SHOCKWAVE

VACUUM EXPLOSION TRIPLATE

The State-of-the-Art

Transition Joint Technology

Comparative Technical-Scientific Analysis

SHOCKWAVE METALWORKING TECHNOLOGIES BV
Scherpenbergsebaan 49 · NL 4721 ST · Schijf · The Netherlands
Tel: +31 165 343451 · www.shockwave-clad.com · info@shockwave-clad.com

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1. Introduction and Industrial Context

Joining aluminium to steel is one of the most persistent structural challenges in marine engineering, offshore construction, and naval architecture. The two metals are **fundamentally incompatible for direct fusion welding**: when melted together they form brittle intermetallic compounds, iron aluminides (Fe_2Al_5, $FeAl_3$), that make any fusion weld zone a point of catastrophic weakness. Beyond the metallurgical incompatibility, aluminium and steel are separated in the galvanic series, meaning direct contact in a marine environment leads to accelerated corrosion of the aluminium. Their thermal expansion coefficients differ by a factor of approximately two, so every temperature cycle builds cumulative stress at the interface.

The industry solution is the aluminium-to-steel transition joint: a precision-engineered composite strip that contains the steel-to-aluminium transition within itself, manufactured under controlled factory conditions using a process designed specifically for the purpose. Each outer face of the strip presents the same metal as the structure to which it will be welded steel on the hull side, aluminium alloy on the superstructure side allowing conventional fusion welding on both sides using standard procedures.

The quality of the bond within that transition strip determines everything. A joint that passes a static tensile test is not the same as one that will survive 20 to 30 years of wave-induced cyclic loading, corrosive marine exposure, and thermal cycling. The difference is invisible to the naked eye it lies in the state of the steel-aluminium interface deep within the strip and it is determined entirely by the manufacturing process.

There are two fundamentally different approaches to manufacturing transition joints: **vacuum explosive cladding and open-air explosive cladding**. This document analyses both approaches from a technical and economic perspective.

> ***Triplate® The Industry Benchmark***
>
> *Triplate®, manufactured by Shockwave Metalworking Technologies BV, is the world's leading vacuum explosive-clad aluminium-to-steel transition joint. Approved by Lloyd's Register, DNV, ABS, RINA and Bureau Veritas. Zero reported defects in service since 2008.*
> *Applications: shipbuilding (hull-to-superstructure), offshore living quarters, naval vessels, LNG tankers, wind turbine towers, and any structure requiring a permanent welded connection between aluminium and steel.*

2. Transition Joints Under Vacuum: Triplate® In-Depth Analysis

2.1 Operating Principle and Three-Layer Construction

Triplate® is a composite strip of three metallurgically bonded layers, produced by explosive cladding inside a sealed, evacuated vacuum chamber at 50 mBar:

- Steel base layer (Shipbuilding Grade A/D/DH36, or St52-3N): fully compatible with conventional steel welding processes SMAW, GMAW, FCAW.
- Pure aluminium interlayer (Al 99.5%, Alloy 1050A): the critical buffer zone. High ductility absorbs the shock of the bonding process and accommodates differential thermal expansion in service. Because carbon steel expands less thermally than aluminium, a responsible compressive stress builds up in the aluminium when the temperature increases. This is the reason why the strip does not warp.
- Marine aluminium top layer (AlMg4.5Mn, Alloy 5083): seawater-corrosion-resistant alloy, weldable by standard TIG/MIG procedures directly to aluminium superstructures.

Figure 1. Triplate® transition joint, three-layer composite strip (steel / Al 99.5% / AlMg4.5Mn). The three layers are visible on the end face.

Standard strip dimensions: 19, 28, and 34 mm thickness; lengths up to 3,800 mm; widths up to 1,350 mm. Custom profiles available via water-jet cutting. The recommended strip width is four times the aluminium plate thickness (4 × t). The reason for this is that it compensates for the lower mechanical value of the aluminium.

The explosive cladding process is a **cold solid-state process: no melting, no heat-affected zone, no intermetallic formation**. A precisely calibrated explosive charge accelerates the upper plate against the lower plate at supersonic velocity (200–500 m/s). The collision pressure far exceeds the yield strength of both metals just at the point of the impact, causing them to flow together at the atomic level, creating a true metallurgical bond because the valence electrons of both metals enter each other's sphere of influence. The result is a characteristic wavy interface pattern that maximises bonding surface area and shear resistance. The wavy transition is caused by the development of super-plasticity at the site of impact, allowing the shockwave to mark-off.

Optional stainless steel variant: Instead of carbon steel as the base material, stainless steel type AISI 316L can also be specified. In that configuration, a thin titanium interlayer is applied between the aluminium and the stainless steel.

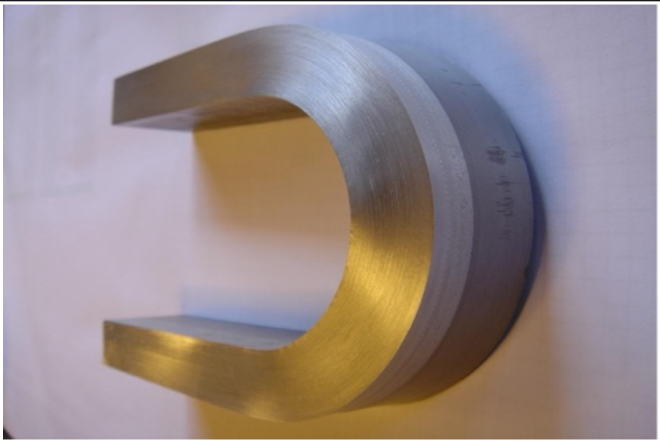

Figure 2. 180° side-bend test on Triplate®. The bond shows no cracking or delamination after bending through 180° — a direct consequence of the oxide-free vacuum-clad interface.

2.2 Interface Quality: Evidence from Science and Production

2.2.1 The Critical Role of Vacuum

The single most important differentiator between vacuum and open-air explosive cladding is what happens at the interface during the microseconds of explosive impact. In open air, atmospheric oxygen contacts the hot metal surfaces instantaneously, aluminium forms its native oxide (Al_2O_3) within microseconds of exposure. These oxides become **permanently trapped at the interface**. They cannot be removed after the fact.

In the Shockwave vacuum process, **all atmospheric oxygen is evacuated from the chamber before detonation**. There is no oxygen to react, no oxide layer to form, and no contamination at the interface. Li et al. (2024) quantified the effect of vacuum on the explosive welding process in the most comprehensive experimental study available, measuring hazard and microstructural parameters in CP-Ti/Q235 systems at 0.1 atm:

Hazard / Quality Parameter	Open-Air	Vacuum (0.1 atm)	Reduction
Peak shock wave overpressure	Reference	Reduced	−69.27%
Interstitial gas shock wave — tail end	9.27 MPa	1.16 MPa	−87.5%
Peak vessel vibration velocity	Reference	Reduced	−74.46%
Maximum sound pressure level	80–90 dB at 5 km	Reduced	−45.31%

Source: Li, X. et al. (2024). Int. J. Adv. Manuf. Technol., 130, 3741–3754. https://doi.org/10.1007/s00170-023-12892-y

Hu et al. (2025) performed a direct vacuum-vs-air comparison of Al-steel explosive welding, confirming that vacuum-welded joints show no interfacial oxidation cracks, while air-welded joints exhibit both interfacial and vertical cracking. The absence of crack nucleation sites in the vacuum-produced bond is the physical mechanism behind Triplate®'s superior fatigue performance.

2.2.2 100% Dye-Penetrant Inspection Guarantee

Because the Triplate® interface contains no oxide inclusions, every strip is subjected to **100% Dye-Penetrant (DP) inspection** before despatch. This guarantee is unique to vacuum-clad transition joints. Open-air clad manufacturers cannot offer it: the inherent oxide inclusions in their product would generate indications on every DP test, making the guarantee meaningless. The DP inspection is not a post-production check, it is the proof of process.

2.3 Mechanical Properties and Fatigue Resistance

2.3.1 Schielab b.v. Fatigue Study: Report SL 04.8939 (2004)

Schielab b.v. (Breda, Netherlands, RvA accredited laboratory L063) conducted a comprehensive fatigue characterisation of vacuum explosive welded Triplate®, commissioned by Shockwave Metalworking Technologies BV and Bayards Aluminium Constructions b.v. Five strips of Triplate® (St52.3–Al99.5–AlMg4.5Mn, 20 mm thick) were welded to test plates and machined into 15 fatigue specimens (43 × 16–17 mm cross-section, 250 mm gauge length). Testing was performed in tensile-tensile fatigue at R = 0.1, frequencies 10–12 Hz, stress range 45–90 N/mm².

Specimen	Max. Stress (N/mm²)	Cycles to Failure	Failure Location
B1	90	15,823	Al / AlMg4.5Mn interface (weld zone)
D1	85	91,924	In the Al layer
C1	80	150,215	Al / AlMg4.5Mn interface (weld zone)
D3	75	203,368	In the Al layer
A2	60	1,963,298	In the Al layer
A1	45	8,203,132*	No failure (run-out)

**Run-out — no failure after 8.2 million cycles at 45 N/mm². Source: Schielab Report SL 04.8939 rev.1, 2004.*

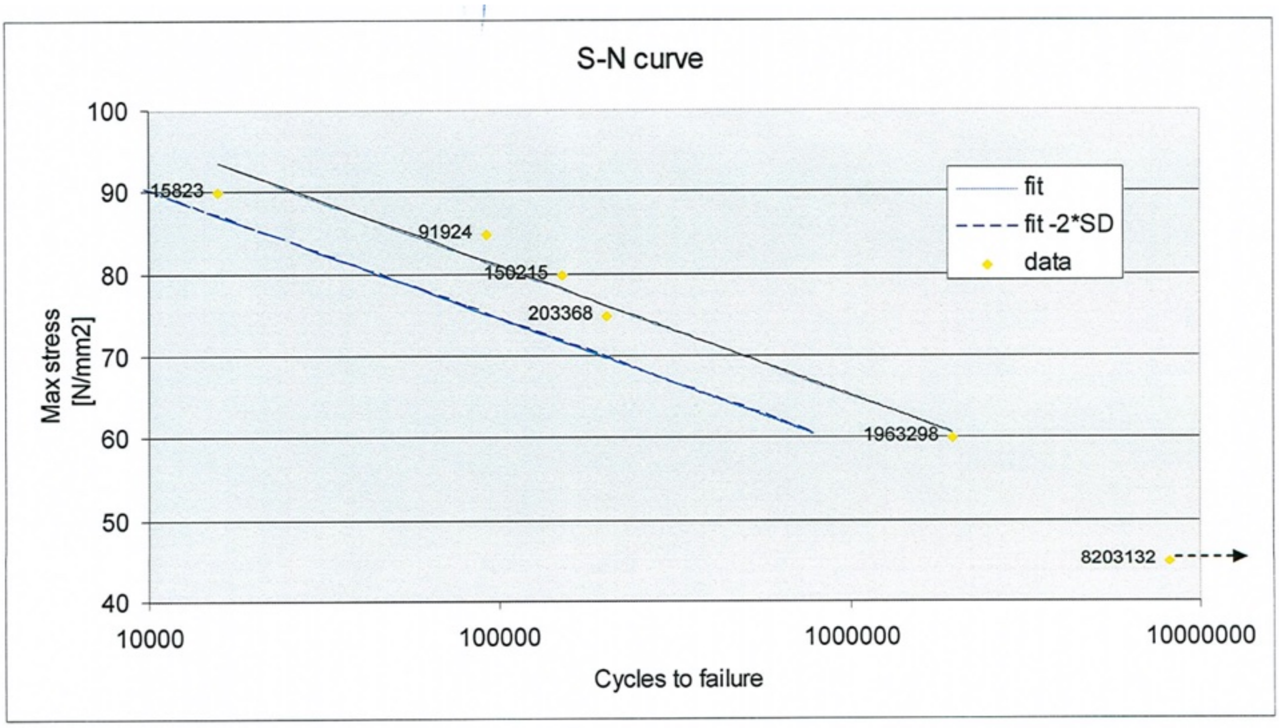

Figure 3. Fatigue Test Results: Stress Amplitude vs. Number of Cycles to Failure (N) interface.

Critical Finding: The Triplate® Bond Is Not the Fatigue Weak Link

*Apart from preliminary failures at butt weld defects, all fractures occurred at the explosive-clad interface between the two types of aluminium, or inside the Al 99.5% layer, **never at the steel-to-aluminium bond itself**. The Triplate® vacuum-clad interface outperformed the surrounding aluminium material under cyclic loading. For structural designers, this means the transition joint is not the fatigue-critical element in the connection.*

In contrast, open-air clad joints with oxide inclusions provide pre-existing crack nucleation sites precisely at the bond, the location of maximum stress concentration in any joint.

2.3.2 Meyer Werft Welding Qualification Programme

Meyer Werft (Papenburg, Germany), one of the world's leading cruise shipbuilders, conducted an extensive tensile and shear qualification programme on welded Triplate transition joints, covering eight weld configurations (1A, 1C, 2A, 3B, 4B, 5B, 6B, 8A) with varying joint geometries, weld sequences, and heat inputs.

For all configurations following the correct weld sequence (aluminium side first, steel side second, with interpass temperatures remaining well below the critical 350°C limit, recorded maxima of 182–311°C across all tests), tensile strength consistently exceeded the required 75 N/mm² minimum. Where fractures occurred, they were invariably in the AlMg4.5Mn–Al99.5% aluminium alloy zone, confirming that Triplate®'s bond integrity is not the performance-limiting factor when correct procedures are followed.

2.4 Asymmetric Welding: A Practical Advantage

In shipyard practice, structural geometry and access constraints frequently result in the transition joint being positioned off-centre relative to the neutral axis of the joint, placing it under combined tension, shear, and bending moment simultaneously. This condition is known as asymmetric welding.

For open-air clad transition joints, asymmetric welding is not acceptable. The more brittle interface, compromised by oxide inclusions, cannot withstand the additional eccentric loading without delamination risk. Classification society and fabrication standards for open-air clad products typically prohibit or restrict this configuration.

For Triplate, **asymmetric welding is acceptable**. The fully ductile, oxide-free interface absorbs eccentric loading without delamination. This advantage is verified by the Meyer Werft test programme and reflects the fundamental difference in interface ductility between the two processes. In practical terms, it simplifies joint design, reduces fabrication constraints, and lowers the risk of non-compliance during production.

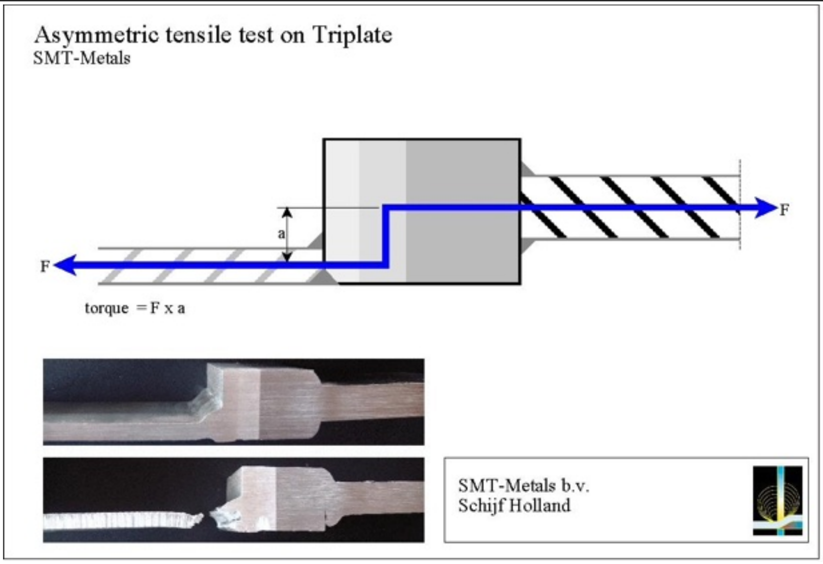

Figure 4. Asymmetric tensile test on Triplate® (SMT-Metals). The diagram shows the eccentric load path (torque = F × a). The lower photos show specimens after testing — fracture occurred in the aluminium zone, not at the bond interface.

2.5 Corrosion Resistance: The 100% Dense Interface

Interface density is not only a mechanical property, it is the primary long-term corrosion barrier. In open-air clad joints, oxide inclusions create microporosity at the interface: geometric crevices where seawater Cl^- and SO_4^{2-} concentrate, initiating galvanic and pitting corrosion. In submerged applications, the confined geometry of these crevices additionally causes oxygen depletion: once O_2 is consumed by the cathodic reaction, metal ions attract chloride ions and the resulting metal chlorides hydrolyse to produce hydrochloric acid, driving the crevice pH down and making the process self-accelerating.

The 100% dense, oxide-free Triplate® interface eliminates these pathways entirely. The bond is helium-tight, the most demanding leak-tightness standard in industrial quality control, confirming the complete absence of microporosity, as verified in production, and remains corrosion-free throughout the service life of the vessel.

Since 2008, not a single Triplate® transition joint has shown any interface defect in service. This is a **documented production quality record**, verified against the requirements of DNV, Lloyd's Register, ABS, RINA, and Bureau Veritas.

3. Open-Air Transition Joints: Limitations of the Conventional Process

3.1 The Oxide Inclusion Problem

In open-air explosive cladding, the metal plates are assembled and detonated in the open atmosphere. The interstitial gas (air) in the standoff gap is compressed by the advancing detonation front, generating a shock wave that disrupts the interface morphology and creates gas-entrapment pores.

At the moment of impact, atmospheric oxygen contacts the hot metal surfaces and forms oxide layers, Al_2O_3 in the aluminium and iron oxides in the steel. While the majority of these oxides are expelled ahead of the detonation front as part of the jet, a fraction becomes permanently trapped within the turbulent transition layer that forms preferentially during atmospheric cladding. In corrosion-critical and fatigue-loaded applications, even a minor oxide presence at the interface is sufficient to initiate the degradation mechanisms it only takes one nucleation site.

These oxides cannot be removed after production, they are built into the bond. Their consequences are:

- Crack nucleation sites: oxide inclusions are the preferred initiation points for fatigue cracks under cyclic loading. Derda et al. (2023) confirmed that 100% of fatigue failures in explosively welded bimetallic plates initiate at the interface. Under Paris Law crack growth ($da/dN = C \cdot \Delta K^n$), pre-existing interface defects bypass the crack initiation phase entirely — they are ready-made fatigue nuclei from the moment of manufacture.
- Galvanic and pitting corrosion mechanisms: oxide clusters create microporosity through which electrolytes can penetrate the interface, initiating galvanic corrosion between the dissimilar metals.
- Reduced ductility: the turbulent wave interface produced by open-air cladding is more brittle than the smooth vacuum-clad interface. Open-air clad joints are prone to cracking during bending and cannot tolerate asymmetric welding loads.
- No Dye-Penetrant inspection guarantee: because oxide inclusions are inherent to the process, a full Dye-Penetrant inspection would generate indications across the interface. Open-air clad manufacturers therefore do not offer a Dye-Penetrant guarantee.

Hammer Bend Test: visual demonstration of trapped oxide consequences: The consequences of turbulence-trapped oxides can be directly demonstrated by the Hammer Bend Test (MIL-J-24445A). A narrow clad strip is clamped at the bonding interface in a bench vice and the protruding part is bent 90° with a hammer. In open-air clad joints, the oxide conglomerates trapped in the turbulent transition layer open out visibly during this test, confirming the presence of interface defects that no post-production inspection can eliminate. In vacuum-clad Triplate® joints, the clean laminar or mildly wavy interface withstands the test without any visible defect formation.

Figure 5. The consequences of the Hammer Bend Test (MIL-J-24445A). Left: vacuum-clad Triplate®: interface intact, no defect formation. Right: open-air cladding: oxide conglomerates open out visibly at the turbulent transition layer. Source: Buijs, N.W. (2010). Explosive Welding of Metals in a Vacuum Environment. Stainless Steel World, March 2010. (Photo: Innomet b.v.)

3.2 In-Service Failure Evidence: The BAM Naval Vessel Case

The consequences of open-air clad interface defects in service are documented in an official investigation report published by the Spanish Navy's Arsenal de Las Palmas in July 2019 (Informe grieta en las placas bimetalálicas de los buques de acción marítima (BAM), Jesús Moreno Rodríguez, 09/07/2019).

During routine maintenance of the four BAM-class offshore patrol vessels (Meteoro, Rayo, Relámpago, Tornado), **fatigue cracks were discovered** in the open-air clad bimetallic transition plates connecting the aluminium superstructure to the steel hull. Key findings:

- Cracks consistently located at the steel-aluminium interface boundary of the bimetallic plate, exactly where oxide inclusions act as nucleation sites.
- Crack lengths of 135 to 200 cm, with gap widths of 0.9 to over 3 mm. On the Relámpago, air conditioning air was detectable escaping through the cracks in the mast.
- Cracks originated at structural corners, the highest stress concentration points under hull bending moments. The investigation confirmed these locations correspond to the master frame, one of the structurally most demanding positions on the vessel.
- All four vessels affected. Three vessels showed through-cracks in the guardacalores (funnel casing); one vessel showed through-cracks in the mast bimetallic plate as well.
- The report explicitly concluded: "es de esperar que estas grietas se sigan propagando" (these cracks are expected to continue propagating).

Figure 6. Crack in the port-side (Br) heat shield of the Meteoro

Figure 7. Crack in the port-side (Br) heat shield of the Meteoro

Figure 8. Crack in the port-side (Br) heat shield of the Meteoro

Figure 9. Crack in the startboard-side (Er) heat shield of the Rayo

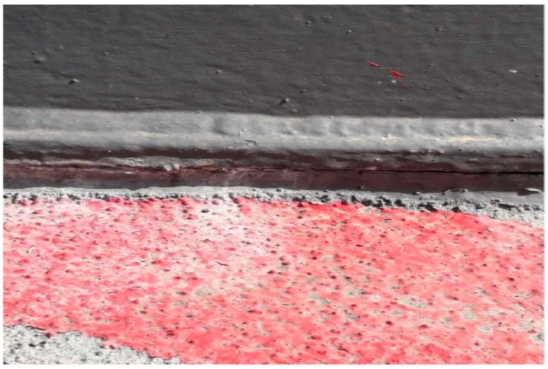

Figure 10. Crack in the port-side (Br) heat shield of the Meteoro

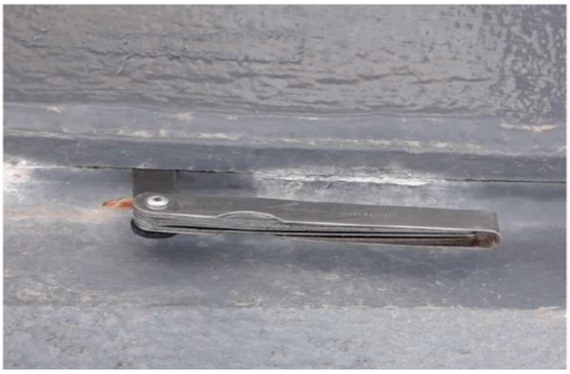

Figure 11. Continuation of the crack at the port-side (Br) bow corner of the Rayo's mast, with a 0.9 mm feeler gauge inserted

Sources: Moreno Rodríguez, Spanish Navy (2019). Several cases of disbonding in Open-Air Transition-Joints

The BAM Failure Mode: A Textbook Open-Air Clad Consequence

The BAM failures are not anomalies. They are the predictable result of oxide inclusions at an open-air clad interface acting as pre-existing fatigue nuclei under hull bending cycles. The sequence is: (1)oxide inclusion at interface acts as stress concentrator; (2) crack initiates at oxide cluster under first cyclic loading; (3) crack propagates under Paris Law with each wave-induced bending cycle; (4) through-crack develops after sufficient cycles; (5) structural integrity compromised.

This failure mode is ***physically impossible in a vacuum-clad Triplate® joint****. There are no oxide inclusions to initiate the crack. The interface is the fatigue-strong element: not the fatigue-weak element.*

3.3 Comparative Performance Table

Property	Open-Air Explosive Cladding	Vacuum Cladding (Triplate®)
Interface oxides	Present: trapped permanently	None: oxygen-free process
DP inspection guarantee	Not available	100% guaranteed, every strip
Bending without cracking	Limited: brittle interface	Full 180° side-bend, no cracking
Fatigue strength	Limited: pre-existing nuclei at bond	Optimised: failures in Al layer, not bond
Asymmetric welding	Not acceptable	Acceptable: independently verified
Corrosion at interface	Oxides initiate galvanic / pitting corrosion	No pitting or galvanic corrosion
Interface ductility	Reduced: turbulent wave morphology	Full ductility: smooth wave morphology
In-service defects	BAM vessel cracks (2019) + others	Zero defects reported since 2008
Class approvals	Variable by manufacturer	DNV, Lloyd's, ABS, RINA, BV

Sources: Li et al. (2024); Hu et al. (2025); Schielab SL 04.8939 (2004); Meyer Werft testing; Moreno Rodríguez, Spanish Navy (2019).

4. Cost Analysis: Initial Cost vs. Total Cost of Ownership

A cost comparison that considers only the initial purchase price of transition joints is fundamentally misleading. The correct basis for comparison is **Total Cost of Ownership (TCO) over the design life** of the vessel or structure, typically 20 to 30 years. The modest premium, if any, of vacuum-clad Triplate® over open-air clad alternatives is recovered within the first avoided maintenance event.

4.1 Initial Material and Process Cost

Cost Factor	Open-Air Explosive Cladding	Vacuum Cladding (Triplate®)
CRA material efficiency	100%: no dilution	100%: no dilution
Interface defect rejection rate	5–15% (edge / tail-end defects)	<0.1%: vacuum process control
DP inspection pass guarantee	Not offered	100% guaranteed
Logistics cost	Higher: remote site production at some suppliers	Low: full factory production
Relative initial price index (*)	~100	~100–110

The initial cost difference between vacuum and open-air clad transition joints is marginal, typically 0–10% depending on the supplier and specification. This premium exists because of the more controlled production environment and the additional quality assurance steps (100% DP inspection). It does not reflect a difference in raw material cost, since both processes use the same alloy combinations.

4.2 Total Cost of Ownership (TCO)

TCO Component	Open-Air Cladding	Vacuum Cladding (Triplate®)
Initial bond quality	Moderate: gas/oxide cracks present	✓ Highest: all defects eliminated
In-service inspection interval	Shorter: pre-existing crack nuclei	✓ Longest: minimal a_0, slower crack growth
Fatigue crack growth risk	Elevated: Paris Law from $a_0 > 0$	✓ Lowest: no pre-existing nuclei
Corrosion maintenance cost	Moderate: oxide pathways degrade with time	✓ Lowest: no interface corrosion pathways
Unplanned downtime risk	Moderate to high (BAM case: 200 cm cracks)	✓ Lowest: zero service defects since 2008
Repair / replacement cost	High: requires dry-dock, structural work	✓ Avoided entirely
Overall TCO assessment	Moderate to high lifecycle cost	✓ Lowest lifecycle cost

Figure 12. Unscheduled repainting job with Open-Air Transition-Joints (Condor)

Figure 13. Crack in the port-side (Br) heat shield of the Meteoro

Figure 14. Corner of the Meteoro's mast

Figure 15. Corner of the port-side (Br) heat shield of the Relámpago

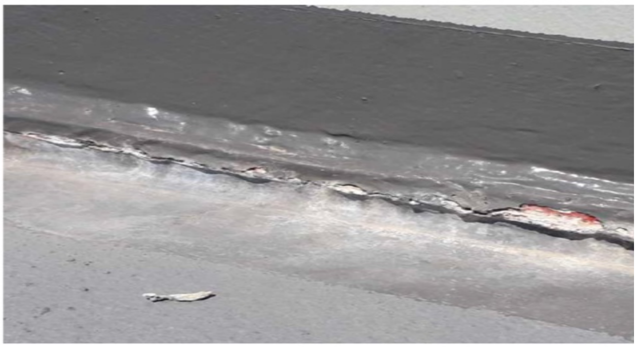

Figure 16. Continuation of the crack from the bow to starboar-side (Er) corner of the Relámpago's mast

4.3 The Cost of Failure: A Real Case Study

The BAM naval vessel case provides a concrete quantification of the cost consequences of open-air clad transition joint failure. The four vessels required:

- Immediate investigation by specialist hull engineers, dry-dock inspection across all four vessels.
- Temporary repair by epoxy filling (Hempel Epoxi filler) to seal through-cracks up to 200 cm long and 3 mm wide, not a structural repair, only a temporary seal.
- Structural repair at next scheduled dry-dock: removal and replacement of the cracked bimetallic plates. For cracks 135–200 cm long in structural positions at the master frame, this is a significant shipyard operation involving cutting, fit-up, welding, NDT, and repainting.
- Operational impact: vessels affected while in service (the Relámpago had air conditioning air escaping through cracks in the mast, indicating compromise of a pressure-separated space).

The total cost of this event, inspection, temporary repair, permanent repair, downtime, and classification society involvement, across four vessels **substantially exceeds the entire cost of the transition joints originally installed**. A transition joint that costs marginally more at purchase but eliminates this failure mode entirely is not a cost premium, it is cost elimination.

> ***The TCO Argument***
>
> *The premium for Vacuum Explosion Triplate® over open-air clad alternatives is typically 0–10% on initial manufacturing cost. A single avoided crack repair in dry-dock covers this premium several times over. For operators with vessels in demanding cyclic loading environments, the choice is not between a cheap joint and an expensive one: it is between a joint that requires eventual expensive repair and one that does not.*
>
> *Since 2008, Shockwave Metalworking Technologies BV has not received a single defect report from any Triplate® transition joint in service. This is the most powerful cost argument available.*

5. Conclusion

The analysis presented in this document leads to three conclusions that are supported by independent experimental data, classification society approvals, and in-service evidence spanning more than 15 years of production.

First: The vacuum explosive cladding process is **the only transition joint manufacturing method that eliminates oxide inclusions** at the steel-aluminium interface. This difference is not cosmetic, it directly determines fatigue performance, ductility, resistance to asymmetric welding, and long-term corrosion behaviour. The physics are clear: no oxides means no pre-existing crack nucleation sites, which means longer fatigue life, higher ductility, acceptable asymmetric welding, and a corrosion-tight interface. These properties cannot be achieved through post-production treatment, they are either built in during the vacuum process or they are absent.

Second: The consequences of open-air clad transition joint failure in service are severe and well-documented. The Spanish Navy BAM investigation is not an isolated incident, it is a representative example of the failure mode that all open-air clad products carry as an inherent risk. The mechanism (oxide inclusion → fatigue crack initiation → Paris Law propagation → through-crack) is predictable, and the consequences (dry-dock repair, operational disruption, replacement cost) are disproportionate to the initial cost saving that motivated the specification of an inferior product.

Third: The Total Cost of Ownership argument strongly favours Triplate®. The initial price premium, where it exists, is marginal and recoverable within a single avoided maintenance event. The **zero-defect record since 2008** is not a marketing claim, it is a documented quality record that no open-air clad manufacturer can match. For any application where long-term structural reliability matters, Triplate® is not the expensive choice: it is the economically rational choice.

Final Scientific Synthesis

Triplate® vacuum explosive-clad transition joints deliver quantified superiority on every dimension that determines long-term value: (1) maximum interface quality, gas and oxidation defects eliminated at source; (2) optimised fatigue strength, the bond outperforms the surrounding aluminium material under cyclic loading; (3) full ductility, 180° side-bend without cracking, asymmetric welding acceptable; (4) 100% dense, corrosion-tight interface, no galvanic or pitting corrosion pathways; (5) lowest Total Cost of Ownership of any available transition joint process.

Sources: Li et al. (2024); Hu et al. (2025); Schielab SL 04.8939 (2004); Meyer Werft qualification programme; Moreno Rodríguez, Spanish Navy (2019); DNV, Lloyd's Register, ABS approval certificates.

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All numerical data and technical claims in this document are traceable to primary sources. Links are provided for direct access to each publication.

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