Dispersoid-strengthened High Entropy Alloy (HEA) Coatings for Hydrogen Embrittlement Resistance Developed Via Thermal Spraying

Brian Pitt Excellence Award Competition

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AHTST Lab
Advanced Heat Transfer and Surface Technologies Laboratory

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Introduction

Hydrogen to Power 13% of Global Energy by 2050

"…according to the report "Net Zero by 2050: a Roadmap" for the Global Energy Sector, the use of H and H-based fuels is expected to grow sixfold from today's levels to meet 13 % of worldwide total final energy consumption in 2050…"

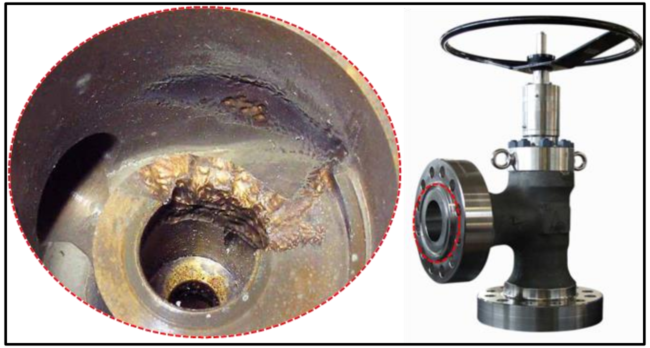
(International Energy Agency (IEA))

Oil & Gas Equipment MRO Market to Hit $17.9B

"…the global oil and gas equipment MRO market is estimated to reach $13.8 billion in 2025, with a projected growth to $17.9 billion by 2032…" *(Metastat)*

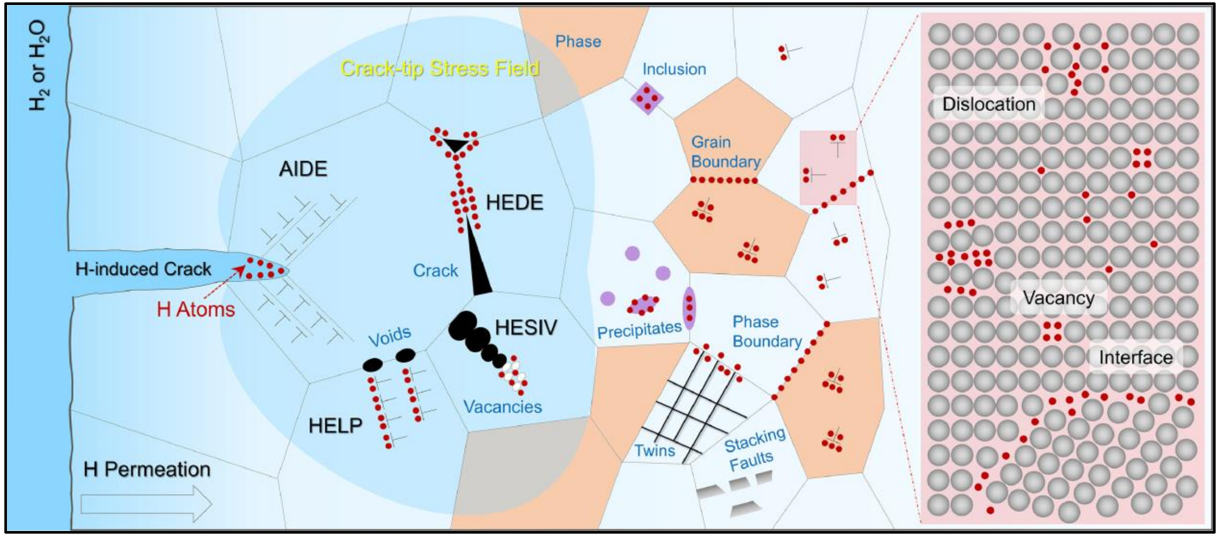
"…turbine repairs alone cost the industry an estimated $8 billion in 2019…" *(Wood Mackenzie)*

INDUSTRIAL PROBLEM



Erosive wear attack on choke valve

(Tornton et al., 2022)



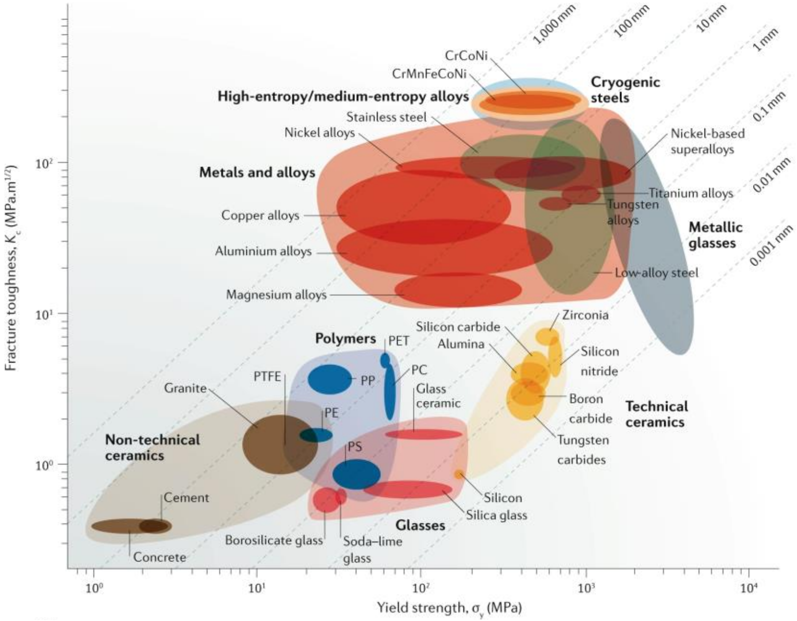
Hydrogen embrittlement mechanism

(Sun *et al.*, 2024)

Material Solution

High Entropy Alloys (HEA)

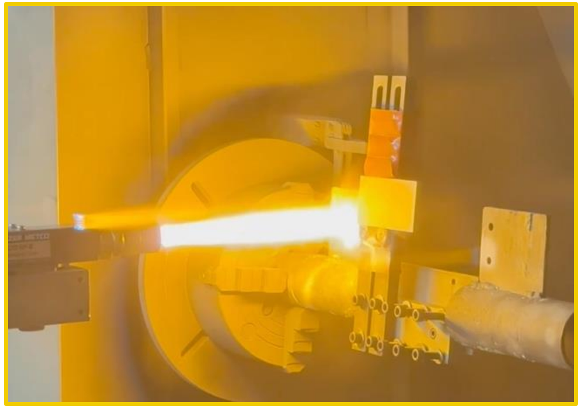
- Equiatomic or near-equiatomic concentrations of five or more elements.
- High configurational entropy
- Form solid solution phases

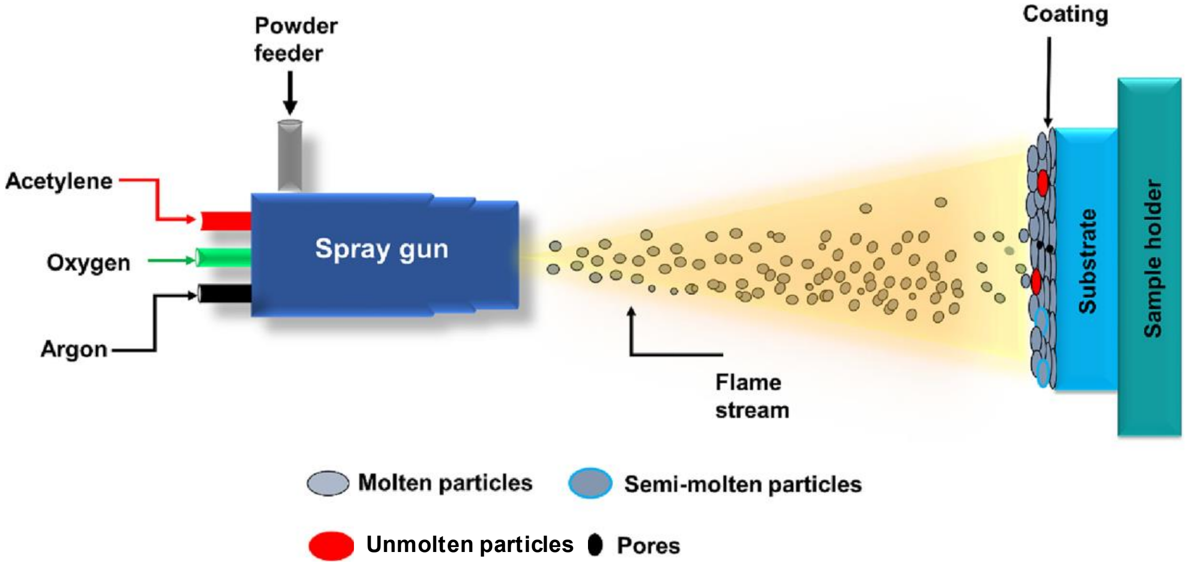


Ashby plot (George *et al.*, 2019)

Excellent thermal stability, outstanding mechanical properties, high hardness and wear resistance, exceptionally high-temperature strength, irradiation resistance and excellent corrosion and oxidation resistance.

Flame Spray Process





Flame spray HEA coatings

- High hardness (Kumar *et al*., 2025)
- High wear resistance (Kumar *et al*., 2025, Wear)
- Promising oxidation resistance (Yeh *et al*., 2004)
- Good corrosion resistance (Nair *et al*., 2022)

Motivation

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- Flame sprayed AlCoCrFeMo HEA has shown excellent performance against wear, erosion, and chloride-induced corrosion (Nair *et al.*, 2022).

- Zirconium (Zr) is a strategic additive : (Zhao *et al.*, 2023)

  - forms hard Laves phases and ZrO_2

  - ZrO_2 acts as a thermodynamically stable hydrogen barrier

  - facilitates hydride formation and hydrogen trapping

This study investigates how Zr addition can unlock new frontiers in flame sprayed HEA coating performance by integrating wear, corrosion, and hydrogen resistance into a single coating system.

Objectives

- Development of AlCoCrFeMo-Zr_x (x = 0, 5, 10, 15 wt.%) coatings via flame spray process.
- Evaluation of mechanical performance under impact-dominated loading conditions.
- Assessment of corrosion behaviour in a chemically aggressive environment.
- Investigation of hydrogen embrittlement resistance using permeation-based testing.

Experimental Methods

Feedstock Powder Preparation
Tumble Mixing Zr 5, 10, 15 wt.% to AlCoCrFeMo
Characterization of Powder using XRD, SEM and EDS

↓

Coating Fabrication
Flame Spraying on 316L SS Substrates
Characterization of Coating using XRD, SEM and EDS

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Coating Performance Assessment

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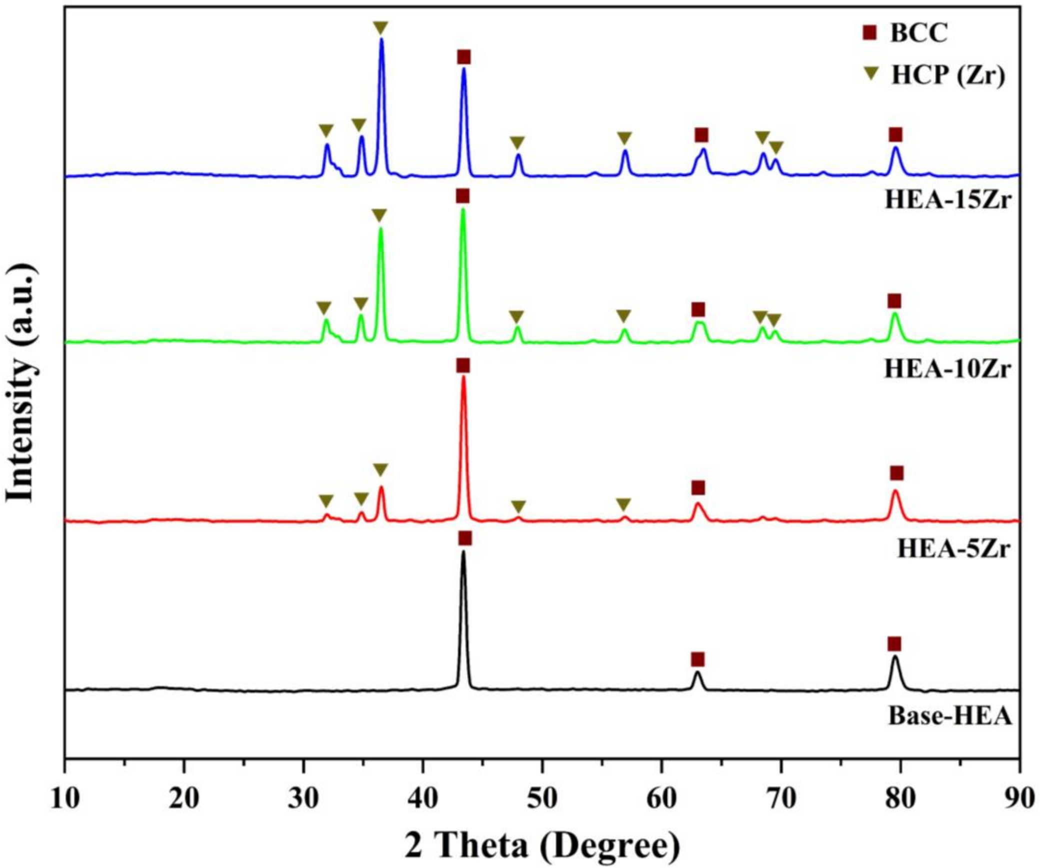
Mechanical Tests
Microhardness Testing
Coating Adhesion Testing
Solid Particle Erosion Testing

Electrochemical Tests
Electrochemical Corrosion Testing
Devanathan-Stachurski Hydrogen Permeation Test

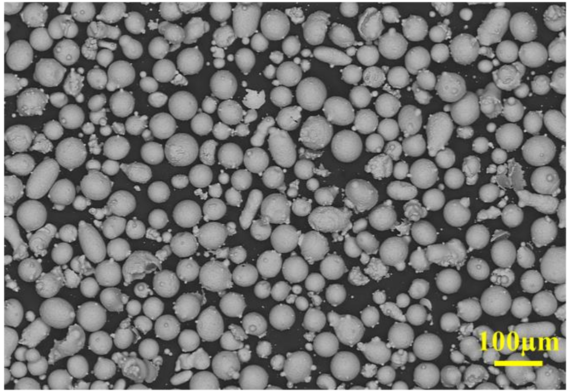
Feedsctock Powder Phase Analysis



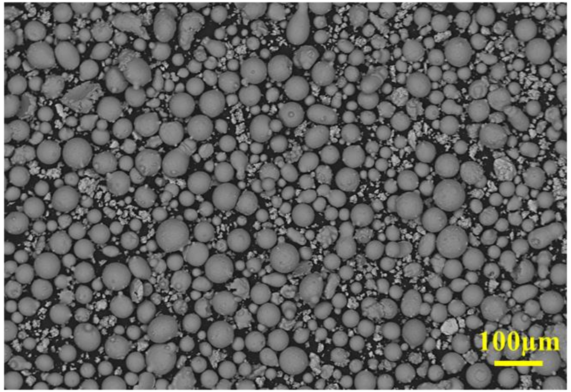
Sample Name	Wt. % Zr Addition
Base-HEA	0
HEA-5Zr	5
HEA-10Zr	10
HEA-15Zr	15

- BCC structure in Base-HEA
- Zr-induced HCP phase formation
- Dual-phase microstructure evolution

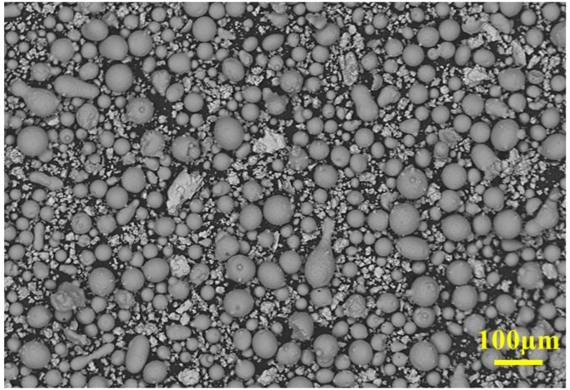
Morphology of Powder Feedstock



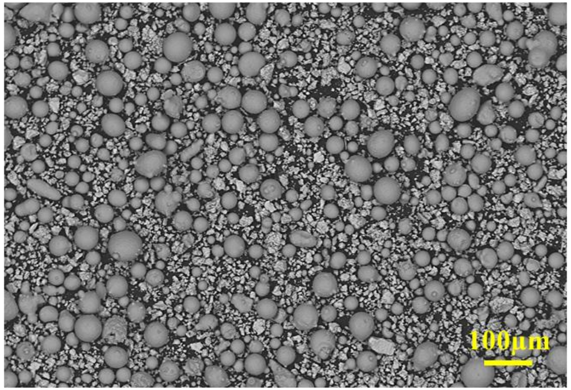
Base-HEA



HEA-5Zr



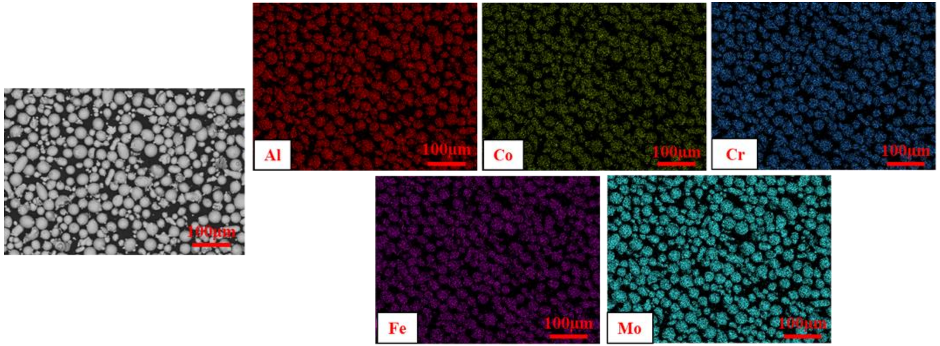
HEA-10Zr



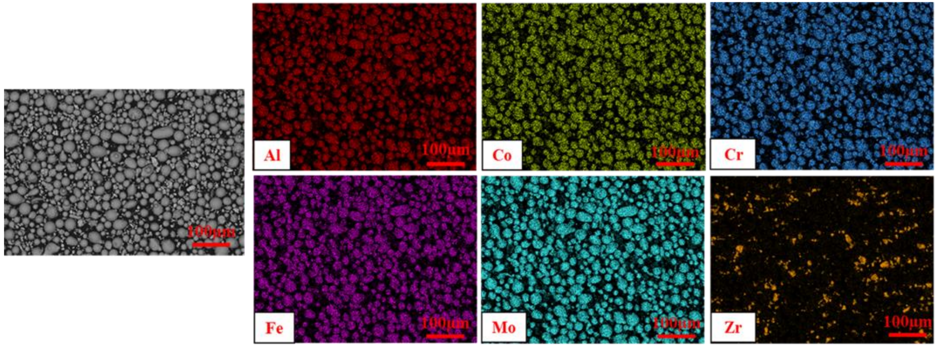
HEA-15Zr

- Average particle size: 38–42 μm
- Improved homogeneity
- Spherical/regular morphology

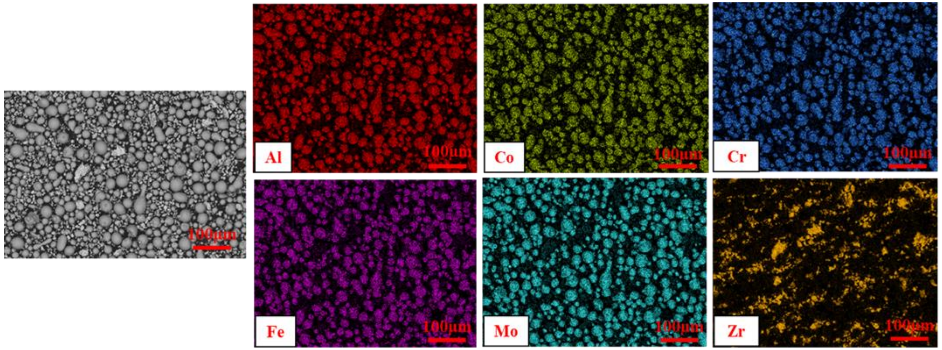
EDS Elemental Maps of As-mixed Powder Feedstock



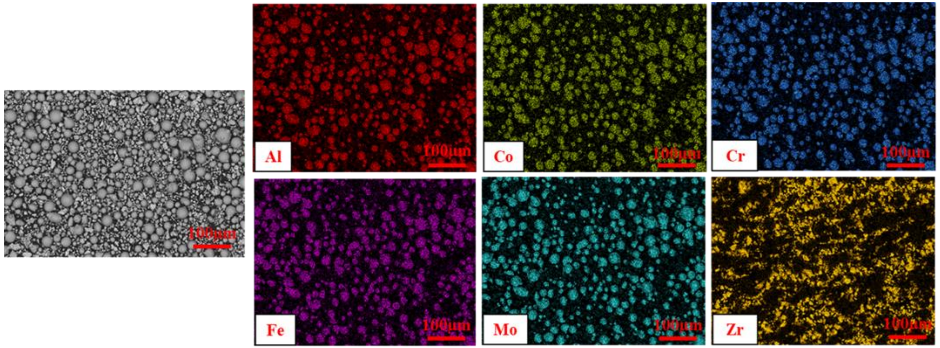
Base-HEA



HEA-5Zr



HEA-10Zr



HEA-15Zr

- Well-homogenized powder mixture after tumble mixing

Phase Analysis of As-sprayed Coatings

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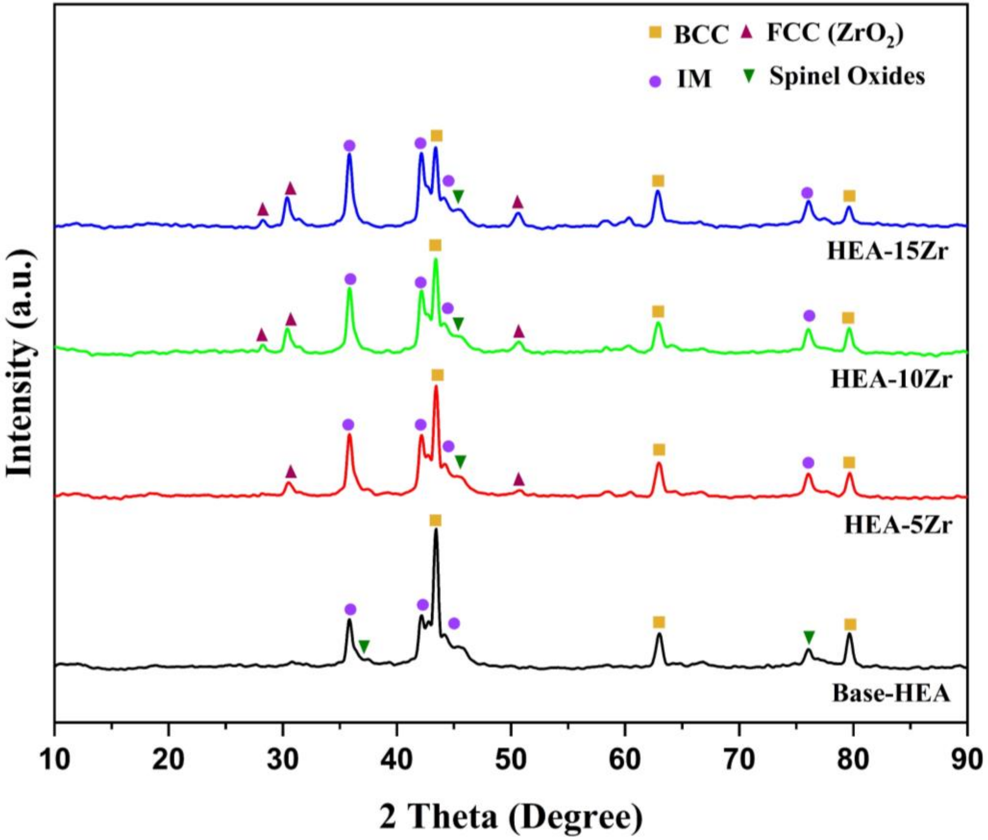
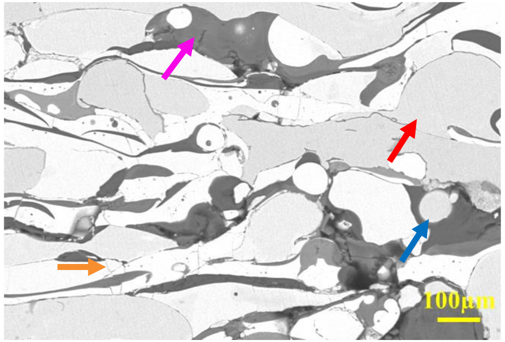


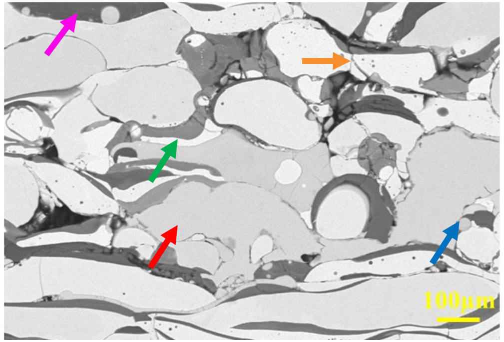
Phases	Base-HEA	HEA-5Zr	HEA-10Zr	HEA-15Zr
BCC	59 ± 3	46 ± 9	42 ± 8	34 ± 9
Intermetallic	34 ± 5	45 ± 7	44 ± 6	43 ± 7
FCC (ZrO_2)	-	7 ± 3	11 ± 2	20 ± 3
Spinel Oxides	7 ± 4	2 ± 4	3 ± 2	3 ± 4

- BCC, IM, FCC ZrO_2, spinel oxides
- BCC phase decreases with increasing Zr
- ZrO_2 content increases significantly

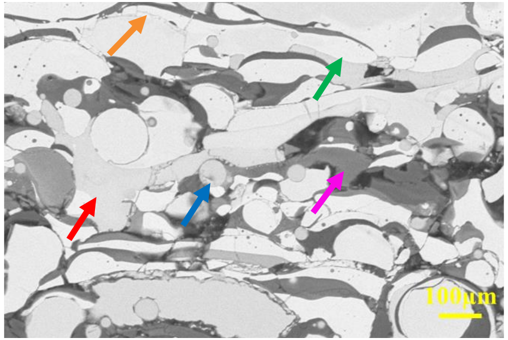
Microstructure of As-sprayed Coatings



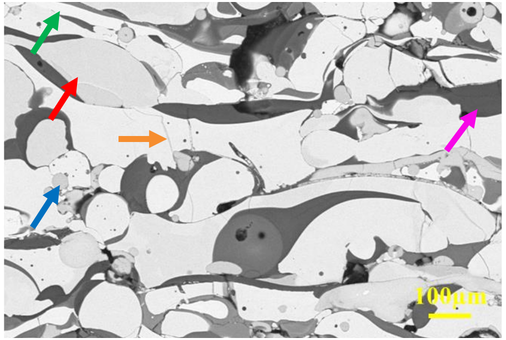
Base-HEA



HEA-5Zr



HEA-10Zr



HEA-15Zr

- Splat-based morphology
- Coating thickness ~450 μm
- Zr addition increases heterogeneity

BCC Phase

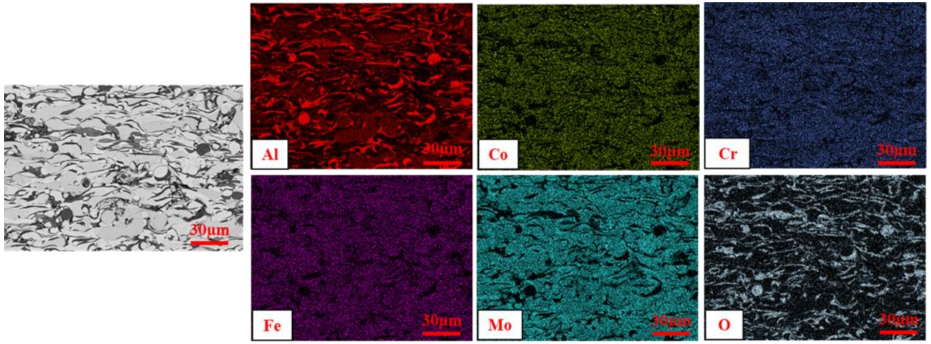
Spinel Oxides

FCC (ZrO_2) Phase

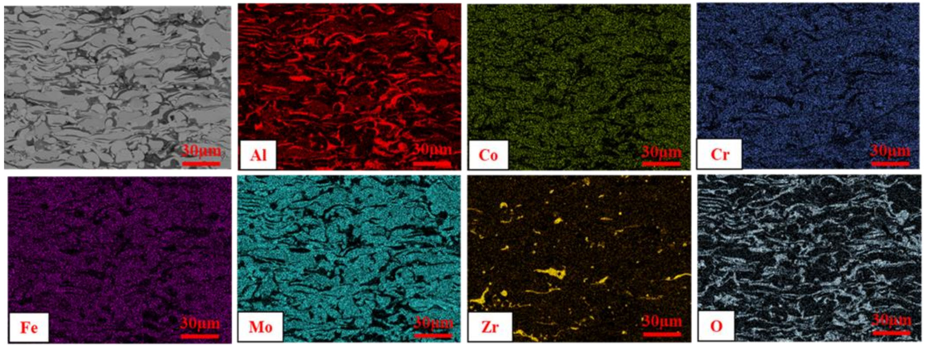
Interlamellar cracks

Partially melted particles

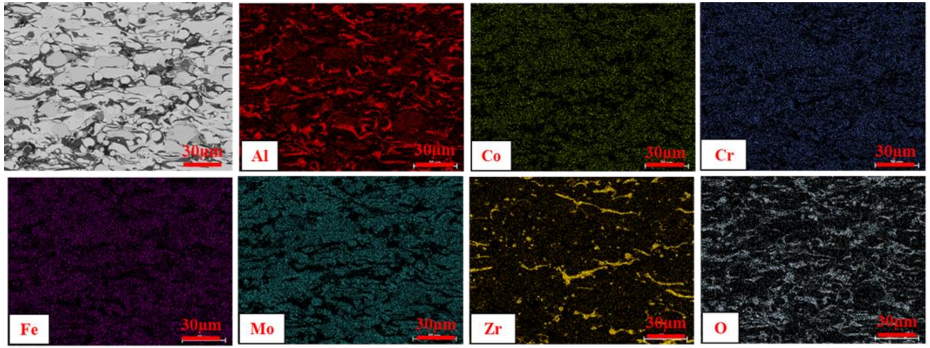
EDS Elemental Maps of As-sprayed Coatings



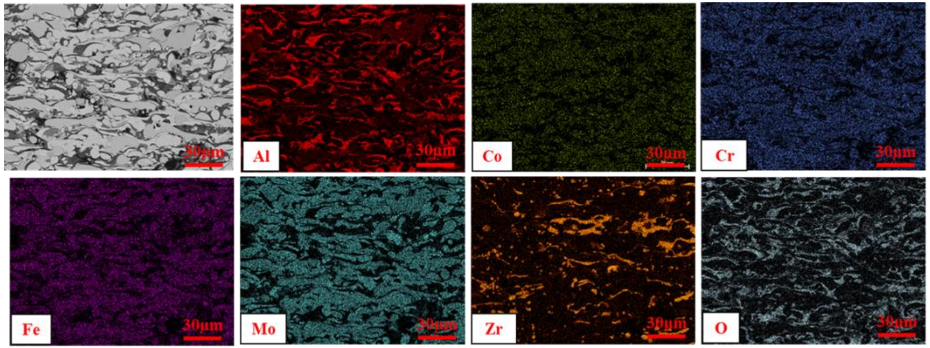
Base-HEA



HEA-5Zr



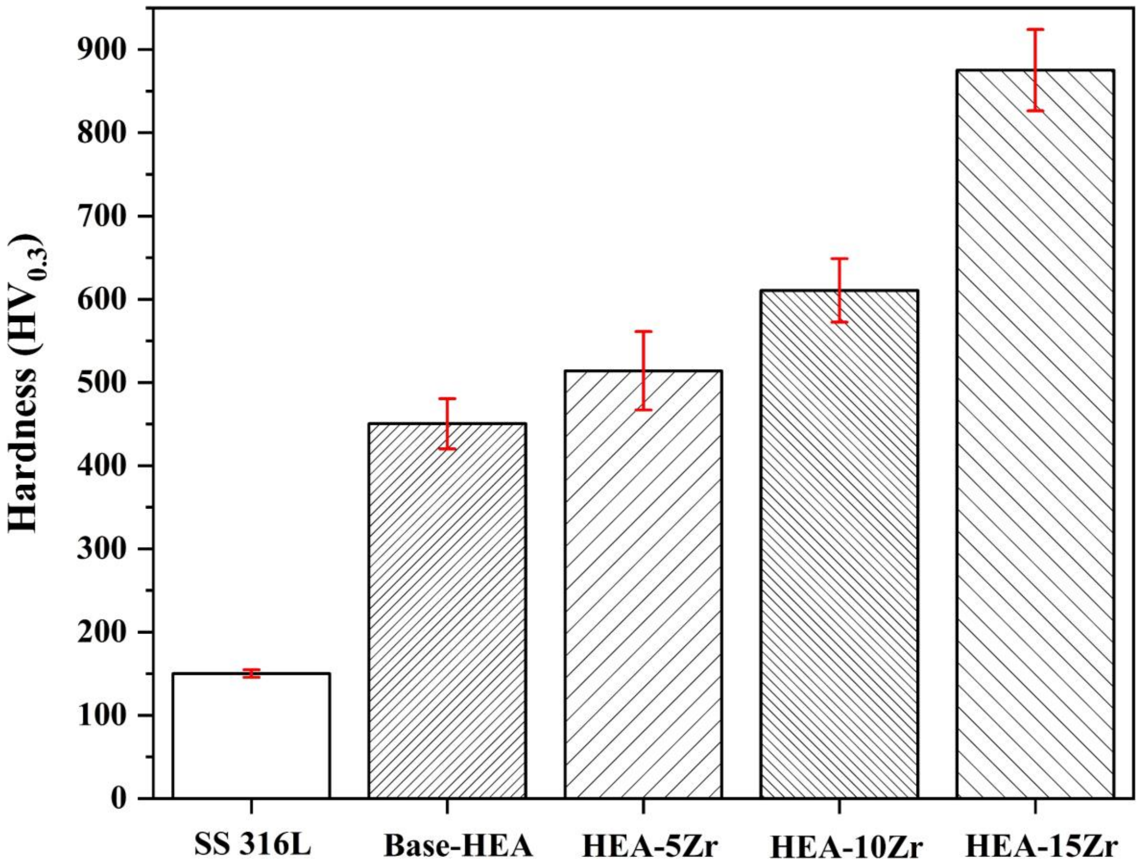
HEA-10Zr



HEA-15Zr

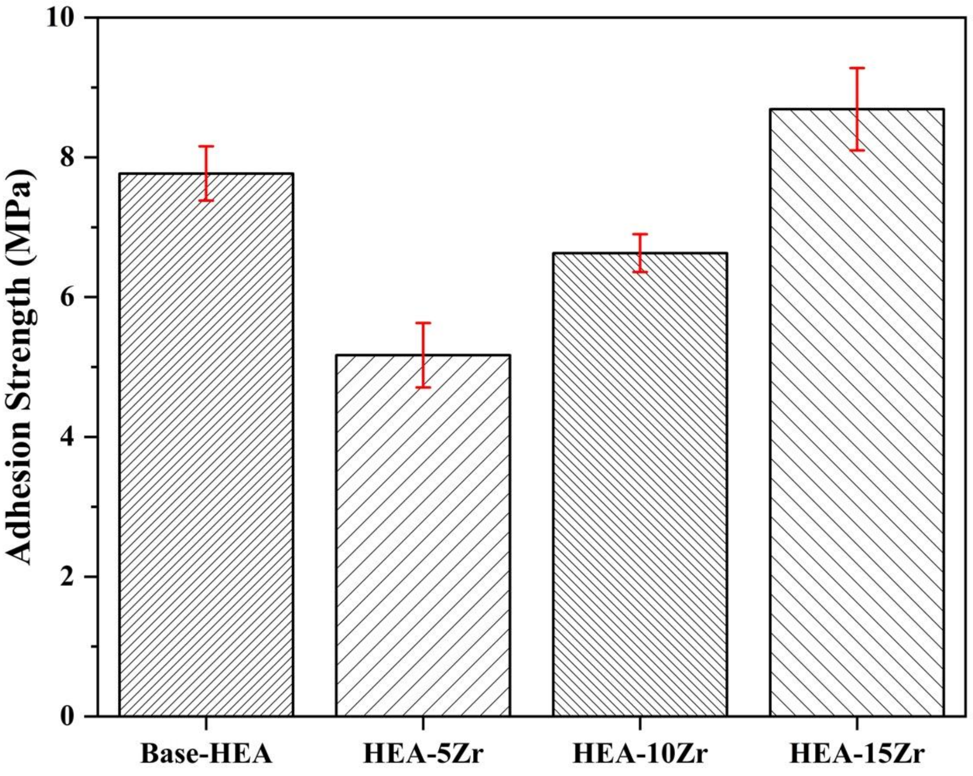
- Progressive formation of ZrO_2-rich regions

Microhardness Evaluation



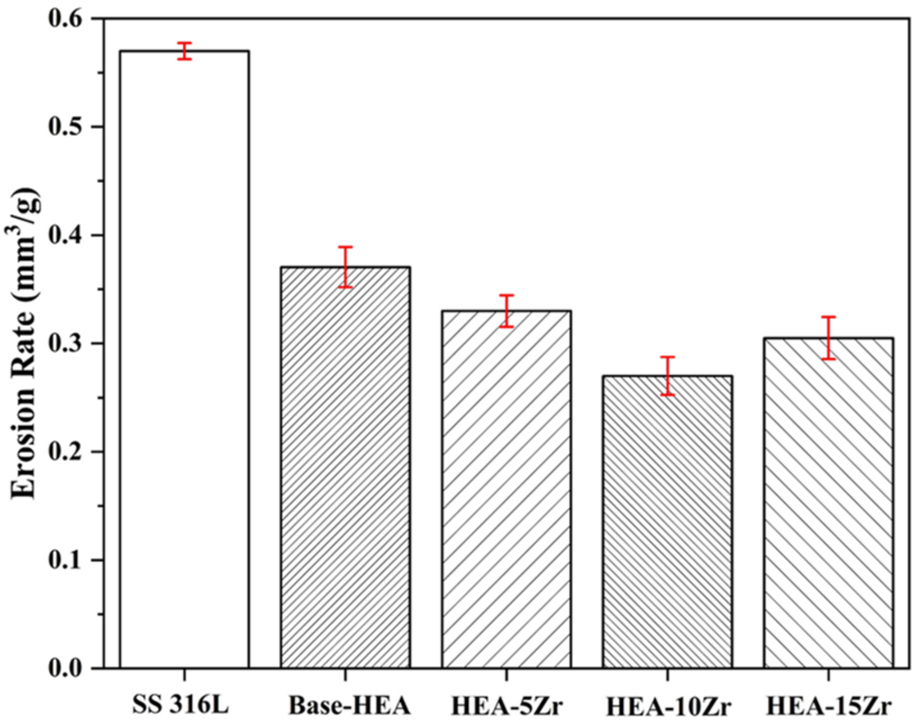
- Hardness increases with Zr
- Solid solution strengthening

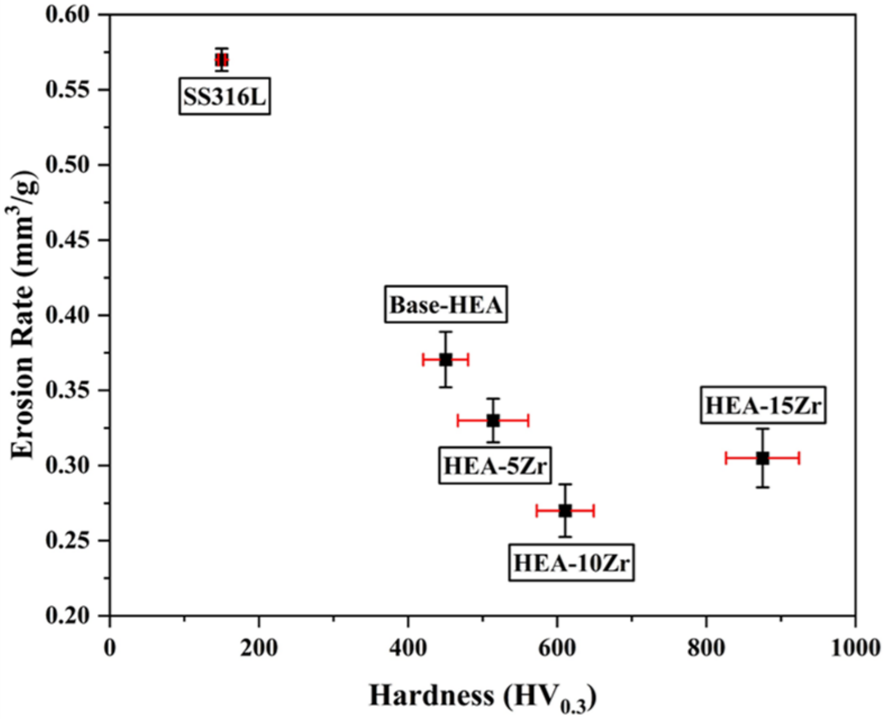
Adhesion Strength of As-sprayed Coatings



- Cohesive failure mode
- ZrO_2-induced brittleness
- Zr improves mechanical interlocking and densification

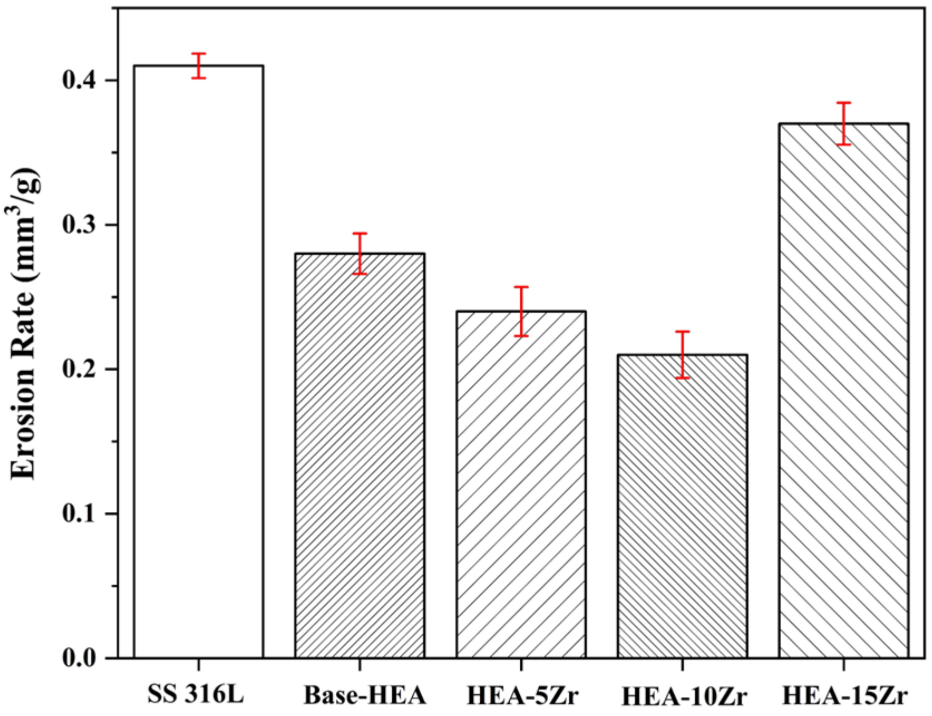
Solid Particle Erosion at 30° Impact Angle

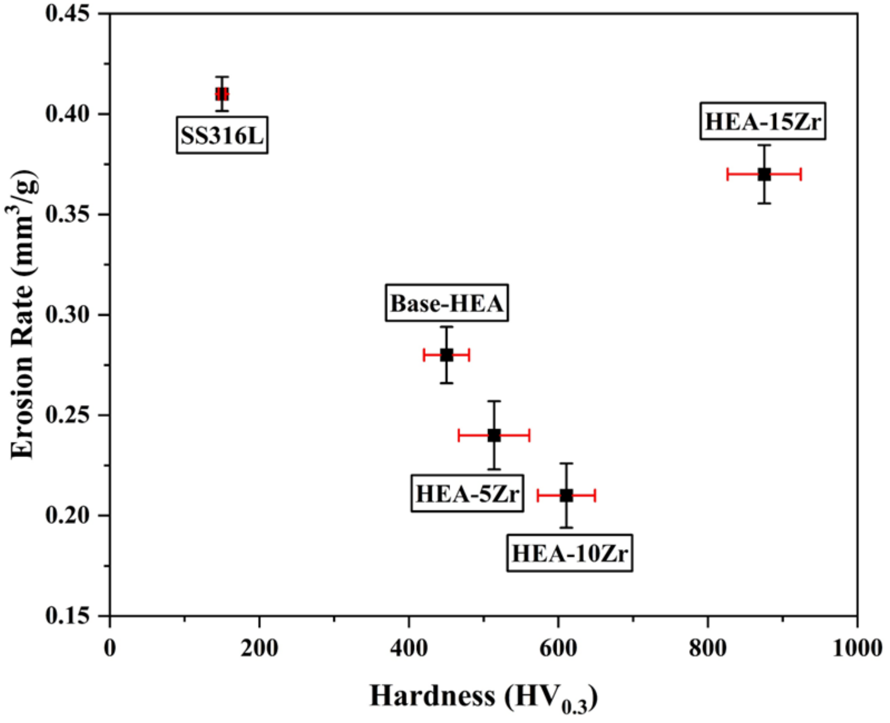




- Erosion resistance improved with Zr addition up to 10 wt.%.

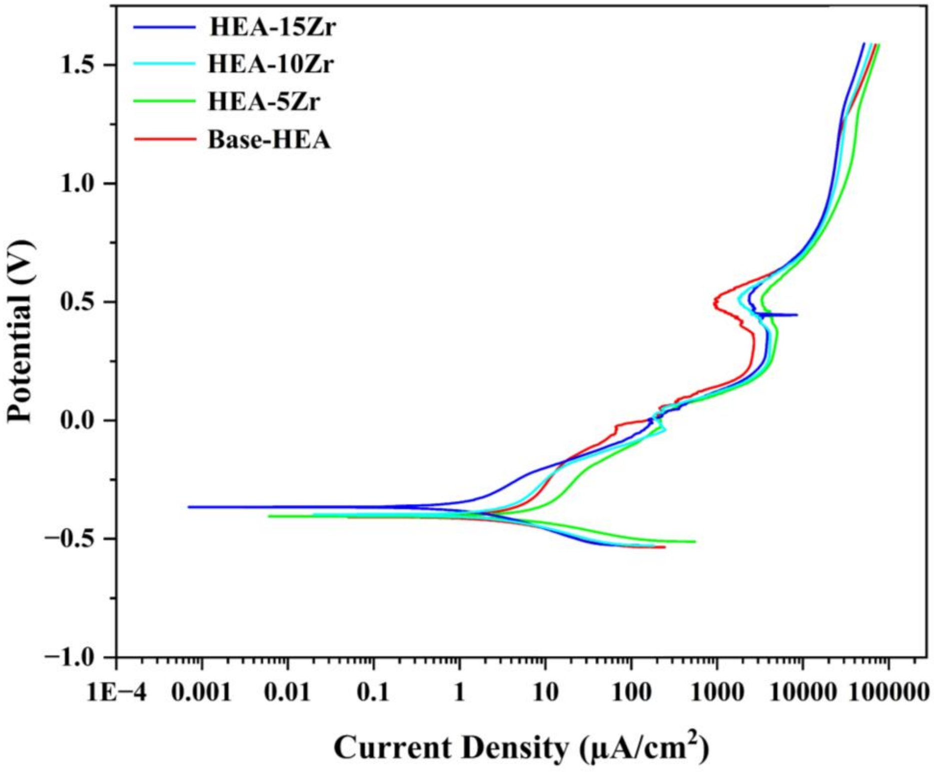
Solid Particle Erosion at 90° Impact Angle





- Erosion resistance improved with Zr addition up to 10 wt.%.

Electrochemical Corrosion Performance



Composition	SS316L	Base-HEA	HEA-5Zr	HEA-10Zr	HEA-15Zr
I_{corr} ($\mu A/cm^2$)	1.2201	0.549	0.684	0.411	0.053
E_{corr} (V)	-0.358	-0.405	-0.409	-0.388	-0.354
E_o (V)	-0.288	-0.407	-0.404	-0.396	-0.365
CR (mpy)	88.9×10^{-2}	3.6×10^{-3}	4.7×10^{-3}	3.05×10^{-3}	4.1×10^{-4}

- Corrosion resistance improves with Zr
- Stable ZrO_2 and Al_2O_3 phases
- Base-HEA shows galvanic corrosion

Hydrogen Permeation Assessment

Composition	D_{eff} (10^{-7} cm^2/s)	N_t (10^{-4} mol/cm^3)	c_{app} (mol/cm^3)
SS316L	0.64	0.0000014	0.1917
HEA-15Zr	2.3	4.6	0.0077

- HEA-15Zr shows high trap density
- Low hydrogen solubility
- High D_{eff} reflects initial ingress
- ZrO_2 and laves phases act as effective hydrogen barriers
- HEA-15Zr outperforms SS316L

Conclusions

- AlCoCrFeMo-Zr_x coatings were successfully fabricated using flame spray deposition technique.
- Mechanical performance improved, with the HEA-15Zr exhibiting the highest microhardness and adhesion strength.
- HEA-10Zr is the most erosion-resistant composition, while HEA-15Zr, although harder, exhibited increased brittleness and susceptibility to impact-induced fracture.
- Zr addition enhanced corrosion resistance, with HEA-15Zr showing the lowest corrosion current density and passivation.
- HEA-15Zr is an effective hydrogen barrier, due to high trap density and low hydrogen solubility.

Acknowledgments & Contact

- I would like to thank:

  - Dr. André McDonald

  - AHTSTL members

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Thank you!

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