



Cryogenic-Mechanical Properties and Applications of Multiple-Basis-Element Alloys

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Abstract: Multiple-basis-element (MBE) alloy was defined as the entropy of mixing over 1R (R is the gas constant, 8.31 J/k), and contains at least three principal elements, each one at over 5%. Thus, MBE alloys can include high-entropy alloys (HEAs), medium-entropy alloys (MEAs), amorphous alloys, and some martensite stainless steels, which have been reported to possess excellent cryogenic properties. This paper reviews the progress of the cryogenic-mechanical properties and applications of MBE alloys. It has been concluded that, with the increase of entropy, the ductile-brittle-transition temperatures (DBTT) can be decreased to the liquid helium temperature (4.2 K). In summary, the cryogenic toughness of MBE alloys can be greatly enhanced by entropy adjustments, which is beneficial to their application at low temperatures.

Keywords: high-entropy alloys; amorphous alloys; cryogenic-mechanical properties; applications; multiple-basis-element (MBE) alloy



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1. Introduction

Multiple-basis-element (MBE) alloy is defined as the entropy of mixing over 1R (R is the gas constant, 8.31 J/k), and contains at least three principal elements, each one at over 5%. Thus, MBE alloys can include high-entropy alloys (HEAs), medium-entropy alloys(MEAs), amorphous alloys and some martensite stainless alloys. Amorphous alloys, also known as metallic glasses, are a new type of high-performance metallic materials discovered in 1960. Different from traditional crystalline alloys, their internal atomic arrangement presents the characteristics of long-range disorder and short-range order. Metallic glasses are mainly prepared by rapid cooling of a metal melt to avoid crystallization during solidification. At present, amorphous alloys have been successfully used in the sports goods industry, such as in golf clubs, mobile phone shells, medical devices and other fields. From the thermodynamic point of view, a high-entropy property makes the Gibbs free energy drop faster along with decreasing temperature, which is conducive to the formation of amorphous structure in the solidification process.

In recent years, HEAs, designed based on the concept of "entropy", have subverted the design concept of traditional materials and made breakthroughs in material properties. This proposal for HEAs was based on the development of bulk amorphous alloys in the 1990s. A Taiwanese scholar, Ye Junwei, proposed the concept of HEAs [1]. HEAs can generally be defined as alloys composed of five or more elements and the atomic fraction of each component is between 5% and 35%. HEAs is a kind of structural material which can be used in many fields because of its high mixing entropy, lattice distortion, slow diffusion and cocktail effect.

The cryogenic application potential of MBE alloys is shown in a good low temperature toughness, no ductile brittle transition in the low temperature region, and it can be used for aerospace structures, serving under conditions of large temperature difference. The properties of metallic alloys usually change from the ductile to brittle mode with decreasing

temperature, known as the ductile-to-brittle transition. The temperature at which the transition takes place is called the ductile-brittle-transition temperature. Not all materials show a ductile-brittle-transition phenomenon. Alloys of FCC structure are ductile at all temperatures. BCC and some hexagonal close packing (HCP) metals and alloys have obvious ductile-to-brittle transitions. The excellent cryogenic mechanical properties of the MBE alloys are attributed to multiple components, complex structures and variable mechanisms. Therefore, the development of MBE alloys has a significant role in promoting the basic research of materials and the industrial application and development of modern alloys [2].

2. Methods

The raw materials used in the test are metals with a purity of 99.9 wt.% or more. A vacuum arc melting furnace is used for melting alloy ingots, and high-purity argon is used for protection during arc melting. In order to obtain uniform alloy composition, the alloy was repeatedly turned over and smelted four times. The bar, with a certain diameter and height, was prepared by copper mold suction casting. If there are volatile elements in the alloy during arc melting, the content of such elements is appropriately increased in the raw materials, and 0.05 MPa argon pressure is used during smelting. After solidification and cooling for 20 min, the ingot is taken out.

The specimen to be tested for mechanical properties at low temperature is immersed into liquid nitrogen to ensure a temperature at 77 K. The specimen to be tested for mechanical properties is immersed at low temperature into liquid helium to ensure a temperature of 4.2 K. The low temperature of 0.5 K is realized by the relatively high refrigerating capacity of the liquid ³He vapors. Rectangular dog-bone shape tensile specimens and cylindrical compression specimens were machined from ingots by electric-discharged machinery. The temperature and strain rate are set on the testing machine and then stretching or compression occurs.

3. Results

3.1. Cryogenic-Mechanical Properties of Amorphous Alloys

Research on the mechanical properties of bulk-amorphous alloys at low temperatures has mostly focused on tension and compression studies and there are relatively few studies on their low-temperature impact properties. In order to expand the application of bulk amorphous alloys in low-temperature extreme environments, it is necessary to continue to explore other properties of bulk-amorphous alloys and to reveal the response mechanism of their microstructures and properties at low temperatures [3].

3.1.1. Cryogenic-Mechanical Properties of BMGs

The mechanical behavior of amorphous alloys is closely related to the temperature, strain rate and loading mode. Amorphous alloys exhibit different deformation characteristics at various temperatures and strain rates. At high temperatures or low strain rates, amorphous alloys exhibit macroscopic uniform plastic deformation (viscous flow), while at low temperatures or high strain rates the deformation of amorphous alloys is limited to the deformation region of nano-sized shear bands and the plastic deformation is non-uniform and highly localized [4,5].

At low temperature, the mechanism of the strength and plasticity of amorphous alloys are also studied. For example, Li [6] of Dalian University of Technology investigated the effect of low temperature on the mechanical behavior of a Zr₆₀Ni₂₅Al₁₅ BMG with high glass-forming ability through uniaxial compression and tensile tests. As shown in Figure 1 [6], as the temperature decreased from room temperature (293 K) to liquid-nitrogen temperature (77 K), the compressive yield stress increased from 1791 MPa to 2217 MPa, the compressive plastic strain increased from 3.5% to 16.7%, the tensile fracture stress increased from 1743 MPa to 2036 MPa and the tensile plastic strain increased from 0 to 0.14%. Enhanced atomic bonding and shortened effective atomic distances at low

temperatures lead to increased strength, while the inhibition of free-volume migration and aggregation leads to enhanced plasticity.



Figure 1. Nominal compressive stress–strain curves of the Zr₆₀Ni₂₅Al₁₅ BMG conducted at temperatures of 293, 173 and 77 K. Reprinted with permission from Ref. [6]. Copyright 2013, Elsevier.

Li et al. [7] reported the temperature-dependent mechanical property of Zr-based metallic glasses. Compression tests were conducted on four Zr-based BMGs with different Nb contents of 1–4% (atomic percent). The results show that adding a small number of elements has no obvious effect on the mechanical properties. The phenomenon is quite different from that observed in crystalline materials. In crystal materials, adding a small number of alloying elements can significantly improve the strength. At 77 K, the strength increases significantly without embrittlement. The normalized intensity (strength/E, E: Young's modules) is linear with the normalized temperature(T/T_g). At 300 K, strength is insensitive to strain rate. At low and high temperatures, BMGs exhibit strain-rate sensitivity. The strength depends on the strain rate at high and low temperatures.

Yao Jian [8] of Northwestern Polytechnical University also studied the ductile-to-brittle transition of amorphous alloy from room temperature to liquid nitrogen temperature. They mainly studied the quasi-static compressive mechanical behavior of Ti₄₀Zr₂₅Ni₈Cu₈Be₁₈ bulk-amorphous alloy at low temperature, and compared the room temperature and low temperature mechanical properties of the alloy at different strain rates. At room temperature, the plastic strain of Ti-based amorphous alloy is 1.8% and the plastic strain decreases with the increase of strain rate. The mechanical properties of Ti₄₀Zr₂₅Ni₈Cu₈Be₁₈ bulk amorphous alloy under a compression load are strongly dependent on ambient temperature and strain rate. The ductile-brittle-transition temperature of the alloy is above 77 K. Sun et al. [9] studied the dynamic compression performance of the alloy at cryogenic temperatures. During dynamic compression at room temperature, the compressive strength does not change significantly with the increase of the strain rate. Under dynamic compression at 77 K, the compressive strength increases significantly with the increase of strain rate, which means that the strain-rate-hardening effect exists. At room temperature, Ti₄₀Zr₂₅Ni₈Cu₈Be₁₈ bulk amorphous alloy shows obvious yield after elastic deformation and the alloy shows typical brittle fracture characteristics. The dynamic compressive strength at 77 K is obviously higher than that at room temperature.

Li et al. [10] studied the mechanical behavior of an $Mg_{61}Cu_{20.3}Ag_{8.7}Er_{10}$ amorphous alloy. At these two temperatures, amorphous alloys show brittle fracture to a large extent. When the strain rate is 1×10^{-4} s⁻¹, the amorphous alloy has the highest compressive fracture strength of 970 MPa. With the increase of strain rate, the yield strength of the amorphous alloy gradually decreases. However, the amorphous alloy has no compressive plasticity under different loading rates. At lower temperatures, the compressive strength of the amorphous alloy not only slightly increases to 1046 MPa, but also shows a small amount of plastic deformation (about 0.6%). The effect of loading rate on the strength and ductility of amorphous alloys is not as pronounced at room temperature.

The formation of highly localized shear bands during room-temperature deformation results in the fracture of a metallic glass with almost no macroscopic plastic deformation. In recent years, scholars have proposed a deep cryogenic cycle treatment (DCT), which can effectively improve the room-temperature plasticity and toughness of amorphous alloys without reducing strength and hardness. DCT refers to a heat-treatment method that circulates between room temperature and low temperature. There is a large temperature difference in the process of deep cryogenic cycle treatment. The process of temperature change induces internal stress, which causes atomic rearrangement in the alloy, and the amorphous alloy may rejuvenate. The rejuvenation gives the amorphous alloy a higher energy state, so it has higher plasticity [11].

3.1.2. Cryogenic-Mechanical Properties of BMG Matrix Composites

The brittleness of BMGs at room temperature seriously limits their wide application as structural engineering materials. In order to improve the macroscopic plasticity of BMGs at room temperature and their performance, how to effectively prevent a rapid expansion of shear bands and promote the proliferation of shear bands is very important. For this reason, people draw lessons from the concept of introducing second-phase strengthening and toughening into crystalline materials, introducing the second phase into the BMG in situ or ex situ, and developing BMG matrix composites in various alloy systems, so as to achieve the purpose of improving plastic properties [12]. Regardless of an in-situ or ex-situ method, the addition of the second phase improves the plastic-deformation ability of the BMG to varying degrees, especially in the state of compression deformation. In comparison, it is more common to prepare BMG-matrix composites by in-situ methods, and the prepared composites also have better plastic-deformation ability [13].

Li et al. [14] first found that in-situ dendrite-reinforced BMG composites exhibited excellent cryogenic-mechanical properties. The fracture strength of the $Ti_{48}Zr_{20}Nb_{12}Cu_5Be_{15}$ BMG composite at 77 K is 2760 MPa and the plastic strain is 18.4%. The effective interaction between the dendrites and shear bands results in good low-temperature plasticity of dendrites, which determines the low-temperature plasticity of composites. The increase of the low-temperature yield strength of dendrites leads to a corresponding increase in lowtemperature yield strengths of composites. A continuous matrix rather than the dendrite is considered to be the cause of fracture behavior.

The low-temperature mechanical properties of bulk amorphous-alloy composites reinforced in situ by plastic particles were studied. As the test temperature decreased from 298 K to 77 K, the yield strength of the W-containing bulk-amorphous alloy composites increased from 930 MPa to 1300 MPa and the plastic strain decreased from 58% to 20%. However, the yield strengths of Ta-containing bulk-amorphous alloy composites increased from 1760 MPa to 2040 MPa, the maximum strength increased from 1830 MPa to 2020 MPa, and the plastic strain remained unchanged. The difference in plastic particles leads to different changes in the plastic behavior of the two composites. W is the BCC structural metal and the ductile-to-brittle transition occurs at 253~263 K, resulting in a significant decrease in the low-temperature plasticity of tungsten-containing composites. Although Ta is a BCC structure, the ductile-to-brittle transition does not occur when it is reduced to 30 K [15].

Amorphous-matrix composites, with a Zr-based amorphous alloy as the matrix and tungsten continuous fibers or porous foams as the reinforced phase, were prepared by the liquid-pressing process and their dynamic compressive properties were evaluated. Tungsten fibers or foams at about 65 to 69 volume percent were uniformly distributed in the amorphous matrix, while defects, such as pores, were eliminated. According to the dynamic-compressive test results of amorphous-matrix composites, tungsten fibers can permit large loads to be carried when working, while the amorphous matrix can bear the load of bent or bucked fibers, so that the maximum strength reaches 3328 MPa and a plastic strain of 2.6%. In amorphous-matrix composites, the compressive stress continued to

increase according to the work-hardening degree after the yielding, resulting in a maximum strength of 3458 MPa and a plastic strain of 20.6%. The significant increase in the maximum strength and plastic strain was attributed to the uniform deformation at the tungsten foams and amorphous matrix at the same time, because tungsten foams did not show anisotropy, and the tungsten/matrix interfaces were excellent [16].

In practical applications, cryogenic-wear behaviors are closely related to the safety and durability of mechanical components. A series of cryogenic-wear tests were conducted on metastable BMG composites at different temperatures. The Ti_{47.2}Zr_{33.9}Cu_{5.9}Be₁₃ (at.%) BMG composite has better tribological properties at low temperatures. For example, the wear resistance at 113 K was 48% higher than at 233 K. At 233 K, there was an obvious martensitic-transformation (β -Ti $\rightarrow \alpha''$ -Ti)-coordinated deformation under the worn surface, while at 113 K, the martensitic transformation was significantly suppressed. This temperature-dependent structural evolution is clarified by artificially inducing a pre-notch by FIB cutting on a β -Ti crystal, demonstrating a strain-dominated martensitic transformation in the BMG composite. The improved strength and hardness of the metallic-glass matrix at cryogenic temperatures contributes to the strong limit of the martensitic transformation and the improvement of wear resistance [17].

3.2. Cryogenic-Mechanical Properties of HEAs

3.2.1. Cryogenic-Mechanical Properties of Single-Phase HEAs

There is no interference of the second phase in the initial matrix during the low-temperature deformation of the single-phase HEAs, which is beneficial in studying the effect of low temperature on the deformation mechanism of the HEA [18].

FCC HEAs and MEAs

The typical representative of FCC single-phase HEAs is the widely studied CoCr-FeMnNi (Cantor alloy) [19]. As shown in Figure 2 [20], CoCrFeMnNi HEA shows the characteristics of "the lower the temperature, the stronger and more ductile". At 77 K, the fracture toughness value of the alloy exceeds 200 MPa·m^{1/2} [21]. This exceeds all known pure metals and alloys, and the tensile strength is also greater than 1 GPa. This is because of the special deformation mechanism of nano-twinning at low temperature of the alloy, resulting in continuous work-hardening. In addition, Liu et al. [22] prepared the CoCr-FeMnNi HEA by SLM. The tensile strength of the specimen at room temperature is 647 MPa and the elongation is 15.8%. The tensile strength of the specimen at 77 K is 893.8 MPa and the elongation reaches 34.6%. With the decrease in temperature, the improvement of the mechanical properties of the specimens is mainly attributed to the existence of nanotwins.



Figure 2. Mechanical response of CoCrFeMnNi under tensile load at 295, 77 and 4.2 K. Reprinted with permission from Ref. [20]. Copyright 2018, Springer Nature.

At low temperature, HEAs and MEAs may have better impact toughness than traditional alloys. For example, CoCrNi MEA has extremely high ultra-low temperature impact toughness, which can be as high as 340 J at 4.2 K [23]. Due to the alloy's low stacking fault energy, coupled with the 4.2 K and high strain rate, deformation twinning becomes exceptionally abundant. The high-density nanotwins formed during the deformation process lead to severe strain hardening in the plastic zone in front of the crack tip, resulting in increased toughness. As shown in Figure 3 [23], the ultimate tensile strength and elongation at break during the 4.2 K all increased simultaneously, compared with those at room temperature and 77 K. When Cr is replaced by a large size V, a severe local lattice distortion occurs in the FCC lattice, resulting in higher strength. CoNiV MEA exhibits the largest lattice-friction stress, resulting in a room-temperature yield strength close to 1 GPa. The ultra-low temperature deformation of CoNiV relies solely on dislocation motion. Due to its high-level dislocation energy, twinning and phase-transition motion are not observed. Adding V to the FCC crystal structure is the key to achieving high strength [24].



Figure 3. Tensile engineering stress–0strain curves of the CoCrNi MEA at 4.2 K, 77 K and 293 K. Reprinted with permission from Ref. [23]. Copyright 2019, Elsevier.

Lin et al. [25] studied the phase transition from FCC to HCP during low-temperature deformation of CoCrFeNi HEA. Liu et al. [26] found that CoCrFeNi HEA has high strength and ductility at liquid helium temperature. At 4.2 K, the maximum tensile strength of the alloy reaches 1251 ± 10 MPa, and the failure strain reaches 62%, as shown in Figure 4 [26]. This is due to the combined effect of phase transformation and deformation twins. From room temperature to 77 K, the strength and ductility increase along with decreasing temperature. The decrease in temperature and twin boundary hinders dislocation movement, which makes the plasticity of the alloy decrease at 4.2 K.



Figure 4. Engineering stress–strain curves and photograph of CoCrFeNi before and after tensile tests from room temperature to low temperatures. Reprinted with permission from Ref. [26]. Copyright 2018, Springer Nature.

The deformation behavior of the CoCrFeNi HEA at room temperature, 140 K, 40 K (no serrated deformation), and 25 K (with massive serrations) was studied by in situ neutron diffraction. As shown in Figure 5 [27], by lowering the temperature from 295 K to 25 K, both strength and plasticity improve. At 25 K and 40 K, the dislocation density is as high as 9.2×10^{15} m⁻². The dislocation strengthening is the main source of strain hardening at all temperatures. The contribution of stacking faults and deformation twinning increase significantly with decreasing temperature [27].



Figure 5. Stress–strain curves of the CrFeCoNi HEA at 295, 140, 40, and 25 K. Reprinted with permission from Ref. [27]. Copyright 2021, Elsevier.

Li et al. [28] fabricated Al_xCoCrFeNi with different Al contents (i.e., x values in molar ratio, where x = 0.1 and 0.3) by vacuum magnetic levitation melting, and then prepared the template by hot forging. It can be seen from Figure 6 [28] that the tensile strength and elongation of the Al_{0.1}CoCrFeNi alloy increase along with the decrease in temperature, reaching 1042 MPa and 81.6% at 77 K, respectively. In current HEA alloys, the enhancement of properties may be due to mechanical nano twins rather than planar slip of dislocations. As shown in Figure 7 [28], the forged Al_xCoCrFeNi HEA has ultra-high Charpy impact toughness at room and low temperatures. At room temperature, the maximum Charpy impact energy of the Al_{0.1}CoCrFeNi alloy is 420 J. Figure 8 shows the bar and strip forged by our research group with Al_{0.3}CoCrFeNi.



Figure 6. Representative engineering stress–strain curves of the (**a**) $Al_{0.1}$ and (**b**) $Al_{0.3}$ alloys at the three testing temperatures. Reprinted with permission from Ref. [28]. Copyright 2016, Elsevier.



Figure 7. Summary of the Charpy impact energy of materials at the different temperatures. The dimension of alloy samples with * is $10 \times 10 \times 55$ mm³. Reprinted with permission from Ref. [28]. Copyright 2016, Elsevier.



Figure 8. Cont.



Figure 8. Forged bars and strips made of Al_{0.3}CoCrFeNi. (**a**–**e**) shows the dimensions of strips, (**f**,**g**) shows the dimensions of bars.

The coordinated deformation of dislocations, twinning, phase transformation and other mechanisms leads to the excellent ultra-low-temperature mechanical properties of FCC single-phase alloys.

BCC HEAs

Compared with FCC HEAs, the cryogenic properties of BCC HEAs are rarely reported. Qiao et al. [29] first studied the low temperature properties of HEA. Compared with those at room temperature, the yield strength and fracture strength of AlCoCrFeNi HEA increased significantly at 77 K. Later, people began to turn their attention to the cryogenic mechanical properties of HEAs and realized the potential application of HEAs at low temperatures.

NbMoTaWV and NbMoTaW HEAs were prepared by Senkov et al. From room temperature to 1400 °C, the two alloys maintain a single-phase BCC disordered solid solution structure. The two alloys exhibit high strength and low plasticity at room temperature. The yield strength reaches 1058 MPa and 1246 MPa and the compression plasticity is 2.1% and 1.7%. The limited compression plastic and quasi cleavage fracture at room temperature show that the ductile-brittle-transition temperature is significantly higher than room temperature [30].

For refractory HEAs, the lack of room-temperature ductility remains one of the key bottlenecks limiting their potential applications, which is associated with a sharp rise in the ductile-brittle-transition temperature. The equi-atomic HfNbTaTiZr is the most commonly studied BCC HEA [31]. The HfNbTaTiZr HEA is also one of the few refractory HEAs with excellent tensile plasticity at room temperature. The deformation of the TiZrHfNbTa alloy at room temperature is mainly dislocation slip. In the process of low-temperature tensile deformation, the activation of nanotwins is accompanied by the deformation-induced transformation of the BCC structure to a ω phase and dislocation slip, which makes the alloy have the combination of high strength and plasticity at low temperature. When the temperature decreases from 277 K to 77 K, the elongation of the alloy decreases slightly to 20.8%, while the yield strength increases significantly to 1549 MPa, without an obvious ductile-to-brittle transition. The strong temperature dependence of yield strength suggests that dislocation slip controls the deformation process [32].

As shown in Figure 9, in order to expand the operating temperature range of HEAs, we can decrease the ductile-brittle-transition temperature and increase the break temperature.



Figure 9. Ways to expand the operating temperature range of HEAs.

3.2.2. Cryogenic-Mechanical Properties of Multiphase HEAs and MEAs

It is difficult to combine high strength and plasticity in traditional HEAs with single solid solutions. Therefore, a reasonable composition design of multiphase HEAs has been conducted to obtain materials with excellent mechanical properties. Moon et al. [33] reported the mechanical and microstructural characteristics of $Co_{17.5}Cr_{12.5}Fe_{55}Ni_{10}Mo_5$ (Mo5 alloy, at.%) at low temperatures. The alloy consists of the μ precipitate and FCC matrix. In the temperature range of 0.5–4.2 K, the alloy exhibits some unusual features, including discontinuous plastic deformation, anomalous temperature dependence of the yield strength and tensile plasticity, and changes in deformation-induced martensitic transformation from the FCC to BCC or, to a lesser extent, to an HCP crystal structure. The Mo5 alloy has excellent low-temperature mechanical properties, including a high yield strength (1075 MPa) and significant strain-hardening ability. The tensile strength is up to 1651 MPa at 4.2 K. At 0.5 K, the properties of the alloy are at least comparable to those at 4.2 K.

Chen et al. [34] designed and prepared the $Fe_{49.85}Cr_{10.03}Mn_{10.03}Co_{10.03}Ni_{10.03}Al_{10.03}$ HEA with a dual-phase fine-grained structure. This as-cast Fe-based HEA consists of FCC and BCC phases, and the rod-like FCC fine grains are generated by the solid-state phase transformation of the BCC phase during cooling. The formation of the fine grain structure is a positive factor for the enhanced mechanical properties of HEAs. The strength and plasticity of the as-cast HEA at 298 K and 77 K are 636.5 MPa, ~30.0%, and 716.3 MPa, ~17.4%, respectively. Lu et al. [35] prepared AlCoCrFeNi_{2.1} eutectic alloys which also achieve high strength and plasticity in a wide temperature range from low temperature -196 °C to high temperature 700 °C.

In the next step, it is necessary to further study the related low-temperature deformation mechanism and low-temperature strengthening and toughening mechanisms of low-temperature HEAs, so as to establish a guiding development system of HEAs and lay a theoretical foundation for the development of HEAs in the future. Table 1 shows the phase composition, microstructure and mechanical properties of some HEAs at room temperature and low temperature.

Alloy	Phase Composition	T/K	Mechanical Properties	Reference
CoCrFeMnNi	FCC	298 K	$\sigma_{\rm V} = 523 \text{ MPa}, \sigma_{\rm u} = 647 \text{ MPa}, \delta = 15.8\%$	[22]
		77 K	$\sigma_{\rm u} = 893.8 \text{ MPa}, \delta = 34.6\%$	
		293 K	$\sigma_v = 446 \text{ MPa}, \sigma_u = 664 \text{ MPa}, \delta = 63\%$	
CoCrFeNi	FCC	77 K	$\sigma_{\rm V} = 590 \text{ MPa}, \sigma_{\rm u} = 1070 \text{ MPa}, \delta = 78\%$	[26]
		4.2 K	$\sigma_{\rm v} = 680$ MPa, $\sigma_{\rm u} = 1251 \pm 10$ MPa, $\delta = 61.6\% \pm 1.6\%$	
		293 K	$\sigma_{\rm v} = 350 \text{ MPa}, \sigma_{\rm u} = 870 \text{ MPa}, \delta = 66\%$	
CoCrNi	FCC	77 K	$\sigma_{\rm V} = 550 \text{ MPa}, \sigma_{\rm u} = 1300 \text{ MPa}, \delta = 82\%$	[23]
		4.2 K	$\sigma_{\rm V} = 590 \text{ MPa}, \sigma_{\rm u} = 1400 \text{ MPa}, \delta = 84\%$	
		298 K	$\sigma_{\rm v} = 620 \text{ MPa}, \sigma_{\rm u} = 1150 \text{ MPa}, \delta = 55\%$	
CoNiV	FCC	77 K	$\sigma_{\rm v} = 790 \text{ MPa}, \sigma_{\rm u} = 1430 \text{ MPa}, \delta = 60\%$	[24]
		4.2 K	$\sigma_{\rm v} = 885 \text{ MPa}, \sigma_{\rm u} = 1565 \text{ MPa}, \delta = 68\%$	
		298 K	$\sigma_v = 250 \text{ MPa}, \sigma_u = 635 \text{ MPa}, \delta = 68\%$	
Al _{0.1} CoCrFeNi	FCC	200 K	$\sigma_{v} = 295 \text{ MPa}, \sigma_{u} = 745 \text{ MPa}, \delta = 76\%$	
		77 K	$\sigma_{\rm v} = 412 \text{ MPa}, \sigma_{\rm u} = 1042 \text{ MPa}, \delta = 103\%$	[28]
		298 K	$\sigma_v = 220 \text{ MPa}, \sigma_u = 620 \text{ MPa}, \delta = 76\%$	
Al _{0.3} CoCrFeNi	FCC	200 K	$\sigma_{v} = 310 \text{ MPa}, \sigma_{u} = 635 \text{ MPa}, \delta = 74\%$	
		77 K	$\sigma_{\rm V} = 515 \text{ MPa}, \sigma_{\rm u} = 1010 \text{ MPa}, \delta = 84\%$	
AlCoCrFeNi	BCC	298 K	$\sigma_v = 1450 \text{ MPa}, \sigma_u = 2960 \text{ MPa}, \delta = 15.5\%$	[29]
		77 K	$\sigma_v = 1880 \text{ MPa}, \sigma_u = 3550 \text{ MPa}, \delta = 14.3\%$	
NbMoTaWV	BCC	298 K	$\sigma_{\rm v} = 1058 \text{ MPa}, \sigma_{\rm u} = 1211 \text{ MPa}, \delta = 2.1\%$	[30]
NbMoTaW	BCC	298 K	$\sigma_{\rm V} = 1246 \text{ MPa}, \sigma_{\rm u} = 1270 \text{ MPa}, \delta = 1.7\%$	[30]
TiZrHfNbTa	BCC	277 K	$\sigma_{\rm v} = 875 \pm 18$ MPa, $\sigma_{\rm u} = 994 \pm 16$ MPa, $\delta = 22.8\% \pm$	
			1.6%	[32]
		77 V	$\sigma_{\rm v}$ = 1549 \pm 10 MPa, $\sigma_{\rm u}$ = 1762 \pm 22 MPa, δ = 20.8%	
		// K	$\pm 0.7\%$	
Co _{17.5} Cr _{12.5} Fe ₅₅ Ni ₁₀ Mo ₅	FCC + µ	4.2 K	$\sigma_v = 1075 \text{ MPa}, \sigma_u = 1651 \text{ MPa}$	[33]
Fe _{49.85} Cr _{10.03} Mn _{10.03}		298 K	$\sigma_{\rm u} = 636.5 \text{ MPa}, \delta = 30.0\%$	[24]
Co _{10.03} Ni _{10.03} Al _{10.03}	$Ji_{10.03}Al_{10.03}$ FCC + bCC	77 K	$\sigma_{\rm u} = 716.3 \text{ MPa}, \delta = 17.4\%$	[34]
AlCoCrFeNi _{2.1}	$L1_2 + B2$	RT −196 °C	σy = 546.4 MPa, σu = 1046 MPa, δ = 17.7% σy = 690 MPa, σu = 1051 MPa, δ = 6.7%	[35]

Table 1. Phase composition, micro-structure and mechanical properties of some HEAs at room temperature and cryogenic temperature.

4. Discussion

HEAs have no obvious ductile-to-brittle transition or low ductile-brittle-transition temperature. The deformation mechanism at low temperature is controversial, including twinning, phase transformation and dislocation movement. In situ neutron diffraction and synchrotron radiation should be further used to observe the change of microstructure during deformation in situ.

5. Conclusions

With the continuous expansion of the field of human exploration, the application of ultra-low carbon martensitic stainless steels has limitations. The application of ultra-low temperature mainly focuses on amorphous and high entropy alloys. With the increase of entropy, the DBTT can be reduced to 4.2 K. To sum up, the increase of entropy modulation can greatly improve the toughness of MBE alloys, making amorphous and high entropy alloys more suitable for low temperature applications.

In aerospace, a bulk-amorphous alloy is one of the most ideal structural materials for spacecraft. Amorphous alloys do not undergo a ductile-to-brittle transition in a wide range of temperatures. The physical and mechanical properties of amorphous alloys are little affected by temperature changes in the temperature range of -200 °C to 400 °C. They can well adapt to the space environment with drastic temperature changes. In addition, the specific strengths of bulk-amorphous alloys are more than three times those of conventional crystalline materials. These excellent properties of amorphous alloys are extremely beneficial to the normal operation of the spacecraft and the reduction of the failure rate [36].

Amorphous alloys have broad application prospects in optical components. Multicomponent amorphous alloy mirrors are used to image the ground in space exploration. As a new material for the integrated manufacture of mirrors and mirror frames, amorphous alloys can greatly shorten the fabrication process of spacecraft mirrors and improve the imaging accuracy.

The stacking fault energy of some HEAs with a cubic-crystal-structure system decreases along with the decrease in temperature. Compared with room temperature, its low-temperature mechanical properties show an improvement trend. It is a promising highperformance low-temperature structural material, which can be used in the polar scientific research, rocket fuel tank and many other cryogenic extreme environments. It is hoped that, through the participation of more researchers in the future, the potential of HEAs can be further explored, so that the development of materials can better benefit 'mankind.

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