

## PRODUCTION OF MULTI COMPONENT AND HIGH ENTROPY ALLOYS AND THEIR PHYSICAL PROPERTIES

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**Abstract:** Multi-component and high-entropy alloys (HEAs) have attracted significant attention as a new class of advanced materials due to their unique composition-driven properties and simple phase structures. Unlike conventional alloys, which are based on one principal element, HEAs consist of multiple principal elements in near-equiatomic proportions, resulting in high configurational entropy and unusual physical behavior. In this study, multi-component and high-entropy alloys were synthesized using vacuum arc melting and mechanical alloying followed by spark plasma sintering. The effects of fabrication routes on phase formation, microstructure, and physical properties were systematically investigated. X-ray diffraction analysis revealed predominantly FCC and BCC solid-solution phases, indicating effective entropy-driven phase stabilization. Microstructural observations showed that mechanically alloyed samples exhibited ultrafine-grained structures, while arc-melted alloys displayed coarser but chemically homogeneous microstructures. The investigated alloys demonstrated high hardness, stable elastic modulus, moderate electrical conductivity, low thermal expansion coefficients, and tunable magnetic behavior. The results confirm that both chemical composition and processing route play critical roles in tailoring the physical properties of high-entropy alloys. This study provides valuable insights into structure–property relationships in multi-component alloy systems and supports the potential of high-entropy alloys for next-generation structural and functional applications.

**Keywords:** High-entropy alloys; Multi-component alloys; Physical properties; Mechanical alloying; Microstructure; Phase stability

### Introduction

In recent decades, the rapid development of advanced engineering systems has imposed increasingly stringent requirements on structural and functional materials. Conventional alloy design strategies, which typically rely on one principal element with minor alloying additions, often face intrinsic limitations in achieving an optimal balance between strength, ductility, thermal stability, and corrosion resistance [1]. In response to these challenges, multi-component alloys and, in particular, high-entropy alloys (HEAs) have emerged as a revolutionary class of materials with exceptional physical and mechanical properties [2].

High-entropy alloys were first proposed at the beginning of the 21st century as metallic systems composed of five or more principal elements in near-equiatomic proportions [2]. Unlike traditional alloys, HEAs are characterized by a high configurational entropy of mixing, which plays a dominant role in stabilizing simple solid-solution phases such as face-centered cubic (FCC), body-centered cubic (BCC), or hexagonal close-packed (HCP) structures [3]. This entropy-driven stabilization suppresses the formation of brittle intermetallic compounds and



significantly alters phase formation mechanisms, diffusion kinetics, and defect behavior within the alloy system [3].

Multi-component alloys, including HEAs, exhibit several unique physical phenomena that distinguish them from conventional materials. These include the high-entropy effect, severe lattice distortion, sluggish diffusion, and the so-called cocktail effect [3,4], which collectively contribute to their outstanding performance. As a result, HEAs have demonstrated remarkable mechanical strength over a wide temperature range, enhanced wear and corrosion resistance, superior thermal stability, and promising magnetic and electrical properties [4]. Such characteristics make them highly attractive for applications in aerospace, nuclear energy, biomedical devices, and high-temperature industrial environments [4,5].

The production routes of multi-component and high-entropy alloys play a crucial role in determining their final microstructure and physical properties. Common fabrication methods include vacuum arc melting, induction melting, powder metallurgy, mechanical alloying, and advanced additive manufacturing techniques [5]. Each method influences elemental distribution, grain size, phase composition, and defect density, thereby directly affecting physical properties such as hardness, elastic modulus, electrical conductivity, thermal expansion, and magnetic behavior [5].

Despite the growing body of research, several fundamental aspects of high-entropy alloy design remain insufficiently understood. In particular, the relationships between chemical composition, processing conditions, microstructural evolution, and resulting physical properties require further systematic investigation [4,5]. A deeper understanding of these correlations is essential for tailoring HEAs with application-specific properties and for advancing predictive alloy design frameworks [5].

Therefore, the present study aims to provide a comprehensive analysis of the methods for producing multi-component and high-entropy alloys and to evaluate their key physical properties. By integrating experimental findings and theoretical considerations, this work seeks to contribute to the optimization of HEA systems and to expand their potential for next-generation engineering applications [5].

## Materials and Methods

Multi-component and high-entropy alloys investigated in this study were designed based on near-equiatomic compositions consisting of five or more principal metallic elements selected according to atomic size difference, mixing enthalpy, and valence electron concentration criteria. High-purity elemental raw materials ( $\geq 99.9$  wt.%) were used to minimize the influence of impurities on phase formation and physical properties. The alloy ingots were synthesized using vacuum arc melting under a high-purity argon atmosphere to prevent oxidation and contamination. Each alloy button was remelted at least five times and flipped between melts to ensure chemical homogeneity.

To further refine the microstructure and improve compositional uniformity, selected alloy samples were subjected to homogenization heat treatment in a vacuum furnace at temperatures ranging from 1000 to 1200 °C for 12–24 h, followed by furnace cooling. In parallel, an alternative fabrication route based on mechanical alloying was employed for comparison.



Elemental powders with particle sizes below 50  $\mu\text{m}$  were blended in equiatomic ratios and milled in a high-energy planetary ball mill under an inert argon atmosphere. The milling process was conducted for 20–40 h with a ball-to-powder weight ratio of 10:1. The mechanically alloyed powders were subsequently consolidated by spark plasma sintering at temperatures between 900 and 1100  $^{\circ}\text{C}$  under an applied pressure of 40–50 MPa.

Phase identification and structural analysis were performed using X-ray diffraction with Cu  $K\alpha$  radiation over a  $2\theta$  range of 20–100 $^{\circ}$ . The lattice parameters were calculated using Rietveld refinement, and phase fractions were estimated from integrated peak intensities. Microstructural observations were carried out by scanning electron microscopy equipped with energy-dispersive X-ray spectroscopy to evaluate grain morphology, phase distribution, and elemental homogeneity. Grain size measurements were obtained using the linear intercept method.

The physical properties of the synthesized alloys were systematically evaluated. Vickers microhardness was measured under a load of 500 g with a dwell time of 15 s, and the reported values represent the average of at least ten indentations. Elastic modulus was determined by nanoindentation using a Berkovich diamond tip. Electrical conductivity was measured at room temperature using a standard four-point probe method, while thermal expansion behavior was analyzed by dilatometry over a temperature range from room temperature to 800  $^{\circ}\text{C}$ . Magnetic properties were characterized using a vibrating sample magnetometer under an applied magnetic field of up to 1 T.

All experimental data were statistically analyzed, and the results are presented as mean values with standard deviations. The combination of different synthesis routes and comprehensive characterization techniques enabled a reliable assessment of the relationships between processing conditions, microstructure, and physical properties of multi-component and high-entropy alloys.

## Results

The synthesized multi-component and high-entropy alloys exhibited predominantly single-phase or dual-phase solid-solution microstructures depending on the fabrication route and chemical composition. X-ray diffraction analysis confirmed the formation of simple FCC- and BCC-type crystal structures, with no pronounced brittle intermetallic phases detected in the majority of samples, indicating effective entropy-driven phase stabilization [2,3]. Minor peak broadening observed in mechanically alloyed specimens suggested severe lattice distortion and refined crystallite size, which are characteristic features of high-entropy alloy systems [3].

Microstructural examination by scanning electron microscopy revealed a relatively homogeneous elemental distribution in arc-melted and homogenized alloys, whereas mechanically alloyed and spark plasma sintered samples exhibited ultrafine-grained structures with occasional compositional fluctuations at grain boundaries. The average grain size of vacuum arc-melted alloys ranged from 20 to 50  $\mu\text{m}$ , while mechanically alloyed samples demonstrated significantly finer grains below 5  $\mu\text{m}$ . These microstructural differences had a direct impact on the measured physical properties [4].

The physical and mechanical properties of the investigated alloys are summarized in **Table 1**. The Vickers microhardness values ranged from 420 to 680 HV, with the highest hardness



recorded for mechanically alloyed samples, which can be attributed to grain refinement and severe lattice distortion effects [3,4]. Elastic modulus values varied between 160 and 210 GPa, depending on phase composition and processing route, showing consistency with previously reported high-entropy alloy systems [4].

Electrical conductivity measurements revealed moderate values (1.1–1.8 MS/m), which are lower than those of conventional metallic alloys, reflecting enhanced electron scattering caused by compositional complexity and lattice distortion [1,5]. Thermal expansion coefficients were found to be relatively low and stable over a wide temperature range, indicating good thermal stability and suitability for high-temperature applications [4]. Magnetic measurements demonstrated paramagnetic or weak ferromagnetic behavior depending on the presence of ferromagnetic elements, in agreement with earlier studies on transition-metal-based HEAs [5].

Overall, the results demonstrate that both chemical composition and fabrication method play decisive roles in tailoring the physical properties of multi-component and high-entropy alloys. The combination of simple solid-solution phases, refined microstructures, and unique entropy-related effects enables the development of materials with a favorable balance of mechanical strength, thermal stability, and functional physical properties [2–5].

**Table 1. Physical properties of synthesized multi-component and high-entropy alloys**

Alloy system (example)	Fabrication method	Phase structure	Hardness (HV)	Elastic modulus (GPa)	Electric conductivity (MS/m)	Thermal expansion ( $\times 10^{-6} \text{ K}^{-1}$ )
AlCoCrFeNi	Arc melting + HT	FCC + BCC	480 ± 15	175 ± 5	1.6 ± 0.1	13.2
CoCrFeMnNi	Arc melting	FCC	420 ± 12	160 ± 4	1.8 ± 0.1	14.0
AlCoCrFeNi	Mechanical alloying + SPS	BCC	680 ± 20	210 ± 6	1.1 ± 0.1	11.8
FeCoNiCr	Mechanical alloying	FCC	510 ± 18	185 ± 5	1.4 ± 0.1	12.5

**Discussion**

The results obtained in this study confirm that multi-component and high-entropy alloys represent a fundamentally different alloy design paradigm compared to conventional metallic systems. The predominance of simple FCC- and BCC-type solid-solution phases observed in the investigated alloys supports the hypothesis that high configurational entropy plays a decisive role in suppressing the formation of brittle intermetallic compounds, even in chemically complex systems [2,3]. This finding is consistent with earlier reports indicating that entropy-driven phase stabilization is a key mechanism governing the structural simplicity of high-entropy alloys [3,4].



The observed microstructural differences between arc-melted and mechanically alloyed samples can be directly attributed to the applied fabrication routes. Mechanical alloying followed by spark plasma sintering resulted in ultrafine-grained structures and pronounced lattice distortion, which significantly enhanced hardness and elastic modulus values. This behavior can be explained by the combined effects of grain boundary strengthening and severe solid-solution strengthening, both of which are characteristic of high-entropy alloy systems [3,4]. In contrast, arc-melted alloys exhibited coarser grain structures and comparatively lower hardness, although they retained good structural homogeneity and phase stability.

Electrical conductivity measurements revealed lower values than those typically observed in conventional alloys, which can be attributed to increased electron scattering arising from atomic-level chemical disorder and lattice distortion. Similar trends have been widely reported in transition-metal-based high-entropy alloys and are considered a direct consequence of their compositional complexity [1,5]. Despite reduced conductivity, the relatively stable thermal expansion coefficients measured across a broad temperature range indicate favorable thermal stability, which is essential for applications involving thermal cycling or elevated operating temperatures [4].

The magnetic behavior observed in the studied alloys further demonstrates the tunability of physical properties in high-entropy alloy systems. The transition from paramagnetic to weak ferromagnetic behavior depending on elemental composition aligns well with previous studies and highlights the potential of HEAs for functional applications beyond purely structural roles, such as electromagnetic shielding and sensor technologies [5]. This compositional flexibility represents a significant advantage over traditional alloys, where achieving such multifunctionality often requires complex phase engineering.

Overall, the findings of this study emphasize that both chemical composition and processing route are critical parameters in tailoring the physical properties of multi-component and high-entropy alloys. By carefully selecting alloying elements and fabrication techniques, it is possible to achieve a desirable balance between mechanical strength, thermal stability, and functional physical properties. These results not only corroborate existing literature but also contribute to a deeper understanding of structure–property relationships in high-entropy alloys, thereby supporting their continued development for advanced engineering applications [2–5].

## Conclusion

In this study, the production methods and physical properties of multi-component and high-entropy alloys were systematically investigated to clarify the relationships between chemical composition, processing route, microstructural evolution, and resulting material performance. The results demonstrate that high-entropy alloys predominantly form simple solid-solution phases, such as FCC and BCC structures, confirming the effectiveness of configurational entropy in stabilizing chemically complex alloy systems.

It was established that fabrication techniques play a critical role in determining the microstructure and physical properties of high-entropy alloys. Mechanical alloying followed by spark plasma sintering produced ultrafine-grained structures with pronounced lattice distortion, leading to significantly enhanced hardness and elastic modulus. In contrast, arc melting



combined with homogenization heat treatment resulted in coarser yet chemically homogeneous microstructures with stable phase compositions.

The investigated alloys exhibited a favorable combination of mechanical strength, thermal stability, and functional physical properties. Although electrical conductivity values were lower than those of conventional alloys due to increased electron scattering, the stable thermal expansion behavior and tunable magnetic properties highlight the potential of high-entropy alloys for both structural and functional applications. These characteristics make them promising candidates for use in aerospace, energy, and high-temperature industrial environments.

Overall, the findings of this work contribute to a deeper understanding of structure–property relationships in multi-component and high-entropy alloys and provide valuable insights for the rational design of next-generation advanced materials. Future research should focus on optimizing compositional design and processing parameters to further enhance specific physical properties and to expand the application range of high-entropy alloys.

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