Additive Manufacturing of High Entropy Alloys

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Alloying has been very common practice in materials engineering to fabricate metals of desirable properties for specific applications. Traditionally, a small amount of the desired material is added to the principal metal. However, a new alloying technique emerged in 2004 with the concept of adding several principal elements in or near equi-atomic concentrations. These are popularly known as high entropy alloys (HEAs) which can have a wide composition range.

high entropy alloys (HEAs) | additive manufacturing (AM) | wear | nuclear applications | irradiation

1. Introduction

1.1. The Definitions of High Entropy Alloys

The first ever definition of HEA was given by Yeh et al. [1] as a class of alloys composed of five or more principal elements having concentration between 5% to 35% for each element. The second definition was also proposed by the same group [2]. In the second definition, the three categories of alloys were introduced on the basis of the configurational entropy: low entropy alloys (configurational entropy alloys (ΔS_{conf}) ≤ 0.69R), medium entropy alloys (0.69R ≤ ΔS_{conf} ≤ 1.61R) and high entropy alloys (ΔS_{conf} ≥ 1.61R) [3], where R is the universal gas constant. Here, the low entropy alloys are mostly conventional alloys with one or two major elements and the medium entropy alloys have two to four major elements. The high entropy alloys contain five or more major elements. The second definition does not require equi-atomic composition. For example, $Ti_2ZrHfV_{0.5}Mo_{0.2}$ [4], $FeCoNiCrTi_{0.2}$ [5] and $Al_{0.1}CoCrFeNi$ [6][7] are categorized as HEAs according to the second definition.

Moreover, these definitions are not strict, and it is not clarified which one should be used to categorize an alloy. For example, an alloy having composition of 5% A, 5% B, 20% C, 35% D and 35% E has the configuration entropy of 1.36R according to Equation (1) derived from Boltzmann's entropy formula [3].

$$\Delta S_{conf} = -R\left[c_1 \ln c_1 \ldots\ldots\ldots c_n \ln c_n\right]$$

where c_n is the atomic fraction of the nth element. In case of equi-atomic composition, Equation (1) reduces to [3]:

$$\Delta S_{conf} = R\ln(n)$$

For example, an alloy having 25 components with equi-atomic concentration has ΔS_{conf} = Rln(n = 25) = 3.22R. This material has the concentration of each element out of the range suggested by the first definition (between 5% to 35%), but it has sufficiently high entropy according to the second definition [8].

2. Manufacturing of HEAs

2.1. Background and Conventional Methods

Brian Cantor estimated the total number of possible metallic alloys with different compositions to be up to around 1078 [9]. This means many new alloys are yet to be discovered. For the manufacturing of HEAs, the initial synthesis strategy was to choose equi-atomic concentration of principle elements to maximize the entropy of the system. However, later, HEAs in non-equi-molar ratios were also developed for various applications. Arc melting was mostly preferred to produce HEAs thanks to its convenience, availability and simplicity. Furthermore, developing a HEA became more complex as more non-equi-atomic compositions were considered and several other manufacturing techniques were used. Alshataif et al. [10] covered almost all kinds of processing techniques used so far for HEAs synthesis. They detailed solid state processing (i.e., powder atomization methods, ball milling, cold/hot pressing, sintering, spark plasma sintering), liquid state processing (i.e., arc melting, vacuum induction melting, directional solidification, infiltration, electromagnetic stirring), thin film deposition (i.e., magnetron sputtering, pulsed laser deposition, plasma spray deposition) and additive manufacturing. Most of these manufacturing techniques are commercially available. That means most HEAs would not require a special manufacturing process and mass-producing HEAs would be possible with the existing alloying technologies and facilities.

The influence of process parameters, such as temperature and pressure, on the properties of HEAs were also studied. The effects of temperature on the properties of HEAs were studied through processes such as: annealing and heat treatments [11][12][13][14][15][16][17][18][19][20][21][22][23][24][25][26][27][28][29][30] and thermomechanical processing [31][32][33][34]. A number of research groups reported how temperature affected the microstructures and mechanical properties of HEAs in various manufacturing processes [22][35][36][37][38]. Moreover, the physical or chemical responses of various HEAs under a variety of thermal histories during manufacturing were studied: thermal aging behavior [12][39][40][41], TaNbHfZrTi synthesis by hydrogenation–dehydrogenation reaction and thermal plasma treatment [42], martensite formation [43][44][45][46], $Al_xCoCrFeNi$ formation with high gravity combustion from oxides [47], laser surface melting [48], precipitation behavior [49][50][51][52] and WTaMoNbV synthesis using inductively coupled thermal plasma [53].

Researchers have also attempted to alter the microstructures and properties of HEAs by high pressure treatments. Regulating pressure during fabrication of HEAs can considerably alter the interaction between the atoms by changing the interatomic distance, bonding nature and packing densities. These changes often convert the microstructures and affect the mechanical and structural properties. Dong et al. [54] reviewed the applications of high pressure technology for HEAs. They reviewed the use of dynamic high pressure, diamond anvil cells, high pressure torsion and hexahedron anvil press. Zhang et al. [55] reviewed high pressure induced phase transitions in

HEAs. Application of high pressure torsion [56][57][58][59][60][61][62][63][64][65][66][67][68][69][70] is more frequent than other pressure techniques [64][71][72][73][74][75][76][77][78].

Furthermore, various researchers successfully welded/brazed HEAs [79][80][81][82][83]. Guo et al. [79] reviewed arc welding, laser welding, electron beam welding, friction stir welding to join HEAs and conducted the microstructural analysis on the welded structures. Filho et al. [81] gave a general review on the properties of welded HEAs parts and Tillmann et al. [83] reviewed HEAs brazing. Lopez et al. [80] reviewed fusion based welding (i.e., for CoCrFeNiMn and other related HEA systems) and solid state welding. Scutelnicu et al. [82] reviewed friction stir, electron and laser beam, tungsten inert gas welding techniques for CoCrFeMnNi, AlCoCrCuFeNi, AlCrFeCoNi and CoCrFeNi alloys.

2.2. Additive Manufacturing of HEAs

3-D printing in manufacturing industries, when properly applied, not only makes a design phase more efficient and economic but also brings thoughtful impacts on product design. Recent advances in additive manufacturing (AM) made it more influential throughout the supply chain which generates revenue as well [84]. The additive manufactured HEAs showed improvement in their mechanical properties in comparison to as-cast HEAs [85][86][87][88][89][90][91][92]. Higher cooling rates in AM processes help suppress diffusional phase transformation and increase the chemical homogeneity of HEAs [93]. Under certain circumstances, AM gives a better control over the material processing and helps tailor application-specific microstructures which become more important for the parts for applications under extreme environments. For example, it was demonstrated that fine and tailorable microstructures in HEAs were obtained using AM techniques [94][95][96][97][98][99][100][101], which implies AM can improve the mechanical performance of at least some HEAs. However, this may not be a trivial task as a good understanding of the AM technique and material behavior during the AM process is required [102].

AM of HEAs has been discussed briefly in a few review papers [103][93][104][105] and books [106][107]. Xiaopeng Li [93] discussed the requirements and challenges of AM of HEAs and bulk metallic glasses. Chen et al. [103] examined the microstructural evolution and mechanical properties of AM-processed CoCrFeNi, $Al_xCoCrFeNi$, CoCrFeMnNi and $Ti_{25}Zr_{50}Nb_{50}Ta_{25}$. Fabricating HEAs by spark plasma sintering (SPS) and their property analyses were discussed in the book chapter “Spark Plasma Sintering of High Entropy Alloys” of [108]. SPS followed by mechanical alloying has largely been used to develop HEAs, which was reviewed in detail by Vaidya et al. [109]. Therefore, SPS studies are not included here.

Here, studies on the AM of HEAs are tabulated and the mechanical properties of these HEAs are discussed. **Table 1**, **Table 2** and **Table 3** detail the HEAs synthesized by selective laser melting (SLM), electron beam melting (EBM) and direct energy deposition (DED), respectively. The performances of these HEAs are discussed in terms of their composition, their microstructure and their mechanical properties, such as ultimate tensile strength (UTS), % elongation at fracture (ε), yield strength (YS), hardness (H), compressive strength (CS), compressive yield strength (CYS), bending strength (BS), bending elongation (δ_b) and % compression at fracture (C).

Table 1. The compositions, microstructures and mechanical properties of SLM manufactured HEAs.

Source	Alloy Composition	Microstructure (Grain Size)	Result UTS (MPa), YS (MPa), BS (MPa), δ_b (mm), ε (%), H, CS (MPa), C (%)
Chen et al. [110]	CoCrFeMnNi	FCC (53.1 µm)	UTS = 281 ± 18, YS = 12.5 ± 0.5, H = 261 ± 7 HV
Niu et al. [101]	CoCrFeMnNi	FCC (<5 µm)	CS = 2447.7
Li et al. [111]	CoCrFeMnNi + TiNp nanoparticles	FCC	UTS = 601–1036, ε = 12–30
Li et al. [112]	CoCrFeMnNi + Fe based metallic glass	FCC	UTS = 916–1517
Li et al. [113]	CoCrFeMnNi + TiN nanoparticles	FCC	-
Kim et al. [114]	(CoCrFeMnNi)C	FCC (180–330 nm)	YS = 800–900, ε = 25–30
Li et al. [115]	CoCrFeMnNi + 12 wt% nano-TiNp	FCC (<2 µm)	UTS = 1100
Piglione et al. [116]	CoCrFeMnNi	FCC (0.52–0.64 µm)	H = 212 HV
Zhu et al. [85]	CoCrFeMnNi	FCC	-
Xu et al. [117]	CoCrFeMnNi	FCC (1–2 µm)	H = 2.84 ± 0.13 GPa

Source	Alloy Composition	Microstructure (Grain Size)	Result
			UTS (MPa), YS (MPa), BS (MPa), δ_b (mm), ε (%), H, CS (MPa), C (%)
Park et al. [86]	CoCrFeMnNi +1 at%C	FCC (20–35 µm)	UTS = 829–989, YS = 741, ε = 24.3
Ren et al. [118]	CoCrFeMnNi	-	-
Dovgyy et al. [119]	CoCrFeMnNi	FCC & cubic (0.2–0.8 µm)	-
Zhou et al. [87]	CoCrFeNi + 0.5 at%C	FCC (40–50 µm)	UTS = 776–797, YS = 630–656, ε = 7.7–13.5
Wu et al. [120]	CoCrFeNi + 0.5 at%C	FCC (40–50 µm)	UTS = 795, YS = 638
Lin et al. [24]	CoCrFeNi	FCC	
Sun et al. [121]	CoCrFeNi	-, ~3 mm in length and ~200 µm in width	UTS = 676.7–691, YS = 556.7–572, ε = 12.4–17.9
Song et al. [122]	CoCrFeNi + N (1.8%)	FCC	UTS = 600–853, YS = 520–650, ε = 27
Zhou et al. [123]	$(CoCrFeNi)_{1-x}(WC)_x$	FCC	H = 603–768 HV
Brif et al. [88]	CoCrFeNi	FCC	UTS = 480–745, YS = 402–600, ε = 8–32, H = 205–238

Source	Alloy Composition	Microstructure (Grain Size)	Result UTS (MPa), YS (MPa), BS (MPa), δ_b (mm), ε (%), H, CS (MPa), C (%)
Niu et al. [124]	AlCoCrFeNi	Disordered (A2) + Ordered (B2) BCC	H = 632.8 HV
Karlsson et al. [102]	AlCoCrFeNi	FCC & BCC (<20 µm)	-
Peyrouzet et al. [89]	$Al_{0.3}CoCrFeNi$	FCC (width~13 and length~70–120 µm)	UTS = 896, YS = 730, ε = 29
Sun et al. [90]	$Al_{0.5}CoCrFeNi$	FCC & BCC (1 µm)	UTS = 878, YS = 609, H = 270HV
Zhou et al. [92]	$Al_{0.5}CoCrFeNi$	FCC	UTS = 721, YS = 579, ε = 22
Luo et al. [125]	AlCrCuFeNi	BCC (avg. width~4 µm)	CS = 1655.2–2052.8, C = 6.5–6.8
Luo et al. [126]	$AlCrCuFeNi_x$ (2 ≤ x ≤ 3)	FCC (thickness~490 nm) & BCC (~140 nm) Avg. thickness of both ~ 650 nm	UTS = 957, ε = 14.3
Li et al. [38]	AlCoCuFeNi	BCC	YS = 744, ε = 13.1, CS = 1600
Yao et al. [127]	AlCrFeNiV	FCC (width~15 µm,	UTS = 1057.47, ε = 30.3

Source	Alloy Composition	Microstructure (Grain Size)	Result UTS (MPa), YS (MPa), BS (MPa), δ_b (mm), ε (%), H, CS (MPa), C (%)
		length~75–200 µm)	
Wang et al. [128]	AlCoCrCuFeNi	FCC & BCC	H = 710.4 HV
Wang et al. [129]	AlMgScZrMn	Al3 (Sc, Zr) (1–10 nm + 7 µm)	UTS = 394, ε = 10.5
Sarawat et al. [130]	$AlCoFeNiV_{0.9}Sm_{0.1}$ $AlCoFeNiSm_{0.1}TiV_{0.9}$ $AlCoFeNiSm_{0.05}TiV_{0.95}Zr$, AlCoFeNiTiVZr	FCC	H~42.8–86.7 HV
Agrawal et al. [131]	$Fe_{40}Mn_{20}Co_{20}Cr_{15}Si_5$	HCP	UTS = 1100, YS = 530, ε = 30
Zhang et al. [132][133]	NbMoTaW	BCC (13.4 µm)	H = 826 HV
Yang et al. [134][135]	$Ni_6Cr_4WFe_9Ti$	FCC (300–1000 nm) + unknown phase	UTS = 972, YS = 742, ε = 12.2
Chen et al. [136]	CoCrFeNiMn	FCC + Mn_2O_3 particles	YS = 620, UTS = 730, ε~12
Litwa et al. [137]	CoCrFeNiMn	FCC	H~320 HV

Source	Alloy Composition	Microstructure (Grain Size)	Result UTS (MPa), YS (MPa), BS (MPa), δ_b (mm), ε (%), H, CS (MPa), C (%)
Zhang et al. [138]	CoCrFeNiMn	FCC	YS~729.6
Kim et al. [139]	CoCrFeNiMn	FCC	YS = 752.6
Choi et al. [140]	CoCrFeNiMn	FCC	
Su et al. [141]	$CrCuFeNi_2$	FCC	
	$Al_{0.5}CrCuFeNi_2$	FCC	
	$Al_{0.75}CrCuFeNi_2$	FCC + BCC/B2	
	$AlCrCuFeNi_2$	FCC + BCC/B2	
Peng et al. [142]	CoCrFeNi + Ti coated diamond	FCC + diamond particles	H = 622 HV, BS = 530, δ_b = 0.64
	CoCrFeNi + diamond	FCC + Cr_7C_3 + diamond particles	H = 615 HV, BS = 925, δ_b = 0.48
Wang et al. [143]	CoCrFeNiMn	FCC	H = 164–370 HV
Sun et al. [144]	$Al_{0.1}CrCuFeNi$	FCC	
	$Al_{0.5}CrCuFeNi$	FCC	

Source	Alloy Composition	Microstructure (Grain Size)	Result UTS (MPa), YS (MPa), BS (MPa), δ_b (mm), ε (%), H, CS (MPa), C

Source	Alloy Composition	Microstructure (Grain Size)	Result UTS (MPa), YS (MPa), ε (%), H, CS (MPa), C (%)
Peng et al. [158]	CoCrFeNiMn	FCC	YS = 196
Wang et al. [159]	CoCrFeMnNi	FCC (65)	UTS = 497, 205, H = 157.1HV
Kuwabara et al. [160]	AlCoCrFeNi	BCC & FCC	UTS = 1073, YS = 769, ε = 0–1.2 YS = 944–1015, CS = 1447–1668, C = 14.5–26.4
Wang et al. [161]	AlCoCrFeNi	BCC	-
Fujieda et al. [162]	CoCrFeNiTi	FCC + Cubic	UTS = 1178, YS = 773, ε = 25.8
Popov et al. [163]	$Al_{0.5}CrMoNbTa_{0.5}$	BCC	

Peng et al. [151]	CoCrFeNiMn	FCC	-

Scheme	Alloy Composition	Microstructure (Grain Size)	Result UTS (MPa), YS (MPa), ε (%), H, CS (MPa), C (%)
Guan et al. [164]	CoCrFeMnNi	FCC (13 μm)	YS = 517, ε = 26
Melia et al. [165]	CoCrFeMnNi	FCC (~4 μm)	UTS = 647–651, YS = 232–424

Scheme	Alloy Composition	Microstructure (Grain Size)	Result UTS (MPa), YS (MPa), ε (%), H, CS (MPa), C (%)
Li et al. [166]	CoCrFeMnNi	FCC	
Gao et al. [167]	CoCrFeMnNi	FCC (30–150 µm) + BCC	UTS = 620, YS = 448
Xiang et al. [168][169]	CoCrFeNiMn	FCC	UTS = 400–600
Chew et al. [170]	CoCrFeNiMn	FCC (3.68 ± 0.85 µm)	UTS = 660, YS = 518
Qiu et al. [171]	CoCrFeMnNi	FCC	UTS = 891, YS = 564
Li et al. [172]	CoCrFeMnNi + WC (0–10 wt%)	FCC	UTS = 550–845, YS = 300–675, ε = 9
Amar et al. [173]	CoCrFeMnNi + TiC (0–5 wt%)	FCC	UTS = 550–723, YS = 300–385, ε = 32
Guan et al. [174]	CoCrFeMnNi $AlCoCrFeNiTi_{0.5}$	FCC (24 µm) BCC (7 µm) + FCC	YS = 888–1100, H = 197–657 HV
Wang et al. [175]	$CoCrFeNiMo_{0.2}$	FCC	UTS = 532–928, ε = 37
Zhou et al. [176]	$CoCrFeNiNb_x$ (x = 0–	FCC	UTS = 400–820, YS = 220–750

Scheme	Alloy Composition	Microstructure (Grain Size)	Result UTS (MPa), YS (MPa), ε (%), H, CS (MPa), C (%)
	0.2)		
Gwalani et al. [177]	AlxCoCrFeNi (x = 0.3–0.7)	FCC	
Nartu et al. [178]	$Al_{0.3}$CoCrFeNi	FCC	YS = 410–630, ε = 18–28
Mohanty et al. [179]	AlxCoCrFeNi (x = 0.3–0.7)	FCC + BCC	H = 170–380 HV
Vikram et al. [180]	AlCoCrFeNi2.1	FCC & BCC	YS = 309–711, H = 278 ± 11–316 ± 14 HV
Gwalani et al. [181]	AlCrFeMoV_x (x = 0–1)	BCC (68–165 µm)	H = 485–581 HV
Guan et al. [182]	AlCoCrFeNi$Ti_{0.5}$	BCC (12 µm)	-
Malatji et al. [183]	AlCrCuFeNi	BCC & FCC	H = 350 HV,
Dada et al. [184][185]	AlCoCrFeNiCu AlTiCrFeCoNi		H = 600 HV, H = 850 HV
Moorehead et al. [186]	NbMoTaW	BCC	-

Scheme	Alloy Composition	Microstructure (Grain Size)	Result UTS (MPa), YS (MPa), ε (%), H, CS (MPa), C (%)
Kunce et al. [187]	TiZrNbMoV	BCC	-
Dobbelstein et al. [188]	TiZrNbHfTa	BCC	H = 509 $HV_{0.2}$
Pegues et al. [189]	CoCrFeNiMn	FCC	-
Li et al. [190]	CoCrFeNiMn	FCC	-
Tong et al. [191]	CoCrFeNiMn Vacuum arc melting 1 impact Laser shock peening 3 impact Laser shock peening 5 impact Laser shock peening	FCC	YS = 320.7, UTS = 531.7 YS = 427.4, UTS = 570.7 YS~435, UTS~600 YS = 489.9, UTS = 639.9
Shen et al. [192]	CoCrFeNi $(SiC)_x$	FCC + Cr_7C_3 (1 µm)	UTS = 2155–2499, YS = 142–713, H = 139–310
Cai et al. [193]	CoCrFeNi AlCoCrFeNi	BCC (102.27 µm) BCC (18.75 µm)	YS = 318, UTS = 440, ε = 8.56 YS = 383, UTS = 533, ε = 10.6

Scheme	Alloy Composition	Microstructure (Grain Size)	Result UTS (MPa), YS (MPa), ε (%), H, CS (MPa), C (%)
Zhang et al. [194]			YS = 1252, CS = 1282, ε = 15
	NbMoTa	BCC	YS = 1200, CS = 1350, ε = 23
	NbMoTaTi	BCC + α-Ti	YS = 1350, CS = 1380, ε = 11
	NbMoTaNi	BCC	YS = 1750, CS = 2277.79, ε = 15
	$NbMoTaTi_{0.5}Ni_{0.5}$	BCC + Ni_3Ta + β-Ti	CS of $NbMoTaTi_{0.5}Ni_{0.5}$ at 600, 800 and 1000 °C is 1699.75 MPa, 1033.63 MPa and 651.85 MPa
Peng et al. [195]	$Al_{0.3}CoCrFeNi$	FCC + B2	YS = 373–476, CS = 473–508, ε = 0.6–62.96, H = 208–221 HV
Kuzminova et al. [196]	CoCrFeNi	FCC	YS = 456–551, UTS = 637–658, H = 209–259 HV
Malatji et al. [197]	AlCuCrFeNi Heat treated (800–1100 °C)	FCC + BCC	H = 310–381 HV
Dong et al. [198]	$AlCoCrFeNi_{2.1}$	FCC + BCC	YS = 388, UTS = 719, ε~27, H = 221–228
Zhou et al. [199]	$CoCrFeNb_{0.2}Ni_{2.1}$ Solution treatment (2 h,1250 °C)	FCC + HCP (Laves C14) + Nb rich carbide	YS~340, UTS~735 YS~239, UTS~607 YS~896, UTS~1127, ε~17

Particle reinforcement in a HEA matrix with AM has been an area of interest for many researchers lately who expect microstructure refinement and mechanical properties enhancement [49][111][142][146][154][155][203][204][205][206][207][208][209][210][211][212][213][214]. Li et al. [111] introduced nano TiN ceramic particles in a CoCrFeMnNi matrix, which

Scheme [122]	Alloy Composition [213]	[113] Microstructure (Grain Size)	Result UTS (MPa), YS (MPa), ε (%), H, CS (MPa), C (%)
	96 h aged (650 °C)		[173]
[172] Zheng et al. [200]	CoCrFeNiMn	FCC	23 6 YS = 330, UTS = 630[115] [205]

llowed by m). Song oped with , YS and NiMn and Similarly, 00 to 675 that TiC UTS of

CoCrFeNiMn up to 1000 MPa by introducing nano-Al_2O_3 particles. Carbon doping was attempted [86][87][114][120] to enhance the mechanical properties of HEAs. Peng et al. [142] added diamond particles into CoCrFeNi and found out the bending strength was 925MPa. Park et al. [146] added carbon into CoCrFeNiMn ($(CoCrFeNiMn)_{99}C_1$) and noticed that the YS and UTS were ~741 MPa and ~874 MPa, respectively. Similarly, Kim et al. [155] also added carbon into CoCrFeNiMn in a ratio $(CoCrFeNiMn)_{100-x}C_x$ (x = 0.5–1.5). The YS for x = 0.5, 1, 1.5 was measured to be 653, 752 and 753 MPa respectively. The UTS for x = 0.5, 1, 1.5 was found to be 766 ± 318.5, 895 ± 22.3 and 911 ± 125.1 MPa, respectively. Shen et al. [192] discussed the effect of SiC particles added to CoCrFeNi. They noticed that adding SiC particles changed the microstructure from the FCC phase to the FCC/Cr_2C_7 dual phase. The hardness and YS improved significantly from ~139 HV to ~310 HV and ~142 MPa to ~713 MPa, respectively.

Various HEAs have exhibited significant improvement in their mechanical properties after AM synthesis as compared to the as-cast structures of the same compositions [85][86]. Zhou et al. [87] reported that arc-melted CoCrFeNi had the YS of 225 MPa whereas SLM-manufactured CoCrFeNi had the YS of 656 MPa. Brif et al. [88] observed that SLM-manufactured CoCrFeNi showed noticeable improvement in YS from 188 MPa (as-cast) to 600 MPa and in UTS from 457 MPa (as-cast) to 745 MPa. Peyrouzet et al. [89] showed that the YS of $Al_{0.3}CoCrFeNi$ increased from 275 MPa (as-cast) to 730 MPa and the UTS from 502 MPa (as-cast) to 896 MPa when manufactured with SLM. The UTS of as-cast $Al_{0.3}CoCrFeNi$ was 522 MPa and it was increased to 878 MPa with SLM processing [90]. Arc-melted $Al_{0.5}CoCrFeNi$ had the YS of 334 MPa and the UTS of 709 MPa [91]. SLM increased the YS up to 579 MPa and the UTS up to 721 MPa [92].

Moreover, the CS of AlCrCuFeNi was 2052 MPa when fabricated with SLM and 1750 ± 15 MPa [215] with arc-melting. The hardness of AlCoCrCuFeNi improved from 500 to 710 Hv [128] by using SLM. The YS of AlMgScZrMn manufactured with arc melting, SPS, and SLM is 188 ± 2.3 MPa, 231 ± 3 Mpa and 394 Mpa respectively [129]. Agrawal et al. [131] reported that the YS of as-cast and SLM-printed $Fe_{40}Mn_{20}Co_{20}Cr_{15}Si_5$ was 420 ± 20 Mpa and 530 ± 40 Mpa, respectively. The YS of CoCrFeNiMn was 2.5 times higher (around 518 Mpa) [170] with DED in comparison to that of cast parts (209 Mpa) [216] at room temperature (RT). Furthermore, the as-cast AlCoCrFeNi had the UTS of 956 MPa, and the EBM specimen had the UTS of 1073 MPa [160]. Similarly, Fujieda et al. [162] reported that EBM-synthesized CoCrFeNiTi showed the improved tensile strength of around 1178 MPa, which is much stronger than various commercial high corrosion resistant materials such as duplex stainless steel: 655 MPa, super duplex stainless steel: 750–800 MPa and Ni-based super alloys (i.e., Alloy C276: 690 MPa, Alloy 718: 1275 MPa).

Refractory HEA NbMoTaW has shown a drastic reduction in grain size when made with AM. The average grain size of BCC phase was 200 µm in as-cast sample [217] and 13.4 µm in SLM-processed sample. Additionally, this alloy did not follow the rule of mixtures. Instead, it showed the cocktail effect for the hardness of the final structure. The hardness of Nb, Mo, Ta and W was in the range of 85–410 HV but the final hardness of SLM processed NbMoTaW was measured to be 826 HV [132]. Senkov et al. [218] commented that NbMoTaW did not have any abrupt hardness changes at high temperatures, consistently exhibiting better hardness properties than superalloys. Moreover, SLM-processed $Ni_6Cr_4WFe_9Ti$ (UTS = 972 MPa, YS = 742 MPa, ε = 12.2%) had ~93% increase in YS, ~50% increase in UTS, and ~77% increase in tensile ductility as compared to the vacuum arc melted samples (UTS = 649 MPa, YS = 385 MPa, ε = 6.9%) [134][135].

In summary, various studies have successfully manufactured SLM, EBM and DED techniques. They have also shown that the properties of HEAs could be altered by changing the input parameters for AM process. For example, CoCrFeNiMn was manufactured with SLM by multiple researchers [85][86][101][110][111][112][113][114][115][116][117][118][119][122][136][137][138][139][140][143][146][148][149][151][154][155] and many of them acquired different mechanical properties for CoCrFeNiMn by changing input parameters in AM processes (refer **Table 1**, **Table 2** and **Table 3**).

3. Applications under Extreme Environments

3.1. Nuclear Applications

Nuclear energy is contributing to around 13% of electricity demand worldwide [219] with negligible carbon emission. The safety, reliability and economy of these nuclear power plants depends heavily on the performances of advanced structural materials under high-energy irradiation and elevated temperatures [220][221]. Radioactive waste handling units also require radiation-tolerant materials. Not to mention nuclear applications, radiation-resistant materials are in great demand in medical and aerospace fields as well.

The typical range of operating temperatures of nuclear reactors spans from 350 to 900 °C as listed in **Table 4** [222]. At high temperatures, several effects come into play such as thermal expansion, vacancy concentration, diffusion rate, phase transformation, precipitation, recovery, recrystallization, dislocation climb, creep, grain weakening/migration/growth, oxidation and intergranular oxygen dispersion. With conventional alloys, design strategies for nuclear reactor materials were mostly concerned with tuning the microstructures by various heat treatments, precipitation, cold working and solute atoms to get desired properties. HEAs, though, introduce the concept of modifying compositional complexity of the structural materials to make them suitable for nuclear applications.

Table 4. Core outlet temperature of different gen-IV nuclear reactor coolant [222].

Reactor System	Core Outlet Temperature (°C)	Coolant
Super critical water-cooled reactor	350–620	Water

Reactor System	Core Outlet Temperature (°C)	Coolant
Sodium-cooled fast reactor	~550	Na liquid metal
Lead-cooled reactor	550–800	Pb, Pb-Bi liquid Metals
Molten salt reactor	700–800	Fluoride salts
Gas-cooled fast reactor	~850	Helium gas
Very high temperature reactor	>900	Helium gas

Currently, reduced activation ferritic/martensitic steels (RAFM) (e.g., F82H, EUROFER 97), are the most popular option for irradiation-resistant structural materials. Oxide dispersion strengthened (ODS) RAFM steels (i.e., EUROFER 97 reinforced with 0.3 wt.% Y_2O_3 particles), C/C, SiC/C, SiC/SiC, refractory metals/alloys (W, Cr), V and Ti-based alloys are also being used [223][224]. HEAs are considered to be potential candidates for nuclear applications [106][225][226][227]. Yeh et al. [228] mentioned that HEAs are potential candidates for structural materials of the 4th generation nuclear reactor. Previously, the irradiation responses and defect behaviors [229][230], intrinsic transport properties [230], irradiation induced structural changes [231] of HEAs were reviewed. Building upon these reviews, this section mainly focuses on ion irradiation resistance of HEAs.

The majority of the previous ion irradiation studies on HEAs are listed in **Table 5** where phases, irradiation conditions and important findings are summarized. These HEAs were studied under Ni, Au, Ag, Ar, He, Kr, or Xe ions irradiation. The most popular strategy to design single-phase HEAs of high irradiation resistance used elements having low activation or thermal neutron absorption cross section [232][233][234][235][236].

Table 5. Summary of irradiation studies on HEAs.

Source	Material (Fabrication)	Phase	Irradiation Conditions (Energy, Ion, Fluence, Temperature)
Jawaharram et al. [237]	CoCrFeNiMn	FCC	2.6 MeV, Ag^{3+}, 1.5 × 10^{-3} & 1.9 × 10^{-3} dpa^{-1} s^{-1}, 23–500 °C
Lu et al. [238]	NiCoFeCr, CoCrFeNiMn	FCC	3 MeV, Ni^{2+}, 5 × 10^{16} ions·cm^{-2}, 500 °C

Source	Material (Fabrication)	Phase	Irradiation Conditions (Energy, Ion, Fluence, Temperature)
Barr et al. [239]	CoCrFeNiMn	FCC	3 MeV, Ni^{2+}, 3 × 10^{15} ions·cm^{-2}, 500 °C
Lu et al. [240]	CoCrFeNi, CoCrFeNiMn	FCC	1.5 MeV, Ni^{+}, 4 × 10^{14} & 3 × 10^{15} ions·cm^{-2} (peak dose~4 dpa), 500 °C 3 MeV, Ni^{+}, 5 × 10^{16} ions·cm^{-2} (peak dose~60 dpa), 500 °C
Tong et al. [241]	CoCrFeNiMn CoCrFeNi CoCrFeNiPd	FCC	16 MeV, Ni^{5+}, 8 MeV Ni^{3+}, 4 MeV Ni^{1+}& 2 MeV Ni^{1+}, 0.1–1 dpa, 420 °C
Jin et al. [242]	CoCrFeNi, CoCrFeNiMn	FCC	3 MeV, Ni^{2+}, 5 × 10^{16} ions·cm^{-2} (peak dose~53 dpa), 500 °C
Chen et al. [243]	CoCrFeMnNi $Al_{0.3}$CoCrFeNi	FCC FCC	1 MeV, Kr ions, 6.3 × 10^{15} ions·cm^{-2}, 300 °C
Wang et al. [244]	CoCrFeNiCu	FCC	100 keV, He^{+}, 2.5 × 10^{17}, 5 × 10^{17} & 1 × 10^{18} ions·cm^{-2}, RT
He et al. [245]	CoCrFeNi, CoCrFeNiMn, CoCrFeNiPd	FCC	electrons, 5 × 10^{18} e·cm^{-2}·s^{-1}, 400 °C

Source	Material (Fabrication)	Phase	Irradiation Conditions (Energy, Ion, Fluence, Temperature)
Yang et al. [246]	CoCrFeNiMn, CoCrFeNiPd	FCC	3MeV, Ni^{2+}, 5 × 10^{16} ions·cm^{-2}, 420, 500 & 580 °C
Yang et al. [247]	CoCrFeNiMn	FCC	-, He ion, -, RT & 450 °C
Hashimoto et al. [248]	CoCrFeNiMn, $CoCrFeNiAl_{0.3}$	FCC	1250 keV, 1.5 dpa, 300–400 °C
Zhang et al. [249]	CoCrFeNiCu	FCC	3 MeV Ni^{2+}, 10^{14} ions·cm^{-2}, RT
Yang et al. [250]	CoNi, FeNi, CoCrFeNi	- FCC	3 MeV, Ni^{2+}, 1.5 × 10^{16} (peak dose~17 dpa) & 5.0 × 10^{16} (peak dose~53 dpa) ions·cm^{-2}, 500 °C
Abhaya et al. [251]	CrCoFeNi	FCC	1.5 MeV, Ni^{2+}, 1 × 10^{15} (peak dose~2 dpa) & 5 × 10^{16} (peak dose~96 dpa) ions·cm^{-2}, RT
Sellami et al. [252]	CoCrFeNi		1.5 MeV, Ni^{2+}, 1 × 10^{13}–1 × 10^{14} ions·cm^{-2} 21 MeV, Ni^{2+}, 2 × 10^{13} & 1 × 10^{14} ions·cm^{-2}, RT
Chen et al. [253]	CoCrFeNi	FCC	275 keV, He^{+}, 5.14 × 10^{20} ions·m^{-2},

Source	Material (Fabrication)	Phase	Irradiation Conditions (Energy, Ion, Fluence, Temperature)
			250, 300, 400 °C
Kombaiah et al. [254]	CoCrFeNi, $Al_{0.12}CoCrFeNi$	FCC	3 MeV, Ni^{2+}, 1 × 10^{17} ions·cm^{-2} (peak dose~100 dpa), 500 °C
Lu et al. [255]	CoCrFeNiPd	FCC	3 MeV, Ni^{2+}, 5 × 10^{16} ions·cm^{-2}, 580 °C
Tunes et al. [256]	CrFeNiMn	FCC	30 keV, Xe^{+}, 2.6 × 10^{16} ions·cm^{-2}, 500 °C
Edmondson et al. [257]	CrFeNiMn	BCC	30 keV, Xe^{+}, 9.3×10^{16} ions·cm^{-2} 6 keV He^{+}, 6.4 × 10^{16} ions·cm^{-2}, RT
Fan et al. [258]	CoCrFeNi	FCC	3 MeV, Ni ions, 5 × 10^{16}–8 × 10^{16} ions/cm^{-2}, 580 °C
Chen et al. [5]	$CoCrFeNiTi_{0.2}$	FCC	275 keV, He^{2+}, 5.14 × 10^{20} ions·m^{-2}, 400 °C
Lyu et al. [259]	$CoCrFeNiMo_{0.2}$	FCC	27 keV, electrons, -, RT
Xu et al. [260]	$(CoCrFeNi)_{95}Ti_1Nb_1Al_3$	FCC	2.5 MeV, Fe ions, 1.5 × 10^{19} ions·m^{-2}, RT-500 °C
Cao et al. [261]	$(CoCrFeNi)_{94}Ti_2Al_4$	FCC	4 MeV, Au ions, 10–49 dpa, RT
Tolstolutskaya et al. [262]	$Cr_{0.18}Fe_{0.4}Mn_{0.28}Ni_{0.14}$	FCC	1.4 MeV, Ar ions, 0, 0.3, 1 & 5 dpa, RT

Source	Material (Fabrication)	Phase	Irradiation Conditions (Energy, Ion, Fluence, Temperature)
	$Cr_{0.18}Fe_{0.28}Mn_{0.27}Ni_{0.28}$ $Cr_{0.2}Fe_{0.4}Mn_{0.2}Ni_{0.2}$		
Kumar et al. [263]	$Fe_{0.27}Ni_{0.28}Mn_{0.27}Cr_{0.18}$	FCC	3 MeV, Ni^{2+}, 4.2 × 10^{13}, 4.2 × 10^{14} & 4.2 × 10^{15} ions·cm^{-2}, RT & 500 °C 3 MeV, Ni^{2+}, 2.43 × 10^{15} & 2.43 × 10^{16} ions·cm^{-2}, 400–700 °C
Li et al. [264]	$Cr_{0.18}Fe_{0.27}Ni_{0.28}Mn_{0.27}$	FCC	Neutron, 8.9 × 10^{14} n·cm^{-2}.s, 60 °C
Voyevodin et al. [265]	$Cr_{0.2}Fe_{0.4}Mn_{0.2}Ni_{0.2}$+ Y_2O_3 + ZrO_2	FCC	1.4 MeV, Ar ions, 2.2 × 10^{15} ions·cm^{-2}, RT
Dias et al. [266]	$Cu_xCrFeTiV$ (x = 0.21–1.7)	BCC + FCC	300 keV, Ar^+, 3 × 10^{20} at·m^{-2}, RT
Yang et al. [234]	$Al_{0.3}CoCrFeNi$	FCC	3 MeV, Au ions, 6 × 10^{15} ion·cm^{-2} (peak dose ~31 dpa), 250–650 °C
Gromov et al. [267]	AlCoCrFeNi	-	18 keV, electrons, -, RT
Zhang et al. [235]	AlCrMoNbZr, (AlCrMoNbZr)N	FCC	400 keV, He^+, 8 × 10^{15} & 8 × 10^{16} ion·cm^{-2}, RT
Yang et al. [6]	$Al_{0.1}CoCrFeNi$, $Al_{0.75}CoCrFeNi$,	FCC FCC + B2	3 MeV, Au ions, 1 × 10^{14}–1 × 10^{16} ions·cm^{-2}, RT

Source	Material (Fabrication)	Phase	Irradiation Conditions (Energy, Ion, Fluence, Temperature)
	$Al_{1.5}CoCrFeNi$,	A2 + B2	
Xia et al. [7]	$Al_{0.1}CoCrFeNi$, $Al_{0.75}CoCrFeNi$, $Al_{1.5}CoCrFeNi$	FCC FCC + B2 B2 + A2	3 MeV, Au ions, 1 × 10^{14}–1 × 10^{16} ions·cm^{-2}, RT
Yang et al. [268]	$Al_{0.1}CoCrFeNi$	FCC	3 MeV, Au ions, 6 × 10^{15} ions·cm^{-2}, 250–650 °C
Zhou et al. [269]	$Al_xCoCrFeNi$ (x = 0–2)	FCC + BCC	1 MeV, Kr^{2+}, -, RT
Zhou et al. [270]	$Al_xCoCrFeNi$, HfNbTaTiZrV	FCC Amorphous	MeV Kr & 200 KeV, electrons, 2 dpa, RT & 150 °C
Zhou et al. [271]	HfNbTaTiZrV	BCC	1 MeV Kr^{2+}, -, RT-150 °C
Moschetti et al. [272]	HfNbTaTiZr	BCC	5 MeV, He^{2+}, 1.6 × 10^{12}–4.4 × 10^{17} ions·cm^{-2}s, 50 °C
Sadeghilaridjani et al. [273]	HfTaTiZrV	BCC	4.4 MeV, Ni^{2+}, 1.08 × 10^{17} ion·cm^{-2}, RT
Li et al. [274]	HfNbTiZr	BCC	1.5 MeV, He ions, 5 × 10^{15}–1 × 10^{17} ions·m^{-2}, 700 °C
Kareer et al. [275]	TaTiVZr, TaTiVCr,	BCC BCC	2 MeV, V^{+}, 2.26 × 10^{15} ions·cm^{-2}, 500 °C

Source	Material (Fabrication)	Phase	Irradiation Conditions (Energy, Ion, Fluence, Temperature)
	TaTiVNb	BCC	
Wang et al. [276]	ZrTiHfCuBe, ZrTiHfCuBeNi, ZrTiHfCuNi	Amorphous	100 keV, He ions, 5.0×10^{17}, 1.0×10^{18} & 2.0×10^{18} ions·cm^{-2}, RT
Lu et al. [4]	$Ti_2ZrHfV_{0.5}Mo_{0.2}$	BCC	3 MeV, He^+, 5×10^{15}, 1×10^{16} & 3×10^{16} ions·cm^{-2}, 600 °C
Atwani et al. [277]	$W_{0.38}Ta_{0.36}Cr_{0.15}V_{0.11}$	BCC	1 MeV, Kr^{+2}, 0.0006–8 dpa·s^{-1}, 800 °C
Komarov et al. [278]	(TiHfZrVNb)N	-	500 KeV He^{2+}, 5×10^{16}–3×10^{17} ions·cm^{-2}, 500 °C
Gandy et al. [279]	SiFeVCrMo SiFeVCr	sigma BCC+ sigma	5 MeV, Au^{2+}, 5×10^{15} ions·cm^{-2}, RT
Patel et al. [280]	$V_{2.5}Cr_{1.2}WMoCo_{0.04}$	BCC	5 MeV, Au^+, 5×10^{15} ion·cm^{-2} (peak dose~42 dpa), RT
Zhang et al. [281]	$Mo_{0.5}NbTiVCr_{0.25}$, $Mo_{0.5}NbTiV_{0.5}Zr_{0.25}$	BCC	400 He^{2+}, 1×10^{17}–5×10^{17} ions·m^{-2}, 350 °C
Zhang et al. [282]	$Mo_{0.5}NbTiVCr_{0.25}$, $Mo_{0.5}NbTiV_{0.5}Zr_{0.25}$	BCC	400 keV, He^{2+}, peak dose~10.5 dpa, 350 °C

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Source	Material (Fabrication)	Phase	Irradiation Conditions (Energy, Ion, Fluence, Temperature)
Atwani et al. [283]	WtaCrV	BCC	2 keV, He^+, 1.65 × 10^{17} ions·cm^{-2}, 950 °C

3.2. Wear Behavior

The wear properties of HEAs were studied mostly with pin/ball on a disc set up with antagonist materials such as Al_2O_3, steels (i.e., SKH51, GCr15, 100Cr6), Si_3N_4, SiC, ZrO_2, 1Cr18Ni9Ti, BN, inconel-718 and WC. For lubrication, mostly dry conditions were used but some studies also used H_2O_2, deionized water and acid rain (pH = 2). Previously, Tsai and Yeh et al. [284], Kasar et al. [285], Senkov et al. [286], Sharma et al. [287], Zhang et al. [56], Li et al. [288], Menghani et al. [289] and Ayyagari et al. [290] discussed the wear behaviors of HEAs. Here, the researchers will analyze the tribological studies of HEAs in terms of HEAs content variation, particle reinforcement, media and nitriding/carburizing/sulfurizing, temperature effects and oxide formation. **Table 6** provides the details of the compositions, microstructures, methods and results (i.e., wear rate or wear resistance, hardness, friction coefficient) of the wear studies performed so far on HEAs.

Table 6. Wear studies of HEAs.

Source	Composition	Microstructure	Method, Medium, Antagonist Material, Temperature, Wear Rate
Joseph et al. [291]	CoCrFeNiMn	FCC	Pin-on-disc, dry, Al_2O_3, 600–800 °C, RT, 0.5 × 10^{-4}–3.8 × 10^{-4} mm^3·N^{-1}·m^{-1}
Wang et al. [292]	CoCrFeNiMn	FCC	Ball-on-disc, MoS_2-oil lubrication, GCr15, RT-140 °C
Xiao et al. [293]	CoCrFeNiMn	FCC	Ball-on-flat, dry, WC-Co, RT, 0.5 × 10^{-4}–5.4 × 10^{-4} mm^3·N^{-1}·m^{-1}
Jones et al. [294]	CoCrFeNiMn	FCC	Rotary tribometer, -, -, ~0.5 × 10^{-6} mm^3·N^{-1}·m^{-1}

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alloy. Mater. Sci. Eng. A 2020, 776, 139003.

Source	Composition	Microstructure	Method, Medium, Antagonist Material, Temperature, Wear Rate
Zhu et al. [295]	CoCrFeNiMn CoCrFeNiMnV CoCrFeNiMnNb CoCrFeNiMnNbV	FCC + HCP (Laves) + σ	Ball-on-disc, dry, Si_3N_4, RT, 1.85 × 10^{-5}–6.39 × 10^{-5} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Deng et al. [296]	$CoCrFeNiMo_x$ (x = 0–0.3)	FCC	Ball-on-disc, dry, GCr15, RT, 0.33 × 10^{-3}–0.53 × 10^{-3} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Lindner et al. [297]	CoCrFeNiMn CoCrFeNi	FCC FCC	Ball-on-disc, dry, Al_2O_3, RT
Sha et al. [298]	(CoCrFeNiMn)N	FCC + BCC	Ball-on-disc, dry, ruby, RT, 1 × 10^{-7}–1.4 × 10^{-6} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Xiao et al. [299]	$CoCrFeNiMnC_x$ (x = 0–1.2)	FCC	Ball-on-disk, dry, Si_3N_4, RT, 0.47 × 10^{-5}–6.5 × 10^{-5} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Zhu et al. [211]	CoCrFeNiMn + TiN-Al_2O_3	FCC + TiN	Ball-on-disc, dry, 440C steel, RT
Cheng et al. [300]	CoCrFeNiMn $Al_{0.5}$CoCrFeNiMn AlCoCrFeNiMn	FCC FCC + BCC FCC + BCC	Ball-on-disc, dry, Si_3N_4, RT-800 °C, 0.5 × 10^{-4}–3.8 × 10^{-4} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Joseph et al. [301]	CoCrFeNiMn	FCC	Pin-on-disc, dry, Al_2O_3, 25 & 900 °C

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Source	Composition	Microstructure	Method, Medium, Antagonist Material, Temperature, Wear Rate
	$Al_{0.3}$CoCrFeNi	FCC	
	$Al_{0.6}$CoCrFeNi	FCC + BCC	
	AlCoCrFeNi	BCC	
Liu et al. [302]	CoCrFeNiMn + Y_2O_3	FCC + Y_2O_3 (particles)	Ball-on-disc, dry, GCr15, RT
Wang et al. [303]	$(CoCrFeMnNi)_{85}Ti_{15}$	FCC + BCC	Ball-on-disc, dry, Si_3N_4, RT-800 °C, 4×10^{-6}–2.23×10^{-5} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Zhang et al. [304]	CoCrFeNi + (Ag or BaF_2/CaF_2)	FCC	Ball-on-disk, dry, Inconel-718, RT, ~4×10^{-5}–40×10^{-5} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Geng et al. [305]	CoCrFeNi	FCC	Pin-on-disc, vacuum (4 Pa) & air, Inconel 718, RT, 0.6×10^{-4}–8×10^{-4} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Zhang et al. [306]	CoCrFeNi + (graphite or MoS_2)	FCC	Ball-on-disk, dry, Si_3N_4, RT-800 °C, ~1×10^{-5}–23×10^{-5} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Zhou et al. [307]	$CoCrFeNiMo_{0.85}$	FCC	Slurry jet test-rig, HCl+NaCl, -, 40 °C, -
	$Al_{0.5}$CoCrFeNi	FCC	
Zhang et al. [308]	CoCrFeNiMo	FCC	Ball-on-disc, dry, -, RT

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Source	Composition	Microstructure	Method, Medium, Antagonist Material, Temperature, Wear Rate
Huang et al. [309]	$FeCoCrNiSi_x$	FCC + BCC	Ball-on-disk, dry, GCr15, RT
Cui et al. [310]	CoCrFeNiMo Sulfurized at 260 °C for 2 h	FCC + FeS/MoS_2 film	Pin-on-disk, dry, GCr15, RT
Li et al. [311]	$CoCrFeNiMo_{0.2}$	FCC	Ball on disc, dry, GCr15, RT, 3.9 × 10^{-4}–5.4 × 10^{-4} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Ji et al. [312]	CoCrFeNiCu + 2% MoS_2	FCC + MoS_2 (particles)	Ball-on-disk, dry, Si_3N_4, RT
	CoCrFeNiCu + 5% MoS_2	FCC + MoS_2 (particles)	
	CoCrFeNiCu + 20% WC	FCC + WC (particles)	
	CoCrFeNiCu + 50% WC	FCC + WC (particles)	
	CoCrFeNiCu + 80% WC	FCC + WC (particles)	
Verma et al. [313]	$CoCrFeNiCu_x$ (x = 0–1)	FCC	Pin-on-disk, dry, -, RT & 600 °C, ~1.3 × 10^{-5}–2.5 × 10^{-5} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Liu et al. [314]	$CoCrFeNiB_x$ (x = 0.5–1.5)	FCC + Borides	Roller friction wear tester, dry, $W_{18}Cr_5V$, RT

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Source	Composition	Microstructure	Method, Medium, Antagonist Material, Temperature, Wear Rate
Jiang et al. [315]	$CoCrFeNiNb_x$ (x = 0–1.2)	FCC + HCP (Laves) HCP (Co_2Nb)	Ball-on-disc, dry, BN, RT
Yu et al. [316]	$CoCrFeNiNb_x$ (x = 0.5–0.8)	FCC + HCP (Laves)	Pin-on-disk, dry, Si_3N_4, RT-800 °C, ~1.8×10^{-4}–9×10^{-4} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Liu et al. [317]	$Co_{10}Cr_{10}Fe_{50}Mn_{30}$ + graphene nanoplatelets (0.2–0.8 wt%)	FCC	Ball-on-plate, dry, GCr15, RT
Wang et al. [318]	$Co_{10}Cr_{10}Fe_{40}Mn_{40}$ + WC (10 wt%)	FCC+ WC + $M_{23}C_6$	Ball-on-disc, dry, Si_3N_4, RT
Derimow et al. [319]	$(CoCrCuTi)_{100-x}Mn_x$ (x = 5–10) $(CoCrCuTi)_{100-x}Mn_x$ (x = 10–20)	FCC + BCC FCC + HCP (Laves)	Ball-on-disc, dry, GCr15, RT
Guo et al. [320]	$CoCrFeNiCuSi_{0.2}$ (Ti or C)$_x$ (x = 0–1.5)	FCC + TiC	Brooks sliding friction & wear tester, dry, RT
Zhang et al. [321]	$(CoCrFeNiTi_{0.5})C_x$ (x = 3–12 wt%)	BCC + $Cr_{23}C_6$ + TiC	ML-100 friction and wear tester, -, -, RT
Erdoğan et al. [322]	$CoCrFeNiTi_{0.5}$ $CoCrFeNiTi_{0.5}Al_{0.5}$ $CoCrFeNiTi_{0.5}Al$	FCC BCC BCC	Ball-on-disc, dry, WC, RT

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Source	Composition	Microstructure	Method, Medium, Antagonist Material, Temperature, Wear Rate
Liu et al. [323]	CoCrFeNiMo $CoCrFeNiMo_x$ (x ≥ 0.3) $CoCrFeNiMo_x$ (x ≥ 1)	FCC FCC + σ FCC + σ + μ	Pin-on-disk, dry, YG6, RT, 1 × 10^{-5}–8.5 × 10^{-5} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Moazzen et al. [324]	$CoCrFe_xNi$ (x = 1–1.6)	FCC + BCC	Pin-on-disk, dry, AISI52100 steel, 20–30 °C, -
Yang et al. [325]	$CoCrFeNiMoSi_x$ (x = 0.5–1.5)	FCC	Pin-on-disk, dry, Si_3N_4, RT, 0.292 × 10^{-4}–0.892 × 10^{-4} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Li et al. [326]	$CoCrFeNi_2V_{0.5}Ti_x$ (x = 0.5–1.25)	BCC + $(Co,Ni)Ti_2$	Ball-on-disc, dry, Si_3N_4, RT, 4.4 × 10^{-5}- 37.5 × 10^{-5} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Islak et al. [327]	CrFeNiMoTi	FCC	Ball-on-flat, dry, 100Cr6, RT, 2.7 × 10^{-3}–9.4 × 10^{-3} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Wen et al. [328]	CrCoNiTiV	FCC + BCC + TiO	HT-1000 tribometer, -, WC, RT & 600 °C
Wang et al. [329]	CuNiSiTiZr	BCC	CJS111A wear tester, dry, -, RT
Cheng et al. [330]	$(Fe_{25}Co_{25}Ni_{25}(B_{0.7}Si_{0.3})_{25})_{100-x}Nb_x$ (x = 0–4 wt%)	BCC + HCP (Laves) + FCC	Ball-on-disc, dry, GCr15, RT, ~1.5 × 10^{-6}–3.6 × 10^{-6} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Yadav et al. [331]	$(CuCrFeTiZn)_{1-x}Pb_x$	FCC + BCC + Pb (particles)	Ball-on-disk, dry, -, SAE 52100, RT, 1.17 × 10^{-5}–50 × 10^{-5}

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Source	Composition	Microstructure	Method, Medium, Antagonist Material, Temperature, Wear Rate
	(x = 0.05–0.2)		$mm^3 \cdot N^{-1} \cdot m^{-1}$
Gou et al. [332]	CoCrFeNi + WC + Mo_2C + NbC	FCC	Ball-on-disc, dry, GCr15, 700 °C
Yadav et al. [333]	$(CuCrFeTiZn)_{100-x}Pb_x$ (x = 0–10) $(CuCrFeTiZn)_{100-x}Bi_x$ (x = 0–10)	FCC + BCC BCC	Ball-on-disk, dry, steel, RT
Cui et al. [334]	Al_xCoCrFeNiMn (x = 0–0.75)	FCC + BCC	MDW- 02 abrasive wear tester, RT
Gwalani et al. [335]	$Al_{0.5}$CoCrFeNi	FCC + B2	Pin-on-disc, dry, Si_3N_4, RT, 1.8 × 10^{-5}–11 × 10^{-5} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Chen et al. [336]	$Al_{0.6}$CoCrFeNi	FCC + BCC	Ball-on-plate, dry, Si_3N_4, RT-600 °C, ~0.5 × 10^{-4}–5 × 10^{-4} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Du et al. [337]	$Al_{0.25}$CoCrFeNi	FCC	Universal wear testing machine, dry, Si_3N_4 20–600 °C, ~1.5 × 10^{-4}–3.5 × 10^{-4} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Chen et al. [338]	$Al_{0.6}$CoCrFeNi	FCC + BCC	Ball-on-block, deionized water & acid rain (pH = 2), seawater, GCr_{15}, RT, 1.58 × 10^{-4}–6.52 × 10^{-4} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Ji et al. [339]	Al_3CoCrFeNi		Jet erosion testing machine, water and 15 wt% SiO_2 particles

compressive strength of an equimolar CoCrFeMnNi high-entropy alloy printed by selective laser melting. Opt. Laser Technol. 2020, 127, 106147.

Source	Composition	Microstructure	Method, Medium, Antagonist Material, Temperature, Wear Rate
			(350–600 mm), RT
Haghdadi et al. [340]	$Al_{0.3}CoCrFeNi$ AlCoCrFeNi	FCC BCC	Scratch testing, dry, -, RT
Fang et al. [341]	$Al_{0.3}CoCrFeNi$	FCC	Pin-on-disc, dry, -, 900 °C
Wu et al. [342]	$Al_{0.1}CoCrFeNi$	FCC	Ball-on-block, dry and deionized water, Si_3N_4, RT, ~0.2×10^{-4}–1.86×10^{-4} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Nair et al. [343]	$Al_{0.1}CoCrFeNi$ AlCoCrFeNi $Al_3CoCrFeNi$	FCC FCC + BCC (B2) BCC (B2) + A2 + σ	Ball-on-disc, dry, WC, RT
Kumar et al. [344]	$Al_{0.4}Co_xCrFeNi$ (x = 0–1)	-	Pin-on-disc, demineralized water & (demineralized water + 3.5 wt% NaCl), EN-31, RT, 0.81×10^{-4}–1.86×10^{-4} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Mu et al. [345]	AlCoCrFeNi	BCC + FCC	Ball-on disc, dry, Si_3N_4, RT
Wu et al. [346]	AlCoCrFeNi $AlCoCrFeNiTi_{0.5}$	BCC	Pin-on-disc, dry, Si_3N_4, RT

heterogeneities in the ultrastrong selectively laser melted carbon-doped CoCrFeMnNi alloy. Mater. Sci. Eng. A 2020, 773, 138726.

115. Li, B.; Qian, B.; Xu, Y.; Liu, Z.; Xuan, F. Fine-structured CoCrFeNiMn high-entropy alloy matrix composite with 12 wt% TiN particle reinforcements via selective laser melting assisted additive

Source	Composition	Microstructure	Method, Medium, Antagonist Material, Temperature, Wear Rate
Zhao et al. [347]	$Al_{0.8}CoCrFeNi$	FCC + BCC	Ball-on-disk, dry, deionized water + 0.5 wt% NaCl, RT, ~2 × 10^{-5}–7.5 × 10^{-5} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Kumar et al. [348]	$Al_{0.4}Co_xCrFeNi$ (x = 0–0.5) $Al_{0.4}Co_xCrFeNi$ (x = 1)	FCC + BCC FCC	Pin-on-disk, engine oil (SAE Grade:20W-40), EN-31 steel, RT, 2.1 × 10^{-5}–11 × 10^{-5} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Li et al. [349]	$Al_{0.8}CoCrFeNiCu_{0.5}Si_x$ (x = 0–0.5)	FCC + BCC1 + BCC2	-, -, CGr_{15}, RT, 0.9 × 10^{-6}–1.19 × 10^{-6} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Li et al. [206]	$(AlCoCrFeNi)_{100-x}$ $(NbC)_x$ (x = 0–30 wt%)	FCC + BCC	Reciprocating tester, dry, N_4Si_3, RT
Kafexhiu et al. [350]	$AlCoCrFeNi_{2.1}$	BCC + FCC	Ball-on-plate, dry, 100Cr6 steel, RT, 7 × 10^{-5}–11 × 10^{-5} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Miao et al. [351]	$AlCoCrFeNi_{2.1}$	FCC (L12) + BCC (B2)	Ball-on-disk, dry, Al_2O_3/Si_3N_4/SiC/GCr15, RT-900 °C, ~1 × 10^{-4}–4.2 × 10^{-4} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Ye et al. [352]	$AlCoCrFeNi_{2.1}$ + TiC (0–15 wt%)	FCC + B2 + TiC	MM-200 wear testing machine, dry, -, RT
Wang et al. [353]	(AlCoCrFeNi)N	BCC + nitrides (AlN,CrN,Fe_4N)	Ball-on block, dry, deionized water & acid rain (pH = 2), Si_3N_4,

127. Yao, H.; Tan, Z.; He, D.; Zhou, Z.; Zhou, Z.; Xue, Y.; Cui, L.; Chen, L.; Wang, G.; Yang, Y. High strength and ductility AlCrFeNiV high entropy alloy with hierarchically heterogeneous

Source	Composition	Microstructure	Method, Medium, Antagonist Material, Temperature, Wear Rate
			RT, 2.8×10^{-5}–7×10^{-5} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Liu et al. [354]	$AlCrCuFeNi_2$		Ball-on-block, dry, simulated rainwater & deionized water, Si_3N_4, RT, 2.163×10^{-3}–0.23×10^{-3} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Kong et al. [355]	$Al_{1.8}CrCuFeNi_2$	BCC	MMS-2A roller friction wear tester, dry, -, RT
Malatji et al. [197]	AlCrCuFeNi	FCC + BCC	Ball-on-disk, dry, SiC, RT
Wang et al. [356]	$Al_{1.3}CoCuFeNi_2$	FCC + BCC	Ball-on block, dry, deionized water & acid rain (pH = 2), Si_3N_4, RT, 1×10^{-4}–12×10^{-4} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Xiao et al. [357]	$Al_xCoCrFeNiSi$ (x = 0.5–1.5)	FCC + BCC	Ball-on-flat, distilled water, WC-12Co, RT, 6.7×10^{-6}–5.5×10^{-5} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Liu et al. [358]	$AlCoCrFeNiSi_x$ (0–0.5)	BCC	Pin-on-disk, dry, ZrO_2, RT, 1.3×10^{-4}–5.1×10^{-4} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Hsu et al. [359]	$Al_{0.5}CoCrFeNiCuBx$ (x = 0–1)	FCC + boride precipitates	Pin-on-disk, dry, Al_2O_3, RT
Chen et al. [360]	$Al_{0.5}CoCrFeNiCuTi_x$ (x = 0–0.2)	FCC FCC + BCC	Pin-on-disk, dry, Al_2O_3, RT

Mater. Sci. Eng. A 2020, 789, 139672.

Source	Composition	Microstructure	Method, Medium, Antagonist Material, Temperature, Wear Rate
	$Al_{0.5}CoCrFeNiCuTi_x$ (x = 0.4–1) $Al_{0.5}CoCrFeNiCuTi_x$ (x = 1.2–2)	FCC + BCC + Ti_2N	
Lobel et al. [361]	AlCoCrFeNiTi	BCC	Ball-on-disc, dry, Al_2O_3, RT
Lobel et al. [362]	AlCoCrFeNiTi	BCC	Ball-on-plate, dry, 100Cr6 Steel, RT
Wu et al. [363]	$AlCoCrFeNiTi_x$ (x = 0.5–1) $AlCoCrFeNiTi_x$ (x = 1.5) $AlCoCrFeNiTi_x$ (x = 2)	FCC + BCC FCC + BCC + Ti_2Ni FCC + BCC + Ti_2Ni + ordered BCC	Cavitation erosion tests, Distilled water+ 3.5 wt% NaCl, RT
Erdogan et al. [364]	$Al_xCoCrFeNiTi_y$ (x = 0–0.5, y = 0–0.5)	FCC + BCC	Ball-on-disc, dry, WC, RT, 0.25 × 10^{-4}–1.78 × 10^{-4} $mm^3 \cdot N^{-1} \cdot m^{-1}$, 0.25 × 10^{-4}–1.78 × 10^{-4} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Xin et al. [365]	$Al_{0.2}Co_{1.5}CrFeNi_{1.5}Ti_{0.5}$ + TiC	FCC	Ball-on-disc, dry, Si_3N_4, RT, 0.3 × 10^{-5}–12.6 × 10^{-5} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Gouvea et al. [366]	$Al_{0.2}Co_{1.5}CrFeNi_{1.5}Ti$	FCC	Ball-on-plate, dry, AISI 52,100 steel, RT, 1.6 × 10^{-8}–7.5 × 10^{-5} $mm^2 \cdot N^{-1}$
Chuang et al. [367]	$Al_xCo_{1.5}CrFeNi_{1.5}Ti_y$	FCC	Pin-on-disk, dry, SKH51 steel, RT, ~4 × 10^{-4}–1.8 × 10^{-4}

149. Jin, M.; Piglione, A.; Dovgyy, B.; Hosseini, E.; Hooper, P.A.; Holdsworth, S.R.; Pham, M.S. Cyclic plasticity and fatigue damage of CrMnFeCoNi high entropy alloy fabricated by laser powder-bed

Source	Composition	Microstructure	Method, Medium, Antagonist Material, Temperature, Wear Rate
	(x = 0–0.2, y = 0.5–1)		$mm^3 \cdot N^{-1} \cdot m^{-1}$
Liu et al. [368]	$AlCoCrFeNiTi_{0.8}$	BCC + B2	Ball-on-disc, dry, Si_3N_4, RT, 1.36 × 10^{-6}–6.96 × 10^{-6} $mm^3 \cdot N^{-1} \cdot m^{-1}$, 0.7 × 10^{-4}–6 × 10^{-4} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Yu et al. [369]	$AlCoCrFeNiTi_{0.5}$	BCC1 + BCC2	Pin-on-disk, H_2O_2, SiC & ZrO_2, RT
Lobel et al. [370]	$AlCoCrFeNiTi_{0.5}$	BCC (A2 + B2)	SRV-Tribometer, dry, Al_2O_3, 22–900 °C
Chen et al. [371]	$Al_{0.6}CoCrFeNiTi$	BCC	Pin-on-disc, Dry, Al_2O_3 RT-500 °C
Yu et al. [372]	$AlCoCrFeNiTi_{0.5}$ AlCoCrFeNiCu		Pin-on-disc, dry, Si_3N_4
Yu et al. [373]	AlCoCrFeNiCu $AlCoCrFeNiTi_{0.5}$	FCC + BCC1 BCC1 + BCC2	Pin-on-disk, H_2O_2, 1Cr18Ni9Ti steel & ZrO_2/SiC ceramic, RT
Jin et al. [374]	AlCoFeNiCu	FCC + BCC	Ball-on-disk, dry, WC, 200–800 °C
Zhu et al. [375]	AlCoFeNiCu + TiC (10–30 wt%)	FCC + BCC	Ball-on-disk, dry, $Si_3N_4$20–600 °C, ~0.1 × 10^{-5}–6.5 × 10^{-5} $mm^3 \cdot N^{-1} \cdot m^{-1}$

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Source	Composition	Microstructure	Method, Medium, Antagonist Material, Temperature, Wear Rate
Wu et al. [376]	$Al_{0.5}CoCrFeNiCu$	FCC	Pin-on-disk, dry, SKH-51 steel, RT
	$Al_{1.0}CoCrFeNiCu$	FCC + BCC	
	$Al_{2.0}CoCrFeNiCu$	BCC	
Yan et al. [377]	AlCoCrFeNiSi + Ti (C, N)	BCC + FCC	Ball-on-disc, dry, GCr15, RT, -
Li et al. [378]	AlCoCrFeNi + Ti (C,N) + TiB_2	FCC	Ball-on-disc, dry, WC-6Co, 200–800 °C, 2.69×10^{-5}–8.66×0^{-5} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Kumar et al. [379]	$AlCoCrCuFeNiSi_{0.3}$	FCC + BCC	Pin-on-disk, dry, -, RT, -
	$AlCoCrCuFeNiSi_{0.6}$	FCC + BCC + σ	
Xin et al. [380]	$Al_{0.2}Co_{1.5}CrFeNi_{1.5}Ti_{0.5}$	FCC	Pin-on-disk, dry, Si_3N_4, 25–800 °C, 1.21×10^{-5}–6.7×10^{-5} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Karakaş et al. [381]	$Al_{0.07}Co_{1.26}Cr_{1.80}Fe_{1.42}Mn_{1.35}Ni_{1.1}$	FCC	Ball-on-disc, 3.5%NaCl & 5%H_2SO_4, -, RT, 16.26×10^{-9}–77.84×10^{-8} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Xin et al. [382]	$Al_{0.2}Co_{1.5}CrFeNi_{1.5}Ti_{(0.5+x)}$ + C_x (x = 0)	FCC	Pin-on-disk, dry, Si_3N_4, 25–800 °C, 3.12×10^{-6}–12.59×10^{-5} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Zhao et al. [383]	$AlCrCoFeNiCTa_x$ (x = 0–1)	BCC	Pin-on-disk, 3.5%NaCl & air, Si_3N_4, RT, 1.67×10^{-6}–$2.22 \times$

WC addition. J. Mater. Sci. Technol. 2019, 35, 2430–2434.

Source	Composition	Microstructure	Method, Medium, Antagonist Material, Temperature, Wear Rate
			10^{-5} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Ghanbariha et al. [384]	AlCoCrFeNi + ZrO_2	FCC + BCC	Pin-on-disk, dry, WC, RT, 1.11 × 10^{-3}–2.52 × 10^{-3} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Li et al. [385]	Al_xCrFeCoNiCu (x = 0–0.5)	FCC	-, dry, GCr15, RT, 6.64 × 10^{-7}–2.26 × 10^{-4} $mm^3 \cdot N^{-1} \cdot m^{-1}$
	Al_xCrFeCoNiCu (x = 0.5–2)	FCC + BCC	
Cai et al. [386]	AlCrTiV, AlCrTiVSi	BCC	Nanoindenter G200, dry, CGr15 &Al_2O_3, RT, -
Chandrakar et al. [387]	AlCoCrCuFeNiSi_x (x = 0–0.9)	BCC	Pin-on-disk, dry, -, RT, -
Erdogan et al. [388]	AlCrFeNiSi	BCC	Ball-on-disc, dry, WC, RT, -
	AlCrFeNi_x (x = Cu,Co)	BCC + FCC	
Duan et al. [389]	AlCoCrFeNiCu	-	Pin-on-disc, H_2O_2, Si_3N_4, RT
Chen et al. [390]	$Al_{0.5}$CoCrFeNiCuV_x (x = 0–0.2)	FCC	Pin-on-disk, dry, Al_2O_3, RT, 1 × 10^{-4}–2.7 × 10^{-4} $mm^3 \cdot N^{-1} \cdot m^{-1}$
	$Al_{0.5}$CoCrFeNiCuV_x (x = 0.4–0.8)	FCC + BCC	
	$Al_{0.5}$CoCrFeNiCuV_x (x = 1–2)	BCC	
Gu et al. [391]	$Al_x$$Mo_{0.5}$NbFeTi$Mn_2$ (x = 1–2)	BCC	Pin-on-disk, dry, Al_2O_3, RT

948.

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Source	Composition	Microstructure	Method, Medium, Antagonist Material, Temperature, Wear Rate
Hsu et al. [392]	$AlCoCrFe_xNiMo_{0.5}$ (x = 0.6–2)	BCC + σ	Pin-on-disk, dry, SKH51 steel, RT
Liang et al. [393]	$AlCrFe_2Ni_2W_{0.2}Mo_{0.75}$	BCC	Ball-on-disc, deionized water, Al_2O_3, RT, ~5 × 10^{-6}–22 × 10^{-6} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Qui et al. [394]	$Al_2CoCrFeCuTiNi_x$ (x = 0–2)	FCC + BCC	Tribometer, -, -, RT
Kanyane et al. [395]	AlTiSiMoW	BCC + $TiSi_2$ (ordered FCC)	Ball-on-disc, dry, stainless steel, RT
Huang et al. [396]	AlTiSiVCr	BCC+ $(Ti,V)_5Si_3$ precipitates	Ball-on-disc, dry, GCr15 steel, RT, 2 × 10^{-5}–2.5 × 10^{-5} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Zhang et al. [397]	AlTiSiVNi	B2 (NiAl) + (Ti,V)5Si_3 + TiN	Ball-on-disc, dry, Si_3N_4, RT & 800 °C
Lin et al. [398]	AlCoCrNiW AlCoCrNiSi	W + AlNi + $Cr_{15.58}Fe_{7.42}C_6$ BCC	Pin-on-disc, dry, AISI 52100, RT
Yadav et al. [399]	AlCrFeMnV $(AlCrFeMnV)_{90}Bi_{10}$ $(AlCrFeMnV)_{90}$Bi10 + 10 wt% TiB_2	BCC BCC + AlV_3 + Bi BCC + AlV_3 + Bi + TiB_2	Ball-on-disk, dry, SAE 52,100 steel, RT, 1.02 × 10^{-5}–7.02 × 10^{-5} $mm^3 \cdot N^{-1} \cdot m^{-1}$

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Source	Composition	Microstructure	Method, Medium, Antagonist Material, Temperature, Wear Rate
	$(AlCrFeMnV)_{90}Bi_{10}$ + 15 wt% TiB_2	BCC + AlV_3 + Bi + TiB_2	
Bhardwaj et al. [400]	AlTiZrNbHf	BCC	Pin-on-disk, dry, CGr15, RT, -
Zhao et al. [401]	$AlNbTaZr_x$ (x = 0.2–1)	BCC + HCP	Ball-on-disc, dry, Si_3N_4, RT, 1.85 × 10^{-4}–2.41 × 10^{-4} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Tuten et al. [402]	TiZrHfNbTa	Amorphous	Ball-on-disc, dry, Al_2O_3, RT
Pole et al. [403]	TiZrHfTaV, TiZrTaVW	BCC	Ball-on-disk, dry, Si_3N_4, RT-500 °C, ~1 × 10^{-4}–8 × 10^{-4} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Ye et al. [404]	TiZrHfNb	BCC	Nano-scratch, dry, diamond indenter, RT
Pogrebnjak et al. [405]	(TiZrHfNbV)N	FCC	Ball-on-disc, dry, Al_2O_3, 20 °C
Gong et al. [406]	TiZrHfBeCu TiZrHfBeNi $Ti_{20}Zr_{20}Hf_{20}Be_{20}Cu_{10}Ni_{10}$ $Ti1_{3.8}Zr_{41.2}Ni_{10}Be_{22.5}Cu_{12.5}$	Amorphous	Nano-scratch, dry, diamond indenter, RT

prepared by laser cladding. J. Alloys Compd. 2019, 788, 485–494.

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Source	Composition	Microstructure	Method, Medium, Antagonist Material, Temperature, Wear Rate
Zhao et al. [407]	TiZrNiBeCu	Amorphous	Nano-scratch, dry, diamond indenter, RT
Jhong et al. [408]	$(TiZrNbCrSi)C_x$ (x = 36.7–87.8 at.%)	FCC	Ball-on-disc, dry, $100Cr_6$ steel, RT, 0.2 × 10^{-3}.3 × 10^{-6} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Mathiou et al. [409]	TiZrNbMoTa	BCC + HCP	Ball-on disc, dry, $100Cr_6$ steel, Al_2O_3, RT, 0.154 × 10^{-1}–0.199 × 10^{-1} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Petroglou et al. [410]	$MoTa_xNbVTi$ (x = 0.25–1)	BCC	Ball-on-disk, dry, $100Cr_6$ steel, RT, 0.19 × 10^{-6}–0.38 × 10^{-6} $g \cdot N^{-1} \cdot m^{-1}$
Poulia et al. [411]	MoTaNbVW	BCC	Ball-on-disc, dry, $100Cr_6$ steel & Al_2O_3, RT
Poulia et al. [412]	MoTaNbVW	BCC	Ball-on-disc, dry, $100Cr_6$ steel & Al_2O_3, RT, 1.05 × 10^{-4}–4.89 × 10^{-4} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Poulia et al. [413]	MoTaNbVTi	BCC + hexagonal C14 Laves + cubic C15 laves	Ball-on disc, dry, $100Cr_6$ steel, Al_2O_3, RT
Alvi et al. [414]	MoTaWVCu	BCC	Ball-on-disc, dry, E52100 steel & Si_3N_4, RT-600 °C, 2.3 × 10^{-2}–5 × 10^{-2} $mm^3 \cdot N^{-1} \cdot m^{-1}$

488, 294–303.

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Source	Composition	Microstructure	Method, Medium, Antagonist Material, Temperature, Wear Rate
Hua et al. [415]	$Ti_xZrNbTaMo$ (x = 0.5–2)	BCC	HSR-2M tester, dry, Si_3N_4, RT, 2.22×10^{-7}–2.42×10^{-7} $mm^3 \cdot N^{-1} \cdot m^{-1}$
Gu et al. [416]	$Ni_{1.5}CrFeTi_{2.0.5}Mo_x$ (x = 0–0.25)	BCC	Ball-on-disc, dry, Al_2O_3, RT, 7.99 $\times 10^7$–2.7×10^7 μm^3
	$Ni_{1.5}CrFeTi_{2.0.5}Mo_x$ (x = 0.5–0.25)	BCC + FCC	

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