercivity were determined.

Electrochemical tests were performed on the CHI760e electrochemical workstation. Electrochemical impedance spectroscopy measurement was done across frequencies of 0.01 Hz and 100,000 Hz.

Potentiodynamic polarization tests were performed to examine corrosion behavior in 3.5% NaCl solution under conventional three-electrode configuration, with saturated calomel electrode (SCE) being used as a reference electrode, a platinum plate functioning as a counter electrode and an alloy sample acting as a working electrode. The voltage was scanned between – 1.6 volts and 1 volt at a speed of 0.01 volts per second.

3 Results and discussion

3.1. X-ray diffraction analysis

Figure 1 X-ray diffraction pattern of $\text{Fe}_2\text{Co}_4\text{Al}_x\text{Cr}_y$ ($x + y = 3$, $x = 1.0, 1.2, 1.4, 1.6, 1.8, 2.0$)

Figure 1 shows the XRD patterns of the $\text{Fe}_2\text{Co}_4\text{Al}_x\text{Cr}_y$ ($x + y = 3$, $x = 1.0, 1.2, 1.4, 1.6, 1.8, 2.0$) alloys. It can be seen that when it has the least amount of Al ($x = 1.0$), the alloy is made up of a mixture of FCC and BCC solid solution phases. Such a phenomenon may be explained by the fact that there is a slight variation in atomic sizes and similar values of electronegativity within the components (Fe, Co, Cr), which are beneficial towards the creation of disordered solid solutions [20, 21]. With further increase in Al content ($x \geq 1.4$), distinct superlattice diffraction peaks (the ordered B2 phase) appear and intensify. This means that there has been a change in structure from a disordered solid solution into a solid that has a BCC matrix and an expanding volume fraction of the ordered B2 phase. A high negative enthalpy of mixing between aluminum and transition metals (Fe and Co) is responsible as a chemical ordering agent [22, 23].

In parallel to this, with the increase of x , all main diffractive peaks of the BCC/B2 phase shift in a systematic manner, towards low angles, which can be seen in the relevant lattice parameter table [24, 25]. It supports continuous lattice expansion, an indirect result of the substitution of smaller Cr atoms (atomic radius $\sim 1.28\text{\AA}$) by larger Al atoms (atomic radius $\sim 1.43\text{\AA}$) results in lattice expansion and peak shifting toward lower diffraction angles. As the atomic sizes are further mismatched, there will be substantial changes in the lattice geometry [26]. In the case where the Al content is high ($x = 1.4\text{--}2.0$) the phase pattern finally tends to be controlled by BCC and ordered BCC (B2) phases. This phase transition from a dual FCC + BCC structure to a predominant BCC/B2 structure is also consistent with the established role of Al as a major factor that stabilizes BCC/B2 structures in multi-principal alloy systems. Based on the analysis discussed earlier, it becomes clear that the level of Al/Cr content has a great effect on the crystal structure of the $\text{Fe}_2\text{Co}_4\text{Al}_x\text{Cr}_y$ alloys.

3.2. Microstructure and morphology

Figure 2 The microstructure and morphology of $\text{Fe}_2\text{Co}_4\text{Al}_x\text{Cr}_y$ ($x + y = 3$, $x = 1.0, 1.2, 1.4, 1.6, 1.8, 2.0$) alloys. (a) $\text{Fe}_2\text{Co}_4\text{Al}_{1.0}\text{Cr}_{2.0}$; (b) $\text{Fe}_2\text{Co}_4\text{Al}_{1.2}\text{Cr}_{1.8}$; (c) $\text{Fe}_2\text{Co}_4\text{Al}_{1.4}\text{Cr}_{1.6}$; (d) $\text{Fe}_2\text{Co}_4\text{Al}_{1.6}\text{Cr}_{1.4}$; (e) $\text{Fe}_2\text{Co}_4\text{Al}_{1.8}\text{Cr}_{1.2}$; (f) $\text{Fe}_2\text{Co}_4\text{Al}_{2.0}\text{Cr}_{1.0}$

The microstructure and morphology of the $\text{Fe}_2\text{Co}_4\text{Al}_x\text{Cr}_y$ ($x + y = 3$, $x = 1.0, 1.2, 1.4, 1.6, 1.8, 2.0$) alloys are shown in Fig. 2. It is noted that SEM observations of the images in Fig. 2 indicate that the microstructure of the alloys experiences a progressive change with an increasing Al/Cr ratio.

The alloy that has the smallest amount of aluminum ($x = 1.0$) has its morphology defined by a dark matrix interwoven through various bright lamellar phases which implies a multiphase solidification where both FCC and BCC are present [27, 28]. When the value of x goes up to 1.4, the microstructure experiences a profound change, starting to form a black-white striped/fibrous structure. The lined morphology remains at all higher values of x . Such microstructural changes in going from dual-phase (FCC+BCC) to a dual-phase structure made up by BCC and B2 will be consistent, in view of the greater quantity of Aluminium contributing significantly towards creation of the BCC phase [29].

The significant change in the microstructure is due to the phase stability and the solidification route being dependent on the Al/Cr content. The complex network structure of the initial stage at $x = 1.0$ is caused by the cooperative growth of several phases during non-equilibrium solidification, under which high Cr content helps to form and keep the disordered BCC phase [30]. Striations are observed with the development of fiber-like structures in the alloy composition above $x \geq 1.4$, which shows that the alloy composition has entered into a spinodal area of the BCC phase domain. The enhanced Al content, and thus reduced Cr leads the phase transition process to be driven by spinodal decomposition instead of nucleation and growth. Such structure exists when the maximum amount of Al is present ($x = 2.0$). It is well known that the addition of Cr favors the formation of the BCC phase over the B2 phase.

Consequently, as the ratio of Al/Cr increases, the structure evolves into a dual-phase of BCC/FCC to a striated fibrous structure owing to spinodal decomposition. This suggests that altering the Al/Cr content allows the regulation of both the solidification path and the self-assembled decomposition process of the Fe-Co-Al-Cr alloy system, allowing accurate structural design.

The formation of the characteristic striped (or fibrous) microstructure suggests that the metastable BCC solid solution undergoes spinodal decomposition, resulting in a continuous compositional modulation rather than a conventional nucleation-and-growth transformation [31]. During this process, the supersaturated BCC phase gradually decomposes into a Fe/Co-rich disordered A2 (BCC) phase and an Al-rich ordered B2 phase through uphill diffusion, giving rise to a characteristic nanoscale modulated morphology with coherent or semi-coherent interfaces [32]. The coherent BCC/B2 interfaces possess a low lattice misfit and interfacial energy, which not only suppress interfacial defects but also generate coherency strain fields that effectively impede dislocation motion, thereby improving strength while maintaining reasonable ductility. In addition, the nanoscale interconnected BCC/B2 network shortens diffusion distances and enhances microstructural stability during phase evolution [32]. More importantly, such coherent heterophase interfaces strongly influence magnetic domain-wall motion. Compared with incoherent interfaces, coherent BCC/B2 interfaces reduce local magnetic discontinuity and provide smoother domain-wall propagation paths, whereas the refined dual-phase distribution promotes a more homogeneous magnetic exchange interaction and decreases pinning at microstructural defects, thereby contributing to improved soft-magnetic behavior [11, 33]. Therefore, spinodal decomposition is not only

responsible for the evolution from the FCC/BCC microstructure to the BCC/B2 dual-phase structure, but also plays a key role in simultaneously tailoring the mechanical and magnetic properties through the formation of coherent heterophase interfaces.

3.3. Microhardness analysis

According to the Vickers hardness variation plot (Fig. 3) and the data shown in Table 1, the hardness of the alloys has a notable non-monotonic pattern when varying with the value of x . When the proportion of Al to Cr changes with the increase of x between 1.0 and 2.0, the alloy hardness initially rises dramatically, peaking at around $x = 1.2$ (approximately 650.6 HV_{0.2}) and then decline slowly until it falls to about 521.4 HV_{0.2} at $x = 2.0$.

The present variant has a close relationship with the change in microstructure and phase composition discussed earlier. The alloy is a two-phase state of the co-existence of FCC and BCC structures when x equals 1.0, which causes only slight initial hardness (about 390.2 HV_{0.2}). With an increase in x up to 1.2, more BCC phase comes out and dense phase-boundary network and interface play an effective role against dislocation movement, greatly improving the work hardening capacity, which finally results in obtaining the highest hardness [34]. Such an equilibrium point corresponds to the highest coercivity, and thus it can be concluded that microstructure at that particular moment has the highest pinning influence on both magnetic domain walls and crystal defects. Further on the addition of x ($x \geq 1.4$) will cause the alloy to become homogenous BCC /B2 two-phase system. The number of phase boundaries becomes weaker with additional Al/Cr content, decreasing the obstruction to the movement of dislocations, causing a slow reduction in hardness towards its peak. However, still the BCC /B2 phase may retain a rather high hardness level ($520 > \text{HV}_{0.2}$) through the solid solution strengthening effect produced by the alloy components like Al and Cr in the BCC phase [35]. Hence, the modification of the Al/Cr ratio will help to improve the total hardness of the alloy.

3.4. Magnetic performance analysis

Figure 4 (a) Hysteresis loop diagram of Fe₂Co₄Al _{x} Cr _{y} ($x + y = 3$, $x = 1.0, 1.2, 1.4, 1.6, 1.8, 2.0$) alloys. (b) Magnification of the central part of the hysteresis loop of Fe₂Co₄Al _{x} Cr _{y} ($x + y = 3$, $x = 1.0, 1.2, 1.4, 1.6, 1.8, 2.0$) alloys

According to the magnetic property graph Fig. 4(a) of the samples, the saturation magnetization (Ms) of the alloy shows an increasing and subsequently saturating trend with rising Al/Cr content. According to the enlarged image of the hysteresis loop (Fig. 4(b)) and Table 2, it can be seen that as the x value increases from 1.0 to 1.4, Ms rises significantly from approximately 30 emu/g to 127.34 emu/g. XRD analysis of the sample at $x = 1.4$ reveals that the transformation from a dual-phase FCC/BCC structure to a dual-phase BCC/B2 structure is already complete; therefore, Ms stabilizes and remains within the high range of 126–128 emu/g. At $x = 1.8$, Al continues to influence the ordering transition of the BCC phase into the B2 phase through its magnetic transformation effect, leading to a further increase in Ms. As the Al content increases further, a decrease in Ms and an increase in coercivity are observed at $x = 2.0$. This

indicates that the enhanced ordering of the BCC phase due to Al leads to greater lattice distortion, the magnetic transformation effect begins to weaken, and consequently, the soft magnetic properties of the alloy deteriorate [33].

With increasing Al content, two synergistic mechanisms contribute to the enhancement of magnetization. First, the gradual decrease in Cr concentration reduces the number of Fe–Cr nearest-neighbor pairs, thereby suppressing antiferromagnetic exchange interactions [37]. Second, Al promotes the formation of the ordered B2 structure, in which Fe and Co preferentially occupy one sublattice while Al mainly occupies the other [38, 39]. Such chemical ordering decreases the probability of Cr atoms occupying magnetically unfavorable nearest-neighbor configurations and strengthens Fe–Fe and Fe–Co ferromagnetic exchange interactions [37]. Density functional theory calculations reported in previous studies have demonstrated that Al-induced B2 ordering broadens the separation between majority- and minority-spin electronic states, increases exchange splitting, and consequently stabilizes the ferromagnetic state [38].

Moreover, Al itself carries almost no magnetic moment; however, by modifying the local electronic environment and reducing the d-electron hybridization associated with Cr, Al indirectly enhances the magnetic moments of Fe and Co atoms [38]. Therefore, the remarkable increase in saturation magnetization observed in the present alloy originates not only from the increased fraction of the BCC/B2 phase but also from the intrinsic strengthening of ferromagnetic exchange caused by the suppression of Cr-induced antiferromagnetic coupling [40]. Consequently, the alloy exhibits a pronounced enhancement in ferromagnetic ordering and saturation magnetization.

Meanwhile, the variation in coercivity (H_c) is more complex, characterized by an initial sharp increase followed by a continuous decrease. H_c reaches its maximum value (195.74 Oe) at $x = 1.2$, then drops rapidly when $x \geq 1.4$, falling to its minimum (5.97 Oe) at $x = 1.8$. With the sample where $x = 1.6$, the XRD peak position goes down, the interplanar distance rises, and the lattice parameter of the bcc phase becomes larger. The release of such small-scale internal strain reduces the influence of the internal strain pinning and decreases the coercive force [9]. This non-monotonic change is a direct manifestation of the variation in pinning strength exerted by micro-defects and phase boundaries on magnetic domain walls. Combined with SEM analysis, in the composition range of $x = 1.0$ – 1.2 where the alloy exists as a dual-phase mixture, the fine lamellar structure generates a high density of phase boundaries. These boundaries act as strong pinning sites for domain walls, leading to the increase in H_c . At $x = 1.2$, the specific ratio of the two phases results in the strongest pinning effect, corresponding to the peak coercivity [11]. This composition also coincides with the peak hardness, jointly confirming that the microstructure at this stage exerts the strongest impediment to both dislocation movement and magnetic domain wall motion. As the value of x increases to 1.4 or above, the alloy transforms into a homogeneous BCC/B2 two-phase structure. The BCC/B2 phase boundaries exert a weaker hindrance to magnetic domain wall motion compared to FCC/BCC phase interfaces, which accounts for the significant reduction in coercivity [11]. The resistance to domain wall motion decreases considerably leading to a sharp decrease in H_c within the low range values needed to produce high quality soft

magnetic materials. In conclusion, a proper adjustment of the Al/Cr ratio allows controlling both the magnetization and coercivity of this alloy.

Figure 5 (a) Nyquist curves of $\text{Fe}_2\text{Co}_4\text{Al}_x\text{Cr}_y$ ($x = 1.0, 1.2, 1.4, 1.6, 1.8, 2.0$, $x + y = 3$) alloys. (b) Polarization curve

3.5 Electrochemical corrosion performance

The Nyquist plots and potentiodynamic polarization curves of the $\text{Fe}_2\text{Co}_4\text{Al}_x\text{Cr}_y$ alloys measured in 3.5 wt.% NaCl solution at room temperature are presented in Fig. 5(a) and (b), respectively, and the corresponding electrochemical parameters are summarized in Table 3. As the Al/Cr ratio increases, the corrosion behavior exhibits a pronounced non-monotonic trend. The corrosion potential (E_{corr}) initially shifts toward more negative values, subsequently shifts positively, and then decreases again with further increasing Al content, whereas the corrosion current density (I_{corr}) exhibits the opposite trend.

However, when the Al content is further increased to $x = 1.8$ and 2.0 , the corrosion resistance decreases again. Although the BCC+B2 dual-phase structure remains stable, the continuous substitution of Cr by Al gradually reduces the Cr content in the alloy, thereby weakening the formation and protective capability of Cr-rich passive oxides. Previous studies have indicated that excessive Al addition may also increase the fraction of Cr-depleted regions and alter the composition of the passive film, resulting in a thicker but less protective oxide layer with increased susceptibility to chloride-induced breakdown [48, 49]. Consequently, the stability of the passive film decreases and localized corrosion becomes more likely. As a result, the corrosion current density increases while the impedance value decreases, leading to a deterioration in corrosion resistance. Therefore, the corrosion resistance of the $\text{Fe}_2\text{Co}_4\text{Al}_x\text{Cr}_y$ alloys exhibits a trend of initially decreasing, subsequently increasing, and finally decreasing with increasing Al/Cr ratio.

Based on the combined results of potentiodynamic polarization and EIS measurements, $\text{Fe}_2\text{Co}_4\text{Al}_{1.4}\text{Cr}_{1.6}$ exhibits the lowest corrosion current density, while $\text{Fe}_2\text{Co}_4\text{Al}_{1.6}\text{Cr}_{1.4}$ shows the highest impedance modulus and the most stable passive film. Therefore, both alloys demonstrate superior corrosion resistance from the perspectives of corrosion kinetics and passive-film protection, respectively. In contrast, the $\text{Fe}_2\text{Co}_4\text{Al}_{1.2}\text{Cr}_{1.8}$ alloy shows the poorest corrosion resistance due to severe micro-galvanic corrosion induced by the FCC + BCC+B2 three-phase microstructure. Meanwhile, the $\text{Fe}_2\text{Co}_4\text{Al}_{1.0}\text{Cr}_{2.0}$ alloy possesses the most noble corrosion potential and a relatively low corrosion current density, indicating a low corrosion tendency and good corrosion resistance. The corrosion behavior is governed primarily by phase constitution rather than elemental concentration alone. The FCC + BCC+B2 three-phase microstructure exhibits the poorest corrosion resistance due to severe micro-galvanic corrosion, whereas the BCC+B2 dual-phase structure promotes the formation of a compact and stable passive film, resulting in superior corrosion resistance.

4 Conclusions

In this study, as-cast $\text{Fe}_2\text{Co}_4\text{Al}_x\text{Cr}_y$ ($x = 1.0, 1.2, 1.4, 1.6, 1.8, 2.0$, $x + y = 3$) alloy samples were fabricated using vacuum arc melting. By varying the Al/Cr ratio to tailor the alloy's microstructure, we aimed to improve its overall properties and examine the influence of nonmagnetic elements on its magnetic transition behavior. The main findings are summarized as follows.

1. The $\text{Fe}_2\text{Co}_4\text{Al}_{1.0}\text{Cr}_{2.0}$ alloy consists of BCC and FCC dual phases. With increasing Al/Cr content, it gradually transforms into a BCC/B2 dual-phase structure. The alloy hardness shows a trend of first increasing and then decreasing, with the $\text{Fe}_2\text{Co}_4\text{Al}_{1.2}\text{Cr}_{1.8}$ alloy reaching the highest hardness of 650.6 HV_{0.2}.
2. The proportion of non-ferromagnetic elements can induce ferromagnetic transition behavior and magnetic ordering evolution in the samples. As the Al/Cr ratio increases, the alloy undergoes a notable magnetic transition, and its soft magnetic properties are significantly improved. Specifically, the $\text{Fe}_2\text{Co}_4\text{Al}_{1.8}\text{Cr}_{1.2}$ alloy exhibits the highest saturation magnetization and the lowest coercivity, representing the composition with the optimal soft magnetic performance.
3. The $\text{Fe}_2\text{Co}_4\text{Al}_{1.0}\text{Cr}_{2.0}$ alloy exhibits the most noble corrosion potential (– 0.459 V) and a relatively low corrosion current density (2.49×10^{-6} A/cm²), indicating the lowest thermodynamic tendency toward corrosion. As the Al/Cr ratio increases, the $\text{Fe}_2\text{Co}_4\text{Al}_{1.4}\text{Cr}_{1.6}$ alloy shows the lowest corrosion current density (2.36×10^{-6} A/cm²), while electrochemical impedance spectroscopy reveals that the $\text{Fe}_2\text{Co}_4\text{Al}_{1.6}\text{Cr}_{1.4}$ alloy possesses the highest impedance value, indicating the formation of the most stable passive film and the best overall corrosion resistance.
4. The $\text{Fe}_2\text{Co}_4\text{Al}_{1.8}\text{Cr}_{1.2}$ alloy exhibits an excellent combination of magnetic, mechanical, and corrosion properties. Although its corrosion resistance is slightly lower than that of the $\text{Fe}_2\text{Co}_4\text{Al}_{1.6}\text{Cr}_{1.4}$ alloy, it still maintains a relatively low corrosion current density (4.65×10^{-6} A/cm²) and good passivation behavior. In addition, the alloy achieves a high hardness of 562.0 HV_{0.2}. Magnetically, it exhibits a high saturation magnetization of 128.06 emu/g and a low coercivity of 5.97 Oe, demonstrating superior comprehensive performance.
5. By tailoring the ratio of non-ferromagnetic elements in the $\text{Fe}_2\text{Co}_4\text{Al}_x\text{Cr}_y$ alloys, it is possible not only to alter the phase composition but also to achieve synergistic optimization of the magnetic properties and corrosion resistance.

Declarations

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

Thank you very much for the Guangxi Key Research and Development Program: Research and Industrialization of Key Technologies for High-Strength Steel Roll-Formed Power Battery Trays with CTB

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Tables

Tables are available in the Supplementary Files section.

Figures

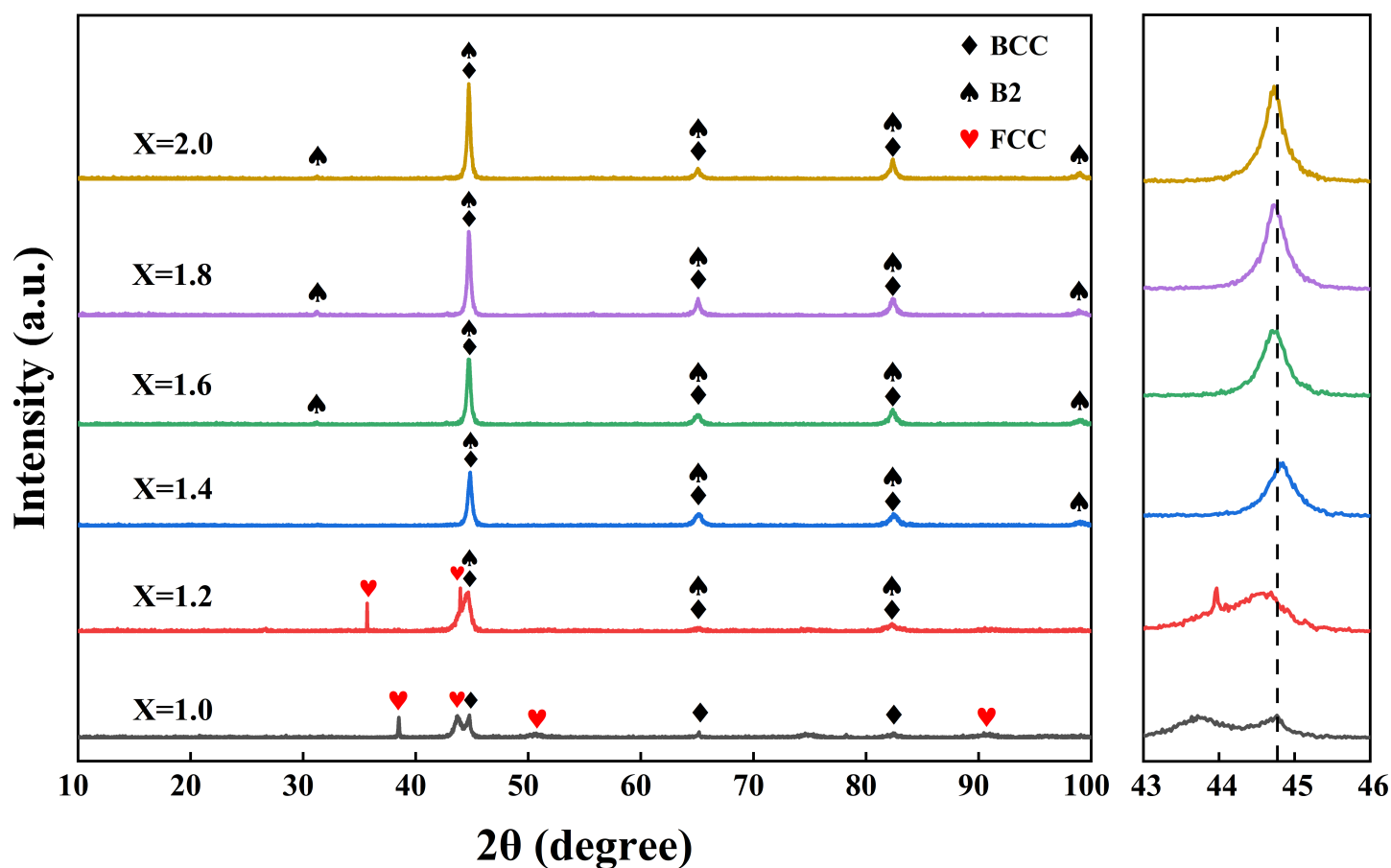


Figure 1

X-ray diffraction pattern of $\text{Fe}_2\text{Co}_4\text{Al}_x\text{Cr}_y$ ($x + y = 3$, $x = 1.0, 1.2, 1.4, 1.6, 1.8, 2.0$)

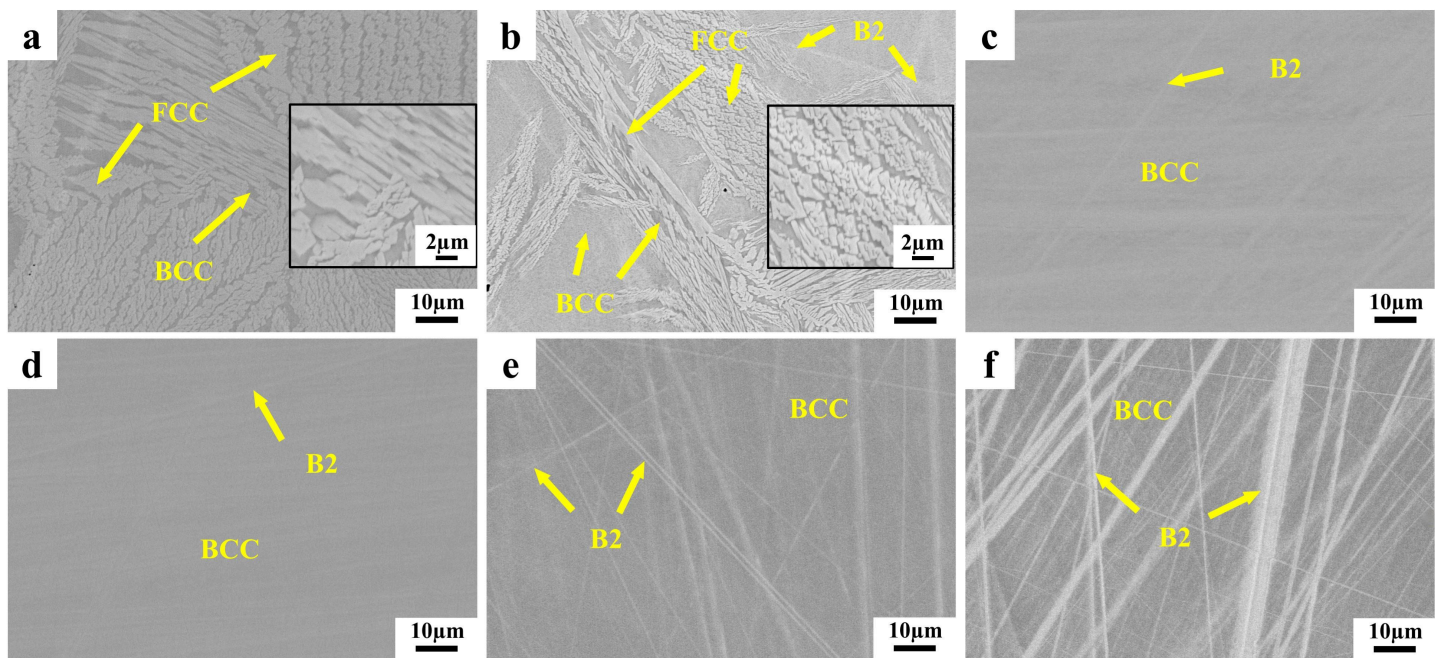


Figure 2

The microstructure and morphology of $\text{Fe}_2\text{Co}_4\text{Al}_x\text{Cr}_{3-x}$ ($x + y = 3$, $x = 1.0, 1.2, 1.4, 1.6, 1.8, 2.0$) alloys. (a) $\text{Fe}_2\text{Co}_4\text{Al}_{1.0}\text{Cr}_{2.0}$; (b) $\text{Fe}_2\text{Co}_4\text{Al}_{1.2}\text{Cr}_{1.8}$; (c) $\text{Fe}_2\text{Co}_4\text{Al}_{1.4}\text{Cr}_{1.6}$; (d) $\text{Fe}_2\text{Co}_4\text{Al}_{1.6}\text{Cr}_{1.4}$; (e) $\text{Fe}_2\text{Co}_4\text{Al}_{1.8}\text{Cr}_{1.2}$; (f) $\text{Fe}_2\text{Co}_4\text{Al}_{2.0}\text{Cr}_{1.0}$

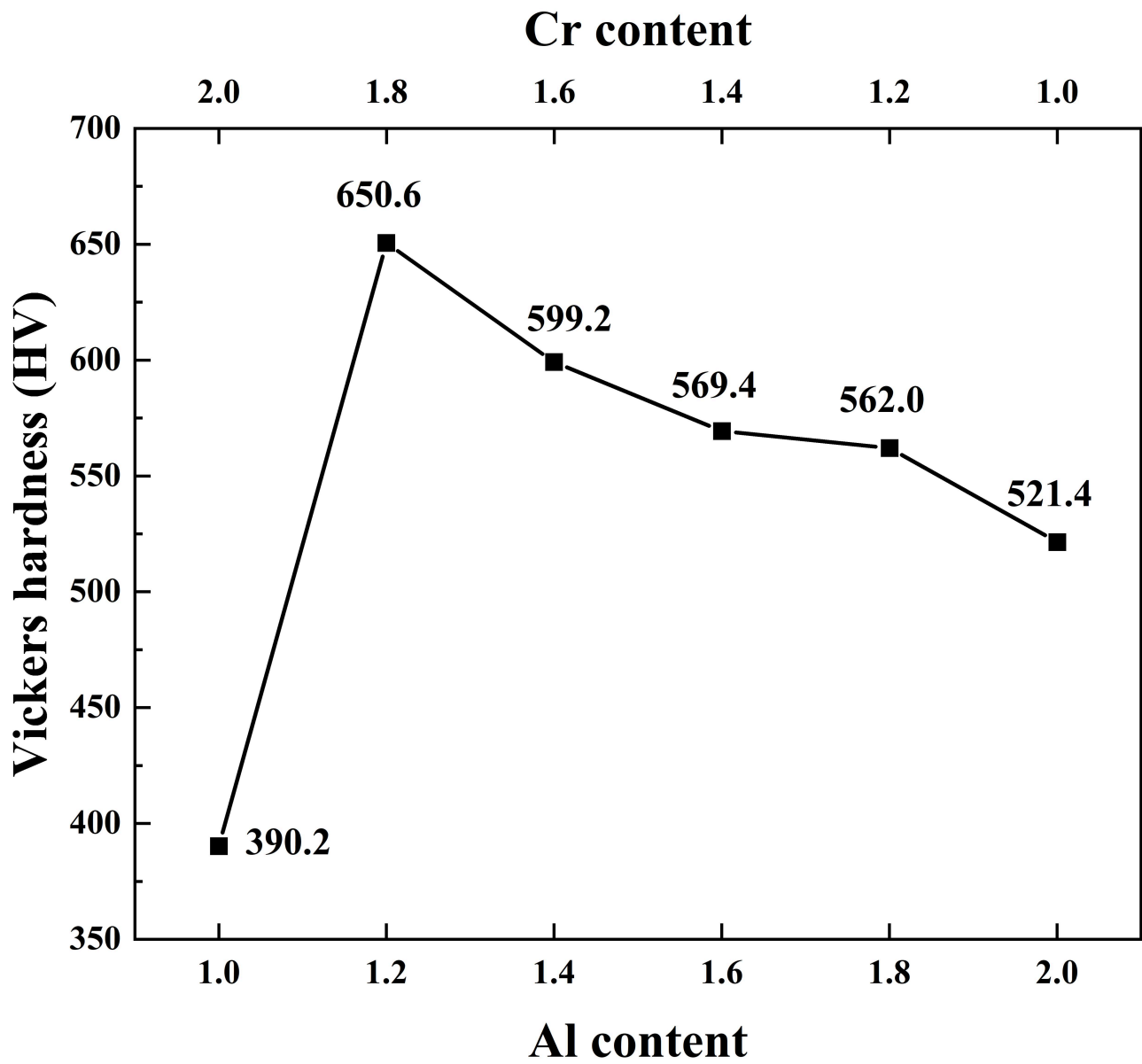


Figure 3

Microhardness variation curve of $\text{Fe}_2\text{Co}_4\text{Al}_x\text{Cr}_{3-x}$ ($x = 1.0, 1.2, 1.4, 1.6, 1.8, 2.0$, $x + y = 3$) alloys ($\text{HV}_{0.2}$)

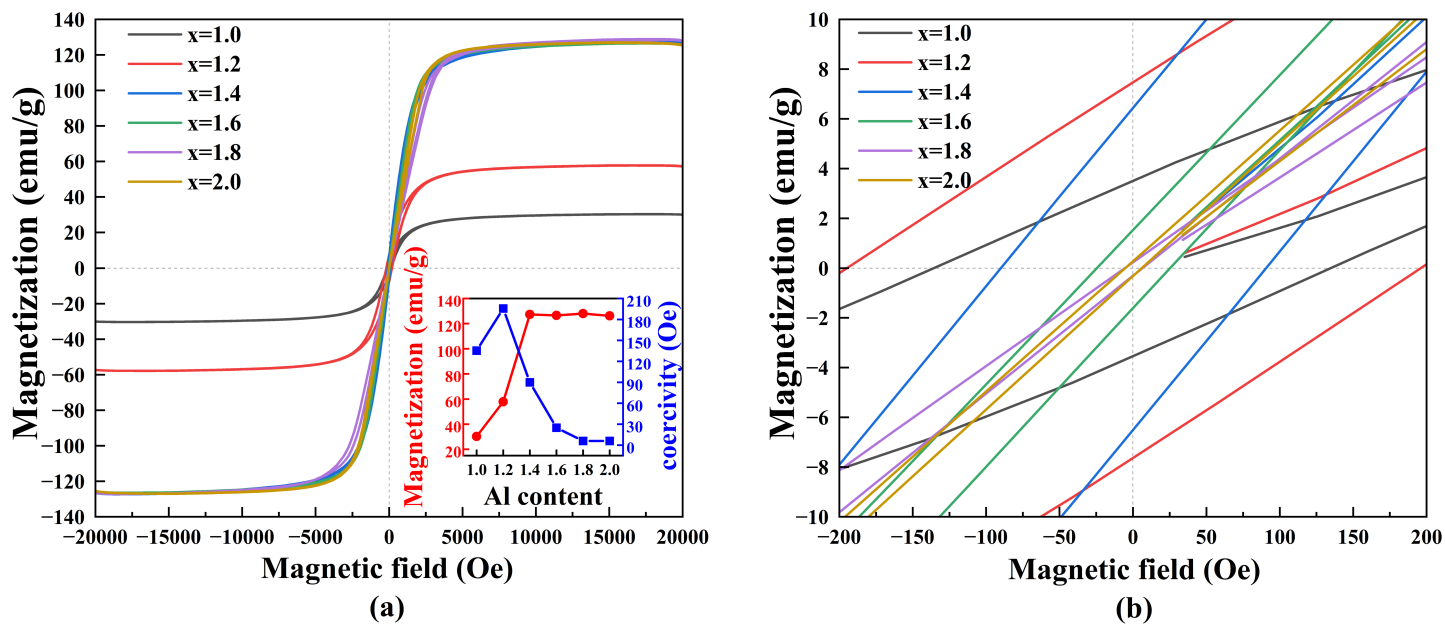


Figure 4

(a) Hysteresis loop diagram of $\text{Fe}_2\text{Co}_4\text{Al}_x\text{Cr}_y$ ($x + y = 3$, $x = 1.0, 1.2, 1.4, 1.6, 1.8, 2.0$) alloys. (b) Magnification of the central part of the hysteresis loop of $\text{Fe}_2\text{Co}_4\text{Al}_x\text{Cr}_y$ ($x + y = 3$, $x = 1.0, 1.2, 1.4, 1.6, 1.8, 2.0$) alloys

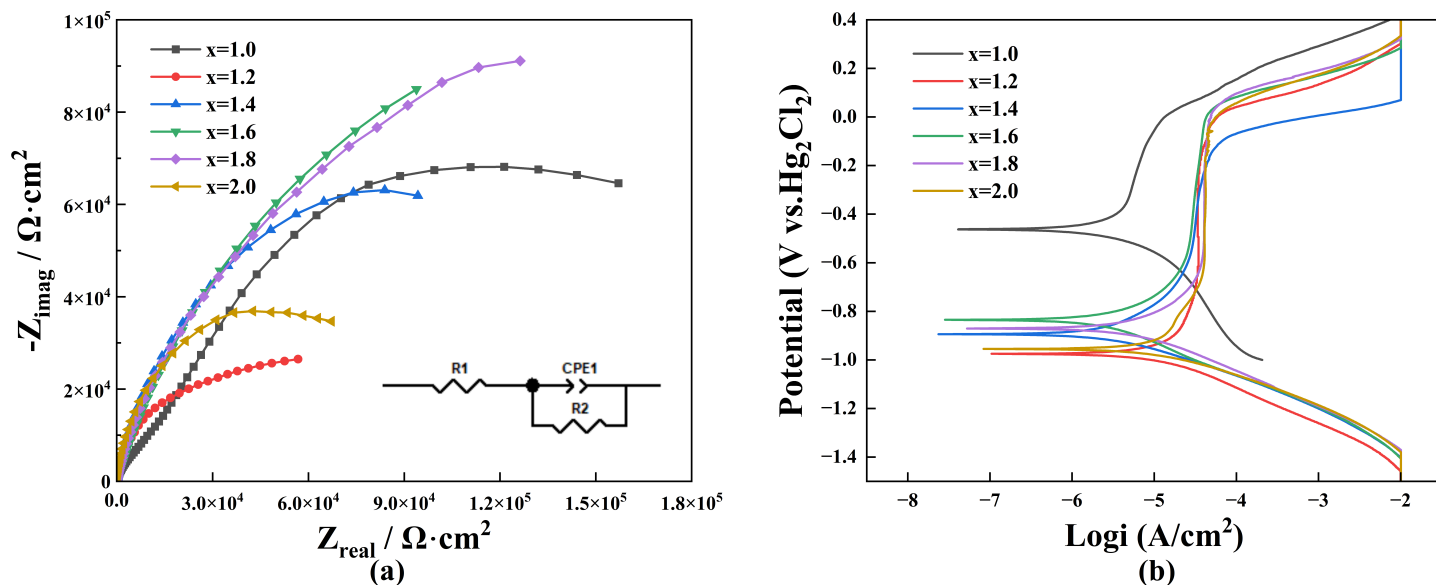


Figure 5

(a) Nyquist curves of $\text{Fe}_2\text{Co}_4\text{Al}_x\text{Cr}_y$ ($x = 1.0, 1.2, 1.4, 1.6, 1.8, 2.0$, $x + y = 3$) alloys. (b) Polarization curve

Supplementary Files

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