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Editorial

Design of High-Entropy Alloys

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1. Introduction

High-entropy alloys (HEAs) and related complex, concentrated alloys (CCAs) have resulted from new approaches to alloy design, which emerged 18 years ago [1,2]. These approaches change the established paradigm of alloy development when small amounts of alloying elements add to a single principle element. Instead, HEAs/CCAs suggest the usage of multiple (at least 3–5) principle elements taken in close to equiatomic proportions with the possible presence of minor components. Due to such a complex chemical composition, the alloys can have unique structures and properties not readily available in conventional alloys [3]. For example, some HEAs/CCAs demonstrate remarkable strength at elevated temperatures, which makes them promising candidates for Ni-based superalloy replacement [4,5] or an unprecedented combination of strength, ductility, and toughness under cryogenic conditions [6]. HEAs/CCAs are often considered promising structural materials; however, they can also offer interesting functional properties [7,8]. Specifically, high-entropy ceramics and coatings have recently emerged and already demonstrated remarkable properties [9–11].

With the above-mentioned scope of the field, the new Special Issue on the Design of High-entropy Alloys was opened for submissions on a variety of different topics. Works on fundamental aspects such as phase formation and transformations, strengthening and deformation mechanisms, as well as diffusion were equally expected with more application-driven research focused on properties. Investigations of the functional properties of HEAs and non-metallic high-entropy materials were also highly anticipated.

As a result, a total of seven papers were published. A brief overview of the published papers is given below.

2. Contributions

The published papers mark several trends in the design of HEAs and associated materials. First is the growing attention to intermetallic phases. HEAs research has been focused on searching for the random solid solution phases in alloys since 2004. However, for almost a decade, there has been a growing understanding that ordered phases in HEAs are needed to ensure reasonable strength. For instance, new AlxCo50−xCu50−xMnx (x = 2.5, 10, and 15 at%) immiscible medium-entropy alloys (IMMEAs) were designed and examined [12]. The alloys were based on Co-Cu binary system, while Al was added as a strong B2 phase former, and Mn provided additional solid solution strengthening. The alloys showed phase separation into two face-centered cubic (FCC) phases due to the miscibility gap of the cobalt-copper binary system with the formation of the CoAl-rich B2 phase. The combination of the hard B2 phase and two softer FCC phases contribute to a good combination of strength and ductility.

Single-phase high-entropy intermetallics (HEICs) are also of interest for various structural and functional applications [13]. In [14], multicomponent alloys with a B2-ordered single phase were designed and fabricated by melting route for the first time. The equiatomic substitution of transition metal elements in the Ni sublattice of binary AlNi was used to produce Al(CoNi), Al(FeNi), Al(CoFe), Al(CoFeNi), Al(CoFeMnNi), and Al(CoCuFeMnNi) multicomponent alloys. Experimental data and the CALculation of PHAse Diagrams (CALPHAD) approach confirmed the B2 ordering in the alloys.

The mechanical behavior of HEAs attracts considerable attention, yet the controlling deformation mechanisms are not always clear. In the following paper [15], the mechanical behavior [001]- and $[\bar{1}44]$-oriented single crystals of $Al_{0.3}CoCrFeNi$ alloy was explored within a wide temperature range of 77–973 K under tension. It was found that a high-stress level at the yield point $\sigma_{0.1} \approx G/100$–$G/160$ (G is the shear modulus) was reached due to the formation of nanotwins, multipoles and dislocations under plastic deformation at 77 K and the subsequent precipitation of ordered $L1_2$ and B2 particles.

Technological aspects of HEAs behavior were addressed in [16], where the structure and properties of $Fe_{49}Mn_{30}Cr_{10}Co_{10}C_1$ TRIP high-entropy alloy friction stir welds were examined. Friction stir welding resulted in a considerable refinement of the microstructure of the stir zone. Post-welding tests showed a considerable increase in the strength and microhardness of the welds.

The growing maturity of the high-entropy materials field is well reflected in the fact that three review papers were published in this Special Issue. The first one [17] summarizes the recent data on an AlCoCrFeNi alloy. The effect of the manufacturing methods, varying component content, and heat treatment on the properties of the AlCoCrFeNi high-entropy alloy is analyzed in detail.

The two other reviews are focused on various coatings. The first one is devoted to nitride coatings [18]. High-entropy nitride (HEN) coatings have a single-phase structure and properties that significantly exceed those of simpler nitride systems. These properties include high hardness, wear resistance, oxidation resistance and thermal stability. The review compares the methods for obtaining HEN coatings, describes their structural features and analyzes the main properties, such as hardness, wear resistance, and oxidation resistance, in order to gain insight into the influence of the number of elements and their role in the composition of coatings. The second review is focused on the use of magnetron sputtering for the preparation of high-entropy coatings [19]. Magnetron sputtering is regarded as one of the most efficient methods for the deposition of HEA-based thin films. Metallic- and nitride-based HEA coatings can be easily deposited by introducing N_2 gas along with Ar in the reaction chamber. The effect of different deposition parameters such as target composition, bias voltage, sputtering power, and, notably, gas flow ratio on the thin film's morphology and mechanical properties is analyzed.

3. Conclusions and Outlook

A total of seven papers were published in the new Special Issue on the Design of High-entropy Alloys. Four of them presented original research results, and three of them were reviews. Five papers focused on High-entropy Alloys, and two papers (reviews) focused on High-entropy Coatings. Specific attention to High-entropy Intermetallics must be noted. The papers published in the Special Issue advanced our understanding of composition–structure–properties relationships in HEAs and related materials and contributed to the design of new materials with unprecedented properties for future applications.

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References

1. Yeh, J.-W.; Chen, S.-K.; Lin, S.-J.; Gan, J.-Y.; Chin, T.-S.; Shun, T.-T.; Tsau, C.-H.; Chang, S.-Y. Nanostructured high-entropy alloys with multiple principal elements: Novel alloy design concepts and outcomes. *Adv. Eng. Mater.* **2004**, *6*, 299–303. [CrossRef]
2. Zhang, Y. *High-Entropy Materials*; Springer: Singapore, 2019; pp. 1–152.
3. Miracle, D.B.; Senkov, O.N. A critical review of high entropy alloys and related concepts. *Acta Mater.* **2017**, *122*, 448–511. [CrossRef]
4. Senkov, O.N.; Miracle, D.B.; Chaput, K.J.; Couzinie, J.-P. Development and exploration of refractory high entropy alloys—A review. *J. Mater. Res.* **2018**, *33*, 3092–3128. [CrossRef]
5. Yurchenko, N.; Panina, E.; Rogal, Ł.; Shekhawat, L.; Zherebtsov, S.; Stepanov, N. Unique precipitations in a novel refractory Nb-Mo-Ti-Co high-entropy superalloy. *Mater. Res. Lett.* **2022**, *10*, 78–87. [CrossRef]
6. Gludovatz, B.; Hohenwarter, A.; Catoor, D.; Chang, E.H.; George, E.P.; Ritchie, R.O. A fracture-resistant high-entropy alloy for cryogenic applications. *Science* **2014**, *345*, 1153–1158. [CrossRef] [PubMed]
7. Han, L.; Rao, Z.; Souza Filho, I.R.; Maccari, F.; Wei, Y.; Wu, G.; Ahmadian, A.; Zhou, X.; Gutfleisch, O.; Ponge, D.; et al. Ultrastrong and Ductile Soft Magnetic High-Entropy Alloys via Coherent Ordered Nanoprecipitates. *Adv. Mater.* **2021**, *33*, 2102139. [CrossRef] [PubMed]
8. Ma, Y.; Ma, Y.; Wang, Q.; Schweidler, S.; Botros, M.; Fu, T.; Hahn, H.; Brezesinski, T.; Breitung, B. High-entropy energy materials: Challenges and new opportunities. *Energy Environ. Sci.* **2021**, *14*, 2883–2905. [CrossRef]
9. Oses, C.; Toher, C.; Curtarolo, S. High-entropy ceramics. *Nat. Rev. Mater.* **2020**, *5*, 295–309. [CrossRef]
10. Pogrebnjak, A.D.; Bagdasaryan, A.A.; Yakushchenko, I.V.; Beresnev, V.M. The structure and properties of high-entropy alloys and nitride coatings based on them. *Russ. Chem. Rev.* **2014**, *83*, 1027–1061. [CrossRef]
11. Moskovskikh, D.; Vorotilo, S.; Buinevich, V.; Sedegov, A.; Kuskov, K.; Khort, A.; Shuck, C.; Zhukovskyi, M.; Mukasyan, A. Extremely hard and tough high entropy nitride ceramics. *Sci. Rep.* **2020**, *10*, 1–8. [CrossRef] [PubMed]
12. Son, S.; Moon, J.; Kwon, H.; Asghari Rad, P.; Kato, H.; Kim, H.S. Novel Co-Cu-Based Immiscible Medium-Entropy Alloys with Promising Mechanical Properties. *Metals* **2021**, *11*, 238. [CrossRef]
13. Yao, K.; Liu, L.; Ren, J.; Guo, Y.; Liu, Y.; Cao, Y.; Feng, R.; Wu, F.; Qi, J.; Luo, J.; et al. High-entropy intermetallic compound with ultra-high strength and thermal stability. *Scr. Mater.* **2021**, *194*, 113674. [CrossRef]
14. Mohan Muralikrishna, G.; Carmel Mary Esther, A.; Guruvidyathri, K.; Watermeyer, P.; Liebscher, C.H.; Kulkarni, K.N.; Wilde, G.; Divinski, S.V.; Murty, B.S. Novel Multicomponent B2-Ordered Aluminides: Compositional Design, Synthesis, Characterization, and Thermal Stability. *Metals* **2020**, *10*, 1411. [CrossRef]
15. Kireeva, I.V.; Chumlyakov, Y.I.; Pobedennaya, Z.V.; Vyrodova, A.V.; Saraeva, A.A. High-Strength Behavior of the Al0.3CoCrFeNi High-Entropy Alloy Single Crystals. *Metals* **2020**, *10*, 1149. [CrossRef]
16. Shaysultanov, D.; Raimov, K.; Stepanov, N.; Zherebtsov, S. Friction Stir Welding of a TRIP Fe49Mn30Cr10Co10C1 High Entropy Alloy. *Metals* **2020**, *11*, 66. [CrossRef]
17. Tokarewicz, M.; Grądzka-Dahlke, M. Review of Recent Research on AlCoCrFeNi High-Entropy Alloy. *Metals* **2021**, *11*, 1302. [CrossRef]
18. Novikov, V.; Stepanov, N.; Zherebtsov, S.; Salishchev, G. Structure and Properties of High-Entropy Nitride Coatings. *Metals* **2022**, *12*, 847. [CrossRef]
19. Padamata, S.K.; Yasinskiy, A.K.; Yanov, V.; Saevarsdottir, G. Magnetron Sputtering High-Entropy Alloy Coatings: A Mini-Review. *Metals* **2022**, *12*, 319. [CrossRef]