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High Entropy Alloys: Production, Properties and Utilization Areas

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Abstract: High entropy alloys (HEA) are composed of elements with atomic concentrations between 5% and 35%, unlike conventional alloys. This new generation of metallic materials has found utilization areas in many engineering applications due to their remarkable properties. High entropy effect, lattice distortion effect, sluggish diffusion effect, and cocktail effect are what give HEAs their properties. In addition to the mentioned effects, basic information regarding the definition, properties, production methods, utilization areas and recent studies of HEAs are given in this study. Furthermore, the recent developments in related areas such as the production of HEAs designed according to the targeted superior characteristics, transfer of outputs to applicable technologic fields, making the advantages of their superior features available in specific application areas such as military, defense and aerospace systems, were presented.

Keywords: alloy design, high-entropy alloys, production methods, solid solution, structural metals, superior properties

Yüksek Entropili Alaşımlar: Üretimi, Özellikleri ve Kullanım Alanları

Öz: Yüksek Entropili Alaşımlar (YEA), %5'den %35'e kadar atomik konsantrasyonlara sahip elementlerden meydana gelmektedir. Yeni nesil bu metalik malzemeler sahip oldukları özellikleri nedeniyle pek çok mühendislik uygulamasında kendilerine kullanım alanı bulmuşlardır. Bu malzemelere sahip oldukları özellikleri, yüksek entropi etkisi, latis bozulma etkisi, yavaş difüzyon etkisi ve karışım etkisi kazandırmaktadır. Bu çalışmada, belirtilen etkilerin yanı sıra yüksek entropili alaşımların tanımı, özellikleri, üretim yöntemleri, kullanım alanları ve konu ile ilgili yapılan son dönem çalışmaları hakkında temel bilgiler verilmektedir. Sonuç olarak, ulaşılması hedeflenen üstün özelliklere göre dizayn edilen YEA'ların üretilmesi, çıktıların uygulanabilir somut teknolojik alanlara transferi, üstün özelliklerin getirdiği avantajların askeri, savunma, havacılık ve uzay gibi spesifik uygulama alanlarında kullanılabilir hale getirilmesi gibi ilgili alandaki son gelişmeler derlenerek sunulmuştur.

Anahtar Kelimeler: alaşım tasarımı, yüksek entropili alaşımlar, üretim yöntemleri, katı çözelti, yapısal metaller, üstün özellikler

1. Introduction

In order to meet the increasing needs, new generation materials are being developed to realize the new generation products which became possible with the developing technology. Among these new generation materials, are high entropy alloys (HEA), which have become one of the most significant research areas of materials science in recent years. In contrast to conventional alloys, which consist

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of one or two basic elements, HEAs are alloy systems that consist of five or more basic elements, each with an atomic concentration between 5% and 35% [1-9]. The basis of HEAs, which are multi-component materials that emerged as a result of the search for materials with better properties, was laid by Franz Karl Achard in the 18th century. Achard produced different alloys with 11 elements, namely iron (Fe), copper (Cu), tin (Sn), lead (Pb), zinc (Zn), bismuth (Bi), antimony (Sb), arsenic (As), silver (Ag), cobalt (Co) and platinum (Pt), in different compositions [10]. However, in the most general sense, the invention of HEAs can be attributed to Ranganathan, Cantor et al. and Yeh et al. [1, 2, 5, 6, 11-17]. The historical development diagram of engineering materials, including the invention of HEAs, is given in Figure 1.

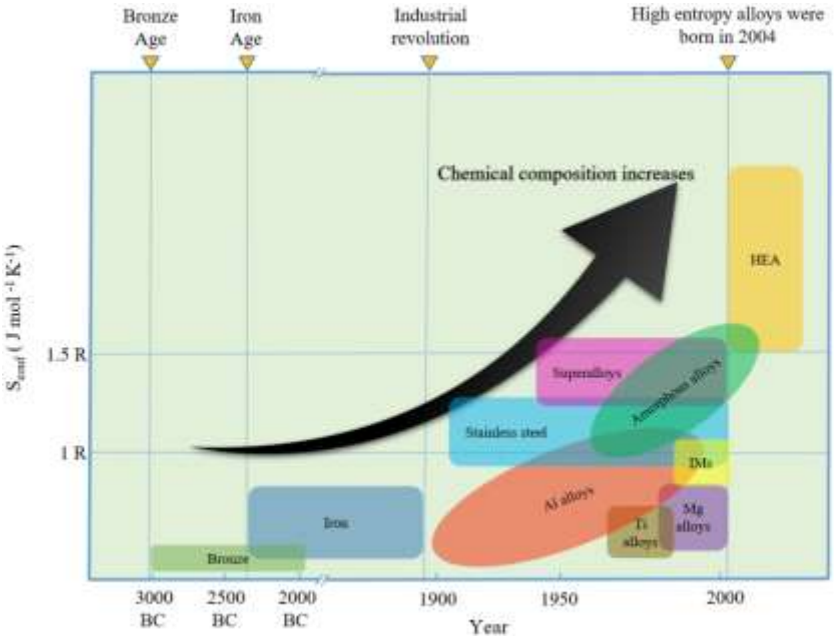

Figure 1. Historical development of engineering materials [18].

According to Yeh's description reported in 2004, elements with a concentration of less than 5% in HEAs are called minor elements [5]. HEAs are designed to have a significantly higher mixture entropy than other alloys, which leads to the formation of solid solutions with simple crystalline phases [8]. HEAs tend to form with simple solid solution phases. These materials accelerate the development of metallic materials and, consequently, the development of high-quality alloys [8, 19]. Figure 2 presents perfect lattice patterns, single alloy lattice patterns and HEA lattice structure, which are formed by a single element composition.

There are different definitions of HEAs in the literature. According to Otto et al., only multi-component alloys that form true solid solutions should be called HEAs. The reason for this is that intermetallic phase multicomponent alloys do not show the “full” configurational entropy of real solid solutions [20]. Miracle et al., defined HEAs as any alloy with an ideal or regular configurational entropy ($\Delta S_{conf} \geq 1.5R$ ($R=8.314\ J \cdot mol^{-1} \cdot K^{-1}$) (R is the gas constant). The ΔS_{conf} in the definition refers to the entropy arising from the structure of the alloy that must be overcome in order to allow the formation of different phases in the high-temperature state [9]. In another study, $\Delta S_{conf} \geq 1.61R$ ($R=13.39\ J \cdot mol^{-1} \cdot K^{-1}$) was used for the configurational entropy of HEAs [21]. These alloys were called equimolar alloys, equiatomic alloys and multi-component alloys [22]. According to Cantor, some multi-component alloys do not have high entropy properties and therefore it is more accurate to make a general nomenclature as multi-component alloys [23, 24]. Figure 3 shows that the types of alloys based on configurational entropy and Yeh divided alloys into three main groups according to their mixture entropies [2]:

- **a) Low entropy alloys** are conventional alloys ($\Delta S_{conf} \leq 0.69R$).
- **b) Medium entropy alloys** include 2-4 main elements. The high entropy effect seen in HEAs that increases the disordered solution phase is less observed in these ($0.69R \leq \Delta S_{conf} \leq 1.61R$).
- **c) HEAs** include at least 5 main elements ($\Delta S_{conf} \geq 1.61R$).

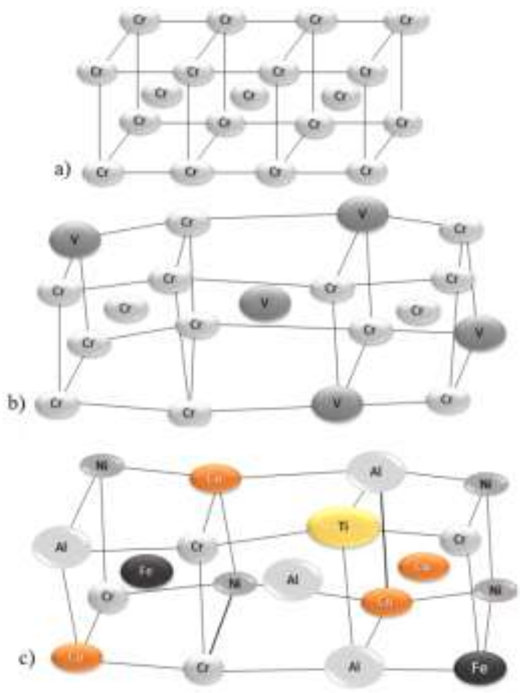

Figure 2. Body-centered cubic cell lattice with a) one element (Cr), b) two elements (Cr, V) and c) six elements (Cr, Ni, Fe, Co, Al, Ti), in which atoms are distributed randomly [25].

Conventional alloys include one main metal and one or two other metals together [5, 16, 17]. HEAs, which were developed after conventional alloys reached maturity, make it available to produce alloys that include five or more metals [5, 17].

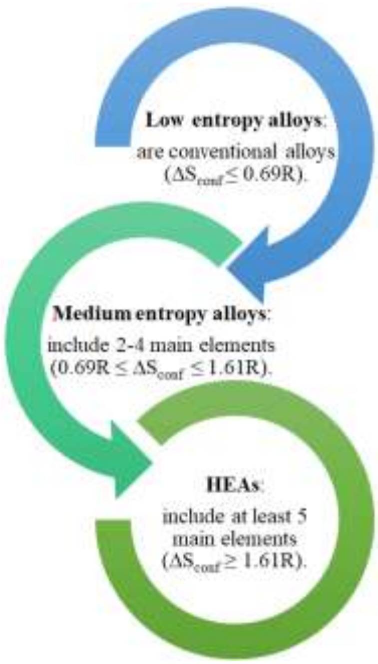

Figure 3. Types of alloys based on configurational entropy.

Alloys of different microstructures and functionalities can be obtained with different compositions of the metals [8, 26]. The Co20Cr20Fe20Mn20Ni20 alloy developed by Cantor in his study is one of the first examples of high entropy alloys, otherwise known as equiatomic multi-component alloys [6, 23]. In addition, the presence of more component elements in an alloy causes it to have a higher configuration entropy. The correlation between temperature and change in configuration enthalpy may be used to classify alloys as shown in Figure 4 [27].

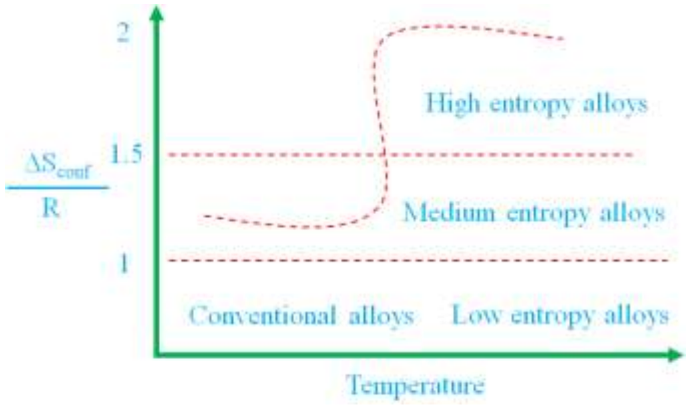

Figure 4. Representation of entropy against temperature invariant alloys [27].

2. Factors that Affect the Microstructures and Properties of HEA Materials

When compared with conventional alloys, HEAs have four main effects that give them their distinctive properties and make them so attractive. These are high-entropy, lattice distortion, sluggish diffusion and cocktail effects. These effects significantly affect the microstructure and properties of the alloys. The four main effects of HEAs are given in Figure 5 [8, 22, 28-33].

Figure 5. Schematic diagram of the four main core effects of HEAs.

2.1. High Entropy Effect

As can be understood from the name of HEAs, high entropy is the first major core effect among of the four main effects. This effect can increase the formation of solution phases and make the microstructure simpler than previously expected. Therefore, this effect has the potential to increase the strength and ductility of the solution phases due to the solution hardening. The high entropy effect makes it easy to form face-centered cubic cell (FCCs), body-centered cubic cells (BCCs) and hexagonal close-packed cells (HCPs) in the solid solution phases [8, 34].

2.2. Lattice Distortion Effect

HEAs contain many elements in different sizes. Therefore, distortion takes place in the lattice structure. For this reason, these alloys have a great inner stress-strain field. The stress field in these alloys is uneven and as a result, has a local stress gradient that slows the movement of ions and causes sluggish diffusion. This effect is very important in order to have a consistent solid solution phase. If the lattice distortion energy is too high, the crystal structure collapses into the amorphous state [25, 33]. The differences revealed by lattice distortions in the lattice structures are shown in Figure 6.

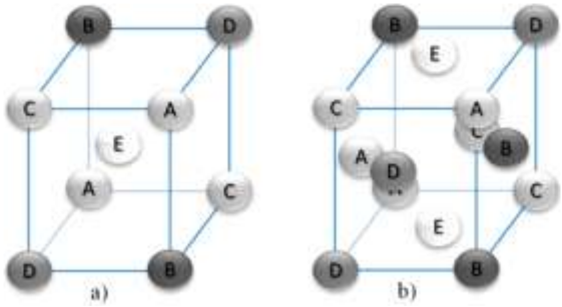

Figure 6. a) BCC and b) FCC crystal structures with five primary elements [28].

In fact, these structures are not surprising as many elements prefer these structures. Due to the structure of the atoms that form HEAs, in a multi-element lattice, the lattice structure is severely impaired as all atoms cannot be symmetrically connected to each other. In such cases, this is called the lattice distortion effect or severe lattice distortion effect of HEAs.

2.3. Sluggish Diffusion Effect

It is easy to tell that diffusion in HEAs works slower than it does in conventional alloys. Normally, phase changes are expected to happen during cooling in HEAs, however, this might not happen due to sluggish diffusion. Sluggish atomic diffusion means that the atoms move very slowly. The surrounding of the atoms is also affected by the movement of the atoms. As the local atomic configuration changes, atoms make different bonds with the surrounding atoms and the local potential also changes. Therefore, if an atom bounces to a low-potential state, it becomes trapped there and the time it spends in this state increases. On the other hand, if it jumps to a high-potential state, there is a high chance of it jumping back to its initial position. In both cases, diffusion slows down. This situation does not happen in conventional alloys [33].

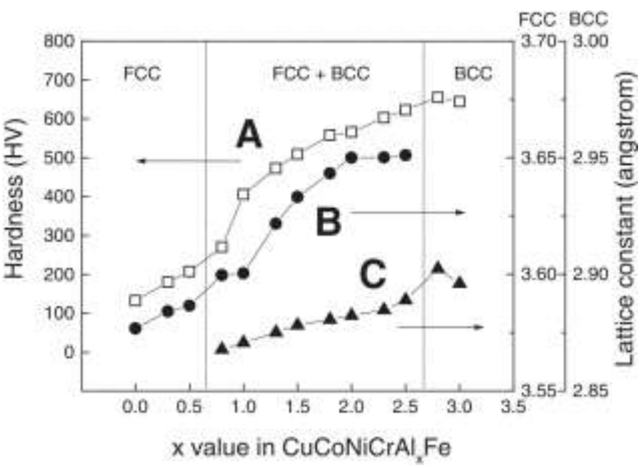

Figure 7. Hardness and lattice constants of the $CuCoNiCrAl_XFe$ alloy system with different x values: a) Hardness of the $CuCoNiCrAl_XFe$ alloy, b) Lattice of the FCC phase, and c) Lattice constant of the BCC phase [5].

2.4. Cocktail Effect

HEAs include many elements. In addition to the properties of each element the interactions between these elements also have an effect on the properties of HEAs. Cocktail effects in alloys point out that the properties that cannot be obtained from one element alone can be obtained after many elements are mixed together and give many facilities for materials with different properties. This effect was first suggested by Ranganathan [17]. The cocktail effect in HEAs means that alloy properties can be largely adjusted by changing the composition and adding different alloy elements. One of them Aluminium (Al) alloys is materials of choice in many engineering applications [35, 36]. Figure 7 presents the changes in hardness, lattice structure and lattice constants that occurred by changing the aluminium (Al) content in $CuCrCuNiAl_XFe$ HEAs.

3. Properties and Utilization Areas of HEAs

The properties of HEAs are affected by the properties of the metals that constitute them. The following information is presented in the literature about the characteristics of the new generation HEAs and shown in Figure 8.

3.1. Thermal Resistivity

Studies in the literature have reported that HEAs have a high-temperature resistance [12, 13, 17, 37-43]. It has been determined that HEAs are suitable for high-temperature applications due to their sluggish diffusion effect. Additionally, they are more efficient in high-temperature applications compare to superalloys [44]. HEAs have high thermal softening resistance [45-48] and their diffusion effect affects their stability in terms of mechanical properties and microstructure at high temperatures [32, 49].

3.2. Thermal Conductivity

The thermal conductivities of HEAs are very low. It has been reported in the literature that the reason for this is that the distorted lattice structure of these materials has a significant effect on the dissipation of phonons [50].

3.3. Corrosion and Wear Resistance

In the literature, HEAs are mostly mentioned in relation to their high corrosion and wear resistance properties [7, 12, 13, 17, 37-40, 48, 51-55]. It has been stated that if an element with a self-lubricating effect is added to an alloy, wear resistance can be increased by reducing the friction [56]. In addition, it has been reported that the wear resistance of these materials can be increased by nitration [57, 58]. The addition of titanium (Ti), Al, manganese (Mn), molybdenum (Mo) and niobium (Nb) to HEAs can provide high temperature wear resistance and also increase corrosion resistance [20, 59-61]. Therefore, the materials used in an alloy have a significant role in the determination of abrasion and corrosion resistance [52, 62].

3.4. Hardness

It has been reported that HEAs have high hardness values that vary between 100 Hv and 1100 Hv [12, 13, 17, 37-40, 48]. Alloys that contain Al have been determined to have high hardness values

[33, 63, 64]. Moreover, adding elements such as Ti, Al, Mn, Mo, and Nb to alloys, even in small amounts, has been found to improve their hardness [20, 59-61]. In addition to alloy content, which has a high effect on hardness, it is thought that annealing may also have some effect on this property [34]. The lattice distortion effect in HEAs causes their hardness values to increase [16, 31, 65].

3.5. High strength

The strength of HEAs has been mentioned in many studies in the literature [8, 12, 13, 17, 37-40, 66-69]. Strength can be increased by the use of different elements [20, 59-61, 66]. The crystal structure of the HEAs affects their properties. Therefore this structure should be determined according to the desired property [8, 70, 71]. The lattice distortion effect in HEAs causes the hardness and strength values to increase [16, 31, 65].

3.6. Electrical and Magnetic Properties

HEAs are known to have high electrical resistance and good magnetic properties, and therefore, can be used in high-frequency communication inductors [48, 72, 73]. The use of more magnetic elements in alloys causes high magnetization, while the use of elements such as Cr reduces this value [50, 74]. HEAs have high electrical resistance due to the fact that they have high lattice disturbances that distribute electron waves [32, 50, 75].

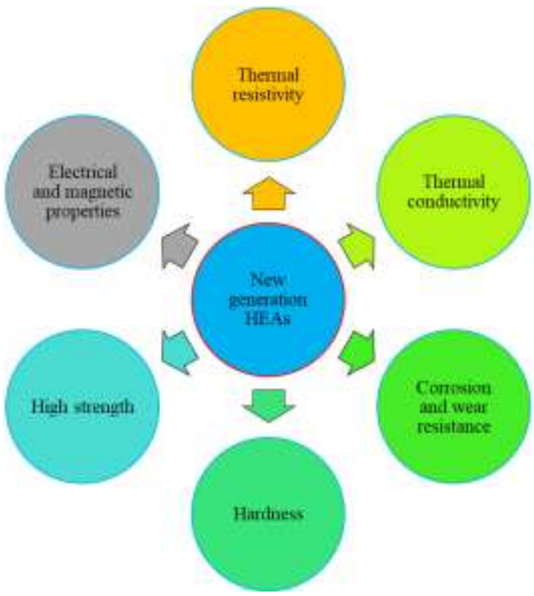

Figure 8. Schematic diagram of the new generation HEAs.

Along with the aforementioned properties, various sources have reported that HEAs have high dimensional stability, high creep resistance and high oxidation resistance [76-78]. HEAs can be used in many industrial areas in which these features are required. In addition, they provide a good alternative in areas where high-temperature resistance, good dimensional stability, high wear and corrosion resistance are needed. Therefore, HEAs are used in many functional and structural applications [32]. As stated by Tong et al., HEAs have "a high potential for applications such as cutting tools, molds, oven parts and mechanical parts which require high strength, thermal stability, abrasion and oxidation resistance, and high temperatures." [5, 12-14, 79].

Due to their high corrosion resistance, HEAs can be used in marine applications, chemical plants etc. [55, 79]. Likewise, as a result of their high corrosion resistance, it is also possible to use them in parts of liquid propellant rockets, which are exposed to high concentration hydrogen peroxide [80].

Owing to their resistance to high temperatures, they are and/or can be used as building materials in power plants, defense and military applications, aerospace materials, industrial furnaces, gas turbine engines, rocket nozzles, nuclear structures and rotating anodes [7, 43, 55, 56, 81-84]. In their study, Zhou et al. stated that HEAs have the potential to become matrix material for tungsten heavy alloys used as kinetic energy bullets [85]. HEAs also can be used in other potential applications in different fields and have become promising advanced materials that satisfy sensitive service conditions, especially in the military, defense and aviation industries [86-88].

4. Production Methods of HEAs

As a result of their superior features the popularity of HEAs is increasing day by day. Information on the properties of these alloys, which contain five or more elements, has been given in the previous section. The elements intended to be used in the structure of HEAs must be selected prior to starting their production. In this study, these elements were primarily defined with the help of the standards and information given in the literature. Many parameters are effective in determining the solid solution-forming capabilities of the elements that are selected according to the properties expected from the alloy [89]. In this study, it was important that the atomic diameters, electronegativity values, crystal structures and valence electron densities of the elements were in accordance with the Hume-Rothery rule [79, 90]. However, this alone was not sufficient.

There are a variety of methods that can be used in the production of HEAs [91-93], during which it is possible to carry out mass production with existing equipment and technologies as no special equipment is needed [33]. Three methods, namely solid-state, liquid-state and gas-state mixing [34], are shown in Figure 9.

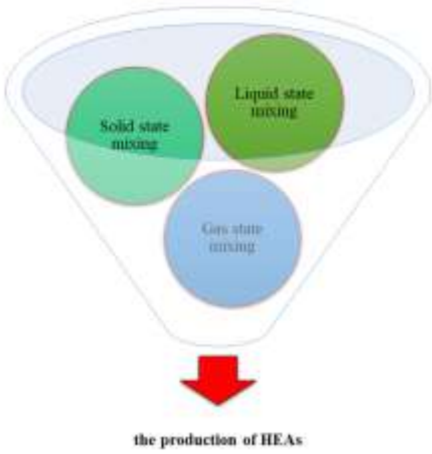

Figure 9. Schematic diagram of the production of HEAs.

It has been examined in three groups as melting and casting method, powder metallurgy method, and deposition techniques [16]. HEAs can be easily fabricated into different forms, such as powders, thin films and bulk materials [94]. The three production stages of HEAs are summarized in Figure 10.

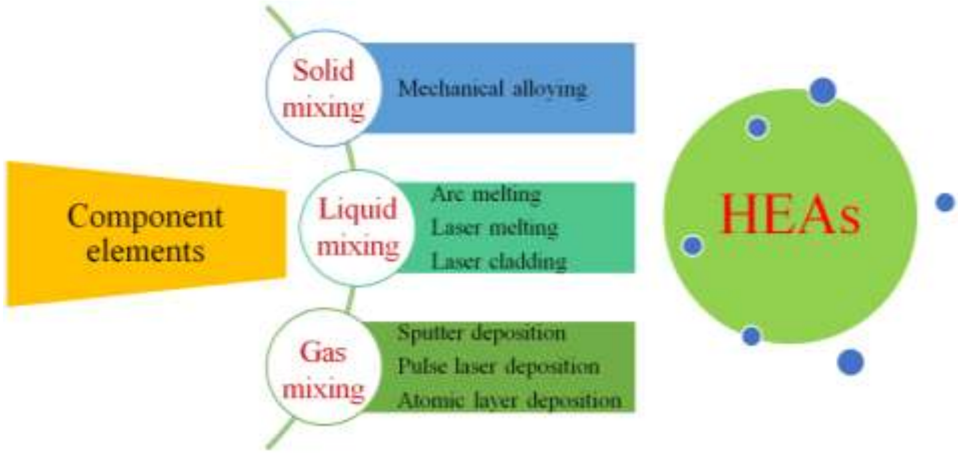

Figure 10. Production stages of HEAs [95].

4.1. Solid-State Mixing

Solid-state mixing is called the mechanical alloying (MA) method. By using this method, equimolar HEAs can be formed with ball milling systems [34]. It includes the MA process of elemental mixtures followed by a consolidation process in the production of HEAs from solid state [16]. MA is a solid-state powder production technique that is repeated in a high energy ball mill and involves the cold welding, fragmentation, and recombination of dust particles [8]. Figure 11 presents a schematic diagram of the dust particles during the MA method.

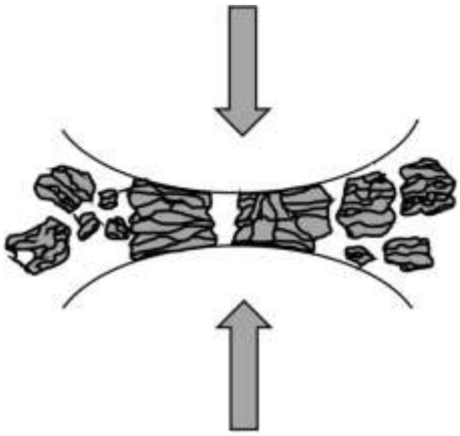

Figure 11. Fracture and welding events during the collision of balls and powders in MA [16].

MA is carried out in three stages. First, the alloy materials are ground to very fine powders in a ball mill, and then using hot isostatic pressing (HIP) the powders are sintered. Finally, a heat treatment is applied to remove the internal stresses that occur during cold compression [96].

MA has several advantages, one of which is the fact that all kinds of materials can be produced including intermetallic compounds with fragile structures and composite ductile metal alloys. However, contamination can occur due to air or device during milling, which is a disadvantage [34].

4.2. Liquid-State Mixing

Liquid state mixing includes the methods of arc melting, laser cladding and Bridgman solidification casting. Among these, arc melting is the most used one in the production of HEAs. In arc melting, the liquid materials are mixed in a melting pot. Homogeneity is increased by repeating this process. The disadvantage of arc melting is that it is not an easily controlled process due to rapid solidification. In the production of HEAs using the Bridgman solidification casting method, microstructure control and feature optimization can be performed, as opposed to normal casting. The laser melting and cladding methods focus on a small area to prevent fractures and voids and, thus, obtain a good microstructure and a strong bond [34].

The vacuum induction method is also used in the production of HEAs in addition to the vacuum arc melting method, which is the most widely used HEA production method. The vacuum arc melting method is a popular method because the temperature (about 3000 °C) released during arc melting is sufficient for melting many metals used in HEA production [16].

The production of HEAs using the arc melting method is achieved by severally melting various elements in the arc melting furnace. The torch temperature of the arc melting furnace can be very high (3000 °C) and controlled by adjusting the electrical power. Therefore most high melting elements can be mixed in their liquid state using this kind of furnace. This method is suitable for elements with high melting points, however, it can be difficult to achieve composition control as low melting point elements (such as Mg, Zn, and Mn) can easily evaporate [96].

Another limitation of the melting and casting methods is the appearance of a heterogeneous structure with different separation mechanisms caused by low solidification. Figure 12 shows the dendritic and interdendritic structures in the typical solidification microstructure encountered in the production of HEAs using the vacuum arc technique.

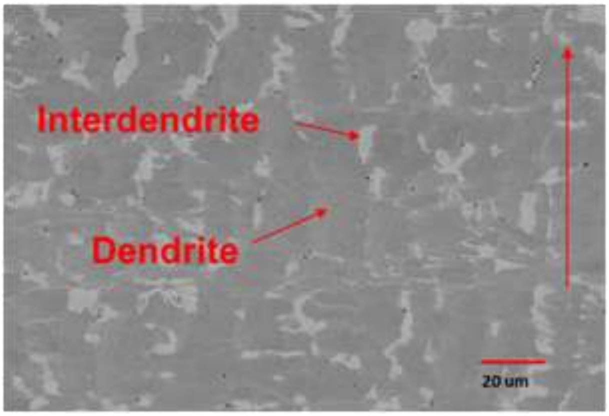

Figure 12. The microstructure of the $Al_{0,5}$CoCrCuFeNi alloy produced using the vacuum arc melting and casting method [97].

4.3. Gas-State Mixing

The gas state mixing method includes physical vapor deposition (PVD). With this method, thin HEA film coatings can be obtained [16, 34]. Magnetron sputtering deposition is the most popular method used to produce HEA films. As can be seen in Figure 13, sputtered atoms close to the atomic fractions of the deposited HEA are thrown from the sputtering gas by atomic or ion bombardment. These sprayed atoms are deposited randomly on the surface to be coated but HEA film nucleation and growth. Therefore microstructure of the HEA films is specified by the parameters including the form of the source material, power, atmosphere composition, base pressure and workpiece temperature [34].

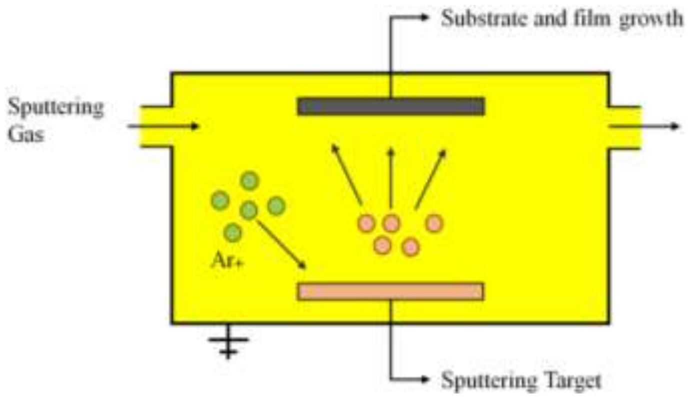

Figure 13. Schematic representation of the magnetron spraying method [34].

5. Recent Progress in HEAs

As mentioned in the previous chapters, HEAs have attracted the attention of material scientists in recent years and numerous studies have been conducted on this subject especially after the 2000s. In this section, important studies of recent years are mentioned briefly and the literature review of the studies is given in Table 1.
Stepanov et al. produced a HfNbTaTiZr HEA, which is one of the most studied BCC phase HEAs by vacuum arc melting method. They homogenized it at 1200 °C and annealed at 600 °C -1000 °C for 1-100 hours. They examined the structure and microhardness of annealed alloy and observed a significant increase in the microhardness as a result of the aging process at 600 °C. After annealing at 600 °C and 800 °C, second HCP phase particles were formed in the BCC matrix. In addition, the effect of precipitation of the second phase particles on the microhardness was also analyzed [98].

Wong et al. investigated how the addition of Mn affected the microstructure and the mechanical and electrochemical properties of $Al_{0.3}CoCrFeNiMn_x$ (x= 0, 0.1, and 0.3) HEAs. All of the solutions in the study were simple FCC solid solutions. They reported that after the addition of Mn to the $Al_{0.3}CoCrFeNi$ alloy, the lattice parameter increased from 3.591 Å to 3.611 Å and the hardness values increased from HV141 to HV156. They also stated that the yield stress increased from 119 MPa to 158 MPa and the ultimate tensile strength increased from 295 MPa to 371 MPa. In accordance with the polarization curves of the alloys, it was indicated that the corrosion resistance increased after the addition of Mn [99].

Seol et al. conducted a study in which they added boron (B) to the equiatomic FeMnCrCoNi and $Fe_{40}Mn_{40}Cr_{10}Co_{10}$ alloys. They stated that even an addition of around 30 ppm increased the mechanical properties of the alloys. The yield strength increased by 100%, ultimate tensile strength increased by approximately 40%, and ductility was found to be comparable and even higher than the alloys without addition [100].

Yu et al. conducted a study on the high concentration hydrogen peroxide solutions, which are described as the fuel of the future. They examined the corrosive and tribological behavior of AlCoCrFeNi-M HEA against these solutions and studied the wear mechanisms and alloy-structure effect. They reported that it was easier to achieve effective lubrication with HEAs that had low corrosion resistance and high strength. Furthermore, it was noted that the component heterogeneity of different structures could improve corrosion behavior [80].

In the study of Vaidya et al., the phase formation and thermal stability of nanocrystalline CoCrFeNi and CoCrFeMnNi HEAs produced by using the mechanical alloying and subsequent spark plasma sintering (SPS) processes were investigated. As a result, the presence of a single-phase field in the phase diagrams, the similar atomic size of the components and homogeneous structure of the mechanical alloying together allow a high stability FCC phase in the studied nanocrystalline HEAs [101].

Cheng et al. investigated the microstructures and mechanical properties of $FeCoCrNiMnAl_x$ HEAs produced by the mechanical alloying and hot press sintering processes. The effect of the concentration of Al on the microstructure and mechanical properties was evaluated. The Al-containing alloys were found to include FCC or FCC + BCC two-phase solid solution phases and some M_7C_3 + $M_{23}C_6$ (M=Cr, Mn, Fe) carbides along with Al_2O_3 phases. They reported that high Al concentration caused BCC precipitates in the alloy and that the crystalline structure of the matrix solid solution phase changed from FCC to BCC with increasing Al concentration. In addition, they stated that the addition of Al increased strength [102].

Karati et al. conducted a study on the thermal stability of AlCoFeMnNi HEAs. They modified the AlCoCrFeNi alloy by changing Cr with Mn and produced the alloy using the vacuum arc melting method. The as-cast alloy exhibited the B2 phase. Irregular B2 and FCC phases were formed after 50 hours of heat treatment at 1050 °C. They reported that the absence of the embrittling σ-phase would lead to a general application of the alloy [103].

In their study, Mishra et al. synthesized AlCrFeMnNiTi HEA by mechanical alloying and examined the phase formation and the magnetic and corrosion behavior of the produced alloy. They stated that the FCC and BCC phases formed in a simple solid solution as a result of 25 hours of mechanical alloying. According to the DSC analysis, the synthesized AlCrFeMn-NiTi phases were stable up to 550 °C and recrystallization occurred above this temperature. The synthesized HEA was annealed for 1 hour at 700 °C to observe the effect of annealing on phase formation and magnetic characteristics. As a result, it was observed that the BCC phase decreased. They reported that the resultant HEA showed better ferromagnetic properties and that the annealed alloy exhibited good corrosion resistance in a 0.5 M NaCl solution due to the presence of Al [104].

Table1. Literature summary of the research studies on HEAs materials.

Names	Year	Product	Production	Lattice	Properties Analyzed	Results
Stepanov et al.	2018	HfNbTaTiZr	Vacuum arc melting	BCC	Structure, microhardness	- Microhardness increase. - Hardening effect low.
Wong et al.	2018	$Al_{0.3}CoCrFeNiMn_x$	Induction melting and casting in air	FCC	Microstructure, mechanical, electrochemical properties	- Addition of Mn to alloy increases mechanical properties.
Seol et al.	2018	$Fe_{40}Mn_{40}Cr_{10}Co_{10}$	Cast in a vacuum induction furnace	FCC	Corrosive, tribological	- Improve mechanical properties.
Yu et al.	2019	AlCoCrFeNi-M	Arc-melting	BCC, B2	Wear mechanism, structure effect	- Improve tribological properties.
Vaidya et al.	2019	CoCrFeMnNi	MA, SPS	FCC	MA powders and SPS pellets	- High stability FCC.
Cheng et al.	2019	$FeCoCrNiMnAl_x$	MA, hot press sintering	FCC + BCC	Microstructure, mechanical properties	- FCC to BCC with increasing Al concentration. - Al increase strength.
Karati et al.	2019	AlCoFeMnNi	Vacuum arc melting	B2 + FCC	Thermal stability Behaviour	- Absence of the embrittling σ-phase.
Mishra et al.	2019	AlCrFeMnNiTi	MA	FCC + BCC	Phase formation, magnetic characteristics	- Good corrosion resistance.

6. Conclusions

Up until now, most conventional alloys have been based on a single element and are usually added to conventional materials to improve their strength, ductility, hardness and high-temperature wear. HEAs are a new phenomenon of advanced materials with unique properties. The superior properties of HEAs are what have made these materials very popular and of significant interest in recent years. Most researcher/scientists who have studied HEAs have focused on five or more metallic elements to improve a new concept of engineering alloys for the future. In this study, information regarding the definitions, properties, production methods, application areas and technological applications of HEAs were given in detail. Contemporary innovative advances and this new area, where there is a high potential to provide HEAs with superior features, offers us a broad perspective in the development of new materials and properties, particularly in the military, aviation and defense industry applications, and aerospace technologies. It is foreseen that the use of HEAs will increase in the near future due to these developments.

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