Surface, Microstructure, andWear Characterization of Annealed Cold-Sprayed HEA Coatings

engineering proceedings

MDPI

Proceeding Paper

Surface, Microstructure, and Wear Characterization of Annealed Cold-Sprayed HEA Coatings †

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† Presented at the 53rd Conference of the Italian Scientific Society of Mechanical Engineering Design (AIAS 2024), Naples, Italy, 4–7 September 2024.

Abstract: Surface coatings are essential for enhancing the mechanical and functional properties of materials. Among these, annealed high-entropy alloy (HEA) coatings have gained attention for improving wear resistance and durability. This study comprehensively analyzes HEA-annealed coatings, focusing on their surface roughness and wear behavior. A systematic and thorough approach is employed to examine the impact of annealing on coating characteristics. The research involves depositing $Al_{0.1–0.5}$ CoCrCuFeNi and MnCoCrCuFeNi coatings using the cold spray (CS) method, followed by a controlled annealing process. Surface roughness is evaluated through profilometry and microscopy techniques to assess modifications due to annealing. Tribological tests are conducted to investigate the wear performance of the coatings, and the findings are correlated with roughness measurements, offering insights into the relationship between surface texture and wear resistance.

Keywords: cold spray (CS); high-entropy alloy (HEA); surface characterization; wear

Academic Editors: Umberto Galietti, Gabriele Arcidiacono, Enrico Armentani, Davide Castagnetti, Vigilio Fontanari, Aurelio Somà and Nicola Bonora

Published: 6 March 2025

Citation: Sheibanian, N.; Sesana, R.; Abyaneh, M.D.; Özbilen, S.; Lupoi, R. Surface, Microstructure, and Wear Characterization of Annealed Cold-Sprayed HEA Coatings. *Eng. Proc.* **2025**, *85*, 35. https://doi.org/10.3390/engproc2025085035

1. Introduction

Advancements in metallurgical science have led to the creation of alloys that exhibit enhanced and more tailored properties than single metals. Traditional alloys are typically composed of a single primary element, which restricts the compositional flexibility of the alloy. A novel alloy concept introduced by J. W. Yeh and B. Cantoris is known as high-entropy alloys (HEAs). These alloys contain a minimum of five principal elements, each present in atomic percentages ranging from 5% to 35%. In contrast, secondary alloying elements constitute less than 5% of the composition [1–11].

Currently, the majority of research focuses on HEAs that incorporate aluminum (Al), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), and nickel (Ni), along with derivatives that involve the addition or substitution of other elements. However, a vast array of alloy compositions remains to be explored. In terms of structural and functional applications, HEAs demonstrate significant potential [1,3].

High mixing entropy is a key factor that drives the formation of solid solutions with simple microstructures, leading to remarkable material properties [1,3]. The high strains and stresses within crystal lattices enhance strength and hardness while minimizing sensitivity to temperature fluctuations [1–3,10,11]. High-entropy alloys (HEAs) stand out for their exceptional characteristics thanks to their carefully balanced chemical composition of multiple primary elements. These alloys deliver outstanding performance, including superior strength and hardness, impressive wear resistance, remarkable stability under high temperatures, and exceptional resistance to corrosion and oxidation. Furthermore, their versatility is evident because HEAs can be produced using existing manufacturing technologies without requiring specialized techniques or facilities, making them a practical choice for various applications. The presence of multiple primary elements in high-entropy alloys (HEAs) leads to "core effects" that significantly influence their microstructural characteristics and exceptional properties. These effects result in high mixing entropy, considerable crystal lattice distortion, sluggish diffusion, and a cocktail effect [1–3,6,7,10,11].

According to reference [1,12], samples of the $Al_{0.5}CoCrCuFeNi$ alloy quenched in water and cold-rolled demonstrated better performance than many conventional alloys, with fatigue strength limits ranging from 540 to 945 MPa. This HEA system is potentially valuable for future applications where fatigue strength is crucial. Additionally, the chemical composition of HEAs plays a vital role in determining their tribological properties. Adding elements such as Al, Fe, and Nb leads to refined grains and the formation of phases with a body-centered cubic (BCC) structure [1,6].

Manganese (Mn) and chromium (Cr) play a significant role in forming hard phases in materials. As the concentrations of carbon (C), nitrogen (N), boron (B), and silicon (Si) increase, various compounds such as carbides, silicates, and boron compounds may form, or a phase transition can occur from face-centered cubic (FCC) to body-centered cubic (BCC) or B2 structures. Heat treatment methods similar to those used for AISI 304 stainless steel can enhance the hardness of molybdenum (Mo) more effectively than for AISI 304 stainless steel itself. In high-entropy alloys (HEAs), wear resistance is influenced by the type of phase in the material. Alloys composed solely of simple and disordered phases ("SDPs") typically exhibit wear resistance that is not superior to conventional alloys with comparable hardness. Conversely, when the prevailing phase is complex and ordered (known as "COPs"), the wear resistance of the alloy can significantly surpass that of conventional alloys with similar hardness levels [1,3,13]. Consequently, one of the primary applications of HEAs is the development of coatings that possess high wear resistance, which can be applied using various deposition techniques. Coatings that incorporate particles of ceramic materials within a metal matrix can enhance the overall hardness of the coating and, as a result, reduce its wear rate [1,2,4,7–9,13–19].

This paper presents a characterization of annealed HEA coatings produced through cold spray technology. It emphasizes detailed surface and microstructural analysis and an evaluation of the coatings' mechanical properties (HV) and wear resistance applied to a magnesium substrate. Additionally, we investigated the formation of two distinct HEAs with the compositions $Al_xCoCrCuFeNi$ and MnCoCrCuFeNi, analyzing their performance at three targeted deposition temperatures: 650 °C, 750 °C, and 850 °C.

2. Experimental Procedure

2.1. Materials and Post-MA+CS Vacuum Annealing

This study utilized several pure elemental powders, including Al, Mn, Co, Cr, Cu, Fe, and Ni, all boasting high purity levels exceeding 99.9%. The mechanical alloying (MA) technique formulated the octonary high-entropy alloys (HEAs) $Al_{0.1–0.5}CoCrCuFeNi$ and MnCoCrCuFeNi. For more details on the processes of mechanical mixing (MM) and mechanical alloying (MA), refer to reference [20]. As detailed in Table 1, calculations were carried out using pure elemental powders of Al, Cu, Co, Cr, Fe, and Ni to attain the targeted compositions of Al $_{0.1–0.5}$ CoCrCuFeNi and MnCoCrCuFeNi. After mixing and homogenizing, the materials underwent MA for 5.5 hours. To avoid contamination from the ambient environment, the MA powders were kept in sealed containers filled with argon gas until they were processed via cold spray (CS). For a more comprehensive discussion on the effects of MA on powders, see reference [20].

Table 1. Composition of HEA powders in nominal units.

Sample Designation	Nominal Chemical Composition						
		Al	Cu	Cr	Co	Fe	Ni
$Al_{0.1}CoCrCuFeNi$	at%	4.22	17.38	21.2	18.67	19.74	18.79
	wt%	1.96	19.61	19.61	19.61	19.61	19.61
$Al_{0.2}CoCrCuFeNi$	at%	8.13	16.65	20.33	17.91	18.95	18.02
	wt%	3.85	19.23	19.23	19.23	19.23	19.23
$Al_{0.5}CoCrCuFeNi$	at%	18.3	14.8	18.09	15.96	16.84	16
	wt%	9.15	18.1	18.1	18.1	18.1	18.1
MnCoCrCuFeNi	at%	-	15.62	16.81	13.6	13.6	16.86
	wt%	-	16.7	16.7	16.7	16.7	16.7

In the cold spray deposition process, a magnesium (Mg) substrate was coated with high-entropy alloys (HEAs) such as Al $_{0.1–0.5}$ CoCrCuFeNi and MnCoCrCuFeNi at different nitrogen gas temperatures: specifically, 650 °C, 750 °C, and 850 °C. For this study, Trinity College in Dublin, Ireland, utilized the cold spray deposition system referenced in [20] and [21]. The MA and CS Al $_{0.5}$ HEA coatings achieved various microstructures and properties by carefully regulating the cold spray process parameters. The cold spray process employed nitrogen at a pressure of 30 bar, utilizing a type NZ1 nozzle with a standoff distance of 47 mm, a powder feed rate of 9%, a nozzle velocity of 15 millimeters per second, a beam distance of 2 millimeters, and four layers of coating applied in a circular configuration. The magnesium substrate plate measured 50 mm by 50 mm, and the powder feedstock for the cold spray consisted of -63 mm fractions of MA Al $_{0.5}$ HEA powder. Additionally, vacuum annealing was performed at 600 °C for one hour under a pressure of 0.05 bar in a batch furnace at the National Heat Treatment Center in Kildare, Ireland. Specific pressures and powder feed rates were selected to prevent nozzle clogging. The cold spray (CS) temperatures were chosen based on the existing literature, which typically employed higher temperature ranges, leading to moderate temperatures to reduce the risk of oxidation in the high-entropy alloy (HEA) powder. The 47 mm standoff distance was selected as it provided the optimal experimental configuration for our cold spray (CS) apparatus, facilitating the best feed rate and achieving an effective buildup rate for regulating coating thickness efficiently. Tables 1 and 2 display the coatings' nominal chemical composition and the sample designations.

Table 2. $Al_{0.1–0.5}CoCrCuFeNi$ and $Al_{0.1}CoCrCuFeNi$ chemical composition samples were prepared by cold spray.

Al0.1CoCrCuFeNi	Cold spray temperature [°C] Denomination	650 A	750 B	850 C
Al0.2CoCrCuFeNi	Cold spray temperature [°C] Denomination	650 D	750 E	850 F
Al0.5CoCrCuFeNi	Cold spray temperature [°C] Denomination	650 G	750 H	850 I
MnCoCrCuFeNi	Cold spray temperature [°C]	650	750	850

2.2. Microstructure Characterization

The sample preparation and microstructural characterization procedures are detailed in Ref. [22]. The HEA coating and Mg substrate were deliberately removed, wholly and partially, to examine their interface from a direct plane-on view. Cross-sectional samples were prepared following standard metallographic techniques and polished using 0.06 mm colloidal silica to evaluate the coating microstructure. An energy-dispersive X-ray spectrometer (EDS) integrated with a scanning electron microscope (SEM) was utilized to analyze the coating elements. Figure 1 presents macro photographs of annealed MA+CS Al $_{0.1–0.5}$ (Mn)CoCrCuFeNi HEA coatings at three different process gas (N2) temperatures: 650 °C, 750 °C, and 850 °C.

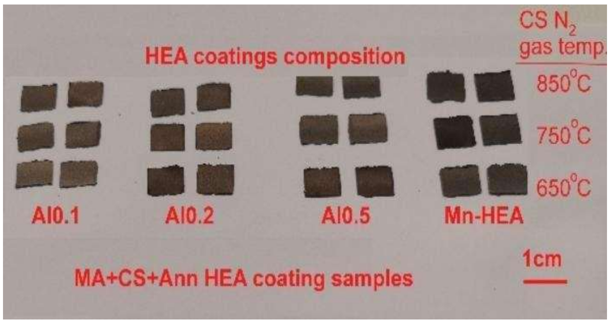

Figure 1. A macrophotograph of MA+CS Al $_{0.1–0.5}$ HEA and Mn-HEA annealed coatings on magnesium.

2.3. Surface Characterization Measurement

The coating's surface roughness was meticulously measured using the cutting-edge RTP80 roughness tester from SM-Instruments, ensuring precise and reliable results. As detailed in Table 3, all specimen coatings thoroughly evaluated the surface roughness, with measurements taken parallel and perpendicular to the deposition direction. Employing a cut-off dimension of 0.25 mm and a measuring length of 1.5 mm, each coating sample was subjected to five rigorous roughness measurements, focusing specifically on three critical parameters: Ra, Rq, and Rt. These parameters, defined by the standard UNI EN ISO 4287 (2011), are key indicators of surface quality, representing the amplitude of roughness that denotes the distance between peaks and valleys. Specifically, Ra indicates the arithmetical mean deviation, providing insight into the average surface irregularities. Rq, the root mean square deviation, offers a robust measure of the average amplitude along the height direction. At the same time, Rt captures the total height of the profile, measuring the distance between its highest peak and lowest valley. This comprehensive analysis ensures a thorough understanding of the coatings' surface characteristics, reinforcing their quality and performance.

Table 3. Detailed specifications for the RTP80 roughness tester.

Characteristic	Description/Value
Measuring range [μm]	±500
Resolution [μm]	0.001
Cut-off length [mm]	0.25
Measuring length [mm]	1.5

2.4. Microhardness Measurement

Innovate Vickers microdurometers were employed to precisely measure the HV30 microhardness profiles of the coating samples, utilizing a controlled preload of 3 N and a standardized indentation time of 15 seconds. To begin with, the annealed coatings were securely bonded to magnesium substrates using a reliable adhesive. The microhardness of each specimen was determined by averaging the results of three carefully executed indentations on the polished-side cross-section, ensuring accurate and consistent data.

2.5. Tribological Analysis

ZCHBWear tests were conducted under ambient conditions using a pin-on-disk tribometer (Anton Paar TriTec, TRB, Turin, Italy) at the Polytechnic University of Turin. A dedicated pin was developed to ensure a tight clamping of the samples during testing. The counterparts used during the wear tests were quenched 100Cr6 steel with a grinding surface. Figure 2 illustrates the experimental setup used during the wear tests. Table 4 demonstrates the wear testing parameters.

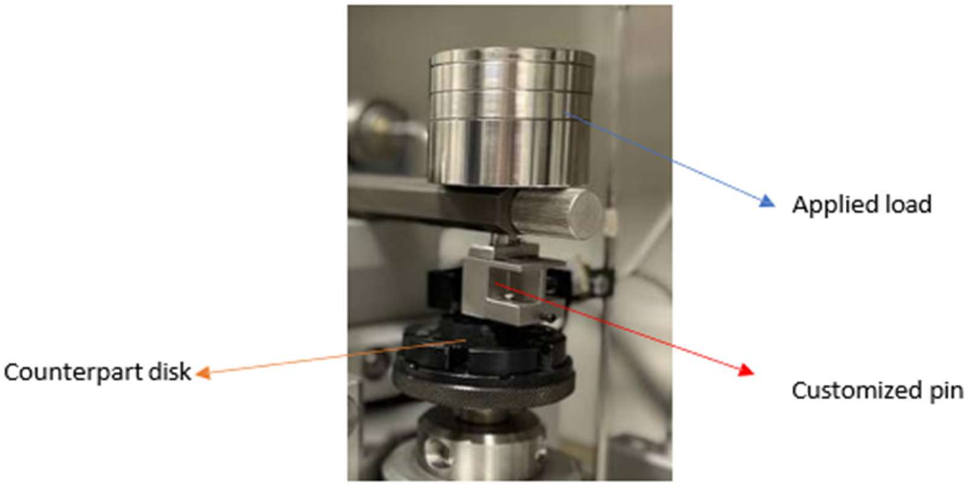

Figure 2. Experimental setup.

Table 4. Parameters wear testing.

Wear Testing Parameters	
Rotational speed [rpm]	250
Normal load [N]	10
Sliding length [m]	200
Linear speed [mm/s]	235.6

3. Results and Discussion

3.1. Microstructural Analysis

Figure 3a illustrates SEM-SE imaging of Al0.5 CS850oC annealed at 600 °C. There is a similar level of roughness on the surface of the coating as in the MA+CS sample. According to [22], the porosity level is very low compared to the MA+CS sample. The surface roughness at the interface between the HEA coating and the customized pin counterpart disk magnesium substrate applied to the customized load indicates good bonding and adhesion. Figure 3b shows the same results for the 600 °C-annealed Mn-HEA CS850 °C sample. The top surface roughness is also similar to that of the MA+CS counterpart. Porosity levels are also very low, interfaces are rough, and the first direct and plane-on surface imaging (viewing) of the interface following mechanical removal of the Mg substrate from the HEA coating following annealing processes indicates the roughness of the interface that is responsible for its excellent bonding with the Mg substrate by the HEA coating.

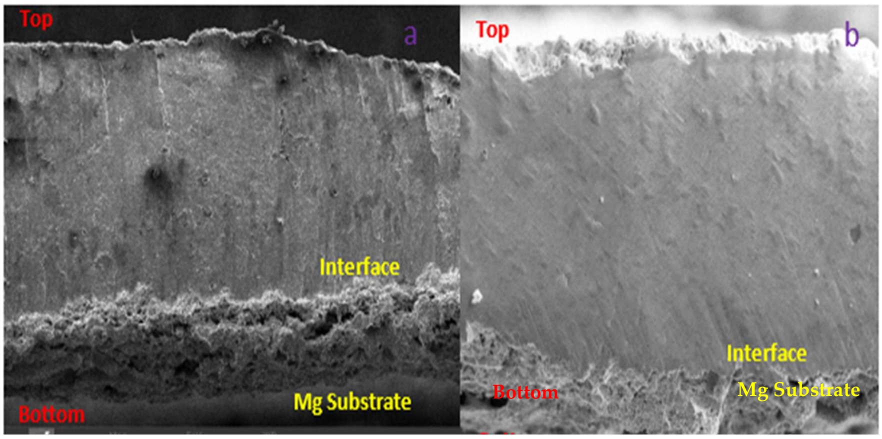

Figure 3. SEM micrograph: (**a**) Al0.5 HEA CS 850 °C, (**b**) Mn-HEA CS 850 °C.

3.2. *Surface Characterization*

Roughness Measurements

Figure 4 analyzes the roughness values obtained for samples with the same chemical composition at different deposition temperatures. For Al $_{0.1–0.5}$ CoCrCuFeNi, all roughness parameters decrease with increasing deposition temperature. However, experimental scattering cannot establish a monotonic relationship between roughness parameters and deposition temperature for other specimens.

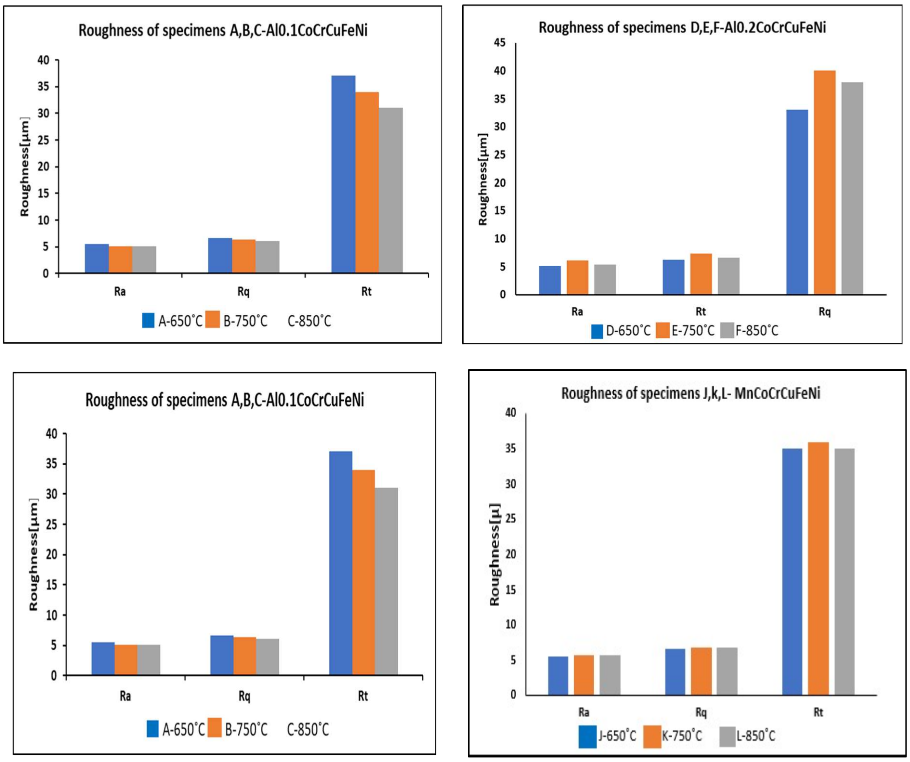

Figure 4. Roughness values of $Al_{0.1–0.5}$CoCrCuFeNi and MnCoCrCuFeNi coatings deposited at different cold spray temperatures. (**a**) $Al_{0.1}$CoCrCuFeNi, (**b**) $Al_{0.2}$CoCrCuFeNi, (**c**) $Al_{0.5}$CoCrCuFeNi, and (**d**) MnCoCrCuFeNi.

3.3. *Microhardness Test*

After carefully polishing the lateral surfaces of the samples, indentations were made at the interface close to the substrate. Based on three measurements, a mean value was calculated for each position. Table 5 indicates that the microhardness of a coating is highly dependent on its chemical composition. Microhardness averages for samples with

$Al_{0.1}$CoCrCuFeNi composition (A–C) are the lowest, whereas mean microhardness averages for samples with Al $_{0.5}$ CoCrCuFeNi (G–I) composition are the highest.

Table 5. Vickers microhardness measurements for all compositions.

Coating			
$Al_{0.1}$CoCrCuFeNi	A (650 °C)	Average	113.26
		Std dev	4.55
	B (750 °C)	Average	79.48
		Std dev	7.76
	C (850 °C)	Average	95.22
		Std dev	9.42
$Al_{0.2}$CoCrCuFeNi	D (650 °C)	Average	151.57
		Std dev	15.33
	E (750 °C)	Average	80.427
		Std dev	14.73
	F (850 °C)	Average	91.21
		Std dev	19.96
$Al_{0.5}$CoCrCuFeNi	G (650 °C)	Average	92.34
		Std dev	4.76
	H (750 °C)	Average	171.49
		Std dev	14.17
	I (850 °C)	Average	131.96
		Std dev	25.78
MnCoCrCuFeNi	J (650 °C)	Average	91.8
		Std dev	18.56
	K (750 °C)	Average	84.123
		Std dev	3.7
	L (850 °C)	Average	152.03
		Std dev	13.09

3.4. Wear Test

Figure 5 illustrates the average friction coefficient observed in each test. The Al $_{0.1–0.5}$ CoCrCuFeNi composition at 750 °C shows the highest friction coefficient. In contrast, for the MnCoCrCuFeNi composition, an increase in the cold spray temperature decreases the friction coefficient.

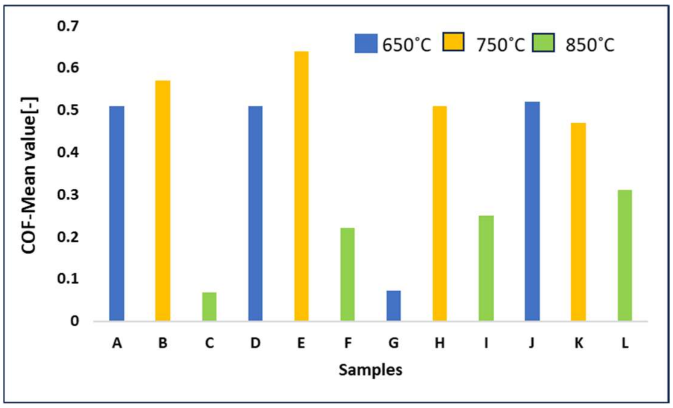

Figure 5. The average coefficient of friction for the coated samples.

4. Conclusions

The study examined the microstructure, roughness, hardness properties, and wear results for Al $_{0.1–0.5}$ (Mn) CoCuCrFeNi high-entropy alloy (HEA) coatings deposited on a magnesium substrate. Nitrogen was used as the process gas at three different temperatures. Vacuum annealing was performed in a batch furnace at a pressure of 0.05 bar for one hour at 600 degrees Celsius. The findings of this study lead to several conclusions.

The experimental data indicate that the chemical composition of the high-entropy alloy does not significantly influence the coating's roughness. However, the composition does have a noteworthy impact on the layer's microhardness. Specifically, a clear trend shows that microhardness increases as the aluminum content in the samples rises.

Annealing leads to significant microstructural changes, such as reduced porosity and improved bonding at the interface between the coating and the magnesium substrate. These changes enhance the coating's overall cohesion.

Annealing results in smoother surfaces by reducing roughness levels compared to non-annealed, cold-sprayed samples, while microhardness decreases after annealing. Due to the softer surface, wear resistance improves, which reduces friction and enhances material contact conditions. These smoother profiles enhance tribological performance by minimizing friction.

Author Contributions: N.S.: Data curation, formal analysis, methodology, writing, review, and editing. R.S.: Data curation, supervision, writing, review, and editing. S.Ö.: Conceptualization, data curation, formal analysis, funding acquisition. R.L.: Funding acquisition, project administration, investigation, and formal analysis. M.D.A.: Data curation, methodology. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Commission, REA, through its Marie Sklodowska Curie European Individual Fellowship to one of the authors (SÖ) [Project No: 101018482] (November 2021–October 2023).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Acknowledgments: The research mentioned here is funded by the European Commission, REA, through its Marie Sklodowska Curie European Individual Fellowship to one of the authors (SÖ) [Project No: 101018482] (November 2021–October 2023), which is gratefully acknowledged. The following are also thanked for their contribution to the experimental part: Brendan Twamley of TSBI, TCD (XRD), John Fitzgerald of NHTC of Ireland, Robert Dunbar (OM, metallography, sample preparation), TCD workshop personnel (sample cutting, machining), and Giacomo Cappelli (help in CS tests).

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Raffaella, S.; Nazanin, S.; Luca, C.; Sedat Oz Rocco, L.; Francesco, A. Cold spray HEA coating surface microstructural characterization and mechanical testing. *Results Mater.* **2024**, *21*, 100540.
2. Murty, B.S.; Yeh, J.W.; Ranganathan, S.; Bhattacharjee, P.P. *High-Entropy Alloys*; Butterworth-Heinemann: Burlington, NJ, USA, 2014.
3. Tsai, M.H.; Yeh, J.W. High-entropy alloys: A critical review, Mater. *Res. Lett.* **2014**, *2*, 107–123. [CrossRef]
4. Yin, S.; Li, W.; Song, B.; Yan, X.; Kuang, M.; Xu, Y.; Wen, K.; Lupoi, R. Deposition of FeCoNiCrMn high entropy alloy (HEA) coating via cold spraying. *J. Mater. Sci. Technol.* **2019**, *6*, 1003–1007. [CrossRef]
5. Nikbakht, R.; Saadati, M.; Kim, T.S.; Jahazi, M.; Kim, H.S.; Jodoin, B. Cold spray deposition characteristic and bonding of CrMnCoFeNi high entropy alloy. *Surf. Coat. Technol.* **2021**, 127748. [CrossRef]

6. Wu, J.; Chen, Y.; Zhu, H. A review on the tribological performances of high-entropy alloys. *Adv. Eng. Mater.* **2022**, *8*, 2101548. [CrossRef]
7. Luo, D.; Zhou, Q.; Huang, Z.; Li, Y.; Liu, Y.; Li, Q.; He, Y.; Wang, H. Tribological behavior of high entropy alloy coatings: A review. *Coatings* **2022**, *12*, 1428.
8. Oppong Boakye, G.; Geambazu, L.E.; Ormsdottir, A.M.; Gunnarsson, B.G.; Csaki, I.; Fanicchia, F.; Kovalov, D.; Karlsdottir, S.N. Microstructural properties and wear resistance of FeCr-Co-Ni-Mo-based high entropy alloy coatings deposited with different coating techniques. *Appl. Sci.* **2022**, *12*, 3156. [CrossRef]
9. Xia, J.; Xin, D.; Chen, X.; Xin, H. Investigation of the microstructure and friction mechanism of novel CoCrCu0.2FeMox high-entropy alloy coating using plasma arc cladding. *J. Mater. Sci.* **2022**, *57*, 19972–19985. [CrossRef]
10. Miracle, D.B.; Senkov, O.N. A critical review of high entropy alloys and related concepts. *Acta Mater.* **2017**, *122*, 448–511. [CrossRef]
11. Zhang, Y.; Zuo, T.T.; Tang, Z.; Gao, M.C.; Dahmen, K.A.; Liaw, P.K.; Lu, Z.P. Microstructures and properties of high-entropy alloys. *Prog. Mater. Sci.* **2014**, *61*, 1–93. [CrossRef]
12. Hemphill, M.A.; Yuan, T.; Wang, G.Y.; Yeh, J.W.; Tsai, C.W.; Chuang, A.; Liaw, P.K. Liaw Fatigue behavior of Al0.5CoCrCuFeNi high entropy alloys. *Acta Mater.* **2012**, *60*, 5723–5734. [CrossRef]
13. Tong, C.J.; Chen, M.R.; Yeh, J.W.; Lin, S.J.; Chen, S.K.; Shun, T.T.; Chang, S.Y. Mechanical performance of the AlxCoCrCuFeNi high-entropy alloy system with multiprincipal elements. *Metall. Mater. Trans. A* **2005**, *36*, 1263–1271. [CrossRef]
14. Zou, Y.; Qiu, Z.; Huang, C.; Zeng, D.; Lupoi, R.; Zhang, N.; Yin, S. Microstructure and tribological properties of Al_2O_3 reinforced FeCoNiCrMn high entropy alloy composite coatings by cold spray. *Surf. Coat. Technol.* **2022**, *434*, 128205. [CrossRef]
15. Wu, J.M.; Lin, S.J.; Yeh, J.W.; Chen, S.K.; Huang, Y.S.; Chen, H.C. Adhesive wear behavior of AlxCoCrCuFeNi high-entropy alloys as a function of aluminum content. *Wear* **2006**, *26*, 513–519. [CrossRef]
16. Xiao, J.K.; Tan, H.; Wu, Y.Q.; Chen, J.; Zhang, C. Microstructure and wear behavior of FeCoNiCrMn high entropy alloy coating deposited by plasma spraying. *Surf. Coat. Technol.* **2020**, *385*, 125430. [CrossRef]
17. Zhang, B.; Yu, Y.; Zhu, S.; Zhang, Z.; Tao, X.; Wang, Z.; Lu, B. Microstructure and wear properties of TiN–Al_2O_3–Cr_2B multiphase ceramics in-situ reinforced CoCrFeMnNi highentropy alloy coating. *Mater. Chem. Phys.* **2022**, *276*, 125352. [CrossRef]
18. Liu, S.S.; Zhang, M.; Zhao, G.L.; Wang, X.H.; Wang, J.F. Microstructure, and properties of ceramic particle reinforced FeCoNiCrMnTi high entropy alloy laser cladding coating. *Intermetallics*, 2022; 140, 107402.
19. Zhu, S.; Yu, Y.; Zhang, B.; Zhang, Z.; Yan, X.; Wang, Z. Microstructure and wear behaviour of in-situ TiN-Al_2O_3 reinforced CoCrFeNiMn high-entropy alloys composite coatings fabricated by plasma cladding. *Mater. Lett.* **2020**, *272*, 127870. [CrossRef]
20. Ozbilen, S.; Lupoi, R. *Al0. 5 HEA Protective Coatings on Mg Based Parts by Mechanical Alloying, Cold Spraying and Argon Annealing*; TSA Technology Transfer Office, TCD: Dublin, Ireland, 2023.
21. Yin, S.; Lupoi, R.; Chen, C. Property enhancement of cold sprayed Al-diamond MMC coating using core-shelled diamond reinforcements. *Proc. Int. Therm. Spray Conf.* **2019**, *2019*, 469–475.
22. Ozbilen, S.; Vasquez, J.F.; Abbott, W.; Yin, S.; Morris, M.; Lupoi, R. Mechanical milling, characterization, and phase prediction of Al0.1-0.5(Mn)CoCrCuFeNi HEA powder feedstock for cold spray deposition processing. *J. Alloys Compd.* **2023**, *961*, 170854.