Chapter

Breaking the Property Trade-Offs by Using Entropic Conceptions

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Abstract

Entropic conception has been used as an effective strategy for developing materials to break the property recordings of current materials, for example, breaking the trade-off between the high-strength and low-ductility structural alloys. The performance of materials usually under a complex circumstance, a balance of multiple properties, for example, combined the high-strength, high ductility, high conductivity, high corrosion resistance, high irradiation resistance, etc., the strategy of high-entropy-alloy (HEA) will provide a materials design and development technology to realize the goal. Magnetic materials usually exhibit excellent magnetic properties but weak mechanical properties and corrosion resistance. The reported unique behaviors of HEAs, for example, self-healing effects may be the mechanism for the high irradiation resistance of the HEAs, and self-sharpening behaviors of the tungsten-based HEAs main closely be related to the serration behaviors.

Keywords: high-entropy-alloy, strength, conductivity, toughness, corrosion resistance, self-healing, self-sharpening, serration behaviors, irradiation resistance, performance, trade-off, properties limits

1. Introduction

1.1 Definition and development of HEAs

Entropy is an important physical parameter to reflect the disordered state of a certain system, which is mainly expressed by three different forms including Clausius entropy, Boltzmann entropy, and Shannon entropy. Among them, entropy measured by Boltzmann's thermodynamic statistics principle is in the form of:

$$\Delta S_{\mathrm{cnof}} = k \ln w \tag{1}$$

where K is the Boltzmann's constant (k = 1.38 × 10^{-23}J/K), and w is the thermodynamic probability, which is the total number of micro-states corresponding to a certain state. Entropy measured by Clausius entropy is in the form of:

$$dS = dQ/T \tag{2}$$

where Q is heat and T is temperature. The physical meaning of this expression is that the entropy of a system is equal to the amount of heat absorbed (or dissipated) by

the system in a certain process divided by its absolute temperature. Different from Boltzmann entropy, Clausius entropy reflects the macroscopic quantity of thermodynamics. Probability is involved in the definition of Boltzmann entropy. The probability is not only used in physics but also in mathematics, information science, etc, which enables the application of entropy in other fields. Shannon entropy is one of the representatives, the expression is as follows:

$$H(X) = -\sum P(a_i) \log_2 P(a_i) \tag{3}$$

Based on this, information entropy has been measured in the form of:

$$S = -K \sum P_i \ln P_i \tag{4}$$

where P_i is the probability of occurrence of the i-th information of the information source. Briefly, the higher the entropy value of the system, the more disordered the system. For a material system, order can be defined in terms of a fully crystalline space group symmetry or another correlation. Ordered materials generally referred to materials with standard crystal structures, such as silicon single crystals, graphite, diamond, and intermetallic. In contrast, the common disordered materials mainly include amorphous materials and continuous solid solution materials (namely high-entropy materials) [1].

The concept of high entropy introduces a new path of developing advanced materials with unique properties, which cannot be achieved by the conventional micro-alloying approach based on only one dominant element. In contrast with traditional alloys composed of one principal element, HEAs generally have equimolar or near-equimolar atomic fractions of multiple constituents (generally more than 4 components), as shown in **Figure 1a**. As displayed in **Figure 1b**, the ternary or pseudo-ternary phase diagram can be roughly divided into the ordered alloys region (blue) near the corners and relatively disordered alloys region (dotted circle) near the center. The center of the phase diagram, relatively high-disordered region, often has few alloy systems available, especially for traditional alloy systems. In recent years, many new alloys with promising properties are likely to be discovered near the centers (as opposed to the corners) of phase diagrams, which no longer contain a single major component, but multiple major elements and form a concentrated solid-solution structure, namely high-entropy alloy systems. The development of HEAs has provided a novel design philosophy for alloy design and draw significant interest in

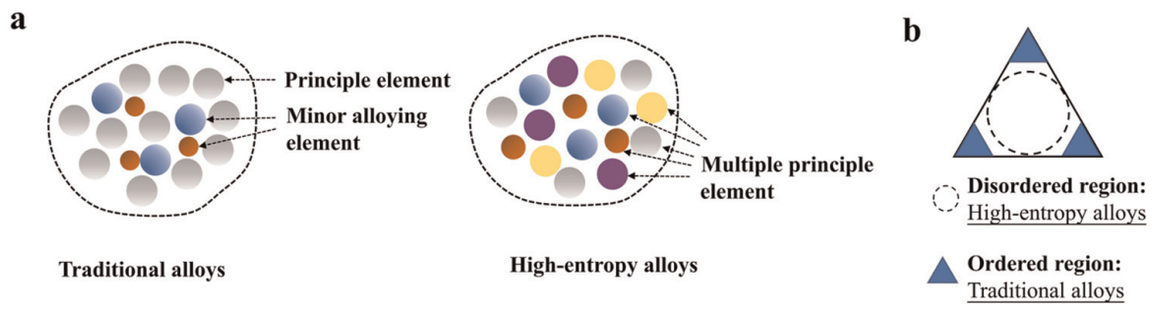


Figure 1.
Schematic diagram of traditional and high-entropy alloy systems. (a) atomic proportions of traditional alloys and high-entropy alloys; and (b) Ordered and disordered regions in a ternary phase diagram.

designing its chemical disorder to bring different structural and physical characteristics.

Here, we would like to discuss the definition of HEAs from the perspective of entropy. For a certain material system, the entropy mainly includes configuration entropy, vibration entropy, magnetic entropy, and thermal entropy. For HEAs with concentrated solid solution structures, the configuration entropy caused by the mixing of different atoms is the primary consideration. In order to simplify the calculation, the regular solution model is usually used to derive the mixed entropy of the HEAs in the state of random mutual dissolution [2]. The calculation formula is as follows:

$$\Delta S_{mix} = -R\sum_{i=1}^{n}(c_i \ln c_i) \tag{5}$$

where R is the gas constant (R = 8.314 J/mol·K); n is the number of alloy components; c_i is the content of the i-th component (at. %). The mixing entropy of HEAs is much greater than that of traditional alloys, and even exceeds the melting entropy of most metals (generally no more than 1R). According to this feature of HEAs, the commonly used definitions of multi-component HEAs are as follows [3]: (1) Alloy contains more than four main elements is equal to or near equal atomic ratio (at. %); (2) The content of each principal element is greater than 5 at. %, and less than 35 at. %. With the development of HEAs, the HEAs can be loosely divided into two generations [4]: the first-generation alloys generally show a single solid-solution structure and contain more than five principal elements in equal atomic ratio, and the second-generation alloys show non-equimolar components and multiple phases, as shown in **Figure 2**.

1.2 Classification of HEAs

With the development of HEAs, various HEAs with different forms have been reported. Here, the HEAs have been classified from different dimensions, as shown in **Figure 3**, mainly including three-dimensional (3-D) bulk materials, two-dimensional (2-D) film and sheet materials, one-dimensional (1-D) fiber materials, and zero-dimensional (0-D) powder materials [5].

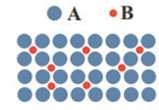
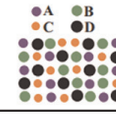
Classification	Component	Feature	Composition	Atoms arrangement	Typical alloys
The traditional alloys	1~2 principal elements	Tougher than the elementary substance			Fe-Ni, Fe-C, Cu-Al, Al-Mg
The 1st generation HEAs	At least 5 principal elements	Single phase, equimolar			CoCrFeNiMn, AlCoCrFeNi
The 2nd generation HEAs	At least 4 principal elements	Dual or complex phases, non-equimolar			NbMoTaW, $Al_{0.3}CoCrFeNi$, $Fe_{50}Mn_{30}Cr_{10}Co_{10}$

Figure 2.
Characteristics for the traditional alloys and two generations of HEAs [4].

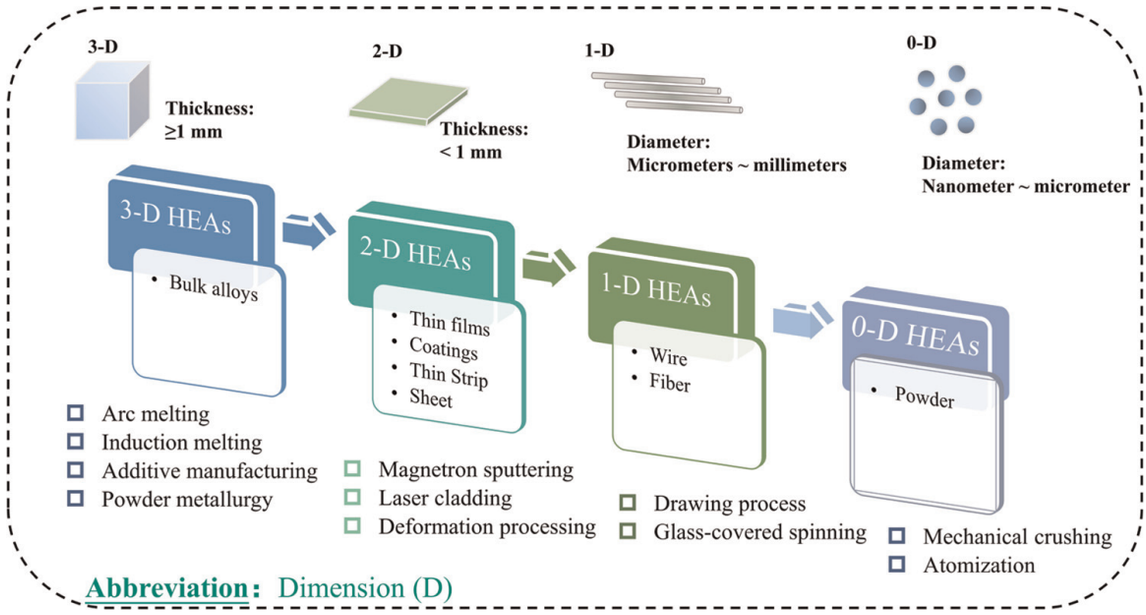


Figure 3.
Classification and general preparation methods of high-entropy alloys with different dimensions [5].

The 3-D HEAs, also referred to as bulk HEAs, are generally fabricated by alloy melting, additive manufacturing, and sintering methods, with a weight from several grams to tens of kilograms. Different cross-sectional shapes can also be obtained by casting, such as round rods and square rods. The 2-D HEAs are thinner than bulk alloys, and have several main types including thin films, coating, sheets, and thin strips. The high-entropy wire and fiber are the 1-D HEAs, which are generally obtained by drawing method and glass-covered spinning method. At present, micron-scale high-entropy wire can be obtained, and possess attractive mechanical properties. For the 0-D HEAs, mainly refers to high-entropy powders, which can be obtained through mechanical crushing and atomization. Currently, the high-entropy powder is used as raw materials for powder metallurgy and additive manufacturing, as well as a novel catalyst for functional applications.

2. Performance properties

2.1 Representative performance advantages

As a novel complex emerging material, many unique characteristics of HEAs in dynamics, thermodynamics, and structure have aroused great interest. The ability of HEAs to be designed with unique properties in an unlimited space of alloy compositions is encouraging. At present, many outstanding works have been carried out and proved many attractive properties that break the trade-offs and limits of properties. Here, several representative performance advantages including overcoming the strength-ductility trade-off, outcoming low-temperature ductility, excellent thermal stability, good corrosion resistance, and irradiation resistance have been illustrated [6].

I. Overcoming the strength-ductility trade-off: In general, strength and plasticity are two opposing properties. In other words, the increase of strength is often

accompanied by the loss of plasticity, and the increase of plasticity requires the sacrifice of strength. It is exciting to find that the HEAs show the potential to break through the strength-plastic trade-off. The high strength of HEAs can be mainly attributed to two strengthening mechanisms. One of the most key issues for breaking strength-ductility trade-off is tailoring the stability of the constituent phases in HEAs, such as designing phase transformation, twinning, and regulating the chemical short-order and nanoprecipitates.

II. Low-temperature ductility: Traditional materials tend to exhibit brittleness at low temperatures, which limits their application in extreme low-temperature conditions. Recent results prove that HEAs with fcc structure show excellent mechanical properties under low temperatures, such as CoCrFeMnNi alloy [7] (Cantor alloy), CoCrFeNi alloy [8], and $Al_{0.3}$CoCrFeNi fiber [9]. This unique property is facilitated by the ability to form twin crystals, enabling defect storage and microstructural refinement at low temperatures.

III. Thermal stability: The diffusion rate is significantly slower than that in conventional materials. Severe lattice distortion directly is the key issue. Multiple components and complex interactions between the different atoms seriously affect the cooperative diffusion, and thereby slowing down the phase transition rate, hindering grain growth, and improving creep resistance.

IV. Corrosion resistance: The synergistic effect of slow diffusion, easy to obtain amorphous, and nanocrystalline structure is the dominant reason for excellent corrosion resistance. At the same time, high content of doping elements also enables the formation of strong passivation layers.

V. Irradiation resistance: Recent results have proved that effective self-healing mechanisms can be designed in HEAs. The particle irradiation could cause atomic displacements, which induces the irradiation defects, such as vacancies and interstitials, and also is accompanied by thermal spikes. For HEAs, the possibility of vacancy-interstitial recombination is higher than in traditional alloys due to complex interactions between atoms. And also, high levels of atomic-level stress in HEAs destabilize the solid solution and facilitate atomic remake to eliminate defects. This part will be discussed in detail in subsequent chapters.

2.2 Key research topics

For the property of HEAs, besides the current efforts on breaking the trade-off between the strength and ductility, we would like to propose several trade-offs between the mechanical properties and the physical properties, such as the deformability and soft magnetic properties, conductivity, and strength. Generally, the functional properties are available from traditional materials. However, traditional materials usually fail to provide a well-service under extreme conditions due to the destabilization of mechanical properties. In this case, outstanding mechanical also is a major boost for developing functional HEAs. Hence, we predict that developing HEAs with unique physical properties is a key research topic for future development. There are also other attractive properties, such as irradiation resistance and self-sharping

properties. In subsequent chapters, we will discuss these performances and related mechanisms in detail.

3. Soft-magnetic and mechanical properties

The performance of the soft magnetic material directly affects the transformer loss rate. Traditional soft magnetic materials, such as steel, Fe-Co alloys, and silicon steels, are often limited in their applications to the brittleness and poor deformability of the alloys. For soft-magnetic materials, it is very important to seek the balance between the magnetic properties and mechanical properties. However, this breakthrough is difficult to achieve in traditional materials, which generally have a relatively high degree of structural order, thereby showing poor deformability. In contrast, the excellent mechanical properties over a wide temperature range guarantee a well-service of HEAs under extreme environments. Moreover, high-entropy soft magnetic materials are expected to break the trade-off between power and frequency, as shown in **Figure 4**. For example, the conventional silicon steel is especially suitable for using in conditions of high power and low frequency. Once silicon steel is used at high frequencies, losses will increase dramatically. On the contrary, the amorphous alloys and ferrite generally possess low coercivity and exhibit lower losses at high frequencies, which give rise to the application of high-frequency transformers. Here, high-entropy soft-magnetic alloys show great advantages in filling the gap between high power/low frequency and low power/high frequency.

As we discussed in the previous chapter, HEAs have good mechanical properties, flexible deformability and excellent thermal stability, which is one of the most important properties for promising soft-magnetic materials. Many efforts have proved that HEAs also show acceptable soft magnetic properties. The promising soft-magnetic materials should have high-electrical resistivity, high-saturation magnetization, and low coercivity. As shown in **Figure 5**, the soft-magnetic HEAs are mainly located in

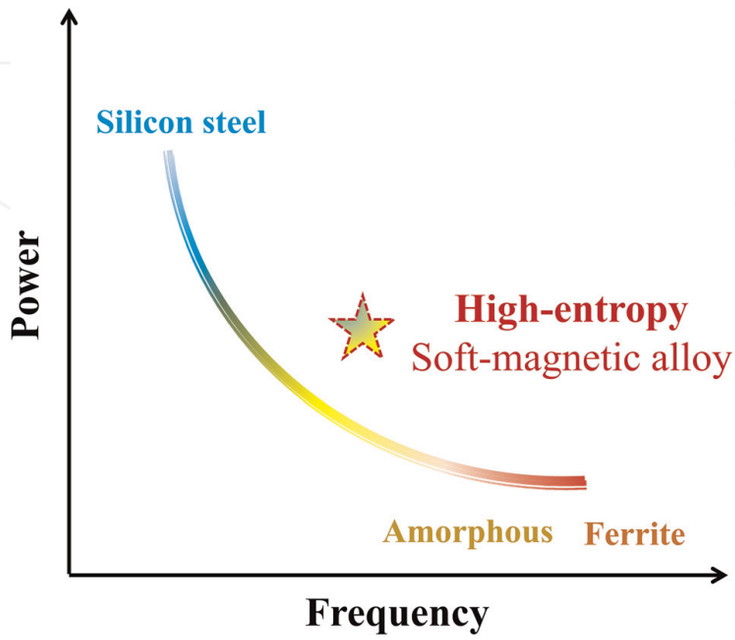


Figure 4.
General relationship of power to frequent for common magnetic materials.

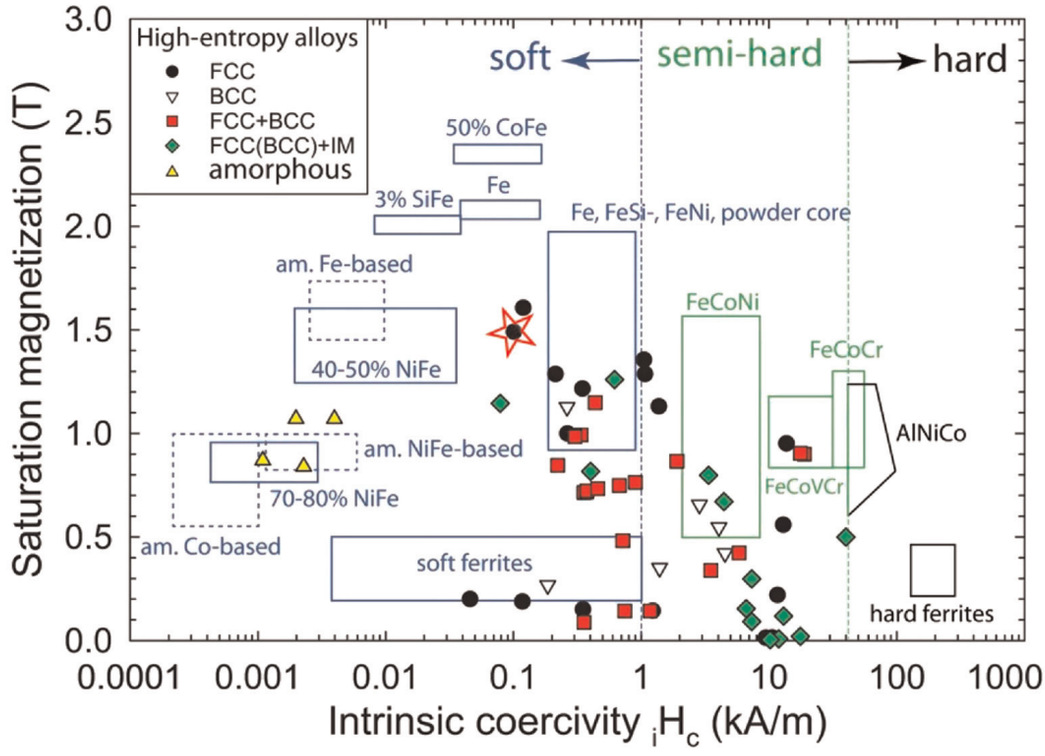


Figure 5.
Saturation magnetization versus coercivity of HEAs compared with major conventional soft and semi-hard magnetic materials [10].

the region of soft and semi-hard regions, and the properties of partial alloys are accepted by the soft-magnetic materials [10].

In addition, HEAs generally possess higher electrical resistivity in comparison with traditional alloys due to large lattice distortion. Chou et al. [11] have investigated the electrical resistivity of CoCrFeNiAlx alloy. Results showed that the resistivity of this series of HEAs is higher, second only to that of bulk amorphous alloys, and the resistivity increases with the increase of temperature, showing a linear relationship with temperature. Currently, many efforts have been conducted to improve the comprehensive soft-magnetic properties of HEAs. Zuo and co-workers [12] have designed a system of CoFeMnNi-X (X=Al, Cr, Ga, and Sn) magnetic alloys. The hysteresis loops of these HEAs are shown in **Figure 6**. Ordered phases form by adding Al/Ga/Sn to the FCC-structured CoFeMnNi alloy. This phase transition leads to the significant enhancement of the saturation magnetization. Especially for CoFeMnNiAl alloy, the alloy has Ms of 147.86 Am^2/kg.

Moreover, Zuo and co-works have tried to optimize soft magnetic properties by changing the fabrication process [13]. They found that the HEAs fabricated by directional solidification process showed a lower coercivity. The coercivity value of $FeCoNiAl_{0.2}Si_{0.2}$ alloy manufactured by directionally solidified is reduced to 315 A/m, which is much lower than the as-cast alloy with 1400 A/m. Results prove that the chemical short-range order in HEAs significantly changes the local environment of atomic, which further reduces the average magnetic moment of magnetic atoms. Zhang and co-workers have also investigated the magnetic properties and mechanical properties of Fe-Co-Ni-Al-Si HEAs [14]. The alloy shows pretty good mechanical properties and deformability. As shown in **Figure 7**, the alloy was fabricated by vacuum magnetic suspension melting, and also can be conducted by cold-rolling to

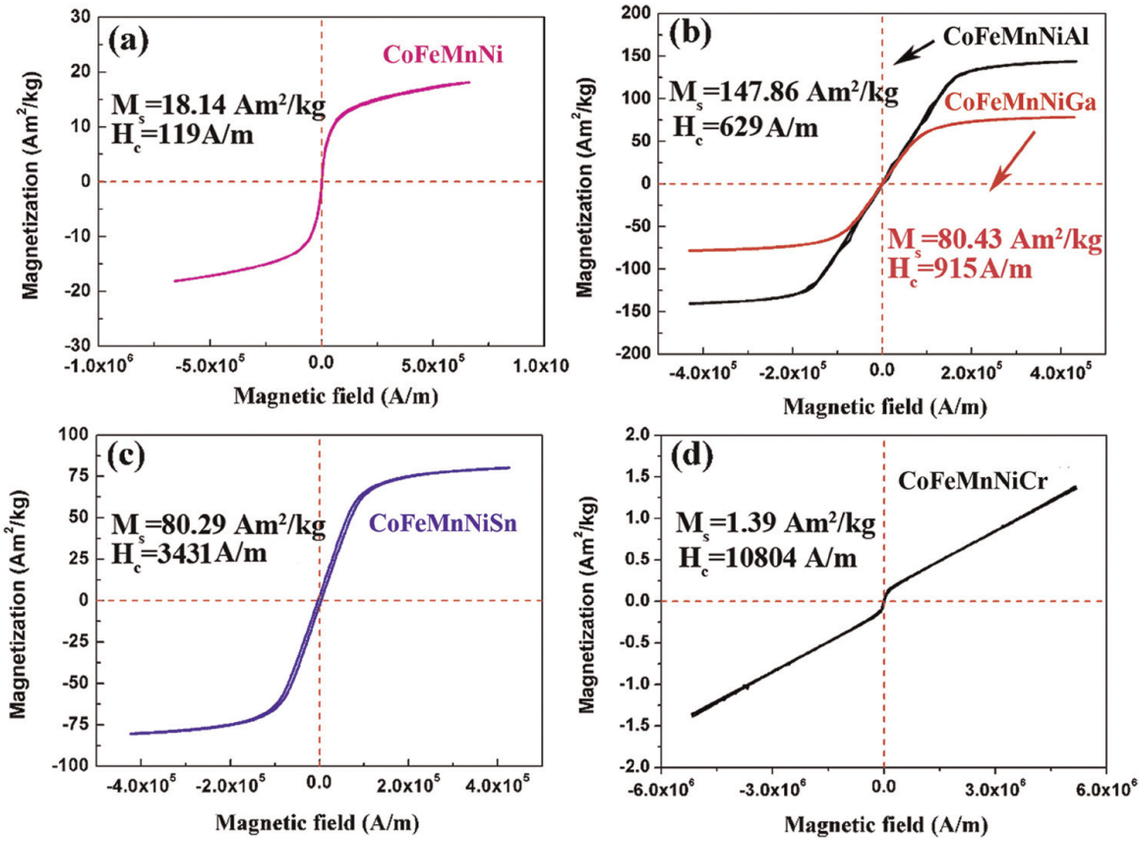


Figure 6.
Hysteresis loops of (a) CoFeMnNiMn, (b) CoFeMnNiAl and CoFeMnNiGa, (c) CoFeMnNiSn, and (d) CoFeMnNiCr alloys at room temperature [12].

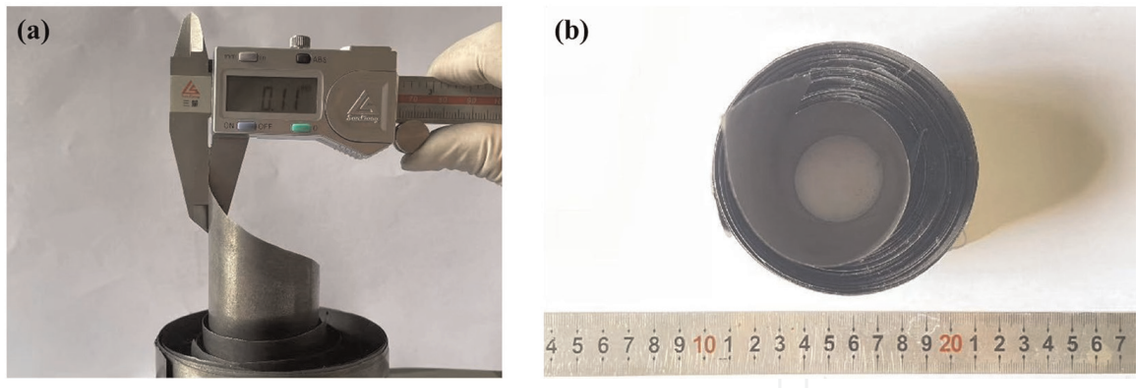


Figure 7.
The macroscopic appearance of $(Fe_{0.3}Co_{0.5}Ni_{0.2})_{95}(Al_{1/3}Si_{2/3})_5$ cold-rolled sheet.

form the sheet. The alloy after annealing exhibits a tensile yield strength of 235 MPa, an ultimate tensile strength of 572 MPa, and an elongation of 38%. The superior ductility of HEAs provides the possibility of preparing thin plates, which can effectively reduce eddy current losses of magnetic devices.

4. Conductivity and strength

Generally, high-purity materials have high conductivity, and the higher the purity, the higher the electrical conductivity accordingly. Also, it is well known that the

higher the purity of the material, the lower the strength. However, due to low strength of high-purity materials, they cannot meet the requirements of industrial applications. In this case, increasing the strength of alloy without significantly reducing the electrical conductivity is essential. There are many methods to strengthen materials, for example:

(i) Fine grain strengthening: Fine grains can be obtained through plastic deformation or other methods, which improves the strength but also hinders the electron transport; (ii) Solid solution strengthening: Solid solution treatment causes the crystal lattice distortion, which enhances the scattering of electrons, thus making the movement of electrons difficult; (iii) Second phase strengthening (precipitation strengthening): The second phase precipitated from the alloy matrix will hinder the movement of dislocations, which can improve the strength of the alloy, but at the same time, it will also block electrons, which will hinder the transmission of electrons; and (iv) Phase transformation strengthening: The lattice is strongly distorted, and the resistance increases sharply. Obviously, these strengthening methods reduce the conductivity. The current research work demonstrates the possibility of breaking the balance between conductivity and strength in the design of HEAs.

Excellent mechanical performance of HEAs is a basic guarantee for using as conductivity materials. Moreover, there have been HEA superconductors discovered to date, which seem to offer some interesting properties. Guo et al. [15] reported the observation of extraordinarily robust zero-resistance superconductivity in the pressurized $(TaNb)_{0.67}(HfZrTi)_{0.33}$ HEAs with a bcc phase structure. The transition to superconductivity (T_C) increases from an initial temperature of 7.7 K at ambient pressure to 10 K at ~60 GPa, and then slowly decreases to 9 K by 190.6 GPa, a pressure that falls within that of the outer core of the earth. High-pressure resistance measurements were performed for four samples that were cut from the material used as the standard for the superconductivity at ambient pressure. The electrical resistance measurements for these samples were performed between 4 and 300 K. They inferred that the continuous existence of the zero-resistance superconductivity from 1 atm up to such a high pressure requires a special combination of electronic and mechanical characteristics. The HEAs superconductor thus may have a bright future for applications under extreme conditions, and also poses a challenge for understanding the underlying quantum physics.

Vrtnik and co-workers [16] designed Ta-Nb-Hf-Zr-Ti HEAs with a structure varying between a homogeneous random solid solution and a partially ordered nanostructure in the form of a three-dimensional grid of short-range ordered atomic clusters enriched in Zr and Hf and investigated the superconducting behaviors. The superconducting transition temperatures T_C of Ta-Nb-Hf-Zr-Ti HEAs are scattered in the range between 5.0 and 7.3 K and this scatter could be related to the degree of structural and chemical inhomogeneity of the samples. They demonstrated the important fact that the formation, stability, and structure of a regular (non-ideal) HEA mixture is determined by both, the minimization of the mixing enthalpy that favors local atomic ordering and the maximization of the mixing entropy that favors a random solid solution. The actual equilibrium state achieved during long-time thermal annealing via the atomic diffusion is generally partially ordered, and the resulting nanostructure is a sensitive function of the number of components constituting the HEA, their concentrations, and the differences in the atomic radii and the annealing temperature and time. This nanostructure essentially determines the electronic properties of HEA materials.

5. Irradiation and self-healing

The unexpected stability of phase structure and mechanical performances in extreme environments makes HEAs attractive candidates for irradiation-resistant materials. It is well known that particle irradiation could cause atomic displacements, which induces the irradiation defects, such as vacancies and interstitials. In contrast with the traditional alloys, the integrated experiment and modeling work indicate that HEAs show a lower volume swelling rate and defect density, which may be attributed to the effective self-healing mechanisms of HEAs under irradiation conditions [6]. The possible self-healing mechanisms of HEAs can be concluded from three aspects, as shown in **Figure 8** [6].

Unlike interstitial atoms in conventional alloys, which migrate in the direction of the Burgers vector in a long-range one-dimensional mode, interstitial atoms and clusters in HEAs have short-range three-dimensional (3D) motion. The short-range 3D motion of interstitial clusters gives rise to the recombination of vacancy-interstitial, thereby reducing the defects in alloys, as shown in **Figure 8**-I. In other words, the chemical disorder and compositional complexity of HEAs promote the novel short-range 3D migration paths, which facilitate the disappearance of radiation damage, and improve the radiation tolerance. High atomic-level stresses caused by mixing of elements with different atomic sizes are the reason for self-healing mechanism in HEAs. Higher atomic-level stresses destabilize the solid solution, which will facilitate amorphization of alloys during irradiation process. In this case, the thermal spikes caused by particle irradiation will bring local melting and recrystallization, which promote the orderliness of the alloy, and further reduce the density of defects, as shown in **Figure 8**-II. Moreover, simulation results show that the electron mean free path decreases significantly with the increase of the number of component elements. In this case, the consumption efficiency in HEAs is lower than that in conventional alloys. This action can help to prolong thermal spike and significantly promote the defect recovery of HEAs.

Nagase and co-workers [17] have investigated the irradiation behavior of CoCrCuFeNi multicomponent nano-crystalline HEAs. A fine-grained fcc single phase was obtained in the sputtered specimens. The fcc solid solution showed high phase

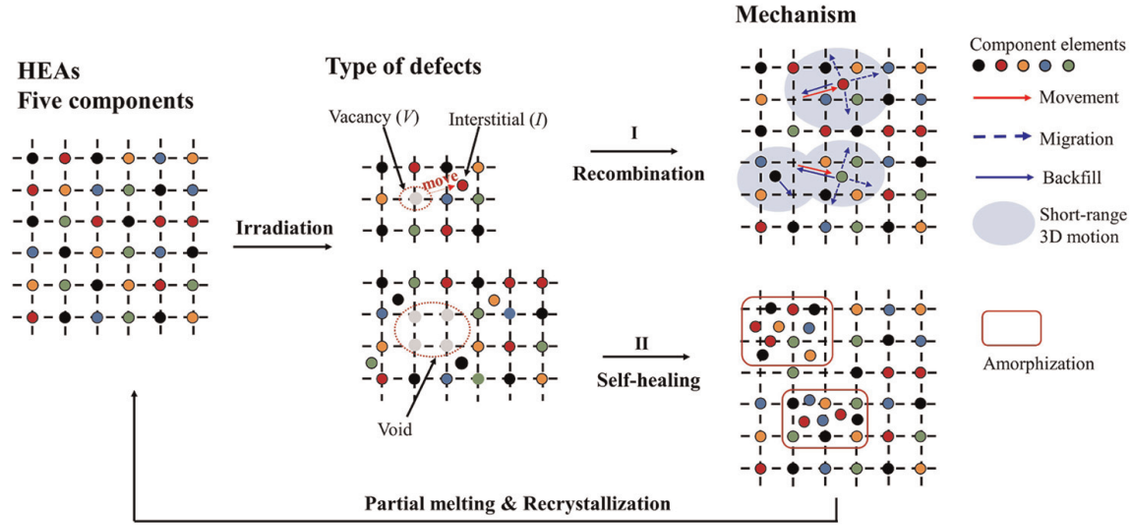


Figure 8.
Schematic diagram for the self-healing mechanism of irradiation resistance HEAs [6].

stability against irradiation over a wide temperature range from 298 to 773 K and remained as the main constituent phase even when the samples were irradiated up to 40 displacement per atom (dpa). Moreover, they found that the irradiation did not seem to induce grain coarsening. Jin et al. [18] have investigated the effects of compositional complexity on the ion-irradiation-induced swelling and hardening in Ni-containing HEAs. They designed four alloys with different component numbers, including Ni, NiCo, NiCoCr, and NiCoFeCrMn alloys. It is reported that the irradiation resistance at the temperature of 500 °C is improved by controlling the number and, especially, the type of alloying elements. Alloying with Fe and Mn has a stronger influence on swelling reduction than does alloying with Co and Cr. The quinary alloy NiCoFeCrMn, with known excellent mechanical properties, has shown 40 times higher swelling tolerance than nickel.

Briefly, the recent progress in HEAs demonstrates the possibility of obtaining high radiation tolerance through unique damage self-healing mechanisms. It is desirable to design high-performance HEAs for serving as irradiation resistance materials.

6. Serration behaviors and self-sharpening

Serration behaviors in plastically deforming solids are related to avalanches of deformation processes. In the stress-strain curves, the serration characteristics are visible as stress drops or strain jumps. In fact, similar serration characteristics are ubiquitous in many structural and functional materials [19], such as amorphous materials, high-entropy alloys (HEAs), superalloys, ordered intermetallic, shape-memory alloys (SMAs), electrochemical noise, carbon steels, twinning-induced plasticity steels, phase transformation-induced plasticity steels, Al-Mg alloys, nanomaterials, magnetic functional materials, and so on.

The serration behaviors are produced by the material under the action of the external field present a disordered distribution in time and space, which is closely related to the rheological structural unit of the material. The zigzag rheological phenomenon of materials in the process of plastic deformation objectively reflects some characteristics of its deformation mechanism, such as the interaction of interstitial solute atoms or replacement solute atoms and dislocations, local shear instability, grain boundary migration, and twinning. At the same time, the rheological characteristics of sawtooth are affected by many factors (such as external factors including temperature, strain rate, and heat treatment process; and internal factors including composition, grain morphology, size, and phase composition of the material).

"Self-sharpening," the capability of a material maintaining its acute head shape during penetration, is a highly required attribute of materials in armor piercing. Liu and co-workers [20] firstly reported the self-sharping behavior of HEAs in a composition of WFeNiCo. It was observed that the remnant of 93 W penetrator has suffered severe plastic deformation and exhibits an obvious mushroom-like head. In contrast, the remnant of WFeNiMo penetrator maintains an acute head shape, demonstrating a conspicuous self-sharpening ability, which is responsible for the improved penetration performance of WFeNiMo penetrators. In comparison with conventional single-principal-element tungsten alloys where precipitated phases are strictly suppressed, they found that the new tungsten HEA by chemical disordered design promotes precipitation of rhombohedral μ phase, which can trigger dynamic recrystallization softening mediated shear banding and give rise to the prominent self-sharpening behaviors. They proved that inhomogeneous deformation and relatively higher strain

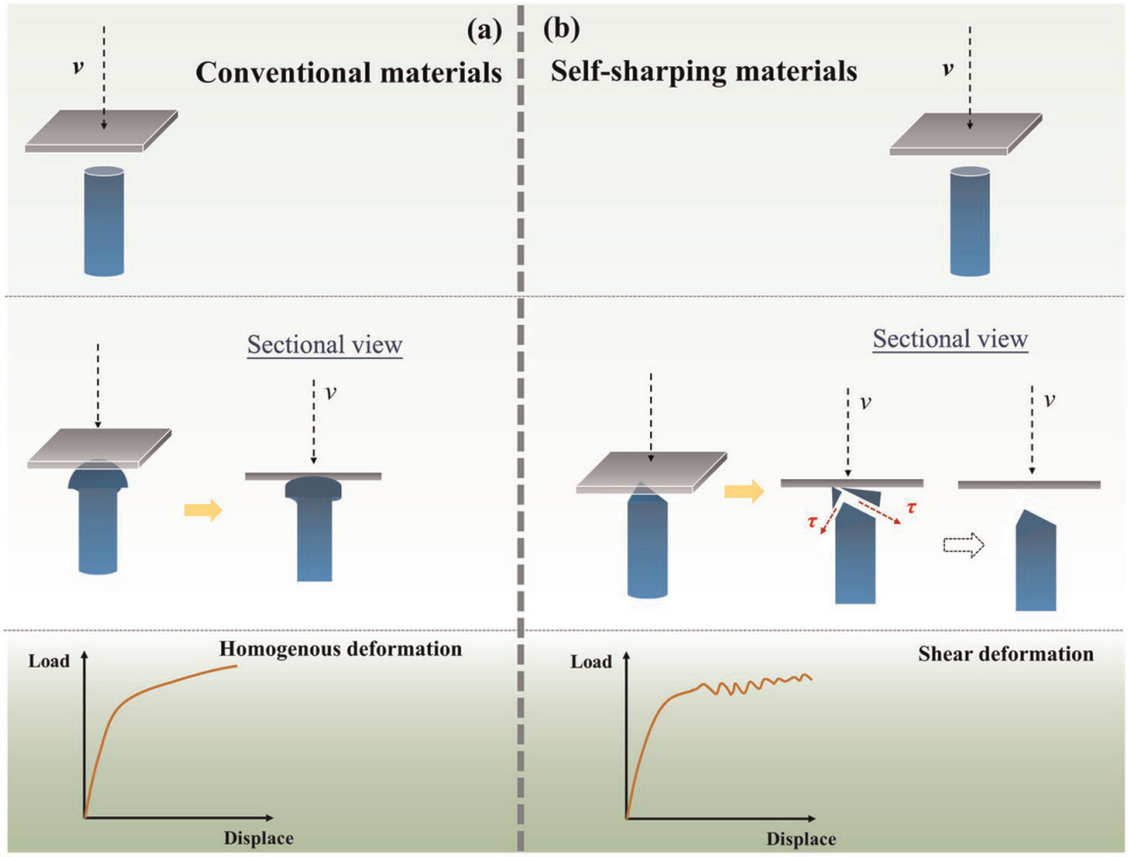


Figure 9.
Deformation diagram of conventional materials and self-sharping materials.

gradients caused by precipitates stimulate dynamic recrystallization and lead to shear band formation.

In this case, the inhomogeneous deformation is a key issue for self-sharping behaviors, and the serration is an important reflection of inhomogeneous deformation, as shown in **Figure 9**. Hence, we infer that there should be a correlation between serration behavior and self-sharpening behavior, which is expected to shed light on the origin of self-sharpening and might open new opportunities for developing high-performance penetrator materials.

7. Strength-ductility trade-off

As an emerging material system, unique characteristics of HEAs in dynamics, thermodynamics, and structure have aroused great interest in potential structural materials. Considerate efforts have been focused on the mechanical properties and related mechanisms of HEAs. As we all know, most metallurgical mechanisms for increasing strength lead to ductility loss. One of the most exciting breakthroughs of HEAs is breaking the trade-off of strength and ductility. It can be attributed to several mechanisms as follows:

(1) Concentrated solid-solution structure: Causing significant solid solution strengthening effect. (2) Severe lattice distortion: A core effect in the design of HEAs, it has been proved that can effectively improve both yield stress and its sensitivity to grain size. In this case, fine grain strengthening effect plays a more positive role in

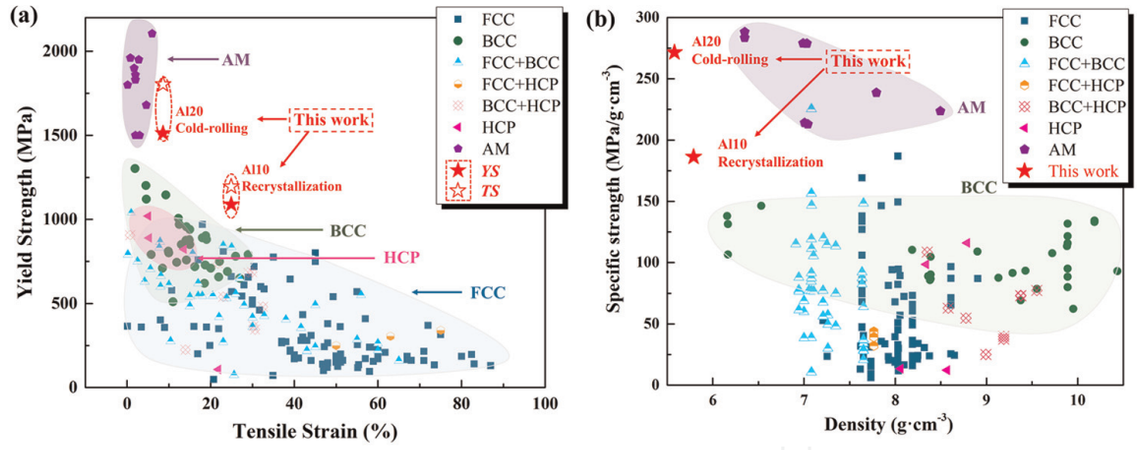


Figure 10.
Comparison of the Zr-Ti-Nb-Al HEAs with existing HEAs and amorphous alloys. (a) Maps of yield strength versus tensile strain of HEAs reported previously at room temperature [Abbreviation: Yield strength (YS), Tensile strength (TS), Amorphous alloy (AM)]. (b) Maps of specific strength versus density of HEAs reported previously at room temperature [22].

HEAs, which improves the strength as well as optimizes the deformation stability. (3) Tailoring the stability of the constituent phases in HEAs in the wide compositional space: such as designing nanoprecipitates, phase transformation, twinning, and regulating the chemical short-order.

There are many salient works that have developed HEAs possess high strength, as well as good ductility, which show great application potential in new generation of structural materials. Li and co-workers [21] have reported that $Fe_{80-x}Mn_xCo_{10}Cr_{10}$ (at. %) alloy systems successfully overcome the strength-ductility trade-off by regulating metastable phase. Transformation-induced plasticity and dual-phase strengthening are two key contributions to such a breakthrough. In the $Fe_{80-x}Mn_xCo_{10}Cr_{10}$ HEA, two contributions lead to enhanced trans-grain and inter-grain slip resistance, and hence, increased strength. The increased strain hardening capacity that is enabled by dislocation hardening of the stable phase and transformation-induced hardening of the metastable phase produces increased ductility.

The high strength is a typical advantage of body-centered-cubic HEAs (BCC-HEAs). However, brittleness and weak strain-hardening ability are still their Achilles' heel. Developing ultra-strong and ductile BCC-HEAs are highly desirable but extremely challenging. Yan and co-workers [22] have reported a $(Zr_{0.5}Ti_{0.35}Nb_{0.15})_{100-x}Al_x$ (x=10 and 20 at. %) HEAs, which show extraordinary strength (~1.2 to 1.8 GPa) together with good tensile ductility (~8% to 25%) at room temperature. Ultrahigh strength and excellent tensile ductility are record-high values over existing BCC-HEAs, as shown in **Figure 10**. Remarkably, relatively low densities of less than 6 g/cm^3 are exhibited in these alloys. They demonstrated that inducing nanoprecipitates and diversifying dislocation motion modes are the key factors to achieving such a remarkable breakthrough.

8. Conclusion

The unique characteristics of HEAs in dynamics, thermodynamics, and structure have aroused great interest in the new generation of structural and functional

materials. The ability of HEAs to be designed with unique properties in an unlimited space of alloy compositions is encouraging. In the past two decades, many salient efforts have been conducted to explore unique and useful properties of HEAs. Many attractive properties that break the limits of traditional materials are reported. It is desirable that the development of HEAs can shed light on the novel alloy design concept and open new opportunities for developing next-generation structural and functional materials.

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Conflict of interest

The authors declare no conflict of interest.

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