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Fabrication of High Entropy Alloy by Powder Metallurgy Process

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Abstract

Recently, High entropy alloys have attracted a lot of interest because of their unique properties. which include outstanding strength, remarkable corrosion resistance, and consistent thermal stability. Powder metallurgy is one of the production procedures commonly used to manufacture these alloys. Metal powders are compacted and sintered to create a cohesive material in the production process known as powder metallurgy. The capacity to produce a fine-grained microstructure and a homogeneous distribution of various elements are two benefits of this technology for the synthesis of high entropy alloys. Moreover, powder metallurgy makes it possible to precisely combine various alloying constituents, which can improve the qualities of high entropy alloys even more. Powder metallurgy allows for the manufacture of intricate shapes and dimensions, rendering it well-suited to a range of uses. With the use of powder metallurgy, high entropy alloys can be fabricated with improved mechanical properties and enhanced performance.

Keywords*: Effects; Oxidation; Magnetic Property; Compression*

1. Introduction

Materials made of high entropy alloys are made of approximately equal proportions of multiple elements[1].These alloys are characterized by their high degree of disorder and randomness in their atomic structure, which is different from traditional alloys that typically have a dominant element with a few secondary alloying elements[2]. The idea behind high entropy alloys was first put out by researchers to explore the potential benefits of mixing multiple elements with similar atomic sizes and electronegativity's in an effort to produce materials with special qualities [3]. These metal combinations have attracted a lot of attention lately because of their exceptional mechanical, thermal, and magnetic properties [4]. Alloys with high entropy exhibit the potential for diverse applications in sectors such as aerospace, automotive, electronics, and energy[5].They have shown great promise in material design and engineering, as they offer a range of desirable properties that traditional alloys cannot achieve [6]. These properties include high strength, excellent corrosion and oxidation resistance, good thermal stability, and enhanced mechanical properties at both high and low temperatures [7].Compositionally, HEA are characterized as alloys containing a minimum of five primary metallic elements, with each element constituting an atomic percentage ranging from 5% to 35%.Solid solution alloys known as HEAs are created by combining multiple metallic elements and demonstrate uncomplicated crystal structures, including hexagonal close-packed lattices, body-centered cubic lattices, and face-centered cubic lattices [9][10].Nearly equal amounts of four or more metals, such as Fe, Cu, Mn, Co, Ti, Cr, Ni, etc., can be added to create HEAs[11].

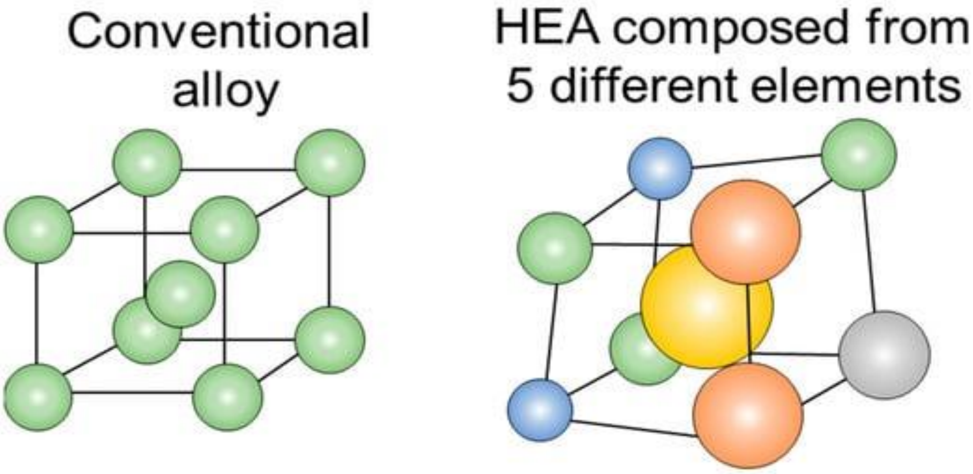

Figure 1 **Crystal Structural Difference Between Conventional Alloy and High Entropy Alloys[12]**

2. High-Entropy Alloys' Four Main Effects

High-entropy alloys display four significant effects, which include the lattice distortion effect and the thermodynamic impact of high entropy. The cocktail effect in performance, the slow diffusion effect in kinetics, and crystallography. High-entropy alloys' unique characteristics and enhanced performance are mostly due to these factors. [13]. Figure 2 illustrates the four core effects. Crystal Structural Difference Between Conventional Alloy and High Entropy Alloys shown in Figure 1.

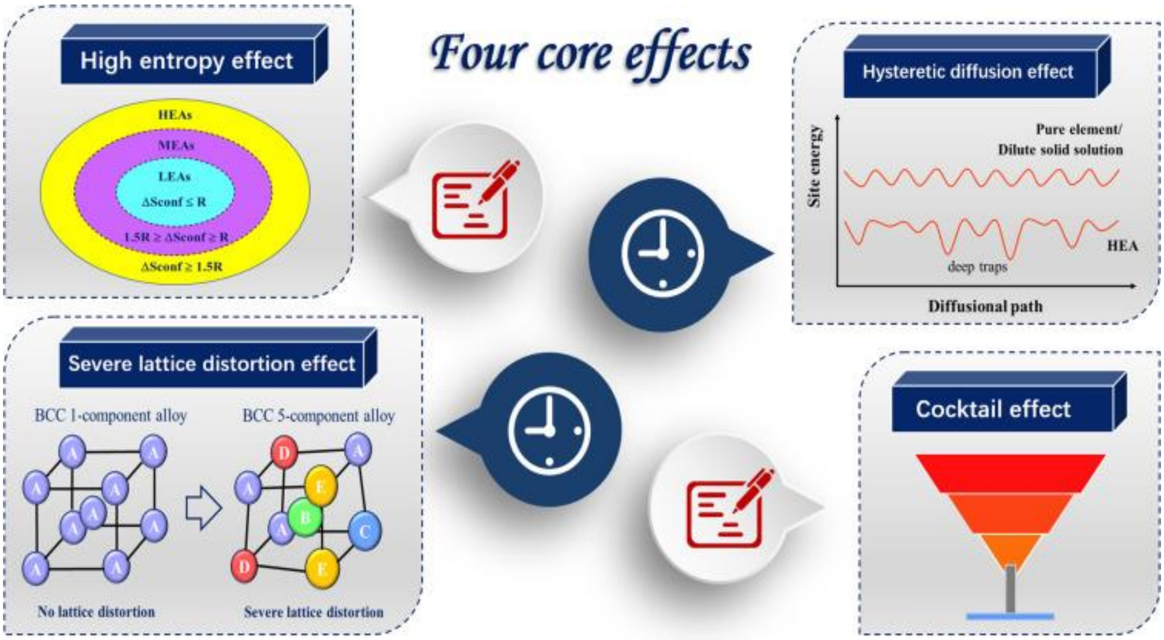

Figure 2 **Four Core Effects** [14]

2.1 High-Entropy Effect

In high entropy alloys, the term "high-entropy effect" describes the special behaviour of these materials as a result of a high level of atomic structural disorder and randomness. Strength, hardness, and resistance to deformation are only a few of the improved mechanical and physical qualities that result from this impact [15]. Additionally, the high-entropy effect also results in improved thermal stability and resistance to corrosion and oxidation [16].

2.2 Lattice Distortion Effect

The lattice distortion phenomenon in high-entropy alloys arises from the incorporation of diverse elements with varying atomic sizes and electronegativities, resulting in an irregular and highly disordered arrangement of atoms within the crystal lattice [17]. Because of structural features, every main element will differ. There will unavoidably be some divergence in the lattice atom as a result of these differences [18]. It then generates the lattice distortion [19]. One distinctive feature that greatly affects the lattice distortion effect is responsible for the microstructure and properties of high-entropy alloys [20]. The remarkable mechanical characteristics of high-entropy alloys, such as increased strength, ductility, and toughness, are a result of this lattice distortion effect [21].

2.3 Sluggish Diffusion Effect

The sluggish diffusion effect in high-entropy alloys refers to the slow movement of atoms within the crystal lattice, which results in reduced diffusion rates compared to traditional alloys [22]. When atoms move from their initial positions, a phenomena known as diffusion takes place, which results in the macroscopic flow of material [23]. The high level of atomic disorder and the existence of several elements with various atomic sizes are the causes of this slow diffusion effect [24]. There are several repercussions from the slow diffusion phenomenon in high-entropy alloys. It first causes a stable solid solution with an even distribution of components to form, improving the alloy's mechanical and physical qualities. Secondly, it prevents phase separation and the production of hazardous intermetallic compounds, both of which can impair the performance of the alloy [25][26]. Finally, the sluggish diffusion effect also promotes improved resistance to grain growth, leading to enhanced stability and longevity of high-entropy alloys [27].

2.4 Cocktail Effect

Professor Ranganthan was the one who first hypothesised the cocktail effect. High-entropy alloys' microstructure and characteristics are influenced by the addition of different elements, and their performance can be significantly affected by altering the composition of their primary component [28]. The performance of the alloy is enhanced by the synergistic interaction of several components with various properties [29]. These synergistic effects arise from the unique interactions between the different elements, such as higher thermal stability, improved corrosion resistance, and strength and toughness [30].

3. Essential Properties of High Entropy Alloys

The Essential Properties of High Entropy Alloys include:

High Degree of Disorder: High entropy alloys exhibit a high degree of disorder in their atomic structure, with multiple elements randomly distributed [31]. This disorder contributes to their unique properties and differentiates them from traditional alloys [32].

Large Mixing Enthalpy: The inclusion of several elements with comparable atomic sizes and electronegativities causes high entropy alloys to have a substantial mixing enthalpy [33]. This substantial mixing enthalpy is thought to improve high entropy alloys' mechanical characteristics and stability [34].

Multicomponent Composition: High entropy alloys are composed of at least 5 or more elements in roughly equal proportions, resulting in a multicomponent composition that contributes to their unique properties and allows for a wide range of material design possibilities [35].

Multifunctional Properties: High entropy alloys exhibit a combination of desirable properties, such as high strength, excellent corrosion and oxidation resistance, good thermal stability, and enhanced mechanical properties at extreme temperatures [36][37].

Easy processability: High entropy alloys are typically easier to process compared to traditional alloys, allowing for easier manufacturing and fabrication of complex components [38]. Additionally, high entropy alloys have shown good ductility, which is important for applications requiring deformation and forming processes [39]. These unique characteristics make high entropy alloys attractive for a variety of applications [40].

4. Elements Used in Preparation OH High Entopy Alloys

Seventy-two of the 118 recognised elements in the periodic table are potentially useful for alloying HEAs because they are not halogens, noble gases, or radioactive. A large number of HEAs have been made with more than 37 elements [41]. The primary 15 elements employed for producing HEAs include Iron, Nickel, Chromium, Cobalt, Aluminum, Copper, Titanium, Manganese, Vanadium(V), Zirconium, Molybdenum, Niobium, Silicon, Tantalum, and Tin. Among these, Co, Cu, Ni, Fe, and Mn have seen extensive usage [42].

5. Preparation of High Entropy Alloys

Typically, arc melting, powder metallurgy, casting, and mechanical alloying are used to make high entropy alloys. High entropy alloys can have varying microstructures and characteristics depending on the preparation techniques used [43]. For instance, in mechanical alloying, elemental powders are repeatedly deformed and then cold welded together to form a solid solution. Arc melting, on the other hand, uses an electric arc to melt and solidify a mixture of elemental powders. A single-phase alloy with a random distribution of components is encouraged to form by this approach [44]. All things considered, the preparation process and elemental makeup are major factors in defining the characteristics and alloying behaviours of high entropy alloys [45].

6. Powder Metallurgy Technique for HEA Preparation

The powder metallurgy technique is commonly used for the preparation of high entropy alloys [46]. This method involves the mixing of elemental powders in a predetermined ratio, followed by compaction and sintering [47]. The compacted powder mixture is then subjected to high temperatures, leading to the atoms' diffusion and the solid solution's creation [13]. More than three-quarters of the developed PMHEAs utilized mechanical alloying as the primary method for powder processing. The resulting alloys exhibited strong thermodynamic stability and favorable mechanical characteristics [48]. Purchasing the right powders for the process is the first step in any PM technique [49]. When it comes to this particular class of alloys that contain when fully prealloyed powders are utilised as the starting material, the PM technique ought to be easier when dealing with at least five different metals [50]. Nonetheless, we have seen numerous publications where the standard mixture of powders is used as the starting point, employing powdered pure metals [51]. A commonly employed technique for producing a complete pre-alloyed HEA powder is atomization, which is well-suited for various additive manufacturing approaches [52][53]. An alternative method of generating fully prealloyed HEA powders involved MA and atomization [54]. Alloys were produced by melting the materials, and then the resulting bulk part was turned into powder using high-energy milling [55]. The powders in these studies underwent a number of shaping procedures, including uniaxial pressing, cold isostatic pressing, and spark plasma sintering [56]. One common method in powder metallurgy for creating spark plasma sintering is used for high entropy alloys [57]. In order to quickly consolidate the powder combination and produce a dense, totally bonded alloy, high electric current and pressure are applied [58][59]. Two of the main advantages of SPS are the early attainment of the sintering temperature and the usually short dwell time [60]. The most common processing method for producing conventional PM in large quantities is the "press and sintering" technique, which is also the second most prevalent method after SPS for producing PM HEAs [61]. A protective milling atmosphere was employed in all instances. Various researchers have chosen distinct approaches to achieve the ideal powder for the process, based on their desired alloy composition goals [62]. Most studies utilize a carbon-based process control agent, but only a limited number of researchers take into account the potential impact or pollution it may have on the ultimate formation of the High entropy alloy [63] One potential drawback of mechanical alloying is the risk of cross-contamination between the powder from two different sources: grinding medium and process control agent (PCA) [64]. For instance, when stainless steel serves as the grinding media and iron and/or chromium are present in the target alloy there may be a transfer of these elements [65] [66]. This transfer can be managed, similar to how tungsten carbide is utilized in creating certain refractory high-entropy alloys [67]. However, it's important to note that the impact of PCA should not be overlooked despite it being often omitted in most analyzed literature [68]. A hardmetal with a HEA binder was created throughout the study. The authors mixed pure Ti with WC, Mo2C, TaC, NbC, and VC in a high-energy mill as opposed to starting with pure elemental powders and combining them with TiC to create the alloying components of the binder [69]. Utilising SPS, the combined powders were sintered at 1500°C in order to reduce all refractory carbides and benefit from titanium's strong carbon affinity. The end result was a BCC HEA matrix reinforced with TiC [70].

7. Structural Properties of Powder Metallurgy HEA

7.1 Tensile Strength

High-entropy alloys (HEAs) obtained by powder metallurgy have been shown to have high tensile strength [71]. Precipitation strengthening and fine-grain strengthening can both increase the tensile strength of HEAs. The HEA showed a 48-hour annealing temperature of 600 °C and a 1.9 GPa tensile strength, but only 8% elongation. However, after 12 hours of annealing at 800 °C, the material had an elongation of 31% and a tensile strength of 1.2 GPa.[72]

7.2 Corrosion Resistance

An alloy containing over 20% (by weight) of chromium, along with titanium and aluminum, strongly indicates the potential for favorable corrosion or oxidation resistance. It has been demonstrated that high-entropy alloys (HEAs) made via powder metallurgy have exceptional resistance to corrosion [73]. The unique properties of HEAs' resistance to corrosion may be explained by the local deformation and disordered chemical environment [74][75]. A layer that is resistant to corrosion forms on the surface of the materials when HEAs, which have a higher resistance to corrosion, are deposited on them [76].

7.3 Compression Strength

The compressive strength of powder metallurgy high-entropy alloys can be significantly enhanced by adjusting the composition and processing parameters [77]. The compressive strength of high-entropy alloys obtained through powder metallurgy can vary depending on the specific composition and processing conditions [78]. For example, a powder metallurgy HEA with a composition of Ti-Fe-Cr-Ni-Co-Al exhibited a compressive strength of 2 GPa [79]

7.4 Wear Resistance

The wear resistance of powder metallurgy high-entropy alloys is typically higher compared to conventional alloys [80]. The wear resistance of powder metallurgy high-entropy alloys can be improved by incorporating reinforcing particles or coatings [81]. For instance, introducing carbide particles such as TiC or WC can significantly boost HEAs' resistance to wear. The durability of powder metallurgy-derived high-entropy alloys may differ based on the particular composition and the presence of reinforcing particles. High tensile elongation and a notable strain hardening capability are characteristics of the CoCrFeNiMn high entropy alloy (HEA), although wear resistance is low [82]. Enhancing the wear resistance of the CoCrFeNiMn HEA through powder metallurgy alloying with carbon element appears to be a workable and economical solution [83].

7.5 Oxidation Resistance

High-entropy alloys have been found to exhibit excellent oxidation resistance, particularly at high temperatures [84]. The high configurational entropy of high-entropy alloys contributes to their exceptional oxidation resistance. Oxidation resistance is an essential characteristic for materials operating at elevated temperatures over extended periods, as it can significantly degrade the mechanical properties of these materials [85]. Aluminum, silicon, and chromium are commonly regarded as elements that form protective oxides. (such as Al2O3, SiO2, and Cr2O3) to stop materials from oxidising any more [86]. Because a protective complex CrTaO4 oxide layer forms, (Mo-Ta-Ti-Nb-Zr-Hf) -(Al, Si, and Cr) systems have recently shown good oxidation resistance within the 900–1100 °C temperature range [87]. MoTaTiCr MEA, shielded by a continuous CrTaO4 scale layer, displayed the highest degree of oxidation resistance [88].

8. Functional Performances

8.1 Thermoelectric Properties

Strong electrical conductivity, low heat conductivity, and a high Seebeck coefficient characterise the ideal thermoelectric materials. But as these three attributes are inextricably related, enhancing one will unavoidably have a detrimental effect on the others [89]. A wide range of intriguing functional characteristics, including charge storage, magneto caloric, thermoelectric (TE), ferroelectric, and magnetic, can also be seen in HEAs [90]. High entropy oxides (HEAs) and their numerous functional properties, including electronic, magnetic, thermoelectric, and magneto dielectric, have been the subject of current research [91][92]. Elevated Entropy Alloys, a promising material for thermoelectric applications, have a thermal conductivity that is several orders of magnitude lower than that of conventional alloys. However, they inevitably lose electrical conductivity as well[93]. Furthermore, it is more likely that the highly symmetrical solid solution structures of HEAs will aid in the convergence of electronic bands, resulting in a greater Seebeck coefficient [94]. It is clear that HEAs have great potential for application as high-performance, effective thermoelectric materials [95].

8.2 Irradiation Resistance

High entropy alloys have also shown promising irradiation resistance, making them suitable for applications in nuclear reactors and other radiation-intensive environments [96] [97]. Irradiation resistance is an important property for materials used in nuclear applications [98]. Due of their remarkable radiation resistance, high entropy alloys have attracted a lot of attention [99]. A recent study found that the high entropy effect of equiatomic CoCrCuFeNi HEA contributes to its better radiation resistance following multiple bombardments [100]. According to another review article, the alloy's irradiation resistance is enhanced by composition complexity because of the high entropy, which alters minimises lattice damage and the interstitial atom-vacancy migration energy barrier [101].

8.3 Magnetic Properties

High entropy alloys also exhibit intriguing magnetic properties. They can be categorized into soft magnetic alloys and hard magnetic alloys based on their magnetization behavior. Soft magnetic high entropy alloys possess low coercivity and can magnetize to saturation when exposed to a weak magnetic field [102]. Conversely, high entropy hard magnetic alloys have a high coercivity and can maintain their magnetic properties even after magnetization [103]. Because of this, high entropy alloys can be used in a variety of magnetism-related applications, including motors, sensors, and magnetic storage devices [104][105]. Numerous research papers have delved into the magnetic properties of high-entropy alloys. One example involves the development of a five-component magnetic alloy through powder metallurgy, providing enhanced manipulation over the characteristics of magnetic storage materials and enabling a broader variety of magnetic configurations. [106][107]. Another work focuses on a high entropy FeCoNiCuMn alloy with good soft magnetic properties, low coercivity (7 Oe), low magnetic remanence ratio (0.03), adequate saturation magnetization (40 emu/g), and soft magnetic properties [108]. Studies have demonstrated that HEAs can enhance mechanical behaviour and soft magnetic characteristics at the same time [109]. This capability is due to the presence of certain ferromagnetic elements, such as Co, Ni, and Fe, which enhance the tribological behaviour, strength, and hardness by producing strong solid solution effects and high magnetic saturation (MS) [110][111].

8.4 Catalytic Properties

High entropy alloys have also demonstrated notable catalytic properties [112]. They have been investigated for their potential use as catalysts in various chemical reactions, including hydrogen evolution reaction, oxygen reduction reaction, and CO2 reduction reaction [113]. These properties make them promising candidates for use in fuel cells, electrochemical devices, and environmental applications [114][115]. The fact that HEAs' solid-solution structure and adaptable composition design offer a tone of configuration options for creating novel catalytic materials is also encouraging.

9. Future Perspectives of Powder Metallurgy High Entropy Alloy Research

In the study of metal materials, high-entropy alloys have emerged as a unique type of material with significant academic significance and a broad range of potential applications [116]. High-entropy alloys' exceptional properties allow them to be customised to satisfy a wide range of performance requirements. These alloys are promising for a variety of applications, including radiation protection materials, surface engineering, mould manufacturing, catalytic materials, aerospace technology, and other fields because of their advantageous mechanical, thermal, and magnetic properties [117]. It's critical to improve already-existing preparatory techniques and develop fresh ones while honing the synthesis methodology. For the purpose of determining, verifying, and analysing the properties, composition, and structure of high-entropy alloys, material characterisation technology is essential [118]. Therefore, it is imperative that future research focus on how to efficiently combine characterization data with material characteristics and use sophisticated methodologies to identify and analyse the features of a high-entropy structure and their interaction. High-entropy alloy nanoparticles still have a lot of undiscovered functional qualities, and further research is needed to understand the underlying performance mechanism [119]. High-entropy alloy industrial production and manufacturing can be greatly accelerated by the utilisation of big data and artificial intelligence, as well as by the development of automated, intelligent, and integrated technologies for these alloys' preparation [120].

Conclusion

The study on HEAs and the process of powder metallurgy manufacture has been covered in this review.PM alloys with improved properties and microstructures mostly rely on the composition of the alloy and the methods used in its production, as outlined in this publication.The distinct properties of high-entropy alloys in dynamics, thermodynamics, and structure have generated significant interest in materials designed for specific functions.[121]. The HEAs may open the door to the creation of fascinating functional materials with previously unheard-of combinations of functional and mechanical characteristics. Rather than merely reproducing present performance, a desirable long-term objective for HEAs is to create and build potentially unique applications to meet the increasing needs.

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