**Nanostructured High-Entropy Materials**

Michel J.R Haché, Changjun Cheng, and Yu Zou

*Department of Materials Science and Engineering, University of Toronto, 184 College St Toronto ON Canada M5S 3E4*

**S1. Summary of Nanocrystalline HEAs**

A summary of the classification, mechanical properties, grain size, and structure of all nanocrystalline HEAs covered in **Sections 2-5** of the manuscript can be found in Table SI. Abbreviations in the table correspond to: Yield Strength (YS), Ultimate Tensile Strength (UTS), Percent Elongation (% Elong), Young’s Modulus (E), Average Grain Size (Avg. G.S), 3d Transition Metals (3D), Interstitial (Int), Refractory (Ref), Light Metal (LM), Precious Metal (PM), Composite (Comp), Precipitate (PCT), High-entropy Oxide (HEO), Mechanical Alloying (MA), DC Magnetron Sputtering (DMSC), RF Magnetron Sputtering (RMFS), High-pressure Torsion (HPT), Equal Channel Angular Pressing (ECAP), Annealing (Ann.), Flame Spray Pyrolysis (FSP), Nebulized Spray Pyrolysis (NSP), Reverse Co-precipitation Process (RCP), Cryo-rolling (CR), Vacuum Arc Deposition (VAD), Cryo-milling (CM), Rapid Solidification Process (RSP). The notation (c) in mechanical properties indicates that the value was obtained via a compression test. Hardness is presented in units of GPa, unless otherwise noted. In many cases of MA-processed HEAs, the mechanical properties reported are for consolidated powders, and as such have larger grain sizes than those reported in Table SI.

Table SI: Summary of NC-HEA methods, mechanical properties, average grain size, and structure.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Material** | **Type** | **Method** | **YS (MPa)** | **UTS (MPa)** | **% Elong** | **E (GPa)** | **Hardness (GPa)** | **Avg G.S (nm)** | **Structure** | **Ref.** |
| Al0.1CoCrFeNi | 3D | HPT |  |  |  |  | 482 HV | 80 | FCC | 1 |
| Al0.25CoCrFeNi | 3D | Cold Rolling | 1280 | 1479 | 2.3 |  |  |  | FCC | 2 |
| Al0.3CoCrFeMnNi | 3D | MA |  | 1800 (c) |  |  | 480 HV | 5 | FCC | 3 |
| Al0.3CoCrFeNi | 3D | HPT |  |  |  |  | 530 HV |  | FCC+BCC | 4 |
| Al0.3CoCrFeNi | 3D | HPT |  |  |  |  |  | 30 | FCC | 5 |
| Al0.3CoCrFeNi | 3D | DCMS |  |  |  | 191-197 | 10.4-12.3 | 10 | BCC+FCC | 6 |
| Al0.4CoFeNiSi0.4 | 3D | MA |  |  |  |  |  |  | FCC+BCC | 7 |
| Al0.5CoCrFeNi | 3D | Ann | 834 | 1220 |  |  |  | 18 | BCC+FCC | 8 |
| Al0.6CoFeNiTi0.4 | 3D | MA | 2732 | 3172 | 10.1 |  | 712 HV | 8.7 | BCC+FCC | 9 |
| Al7.5Co25Cu17.5Fe25Ni25 | 3D | MA | 1795 | 1936 | 10.6 |  | 454 HV | 24 | FCC | 10 |
| AlCoCrCuFe | 3D | MA |  |  |  |  | 770 HV | 10 | BCC | 11 |
| AlCoCrCuFeNi | 3D | MA | 2379 |  |  | 172 | 8.13 | 10 |  | 12 |
| AlCoCrCuFeNi | 3D | DCMS |  |  |  |  |  | 10 |  | 13 |
| AlCoCrCuFeNi | 3D | MA |  |  |  |  |  |  | FCC+BCC | 14,15 |
| AlCoCrCuFeNi | 3D | Ann |  | 1630 | 34 |  | 369.8 HV | 70 | FCC | 16 |
| AlCoCrCuFeZnx | 3D | MA |  |  |  |  |  |  | FCC, sometimes FCC+BCC) | 17 |
| AlCoCrCuNi | 3D | Sol-Gel |  |  |  |  |  | 14 | BCC+FCC | 18 |
| AlCoCrCuNiFeZn | 3D | MA |  |  |  | 152.4 | 7.773 | 20 | BCC | 19 |
| AlCoCrFeMnNi | 3D | MA |  | 2142 (c) |  |  | 662 HV |  | FCC | 20 |
| AlCoCrFeNi | 3D | MA |  |  |  |  | 8 | 30-40 | FCC+BCC | 21 |
| AlCoCrFeNi | 3D | MA |  |  |  |  |  |  | FCC+BCC | 22 |
| AlCoCrFeNi | 3D | MA | 1907 (c) |  |  |  | 625 HV |  | BCC | 23 |
| AlCoCrFeNi | 3D | MA |  |  |  |  |  | 27 | BCC+FCC | 24 |
| AlCoCrFeNi | 3D | Ann |  | 2639 (c) | 40.6 (c) |  |  | as low as 20 | BCCx2 | 25 |
| AlCoCrFeNiSix | 3D | MA |  |  |  |  | 1010 HV | 32 | BCC | 26 |
| AlCoCrFeNiTi | 3D | MA |  |  |  |  |  |  | FCC | 27 |
| AlCoCrFeNiTi + TiB2 | 3D | MA |  |  |  |  | 23.56 | 10 | BCC | 28 |
| AlCoCuZnNi | 3D | MA |  |  |  |  | 649 HVN | 15 | FCC+BCC | 29 |
| AlCoFe Ni(Cr, Cu, Mo, Ti) | 3D | MA |  |  |  |  | 766 HV |  | FCC+BCC | 30 |
| AlCoFeMoNiTi | 3D | (RSP) |  |  |  |  | 896 HV | 11.6-15.4 | BCC | 31 |
| AlCrCrFeMgNi4.75 | 3D | MA |  |  |  |  | 424 HVN |  | FCC+BCC | 32 |
| AlCrCuFeMgx | 3D | MA |  |  |  |  | 853 HV |  | BCC + IM | 33 |
| AlCrCuFeMnW | 3D | MA |  |  |  |  |  | ~25 | FCC+BCC+IM | 34 |
| AlCrCuFeMnWx (x=0,0.05,0.1,0.5) | 3D | MA |  |  |  |  |  | 20 | FCC+BCC | 35 |
| AlCrCuFeNiZn | 3D | MA |  |  |  |  | 700 HV |  | BCC+FCC | 36 |
| AlCrCuFeNiZn | 3D | MA |  |  |  | 148 | 870 HV | 20 | BCC+FCC | 37 |
| AlCrFeMnV | 3D | CM |  |  |  |  |  | 6 | BCC | 38 |
| AlCrFeNiZn | 3D | MA |  |  |  | 153.03 | 7.427 | 62 | Mix FCC BCC | 39 |
| AlCrFeTi | 3D | MA |  |  |  |  |  |  | BCC | 40 |
| AlCrFeTiZn | 3D | MA |  |  |  |  |  |  | BCC | 40 |
| AlCrFeTiZnCu | 3D | MA |  | 2830 (c) |  |  | 10 |  | BCC+FCC | 41 |
| AlCrFeTiZnCu | 3D | MA |  |  |  |  |  |  | BCC | 40 |
| AlCrMoNbZr | 3D | DCMS |  |  |  | 146 | 11.8 |  | BCC | 42 |
| AlFeTi | 3D | MA |  |  |  |  |  |  | BCC | 40 |
| Alx(FeNiCoCu)1-xTix | 3D | HPT |  | 1849 |  |  |  | 50 | FCC+IM | 43 |
| AlxCoCrCuFeNi | 3D | MA |  |  |  |  |  |  | BCC+FCC | 44 |
| AlxCoCrCuFeNi | 3D | Ann |  |  |  |  | 527 HV |  | FCC+BCC | 45 |
| AlxCoCrCuFeNi (x=0.5,1,2) | 3D | DCMS |  |  |  | 156.5 (reduced) | 15.1 |  | FCC(x=0.5), FCC+BCC (x=2) | 46 |
| AlxCoCrFeNiMn | 3D | MA | 2230 | 2552 | 1.69 |  | 622 HV |  | FCC+BCC+ IM | 47 |
| AlxCoCu1-xFeNi1.5V0.5 | 3D | MA | 1720 | 1930 | 9 |  | 541 HV | 7 | FCC+BCC | 48 |
| **Assortment of HEAs/MEAs** | 3D | HPT |  |  |  |  |  | Varies |  | 49 |
| Co0.5CrFeNiTi0.5 | 3D | MA | 2650 | 2690 (c) | 10 |  | 8.46 |  | BCC+FCC | 50 |
| CoCr2-xCuFeNix (x=1,1.2,1.5,1.8) | 3D | MA | 869 | 1856 | 32.2 |  | 321HV | 9-15 | BCC+FCC | 51 |
| CoCrCuFeNi | 3D | MA |  |  |  |  | 494 HV | 100 | FCC | 52 |
| CoCrCuFeNi | 3D | MA |  |  |  |  | 400 HV | 7 | BCC+FCC | 11 |
| CoCrCuFeNi | 3D | DCMS |  |  |  |  |  |  | BCC+FCC | 53 |
| CoCrCuFeNiAlTiXVMo (X=Zn,Mn) | 3D | MA | 2.53 |  |  |  | 7.6 |  | FCC+BCC | 54 |
| CoCrCuFeNiMox | 3D | MA | 1228 (c) | 1448 (c) |  |  | 530 HV |  | FCC+BCT+Rhom | 55 |
| CoCrCuFeNiNbx | 3D | DCMS |  |  |  |  |  |  | FCC | 56 |
| CoCrFeMn0.5NiTi0.5 | 3D | MA |  |  |  |  |  | 14 | BCC | 57 |
| CoCrFeMnNi | 3D | HPT |  |  |  |  | 5.38 | 30 | FCC | 58 |
| CoCrFeMnNi | 3D | MA | 1574 |  |  |  |  | 11.2 | FCC+Cr-carbide | 59 |
| CoCrFeMnNi | 3D | HPT |  |  |  |  | 6.2 | 38 | FCC | 60 |
| CoCrFeMnNi | 3D | HPT |  |  |  |  | 7.5 | 40 | FCC+BCC | 61 |
| CoCrFeMnNi | 3D | HPT |  |  |  |  | 5.2 | 33 | FCC | 62 |
| CoCrFeMnNi | 3D | MA | 1180 (c) | 2660 (c) |  | 184 | 688 HV |  | FCC+IM | 63 |
| CoCrFeMnNi | 3D | HPT |  | ~2000 |  |  | 910 HV | 50 | FCC+IM | 64 |
| CoCrFeMnNi | 3D | MA |  |  |  |  | 587 HV | 100 | FCC | 52 |
| CoCrFeMnNi | 3D | HPT + MA |  |  |  |  | 6.7 | 50 | FCC | 65 |
| CoCrFeMnNi | 3D | MA | 1987 (c) |  |  |  | 646 HV |  | BCC+FCC | 66 |
| CoCrFeMnNi | 3D | HPT |  |  |  |  | 6.5 GPa  500 HV | 40 | FCC | 67 |
| CoCrFeMnNi | 3D | HPT |  | 1750 | 4 |  | 4.41 | 10 | FCC | 68 |
| CoCrFeMnNi | 3D | HPT |  |  |  |  |  | 10 | FCC | 69 |
| CoCrFeMnNi | 3D | ECAP | 980 | 990 | 35 |  | 315 HV | 100 | FCC | 70 |
| CoCrFeMnNi | 3D | CR |  |  |  |  |  | 230-420 | FCC+BCC+IM | 71 |
| CoCrFeMnNi | 3D | MA | 1314 | 2026 | 20.3 |  | 415 HV | 100 | FCC | 72 |
| CoCrFeMnNi | 3D | RFMS |  |  |  | 177 | 6.8 | 10 | FCC+BCC | 73 |
| CoCrFeMnNi | 3D | HPT |  |  |  |  |  | 55 | FCC | 74 |
| CoCrFeMnNi | 3D | HPT |  |  |  | 200 | 7.64 | 50 | FCC | 75 |
| CoCrFeMnNi | 3D | HPT |  |  |  | 214 | 5.8 | 50 | FCC | 76 |
| CoCrFeMnNi | 3D | DCMS |  |  |  |  |  | 10 | FCC+oxides | 77 |
| CoCrFeMnNi | 3D | CM |  |  |  |  |  | 4 | FCC | 38 |
| CoCrFeMnNi/polymer hybrid | 3D | RFMS |  |  |  |  |  | 5 |  | 78 |
| CoCrFeMnNiTi0.1 | 3D | HPT | 1950 | 2220 | 3 |  | 460 HV | 40 | FCC | 79 |
| CoCrFeMnNiTi0.1 | 3D | HPT |  |  |  |  | 450 HV | 10 | FCC | 79 |
| CoCrFeNi | 3D | DCMS |  |  |  | 205 | 9.5 | 7.8 | FCC | 80 |
| CoCrFeNi | 3D | MA |  |  |  |  |  |  | BCC+FCC+IM | 81 |
| CoCrFeNi | 3D | HPT |  |  |  |  |  | 68 |  | 82 |
| CoCrFeNi | 3D | MA |  |  |  |  |  | 30 | FCC+BCC+IM | 83 |
| CoCrFeNi(W1-xMox) | 3D | MA |  |  |  |  | 600 HV |  | BCC+FCC | 84 |
| CoCrFeNiMoNbZr | 3D | MA |  |  |  |  |  | 12.5 |  | 85 |
| CoCrFeNiZr | 3D | MA |  |  |  |  |  | 19 |  | 85 |
| CoCrNi | 3D | HPT |  | 993 |  |  |  | 199 | FCC | 86 |
| CoCrNi | 3D | HPT | 1880 | 2170 | 9 |  |  | 50 | FCC | 87 |
| CoCuNi | 3D | MA |  |  |  |  |  |  | BCC | 88 |
| CoCuNiZn | 3D | MA |  |  |  |  |  |  | FCC | 88 |
| CoCuNiZnAl | 3D | MA |  |  |  |  |  |  | FCC | 88 |
| CoCuNiZnAlTi | 3D | MA |  | 2360 (c) |  |  | 7.55 |  | BCC | 89 |
| CoCuNiZnAlTi | 3D | MA |  | 2760 (c) |  |  | 8.79 |  | FCC | 88 |
| CoFeNi - Mn,Cu,Cr | 3D | MA |  |  |  |  | 570 HV | 8 | BCC+FCC | 90 |
| CoFeNiTi | 3D | HPT | ~2300 | 2700 | 8-10 | ~150 |  | 20-50 | FCC+BCC | 91 |
| CrCoFeMnNi | 3D | MA |  |  |  |  | 7.8 | 9.4 | FCC | 92 |
| CrCoFeNi | 3D | MA |  |  |  |  |  | 43 |  | 85 |
| CrCoFeNi | 3D | MA |  |  |  |  | 6.3 | 22 | FCC | 92 |
| CrCuFeTiZn | 3D | MA |  |  |  |  | 6 | 45 | BCC+FCC | 93 |
| CrFeMnNiVC | 3D | HPT |  |  |  |  | 555 HV | 30 | FCC+Cr-carbide | 94 |
| CrFeNi-M-X (M=Co, Mn, Nb, Ti, Zr; X=B, Si) | 3D | MA |  |  |  |  |  | <10 | assorted, typically single phase | 95 |
| CrNbTiVZn | 3D | MA |  |  |  |  |  | 7 | FCC | 96 |
| CrNiTiZrV | 3D | RSP |  |  |  |  | 8.92 | 15 | Hexagonal Laves | 97 |
| Family of AlCoCrCuFeNiMoTi | 3D | MA |  |  |  |  |  | ~5 | Some FCC, Some BCC, some mixed, some amorphous | 98 |
| Ni45-x(FeCoCr)40(AlTi)15Hfx | 3D | Ann | 1110 |  |  |  |  | 90 | FCC+BCC+IM | 99 |
| NiMoTiNbTa | 3D | MA |  |  |  |  |  | 16 |  | 85 |
| AlTiVNb | Ref | HPT |  |  |  |  | 7.9 | 50 | BCC | 100 |
| HfNbTaTiZr | Ref | Ann |  |  |  |  |  | 25 | HCP+BCC | 101 |
| NbMoTaW | Ref | DCMS |  |  |  | 196.6 | 16 |  | BCC | 102 |
| NbMoTaW | Ref | DCMS |  |  |  |  | 12 | 15.8 | BCC | 103 |
| NbMoTaWVTi | Ref | MA | 2709 (c) | 3115 (c) | 11.4 (c) |  |  |  | BCCx2+FCC precipitates | 104 |
| NbTaMoW | Ref | DCMS | 2000 |  |  |  |  | 70-100 |  | 105 |
| TiVZrNbHf | Ref | VAD |  |  |  | 575 | 64 | 30-50 | FCC | 106 |
| TiVZrNbHf | Ref | VAD |  |  |  |  | 70 | 57 | FCC | 107 |
| TiZrNbHfTa | Ref | HPT |  | 1900 | 7.9 |  | 430 HV | 50 | BCC | 108 |
| Al0.5Co0.3CrFeNiC0.2 | Int (C) | MA | 2131 (c) |  | 3 |  | 617 HV | 12 | BCC+FCC | 109 |
| CoCrFeNi | Int (C) | MA |  |  |  |  | 575 HV | 5 | FCC+BCC+C,O | 110 |
| (Co,Cu,Mg,Ni,Zn)O | Int (O) | FSP, NSP, RCP |  |  |  |  |  |  | FCC | 111 |
| (Co,Mg,Ni,Zn)O | Int (O) | FSP, NSP, RCP |  |  |  |  |  |  | FCC+Oxides | 111 |
| CoCrFeMnNi | Int (O) | MA | 1269 | 1318 | 0.74 | 204.5 |  | 400 | FCC | 112 |
| Al0.5CoCrCuFeNi | Int (N) | DCMS |  |  |  |  | 4.4-10.4 | ~50 | BCC+FCC | 113 |
| AlCoCrCuFeMnNi | Int (N) | DCMS |  |  |  |  | 4.2-11.8 | ~50 | BCC+FCC | 113 |
| CoNiFeAl0.4Ti0.6Cr0.5 + SiC/7075 Al Composites | Comp | MA |  | 712 | 0.82 | 171 |  | 7 | FCC+BCC | 114 |
| CoCrFeMnNi + Al2O3 nanocomposite | Comp | MA | 1600 |  |  |  | 545 HV |  | FCC+oxides+ carbides | 115 |
| NiMgZnCuCo - Oxides | HEO | MA |  |  |  |  |  |  | Single phase - probably Rock Salt structure | 116 |
| Al20Li20Mg10Sc20Ti30 | LM | MA |  |  |  |  | 5.8 (4.9 annealed) | 12 (26 annealed) | FCC (powder) HCP (annealed) | 117 |
| CoCrFeMnNi+SiC | PCT | MA | 1900 (c) | 2000 (c) |  | 214 | 699 HV |  | FCC+IM | 63 |
| CuAgAuPtPd | PM | CM |  |  |  |  |  | 9 | FCC | 38 |

**References**

1. P. F. Yu, H. Cheng, L. J. Zhang, H. Zhang, Q. Jing, M. Z. Ma, P. K. Liaw, G. Li, and R. P. Liu: Effects of high pressure torsion on microstructures and properties of an Al0.1CoCrFeNi high-entropy alloy. *Mater. Sci. Eng. A* **655**, 283 (2016).

2. J. Hou, M. Zhang, S. Ma, Peter. K. Liaw, Y. Zhang, and J. Qiao: Strengthening in Al0.25CoCrFeNi high-entropy alloys by cold rolling. *Mater. Sci. Eng. A* **707**, 593 (2017).

3. R. M. Pohan, B. Gwalani, J. Lee, T. Alam, J. Y. Hwang, H. J. Ryu, R. Banerjee, and S. H. Hong: Microstructures and mechanical properties of mechanically alloyed and spark plasma sintered Al0.3CoCrFeMnNi high entropy alloy. *Mater. Chem. Phys.* **210**, 62 (2018).

4. Q. H. Tang, Y. Huang, Y. Y. Huang, X. Z. Liao, T. G. Langdon, and P. Q. Dai: Hardening of an Al0.3CoCrFeNi high entropy alloy via high-pressure torsion and thermal annealing. *Mater. Lett.* **151**, 126 (2015).

5. Q. Tang, Y. Huang, H. Cheng, X. Liao, T. G. Langdon, and P. Dai: The effect of grain size on the annealing-induced phase transformation in an Al0.3CoCrFeNi high entropy alloy. *Mater. Des.* **105**, 381 (2016).

6. W. Liao, S. Lan, L. Gao, H. Zhang, S. Xu, J. Song, X. Wang, and Y. Lu: Nanocrystalline high-entropy alloy (CoCrFeNiAl0.3) thin-film coating by magnetron sputtering. *Thin Solid Films* **638**, 383 (2017).

7. B. Zhang, Y. Duan, Y. Cui, G. Ma, T. Wang, and X. Dong: Improving electromagnetic properties of FeCoNiSi0.4Al0.4 high entropy alloy powders via their tunable aspect ratio and elemental uniformity. *Mater. Des.* **149**, 173 (2018).

8. S. Niu, H. Kou, T. Guo, Y. Zhang, J. Wang, and J. Li: Strengthening of nanoprecipitations in an annealed Al0.5CoCrFeNi high entropy alloy. *Mater. Sci. Eng. A* **671**, 82 (2016).

9. W. Chen, Z. Fu, S. Fang, Y. Wang, H. Xiao, and D. Zhu: Processing, microstructure and properties of Al0.6CoNiFeTi0.4 high entropy alloy with nanoscale twins. *Mater. Sci. Eng. A* **565**, 439 (2013).

10. Z. Fu, W. Chen, H. Wen, D. Zhang, Z. Chen, B. Zheng, Y. Zhou, and E. J. Lavernia: Microstructure and strengthening mechanisms in an FCC structured single-phase nanocrystalline Co25Ni25Fe25Al7.5Cu17.5 high-entropy alloy. *Acta Mater.* **107**, 59 (2016).

11. S. Praveen, B. S. Murty, and R. S. Kottada: Alloying behavior in multi-component AlCoCrCuFe and NiCoCrCuFe high entropy alloys. *Mater. Sci. Eng. A* **534**, 83 (2012).

12. R. S. Ganji, P. Sai Karthik, K. Bhanu Sankara Rao, and K. V. Rajulapati: Strengthening mechanisms in equiatomic ultrafine grained AlCoCrCuFeNi high-entropy alloy studied by micro- and nanoindentation methods. *Acta Mater.* **125**, 58 (2017).

13. V. Dolique, A.-L. Thomann, P. Brault, Y. Tessier, and P. Gillon: Complex structure/composition relationship in thin films of AlCoCrCuFeNi high entropy alloy. *Mater. Chem. Phys.* **117**(1), 142 (2009).

14. K. B. Zhang, Z. Y. Fu, J. Y. Zhang, J. Shi, W. M. Wang, H. Wang, Y. C. Wang, and Q. J. Zhang: Nanocrystalline CoCrFeNiCuAl high-entropy solid solution synthesized by mechanical alloying. *J. Alloys Compd.* **485**(1–2), L31 (2009).

15. K. B. Zhang, Z. Y. Fu, J. Y. Zhang, W. M. Wang, H. Wang, Y. C. Wang, and Q. J. Zhang: Characterization of nanocrystalline CoCrFeNiCuAl high-entropy alloy powder processed by mechanical alloying. *Mater. Sci. Forum* **620–622**, 383 (2009).

16. K. B. Zhang, Z. Y. Fu, J. Y. Zhang, J. Shi, W. M. Wang, H. Wang, Y. C. Wang, and Q. J. Zhang: Annealing on the structure and properties evolution of the CoCrFeNiCuAl high-entropy alloy. *J. Alloys Compd.* **502**(2), 295 (2010).

17. M. Murali, S. P. K. Babu, B. J. Krishna, and A. Vallimanalan: Synthesis and characterization of AlCoCrCuFeZnx high-entropy alloy by mechanical alloying. *Prog. Nat. Sci. Mater. Int.* **26**(4), 380 (2016).

18. B. Niu, F. Zhang, H. Ping, N. Li, J. Zhou, L. Lei, J. Xie, J. Zhang, W. Wang, and Z. Fu: Sol-gel autocombustion synthesis of nanocrystalline high-entropy alloys. *Sci. Rep.* **7**(1) (2017).

19. C. S. Babu, K. Sivaprasad, V. Muthupandi, and Jerzy. A. Szpunar: Characterization of nanocrystalline AlCoCrCuNiFeZn high entropy alloy produced by mechanical alloying. *Procedia Mater. Sci.* **5**, 1020 (2014).

20. C. Wang, W. Ji, and Z. Fu: Mechanical alloying and spark plasma sintering of CoCrFeNiMnAl high-entropy alloy. *Adv. Powder Technol.* **25**(4), 1334 (2014).

21. S. Mohanty, T. N. Maity, S. Mukhopadhyay, S. Sarkar, N. P. Gurao, S. Bhowmick, and K. Biswas: Powder metallurgical processing of equiatomic AlCoCrFeNi high entropy alloy: Microstructure and mechanical properties. *Mater. Sci. Eng. A* **679**, 299 (2017).

22. M. Vaidya, A. Prasad, A. Parakh, and B. S. Murty: Influence of sequence of elemental addition on phase evolution in nanocrystalline AlCoCrFeNi: Novel approach to alloy synthesis using mechanical alloying. *Mater. Des.* **126**, 37 (2017).

23. W. Ji, Z. Fu, W. Wang, H. Wang, J. Zhang, Y. Wang, and F. Zhang: Mechanical alloying synthesis and spark plasma sintering consolidation of CoCrFeNiAl high-entropy alloy. *J. Alloys Compd.* **589**, 61 (2014).

24. P. Yang, Y. Liu, X. Zhao, J. Cheng, and H. Li: Electromagnetic wave absorption properties of mechanically alloyed FeCoNiCrAl high entropy alloy powders. *Adv. Powder Technol.* **27**(4), 1128 (2016).

25. Y. Zhou, X. Jin, L. Zhang, X. Du, and B. Li: A hierarchical nanostructured Fe34Cr34Ni14Al14Co4 high-entropy alloy with good compressive mechanical properties. *Mater. Sci. Eng. A* **716**, 235 (2018).

26. A. Kumar, A. K. Swarnakar, and M. Chopkar: Phase evolution and mechanical properties of AlCoCrFeNiSix high-entropy alloys synthesized by mechanical alloying and spark plasma sintering. *J. Mater. Eng. Perform.* **27**(7), 3304 (2018).

27. K. B. Zhang, Z. Y. Fu, J. Y. Zhang, W. M. Wang, S. W. Lee, and K. Niihara: Characterization of nanocrystalline CoCrFeNiTiAl high-entropy solid solution processed by mechanical alloying. *J. Alloys Compd.* **495**(1), 33 (2010).

28. W. Ji, J. Zhang, W. Wang, H. Wang, F. Zhang, Y. Wang, and Z. Fu: Fabrication and properties of TiB2-based cermets by spark plasma sintering with CoCrFeNiTiAl high-entropy alloy as sintering aid. *J. Eur. Ceram. Soc.* **35**(3), 879 (2015).

29. S. Mohanty, N. P. Gurao, and K. Biswas: Sinter ageing of equiatomic Al20Co20Cu20Zn20Ni20 high entropy alloy via mechanical alloying. *Mater. Sci. Eng. A* **617**, 211 (2014).

30. C. D. Gómez-Esparza, F. Baldenebro-López, L. González-Rodelas, J. Baldenebro-López, and R. Martínez-Sánchez: Series of nanocrystalline NiCoAlFe(Cr, Cu, Mo, Ti) high-entropy alloys produced by mechanical alloying. *Mater. Res.* **19**(suppl 1), 39 (2016).

31. F. J. Baldenebro-Lopez, J. M. Herrera-Ramírez, S. P. Arredondo-Rea, C. D. Gómez-Esparza, and R. Martínez-Sánchez: Simultaneous effect of mechanical alloying and arc-melting processes in the microstructure and hardness of an AlCoFeMoNiTi high-entropy alloy. *J. Alloys Compd.* **643**, S250 (2015).

32. H. Khanchandani, P. Sharma, R. Kumar, O. Maulik, and V. Kumar: Effect of sintering on phase evolution in AlMgFeCuCrNi4.75 high entropy alloy. *Adv. Powder Technol.* **27**(1), 289 (2016).

33. O. Maulik, D. Kumar, S. Kumar, D. M. Fabijanic, and V. Kumar: Structural evolution of spark plasma sintered AlFeCuCrMgx (x = 0, 0.5, 1, 1.7) high entropy alloys. *Intermetallics* **77**, 46 (2016).

34. D. Kumar, O. Maulik, S. Kumar, Y. V. S. S. Prasad, and V. Kumar: Phase and thermal study of equiatomic AlCuCrFeMnW high entropy alloy processed via spark plasma sintering. *Mater. Chem. Phys.* **210**, 71 (2018).

35. D. Kumar, O. Maulik, S. Kumar, V. K. Sharma, Y. V. S. S. Prasad, and V. Kumar: Impact of tungsten on phase evolution in nanocrystalline AlCuCrFeMnWx (*x* = 0, 0.05, 0.1 and 0.5 mol) high entropy alloys. *Mater. Res. Express* **4**(11), 114004 (2017).

36. N. T. B. N. Koundinya, C. Sajith Babu, K. Sivaprasad, P. Susila, N. Kishore Babu, and J. Baburao: Phase evolution and thermal analysis of nanocrystalline AlCrCuFeNiZn high entropy alloy produced by mechanical alloying. *J. Mater. Eng. Perform.* **22**(10), 3077 (2013).

37. K. G. Pradeep, N. Wanderka, P. Choi, J. Banhart, B. S. Murty, and D. Raabe: Atomic-scale compositional characterization of a nanocrystalline AlCrCuFeNiZn high-entropy alloy using atom probe tomography. *Acta Mater.* **61**(12), 4696 (2013).

38. N. Kumar, C. S. Tiwary, and K. Biswas: Preparation of nanocrystalline high-entropy alloys via cryomilling of cast ingots. *J. Mater. Sci.* **53**(19), 13411 (2018).

39. C. S. Babu, N. T. B. N. Koundinya, K. Sivaprasad, and J. A. Szpunar: Thermal analysis and nanoindentaion studies on nanocrystalline AlCrNiFeZn high entropy alloy. *Procedia Mater. Sci.* **6**, 641 (2014).

40. S. Varalakshmi, M. Kamaraj, and B. S. Murty: Synthesis and characterization of nanocrystalline AlFeTiCrZnCu high entropy solid solution by mechanical alloying. *J. Alloys Compd.* **460**(1–2), 253 (2008).

41. S. Varalakshmi, G. Appa Rao, M. Kamaraj, and B. S. Murty: Hot consolidation and mechanical properties of nanocrystalline equiatomic AlFeTiCrZnCu high entropy alloy after mechanical alloying. *J. Mater. Sci.* **45**(19), 5158 (2010).

42. W. Zhang, R. Tang, Z. B. Yang, C. H. Liu, H. Chang, J. J. Yang, J. L. Liao, Y. Y. Yang, and N. Liu: Preparation, structure, and properties of an AlCrMoNbZr high-entropy alloy coating for accident-tolerant fuel cladding. *Surf. Coat. Technol.* **347**, 13 (2018).

43. R. Zheng, J. Chen, W. Xiao, and C. Ma: Microstructure and tensile properties of nanocrystalline (FeNiCoCu)1−xTixAlx high entropy alloys processed by high pressure torsion. *Intermetallics* **74**, 38 (2016).

44. R. Sriharitha, B. S. Murty, and R. S. Kottada: Phase formation in mechanically alloyed AlxCoCrCuFeNi (x = 0.45, 1, 2.5, 5 mol) high entropy alloys. *Intermetallics* **32**, 119 (2013).

45. W.-R. Wang, W.-L. Wang, S.-C. Wang, Y.-C. Tsai, C.-H. Lai, and J.-W. Yeh: Effects of Al addition on the microstructure and mechanical property of AlxCoCrFeNi high-entropy alloys. *Intermetallics* **26**, 44 (2012).

46. T.-K. Chen, M.-S. Wong, T.-T. Shun, and J.-W. Yeh: Nanostructured nitride films of multi-element high-entropy alloys by reactive DC sputtering. *Surf. Coat. Technol.* **200**(5–6), 1361 (2005).

47. H. Cheng, X. Liu, Q. Tang, W. Wang, X. Yan, and P. Dai: Microstructure and mechanical properties of FeCoCrNiMnAlx high-entropy alloys prepared by mechanical alloying and hot-pressed sintering. *J. Alloys Compd.* **775**, 742 (2019).

48. P. Wang, X. Cheng, H. Cai, Y. Xue, and Y. Zhang: Influence of increasing Al concentration on phase, microstructure and mechanical behaviors of Ni1.5CoFeCu1−xAlxV0.5 high entropy alloys. *Mater. Sci. Eng. A* **708**, 523 (2017).

49. S. Yoshida, T. Ikeuchi, T. Bhattacharjee, Y. Bai, A. Shibata, and N. Tsuji: Effect of elemental combination on friction stress and Hall-Petch relationship in face-centered cubic high / medium entropy alloys. *Acta Mater.* **171**, 201 (2019).

50. Z. Fu, W. Chen, H. Xiao, L. Zhou, D. Zhu, and S. Yang: Fabrication and properties of nanocrystalline Co0.5FeNiCrTi0.5 high entropy alloy by MA–SPS technique. *Mater. Des.* **44**, 535 (2013).

51. P. Wang, H. Cai, and X. Cheng: Effect of Ni/Cr ratio on phase, microstructure and mechanical properties of NixCoCuFeCr2−x (x = 1.0, 1.2, 1.5, 1.8 mol) high entropy alloys. *J. Alloys Compd.* **662**, 20 (2016).

52. P. F. Yu, L. J. Zhang, H. Cheng, H. Zhang, M. Z. Ma, Y. C. Li, G. Li, P. K. Liaw, and R. P. Liu: The high-entropy alloys with high hardness and soft magnetic property prepared by mechanical alloying and high-pressure sintering. *Intermetallics* **70**, 82 (2016).

53. T. Nagase, P. D. Rack, J. H. Noh, and T. Egami: In-situ TEM observation of structural changes in nano-crystalline CoCrCuFeNi multicomponent high-entropy alloy (HEA) under fast electron irradiation by high voltage electron microscopy (HVEM). *Intermetallics* **59**, 32 (2015).

54. É. Fazakas, B. Varga, and L. K. Varga: Processing and properties of nanocrystalline CoCrFeNiCuAlTiXVMo ( X = Zn , Mn ) high entropy alloys by mechanical alloying. *ISRN Mech. Eng.* **2013**, 1 (2013).

55. Q. Yang, Y. Tang, Y. Wen, Q. Zhang, D. Deng, and X. Nai: Microstructures and properties of CoCrCuFeNiMox high-entropy alloys fabricated by mechanical alloying and spark plasma sintering. *Powder Metall.* **61**(2), 115 (2018).

56. B. R. Braeckman and D. Depla: Structure formation and properties of sputter deposited NbxCoCrCuFeNi high entropy alloy thin films. *J. Alloys Compd.* **646**, 810 (2015).

57. B. Niu, W. Ji, N. Li, F. Zhang, and Y. Wu: Alloying and thermal behaviour of CoCrFeNiMn0.5Ti0.5 high-entropy alloy synthesised by mechanical alloying. *Mater. Sci. Technol.* **32**(1), 94 (2016).

58. A. Heczel, M. Kawasaki, J. L. Lábár, J. Jang, T. G. Langdon, and J. Gubicza: Defect structure and hardness in nanocrystalline CoCrFeMnNi high-entropy alloy processed by high-pressure torsion. *J. Alloys Compd.* **711**, 143 (2017).

59. S.-H. Joo, H. Kato, M. J. Jang, J. Moon, E. B. Kim, S.-J. Hong, and H. S. Kim: Structure and properties of ultrafine-grained CoCrFeMnNi high-entropy alloys produced by mechanical alloying and spark plasma sintering. *J. Alloys Compd.* **698**, 591 (2017).

60. D.-H. Lee, I.-C. Choi, G. Yang, Z. Lu, M. Kawasaki, U. Ramamurty, R. Schwaiger, and J. Jang: Activation energy for plastic flow in nanocrystalline CoCrFeMnNi high-entropy alloy: A high temperature nanoindentation study. *Scr. Mater.* **156**, 129 (2018).

61. D.-H. Lee, J.-A. Lee, Y. Zhao, Z. Lu, J.-Y. Suh, J.-Y. Kim, U. Ramamurty, M. Kawasaki, T. G. Langdon, and J. Jang: Annealing effect on plastic flow in nanocrystalline CoCrFeMnNi high-entropy alloy: A nanomechanical analysis. *Acta Mater.* **140**, 443 (2017).

62. D.-H. Lee, M.-Y. Seok, Y. Zhao, I.-C. Choi, J. He, Z. Lu, J.-Y. Suh, U. Ramamurty, M. Kawasaki, T. G. Langdon, and J. Jang: Spherical nanoindentation creep behavior of nanocrystalline and coarse-grained CoCrFeMnNi high-entropy alloys. *Acta Mater.* **109**, 314 (2016).

63. Ł. Rogal, D. Kalita, A. Tarasek, P. Bobrowski, and F. Czerwinski: Effect of SiC nano-particles on microstructure and mechanical properties of the CoCrFeMnNi high entropy alloy. *J. Alloys Compd.* **708**, 344 (2017).

64. B. Schuh, F. Mendez-Martin, B. Völker, E. P. George, H. Clemens, R. Pippan, and A. Hohenwarter: Mechanical properties, microstructure and thermal stability of a nanocrystalline CoCrFeMnNi high-entropy alloy after severe plastic deformation. *Acta Mater.* **96**, 258 (2015).

65. A. Kilmametov, R. Kulagin, A. Mazilkin, S. Seils, T. Boll, M. Heilmaier, and H. Hahn: High-pressure torsion driven mechanical alloying of CoCrFeMnNi high entropy alloy. *Scr. Mater.* **158**, 29 (2019).

66. W. Ji, W. Wang, H. Wang, J. Zhang, Y. Wang, F. Zhang, and Z. Fu: Alloying behavior and novel properties of CoCrFeNiMn high-entropy alloy fabricated by mechanical alloying and spark plasma sintering. *Intermetallics* **56**, 24 (2015).

67. D.-H. Lee, I.-C. Choi, M.-Y. Seok, J. He, Z. Lu, J.-Y. Suh, M. Kawasaki, T. G. Langdon, and J. Jang: Nanomechanical behavior and structural stability of a nanocrystalline CoCrFeNiMn high-entropy alloy processed by high-pressure torsion. *J. Mater. Res.* **30**(18), 2804 (2015).

68. H. Shahmir, J. He, Z. Lu, M. Kawasaki, and T. G. Langdon: Effect of annealing on mechanical properties of a nanocrystalline CoCrFeNiMn high-entropy alloy processed by high-pressure torsion. *Mater. Sci. Eng. A* **676**, 294 (2016).

69. H. Shahmir, J. He, Z. Lu, M. Kawasaki, and T. G. Langdon: Evidence for superplasticity in a CoCrFeNiMn high-entropy alloy processed by high-pressure torsion. *Mater. Sci. Eng. A* **685**, 342 (2017).

70. H. Shahmir, T. Mousavi, J. He, Z. Lu, M. Kawasaki, and T. G. Langdon: Microstructure and properties of a CoCrFeNiMn high-entropy alloy processed by equal-channel angular pressing. *Mater. Sci. Eng. A* **705**, 411 (2017).

71. N. D. Stepanov, D. G. Shaysultanov, M. S. Ozerov, S. V. Zherebtsov, and G. A. Salishchev: Second phase formation in the CoCrFeNiMn high entropy alloy after recrystallization annealing. *Mater. Lett.* **185**, 1 (2016).

72. Y. Xie, H. Cheng, Q. Tang, W. Chen, W. Chen, and P. Dai: Effects of N addition on microstructure and mechanical properties of CoCrFeNiMn high entropy alloy produced by mechanical alloying and vacuum hot pressing sintering. *Intermetallics* **93**, 228 (2018).

73. C. Dang, J. U. Surjadi, L. Gao, and Y. Lu: Mechanical properties of nanostructured CoCrFeNiMn high-entropy alloy (HEA) coating. *Front. Mater.* **5** (2018).

74. Q. Lin, X. An, H. Liu, Q. Tang, P. Dai, and X. Liao: In-situ high-resolution transmission electron microscopy investigation of grain boundary dislocation activities in a nanocrystalline CrMnFeCoNi high-entropy alloy. *J. Alloys Compd.* **709**, 802 (2017).

75. V. Maier-Kiener, B. Schuh, E. P. George, H. Clemens, and A. Hohenwarter: Nanoindentation testing as a powerful screening tool for assessing phase stability of nanocrystalline high-entropy alloys. *Mater. Des.* **115**, 479 (2017).

76. V. Maier-Kiener, B. Schuh, E. P. George, H. Clemens, and A. Hohenwarter: Insights into the deformation behavior of the CrMnFeCoNi high-entropy alloy revealed by elevated temperature nanoindentation. *J. Mater. Res.* **32**(14), 2658 (2017).

77. Y. J. Li, A. Kostka, A. Savan, and A. Ludwig: Atomic-scale investigation of fast oxidation kinetics of nanocrystalline CrMnFeCoNi thin films. *J. Alloys Compd.* **766**, 1080 (2018).

78. J. U. Surjadi, L. Gao, K. Cao, R. Fan, and Y. Lu: Mechanical enhancement of core-shell microlattices through high-entropy alloy coating. *Sci. Rep.* **8**(1) (2018).

79. H. Shahmir, M. Nili-Ahmadabadi, A. Shafie, and T. Langdon: Hardening and thermal stability of a nanocrystalline CoCrFeNiMnTi0.1 high-entropy alloy processed by high-pressure torsion. *IOP Conf. Ser. Mater. Sci. Eng.* **194**, 012017 (2017).

80. W. Huo, X. Liu, S. Tan, F. Fang, Z. Xie, J. Shang, and J. Jiang: Ultrahigh hardness and high electrical resistivity in nano-twinned, nanocrystalline high-entropy alloy films. *Appl. Surf. Sci.* **439**, 222 (2018).

81. S. Praveen, J. Basu, S. Kashyap, and R. S. Kottada: Exceptional resistance to grain growth in nanocrystalline CoCrFeNi high entropy alloy at high homologous temperatures. *J. Alloys Compd.* **662**, 361 (2016).

82. W. Wu, M. Song, S. Ni, J. Wang, Y. Liu, B. Liu, and X. Liao: Dual mechanisms of grain refinement in a FeCoCrNi high-entropy alloy processed by high-pressure torsion. *Sci. Rep.* **7**(1) (2017).

83. R. B. Mane and B. B. Panigrahi: Comparative study on sintering kinetics of as-milled and annealed CoCrFeNi high entropy alloy powders. *Mater. Chem. Phys.* **210**, 49 (2018).

84. C. Shang, E. Axinte, J. Sun, X. Li, P. Li, J. Du, P. Qiao, and Y. Wang: CoCrFeNi(W1−xMox) high-entropy alloy coatings with excellent mechanical properties and corrosion resistance prepared by mechanical alloying and hot pressing sintering. *Mater. Des.* **117**, 193 (2017).

85. N. Zhou, T. Hu, J. Huang, and J. Luo: Stabilization of nanocrystalline alloys at high temperatures via utilizing high-entropy grain boundary complexions. *Scr. Mater.* **124**, 160 (2016).

86. S. Yoshida, T. Bhattacharjee, Y. Bai, and N. Tsuji: Friction stress and Hall-Petch relationship in CoCrNi equi-atomic medium entropy alloy processed by severe plastic deformation and subsequent annealing. *Scr. Mater.* **134**, 33 (2017).

87. S. Praveen, J. W. Bae, P. Asghari-Rad, J. M. Park, and H. S. Kim: Ultra-high tensile strength nanocrystalline CoCrNi equi-atomic medium entropy alloy processed by high-pressure torsion. *Mater. Sci. Eng. A* **735**, 394 (2018).

88. S. Varalakshmi, M. Kamaraj, and B. S. Murty: Formation and stability of equiatomic and nonequiatomic nanocrystalline CuNiCoZnAlTi high-entropy alloys by mechanical alloying. *Metall. Mater. Trans. A* **41**(10), 2703 (2010).

89. S. Varalakshmi, M. Kamaraj, and B. S. Murty: Processing and properties of nanocrystalline CuNiCoZnAlTi high entropy alloys by mechanical alloying. *Mater. Sci. Eng. A* **527**(4–5), 1027 (2010).

90. S. Praveen, B. S. Murty, and R. S. Kottada: Phase evolution and densification behavior of nanocrystalline multicomponent high entropy alloys during spark plasma sintering. *JOM* **65**(12), 1797 (2013).

91. S. Kuramoto, T. Furuta, N. Nagasako, and Z. Horita: Lattice softening for producing ultrahigh strength of iron base nanocrystalline alloy. *Appl. Phys. Lett.* **95**(21), 211901 (2009).

92. A. J. Zaddach, C. Niu, C. C. Koch, and D. L. Irving: Mechanical properties and stacking fault energies of NiFeCrCoMn high-entropy alloy. *JOM* **65**(12), 1780 (2013).

93. S. Mridha, S. Samal, P. Y. Khan, K. Biswas, and Govind: Processing and consolidation of nanocrystalline Cu-Zn-Ti-Fe-Cr high-entropy alloys via mechanical alloying. *Metall. Mater. Trans. A* **44**(10), 4532 (2013).

94. H. Shahmir, E. Tabachnikova, A. Podolskiy, M. Tikhonovsky, and T. G. Langdon: Effect of carbon content and annealing on structure and hardness of CrFe2NiMnV0.25 high-entropy alloys processed by high-pressure torsion. *J. Mater. Sci.* **53**(16), 11813 (2018).

95. M. Vaidya, S. Armugam, S. Kashyap, and B. S. Murty: Amorphization in equiatomic high entropy alloys. *J. Non-Cryst. Solids* **413**, 8 (2015).

96. A. Dwivedi, C. C. Koch, and K. V. Rajulapati: On the single phase fcc solid solution in nanocrystalline Cr-Nb-Ti-V-Zn high-entropy alloy. *Mater. Lett.* **183**, 44 (2016).

97. T. P. Yadav, S. Mukhopadhyay, S. S. Mishra, N. K. Mukhopadhyay, and O. N. Srivastava: Synthesis of a single phase of high-entropy Laves intermetallics in the Ti–Zr–V–Cr–Ni equiatomic alloy. *Philos. Mag. Lett.* **97**(12), 494 (2017).

98. Y.-L. Chen, Y.-H. Hu, C.-W. Tsai, C.-A. Hsieh, S.-W. Kao, J.-W. Yeh, T.-S. Chin, and S.-K. Chen: Alloying behavior of binary to octonary alloys based on Cu–Ni–Al–Co–Cr–Fe–Ti–Mo during mechanical alloying. *J. Alloys Compd.* **477**(1–2), 696 (2009).

99. L. Zhang, Y. Zhou, X. Jin, X. Du, and B. Li: The microstructure and high-temperature properties of novel nano precipitation-hardened face centered cubic high-entropy superalloys. *Scr. Mater.* **146**, 226 (2018).

100. B. Schuh, B. Völker, V. Maier-Kiener, J. Todt, J. Li, and A. Hohenwarter: Phase decomposition of a single-phase AlTiVNb high-entropy alloy after severe plastic deformation and annealing: phase decomposition of a single-phase AlTiVNb high-entropy alloy. *Adv. Eng. Mater.* **19**(4), 1600674 (2017).

101. N. D. Stepanov, N. Yu. Yurchenko, S. V. Zherebtsov, M. A. Tikhonovsky, and G. A. Salishchev: Aging behavior of the HfNbTaTiZr high entropy alloy. *Mater. Lett.* **211**, 87 (2018).

102. X. B. Feng, J. Y. Zhang, Y. Q. Wang, Z. Q. Hou, K. Wu, G. Liu, and J. Sun: Size effects on the mechanical properties of nanocrystalline NbMoTaW refractory high entropy alloy thin films. *Int. J. Plast.* **95**, 264 (2017).

103. H. Kim, S. Nam, A. Roh, M. Son, M.-H. Ham, J.-H. Kim, and H. Choi: Mechanical and electrical properties of NbMoTaW refractory high-entropy alloy thin films. *Int. J. Refract. Met. Hard Mater.* **80**, 286 (2019).

104. Y. Long, K. Su, J. Zhang, X. Liang, H. Peng, and X. Li: Enhanced strength of a mechanical alloyed NbMoTaWVTi refractory high entropy alloy. *Materials* **11**(5), 669 (2018).

105. Y. Zou, J. M. Wheeler, H. Ma, P. Okle, and R. Spolenak: Nanocrystalline high-entropy alloys: a new paradigm in high-temperature strength and stability. *Nano Lett.* **17**(3), 1569 (2017).

106. S. A. Firstov, V. F. Gorban’, N. I. Danilenko, M. V. Karpets, A. A. Andreev, and E. S. Makarenko: Thermal stability of superhard nitride coatings from high-entropy multicomponent Ti–V–Zr–Nb–Hf alloy. *Powder Metall. Met. Ceram.* **52**(9–10), 560 (2014).

107. O. V. Sobol’, A. A. Andreev, V. F. Gorban’, N. A. Krapivka, V. A. Stolbovoi, I. V. Serdyuk, and V. E. Fil’chikov: Reproducibility of the single-phase structural state of the multielement high-entropy Ti-V-Zr-Nb-Hf system and related superhard nitrides formed by the vacuum-arc method. *Tech. Phys. Lett.* **38**(7), 616 (2012).

108. B. Schuh, B. Völker, J. Todt, N. Schell, L. Perrière, J. Li, J. P. Couzinié, and A. Hohenwarter: Thermodynamic instability of a nanocrystalline, single-phase TiZrNbHfTa alloy and its impact on the mechanical properties. *Acta Mater.* **142**, 201 (2018).

109. S. Fang, W. Chen, and Z. Fu: Microstructure and mechanical properties of twinned Al0.5CrFeNiCo0.3C0.2 high entropy alloy processed by mechanical alloying and spark plasma sintering. *Mater. Des. 1980-2015* **54**, 973 (2014).

110. P. Sathiyamoorthi, J. Basu, S. Kashyap, K. G. Pradeep, and R. S. Kottada: Thermal stability and grain boundary strengthening in ultrafine-grained CoCrFeNi high entropy alloy composite. *Mater. Des.* **134**, 426 (2017).

111. A. Sarkar, R. Djenadic, N. J. Usharani, K. P. Sanghvi, V. S. K. Chakravadhanula, A. S. Gandhi, H. Hahn, and S. S. Bhattacharya: Nanocrystalline multicomponent entropy stabilized transition metal oxides. *J. Eur. Ceram. Soc.* **37**(2), 747 (2017).

112. H. Hadraba, Z. Chlup, A. Dlouhy, F. Dobes, P. Roupcova, M. Vilemova, and J. Matejicek: Oxide dispersion strengthened CoCrFeNiMn high-entropy alloy. *Mater. Sci. Eng. A* **689**, 252 (2017).

113. T. K. Chen, T. T. Shun, J. W. Yeh, and M. S. Wong: Nanostructured nitride films of multi-element high-entropy alloys by reactive DC sputtering. *Surf. Coat. Technol.* **188–189**, 193 (2004).

114. T. Lu, S. Scudino, W. Chen, P. Wang, D. Li, M. Mao, L. Kang, Y. Liu, and Z. Fu: The influence of nanocrystalline CoNiFeAl0.4Ti0.6Cr0.5 high-entropy alloy particles addition on microstructure and mechanical properties of SiCp/7075Al composites. *Mater. Sci. Eng. A* **726**, 126 (2018).

115. Ł. Rogal, D. Kalita, and L. Litynska-Dobrzynska: CoCrFeMnNi high entropy alloy matrix nanocomposite with addition of Al2O3. *Intermetallics* **86**, 104 (2017).

116. A. D. Dupuy, X. Wang, and J. M. Schoenung: Entropic phase transformation in nanocrystalline high entropy oxides. *Mater. Res. Lett.* **7**(2), 60 (2019).

117. K. M. Youssef, A. J. Zaddach, C. Niu, D. L. Irving, and C. C. Koch: A novel low-density, high-hardness, high-entropy alloy with close-packed single-phase nanocrystalline structures. *Mater. Res. Lett.* **3**(2), 95 (2015).