Hydrogen Embrittlement in Offshore Wind Structures: Mechanisms, Material Systems and HEA-Coated DIWAAM Inconel 625 / SS 347

HYDROGEN EMBRITTLEMENT · OFFSHORE WIND · ADDITIVE MANUFACTURING

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PRESENTED AT

Advanced Energy Transition Workshop

From Technology to Transition: Building the Energy Systems of Tomorrow

1 · Why hydrogen matters

Atomic hydrogen enters metals during welding, plating, corrosion and cathodic protection, then gathers at dislocations, grain boundaries, inclusions and precipitates.

The result is a sharp loss of **ductility and fracture resistance** while strength and hardness barely change, so failures give little warning.

Offshore wind link: seawater, cathodic protection and high-strength fasteners keep monopiles, jackets and flanges in a hydrogen-charging environment for 25+ years.

Material systems reviewed

Monolithic	Coated	Additive (AM)	Heat-treated	FGM	Foams
GB segregation, carbides, α′-martensite	Porosity, interface stress, delamination	Pores, melt-pool boundaries, cell networks	Tempering, PWHT, δ-phase, ageing	Gradients in traps and residual stress	Cell walls, struts, corrosion-generated H

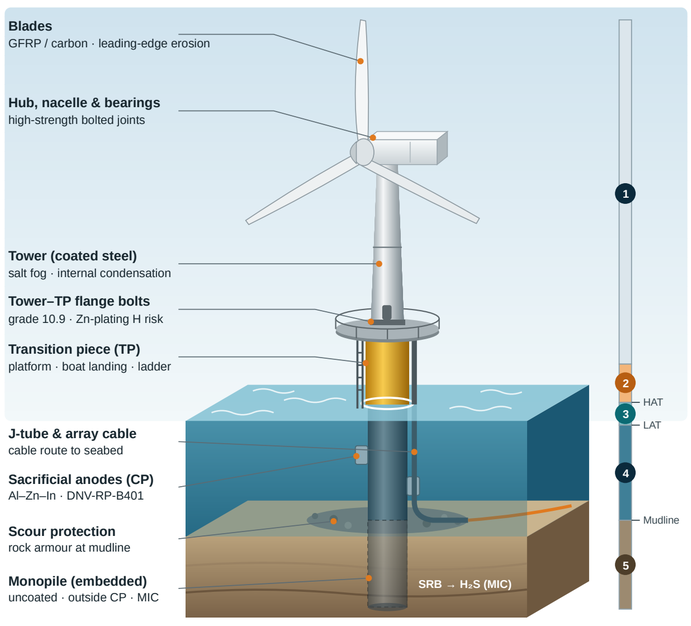
2 · HE mechanisms

HEDE	H at stressed interfaces lowers atomic cohesion → brittle intergranular or {100} cleavage cracking.
HELP	H shields dislocation interactions → localised slip bands, nano-voids, quasi-cleavage.
AIDE	Adsorbed H at the crack tip eases dislocation emission → fine shallow dimples.
HESIV	H stabilises strain-induced vacancies → vacancy clusters, nanovoids, early fracture.
Hydride	Brittle hydrides in Ti, Zr and Mg alloys raise local stress and crack readily.

Mechanisms act alone or together; microstructure, H content, stress and strain rate decide which dominates.

3 · Offshore wind turbine: parts & exposure zones

Monopile foundation · cut-away 3D view, not to scale



1 Atmospheric
Parts: blades, nacelle, tower, flange bolts.
Salt fog and condensation; HE risk in high-strength and Zn-plated fasteners.

2 Splash (above HAT)
Parts: TP, platform, boat landing.
Highest corrosion rate. Wet–dry cycling, coating damage, no effective CP; pits become H-charging sites.

3 Tidal (LAT–HAT)
Parts: TP base, upper monopile, J-tube.
Intermittent immersion, oxygen differential, partial CP coverage.

4 Submerged (LAT–mudline)
Parts: monopile, anodes, J-tube.
CP reduces water to atomic H; over-protection drives H into welds and high-strength steel.

5 Buried / mudline
Parts: embedded pile, scour rock, cable entry.
MIC by sulphate-reducing bacteria forms H_2S, a sour environment (see 4).

4 · MIC: the microbial route to hydrogen

Where: inside monopiles iron-oxidising bacteria dominate near the surface, while SRB and methanogens dominate near the anoxic seabed; the buried mud zone is uncoated and outside CP.

Link to HE: SRB activity generates atomic H, and sulfide poisons its recombination, so H enters the steel and can trigger HIC / SSC in loaded mud-zone connections.

KEY REACTIONS · SRB CATHODIC DEPOLARISATION

$4Fe \rightarrow 4Fe^{2+} + 8e^-$	anode
$8H_2O \rightarrow 8H^+ + 8OH^-$; $8H^+ + 8e^- \rightarrow 8H(ads)$	cathode
$SO_4^{2-} + 8H(ads) \rightarrow S^{2-} + 4H_2O$	SRB
$Fe^{2+} + S^{2-} \rightarrow FeS$; $3Fe^{2+} + 6OH^- \rightarrow 3Fe(OH)_2$	products
$\mathbf{4Fe + SO_4^{2-} + 4H_2O \rightarrow FeS + 3Fe(OH)_2 + 2OH^-}$	overall
$Fe + H_2S \rightarrow FeS + 2H(ads)$	sulfide attack
S^{2-} blocks $2H(ads) \rightarrow H_2$, so $H(ads) \rightarrow H(abs)$	→ HE

Control: CP on the submerged zone, barrier coatings, biocides and asset-specific monitoring of hard-to-reach zones.

5 · PhD work: HEA-coated DIWAAM Inconel 625 / SS 347

Alliance University

STEP 1 · DIWAAM build — Inconel 625 + SS 347 wires deposited layer by layer

STEP 2 · HEA coating — CoCrNiZrCe powder · thermal spray

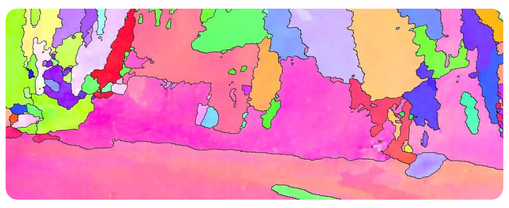
STEP 3 · DONE · Characterisation — SEM · EDS · EBSD

STEP 4 · DONE · HIC test — NACE TM0284 · coated vs uncoated

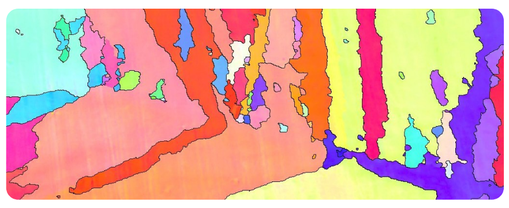
STEP 5 · PLANNED · SSC & H analysis — NACE TM0177 · gas analyser: diffusible H



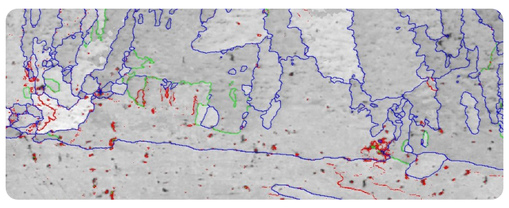
Powder → coated plates · CoCrNiZrCe, 70–120 µm; overlapping clad tracks on the DIWAAM plates.



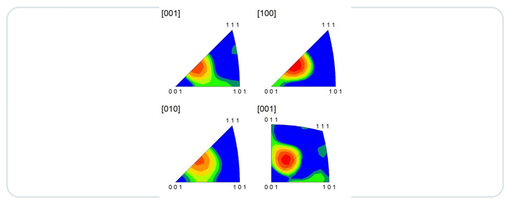
EBSD IPF · Columnar grains along the build direction above a fusion boundary; coarse elongated grains below.



EBSD IPF · Coarse columnar grains growing epitaxially across the layer boundary.



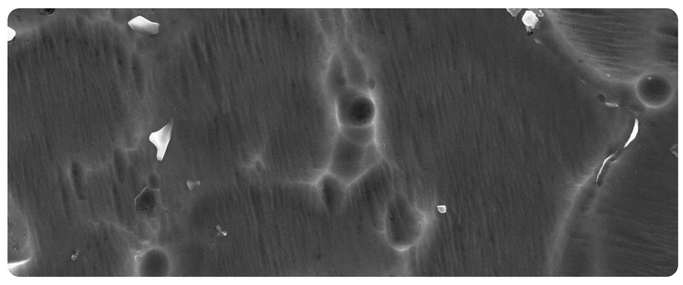
Grain boundaries · High-angle (blue) dominate; low-angle (red) and fine particles in the lower zone are likely H-trap sites.



Texture · Preferred orientation between ⟨001⟩ and ⟨111⟩, typical of directional WAAM solidification.

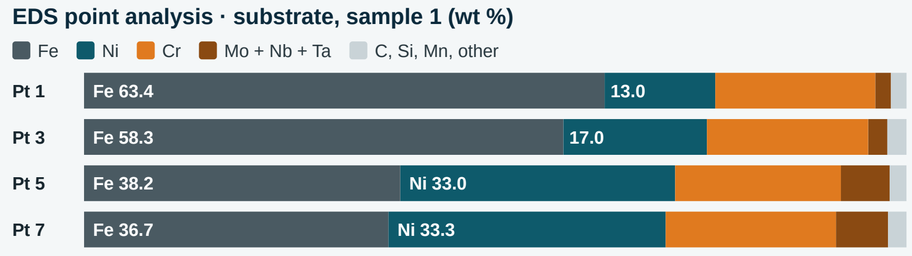


SEM · 50× · Dendritic solidification structure across layers; coating layer at top-left edge; an interlayer defect line with pores at right.



SEM · 5000× · Bright interdendritic precipitates (likely Nb/Mo-rich) and 1–2 µm micropores: potential H-trap sites.

EDS point analysis · substrate, sample 1 (wt %)



Points 1 and 3 are SS 347-like (Fe 58–63, Ni 13–17); points 5 and 7 hold Fe ~37, Ni ~33, Mo ~3.2, Nb 1.8–2.8, showing strong IN625 / SS 347 intermixing. Cr stays ~20–21 throughout. Sample 4 reproduces the trend (Fe 62 → 37, Ni 14 → 34, Mo 0.5 → 3.2).

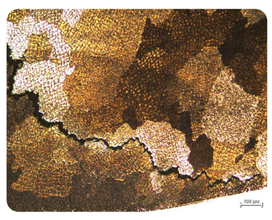
6 · HIC results: coated vs uncoated

NACE TM0284 · cross-sections after test

UNCOATED DIWAAM



Macro section · stepwise crack running across the build.

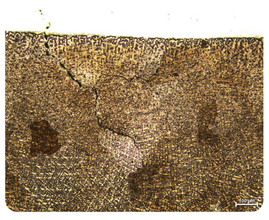


Optical, 100 µm bar · wide, open intergranular crack through coarse grains.

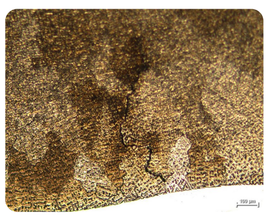
HEA-COATED (CoCrNiZrCe)



Macro section · columnar build; no large crack visible at this magnification.



Optical, 100 µm bar · thin crack from the coated surface into the build.



Optical, 100 µm bar · short, thin crack near the edge.

Result: cracks formed in both conditions, but in the coated build they were shorter and finer. The HEA coating improved HIC resistance; it did not prevent cracking.

7 · Takeaways & next steps

- HIC confirmed the coating benefit: both conditions cracked, but cracks were shorter and finer with the CoCrNiZrCe coating.
- Columnar grains, interdendritic precipitates, micropores and IN625 / SS 347 intermixing in the DIWAAM build are candidate H-trap sites.
- Next: SSC (NACE TM0177) and hydrogen analysis to quantify H uptake in each condition.

Selected references

[1] Arun N M et al., Hydrogen embrittlement review: mechanisms and material systems, under review.

[2] Yang et al., ultrathin nanocrystalline CeO_2 hydrogen barrier coating.
[3] Wu et al., ZrO_2 and YSZ hydrogen permeation barriers on Q235 steel.
[4] Arun N M et al., MIC in offshore environments across asset classes (review), ICICEPC 2026.
[5] NACE TM0284 (HIC) · NACE TM0177 (SSC) · DNV-RP-B401 (CP).