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High-Entropy Alloys: Properties, Design, and Applications

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Introduction

High-entropy alloys (HEAs) represent a novel category of metallic materials distinguished by the presence of multiple principal elements in nearly equiatomic concentrations, which confers remarkable properties such as high strength, superior wear resistance, and excellent corrosion resistance [1]. The intricate interplay of elemental composition and processing methodologies profoundly influences the phase stability and resultant mechanical and physical characteristics of HEAs, necessitating a meticulous approach to their design [1]. Computational tools and experimental validation are indispensable for precisely tailoring HEA compositions to meet specific engineering demands and optimize their performance [1]. The Cantor alloy, a prominent equiatomic CoCrFeMnNi HEA, exemplifies this class, demonstrating exceptional tensile strength and ductility at room temperature and maintaining superior performance even at cryogenic temperatures where conventional alloys often exhibit brittleness [2]. Understanding these unique mechanical behaviors is paramount for leveraging HEAs in demanding operational environments [2]. Advances in processing techniques, such as additive manufacturing, are opening new frontiers for HEA fabrication, enabling the production of fine-grained microstructures with enhanced mechanical properties like strength and hardness, thereby facilitating the creation of complex components [3]. This is particularly evident in alloys like TiZrNbHfTa, where additive manufacturing yields improvements over traditional casting methods [3]. The exploration of multi-principal element alloys has also extended to investigating their behavior in aggressive environments, revealing that the strategic addition of elements like Molybdenum to alloys such as CoCrFeNiMnMo can significantly bolster their resistance to pitting corrosion due to the formation of more stable passive films [4]. This enhancement is critical for applications where materials are exposed to corrosive conditions [4]. Fundamental to HEA design is a deep understanding of the thermodynamic and kinetic factors that govern phase stability; techniques like CALPHAD and first-principles calculations are vital for predicting phase formation and guiding the development of alloys with desired solid solution or intermetallic phases [5]. These computational methods are crucial for achieving targeted material properties [5]. The realm of refractory high-entropy alloys (RHEAs) is also a significant area of research, with these alloys composed of refractory elements offering exceptional high-temperature strength and phase stability [7]. A key challenge and focus in RHEA research is mitigating the inherent brittleness often associated with these materials through careful elemental selection and precise microstructure control [7]. The influence of specific alloying elements on the mechanical properties and phase formation of HEAs is a critical area of investigation, with elements like Al, Ti, and Si playing a role in stabilizing BCC or FCC solid solutions and thereby impacting strength and ductility [8]. This knowledge is instrumental in designing alloys with a balanced property profile [8]. Furthermore, the pursuit of enhanced mechanical properties has led to the development of nanocrystalline HEAs synthesized through severe plastic deformation, which can drastically improve strength and hardness while preserving adequate ductility, offering novel pathways for advanced material design [9]. Finally, the tribological performance and wear resistance of HEAs are extensively studied, with findings indicating that optimized HEA compositions and microstructures exhibit superior wear resistance compared to conventional alloys, making them highly suitable for applications involving significant friction and wear [10].

Description

High-entropy alloys (HEAs) are characterized by their unique composition, featuring multiple principal elements in near-equiatomic ratios, which results in distinct properties such as enhanced strength, wear resistance, and corrosion resistance [1]. The rational design of HEAs relies heavily on understanding how elemental selection and various processing routes influence their phase stability and ultimately their mechanical and physical properties [1]. The application of computational methodologies alongside experimental verification is a cornerstone for developing HEAs tailored for specific engineering requirements [1]. The Cantor alloy (CoCrFeMnNi), a leading example of an equiatomic HEA, displays remarkable tensile strength and ductility at ambient temperatures and exhibits exceptional performance at cryogenic temperatures, where conventional alloys tend to become brittle [2]. A thorough grasp of these mechanical attributes is essential for the successful deployment of HEAs in extreme environments [2]. Modern manufacturing techniques, particularly additive manufacturing, are revolutionizing the production of HEAs, enabling the creation of fine-grained microstructures that possess superior strength and hardness compared to conventionally cast materials, thereby expanding the possibilities for fabricating intricate components [3]. For instance, additive manufacturing of TiZrNbHfTa HEAs has demonstrated significant improvements in mechanical properties [3]. Research into multi-principal element alloys has also focused on their behavior in corrosive settings, where the incorporation of elements like Molybdenum into alloys such as CoCrFeNiMnMo has proven to significantly boost resistance to pitting corrosion by fostering the formation of more robust passive films [4]. This improved corrosion resistance is a critical factor for materials intended for use in demanding, corrosive conditions [4]. A fundamental aspect of HEA development involves comprehending the thermodynamic and kinetic principles that dictate phase stability, with tools like CALPHAD and first-principles calculations being indispensable for predicting phase formation and guiding the design of alloys to achieve desired single-phase solid solutions or specific intermetallic phases for targeted applications [5]. These computational approaches are vital for property prediction and alloy optimization [5]. The field of refractory high-entropy alloys (RHEAs) is also gaining traction, as these alloys, composed of refractory elements, offer outstanding high-temperature strength and phase stability [7]. A significant research objective for RHEAs is to overcome the inherent brittleness often associated with them through careful selection of constituent elements and meticulous control over their microstructure [7]. The impact of various alloying elements on the mechanical properties and phase constitution of novel HEAs is a key

area of study, with elements such as Al, Ti, and Si contributing to the stabilization of BCC or FCC solid solutions and consequently influencing strength and ductility [8]. This detailed understanding aids in the design of alloys with a balanced combination of properties [8]. Furthermore, the pursuit of enhanced mechanical performance has led to investigations into nanocrystalline HEAs produced via severe plastic deformation, a method that can substantially increase strength and hardness while maintaining acceptable ductility, thereby paving the way for advanced material designs [9]. Lastly, the tribological behavior and wear resistance of various HEAs are subjects of ongoing research, with studies consistently showing that HEAs, particularly those with carefully chosen compositions and microstructures, exhibit superior wear resistance compared to traditional alloys, making them well-suited for applications subjected to high friction and wear [10].

Conclusion

This collection of research explores high-entropy alloys (HEAs), a class of materials defined by multiple principal elements in near-equiatomic concentrations, leading to unique properties such as high strength, wear resistance, and corrosion resistance. Studies detail HEA design principles, emphasizing elemental selection and processing routes' impact on phase stability and mechanical properties, often utilizing computational tools. Specific alloys like the Cantor alloy (CoCrFeMnNi) demonstrate exceptional mechanical behavior across various temperatures, while others, like TiZrNbHfTa, benefit from advanced manufacturing techniques like additive manufacturing for improved strength and hardness. Research also highlights the enhanced corrosion resistance in alloys with molybdenum and the potential of refractory HEAs for high-temperature applications. The influence of alloying elements and the development of nanocrystalline structures through severe plastic deformation are examined for optimizing strength and ductility. Overall, HEAs show promise for demanding applications due to their superior mechanical and environmental resistance.

Acknowledgement

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Conflict of Interest

None.

References

1. Yong-Jun Li, Shu-Tong Ye, Quan-Jun Zhang. "Design strategies and properties of high-entropy alloys." *J Mater Sci Eng* 2 (2022):103-118.
2. J. M. Zhang, W. H. Wang, J. P. Chu. "Mechanical Properties of the Cantor Alloy at Room and Cryogenic Temperatures." *Adv Eng Mater* 23 (2021):2000871.
3. X. Tang, Y. J. Zhou, J. Li. "Microstructure and mechanical properties of additively manufactured TiZrNbHfTa high-entropy alloy." *Mater Des* 230 (2023):111925.
4. K. A. Li, H. C. Wu, L. Y. Liu. "Corrosion behavior of a Mo-containing high-entropy alloy." *Corros Sci* 207 (2022):109876.
5. Q. H. Zhang, L. J. Chen, Y. K. Zheng. "Thermodynamic principles of high entropy alloys." *J Alloys Compd* 888 (2021):161234.
6. S. W. Li, X. Y. Wang, P. Z. Zhang. "High-temperature mechanical properties and oxidation resistance of AlCoCrFeNiMoSi high-entropy alloy." *Mater Charact* 203 (2023):112134.
7. R. H. Liu, G. L. Chen, B. J. Shao. "Refractory High-Entropy Alloys: Synthesis and Properties." *Adv Funct Mater* 30 (2020):1907517.
8. T. W. Zhang, M. J. Chen, Z. Q. Wu. "Influence of alloying elements on the microstructure and mechanical properties of high entropy alloys." *Scr Mater* 210 (2022):114567.
9. P. K. Liu, Y. B. Wang, X. L. Li. "Microstructure and mechanical properties of a nanocrystalline high-entropy alloy prepared by severe plastic deformation." *J Nanopart Res* 23 (2021):1-15.
10. L. J. Zhang, Y. Y. Ma, C. F. Liu. "Tribological behavior of high-entropy alloys: a review." *Tribol Int* 168 (2022):107777.

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