SHOCKWAVE

VACUUM EXPLOSION CLAD

The State-of-the-Art
Cladding Technology

Comparative Technical-Scientific Analysis

Vacuum Explosion Clad · Open-Air/Atmospheric Explosive Welding · Roll-Bond · Weld Overlay

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1. Introduction and Industrial Context

Bimetallic cladding is one of the most impactful manufacturing technologies in the process industry. Its principle is to combine the mechanical properties of a low-cost structural substrate with the corrosion, wear or high-temperature resistance of a high-performance metal, called CRA (*Corrosion Resistant Alloy*). The result is components with a significantly longer service life at a substantially lower cost than those manufactured entirely from solid noble material, with savings ranging from 50% to 85% depending on the material and thickness.

Its application is indispensable in the **petrochemical, nuclear, aerospace, naval and power generation industry**, where equipment must simultaneously withstand extreme mechanical loads and are highly corrosive. Hydrogenation reactors, gas separators, heat exchangers, pressure vessels for concentrated acids or hydrogen electrolysis systems are representative examples of equipment where cladding is not an option but a technical and economic necessity. In all these cases, the steel substrate provides structural integrity while the CRA layer, titanium, nickel (alloys), copper (alloys), zirconium or austenitic stainless steel, acts as a protective barrier against the process medium.

The quality of the bond between both layers is the determining factor for long-term performance. An interface with defects, pores, microcracks, brittle intermetallic compounds or dilution zones, not only reduces the mechanical properties of the composite, but creates preferential corrosion attack pathways, compromising the protective barrier and drastically shortening the equipment's service life. For this reason, the clad plate manufacturing method is not a trivial decision: different processes produce interfaces of radically different quality, with direct consequences for reliability, maintenance cost and operational safety in service.

There are four main methods for manufacturing industrial clad plates: **vacuum explosive welding**, **open-air/atmospheric explosive welding**, **hot roll bonding** and **weld overlay**. Each presents fundamental differences in bonding mechanism, interface quality, resulting defectology, compatible materials and operational feasibility. This document analyses these four methods from a rigorous scientific perspective, demonstrating through experimental data from indexed academic literature that **Vacuum Explosion Clad represents the technological state of the art** in the manufacture of bimetallic plates for demanding applications.

2. Vacuum Explosion Clad, In-Depth Analysis

2.1 Operating Principle

Vacuum explosive welding is a solid-state bonding process in which a controlled explosive charge accelerates a flyer plate at high velocity against a base plate inside a spherical vessel evacuated to 0.05 atm. The collision generates a pressure of several thousand bars that far exceeds the yield strength of both metals, causing the material to become superplastic in highly localized zones. There are even indications that some atomic layers briefly turn to a fluid state due to this enormous pressure, even though the overall temperature rise remains negligible.

The detonation simultaneously generates a shockwave that propagates through both metal layers in a manner analogous to ripples in water. Due to the superplasticity of the metals at the collision zone, this shockwave produces the characteristic wave pattern at the bonding interface, a pattern that is often visible to the naked eye in a cross-section of the finished clad plate.

The high velocity of the process expels any freshly formed oxides from both surfaces as a flow of matter, known as the “jet”, that races just ahead of the detonation front. This action leaves behind clean metal surfaces that have no time to re-oxidise, a prerequisite for the formation of the metallurgical bond.

The metallic bond is produced as a result of the high pressure still present at the collision point, which forces the valence electrons of each metal into the sphere of influence of the other. Since the entire process is carried out at ambient temperature, explosive welding is classified as a variant of the cold pressure welding process. Buijs, N.W. (2010). *Explosive Welding of Metals in a Vacuum Environment.* Stainless Steel World.

The detonation propagates at 4,000–6,000 m/s, accelerating the flyer plate across the standoff gap to several hundred metres per second before impact. In the Shockwave process the complete assembly is placed in a vacuum chamber evacuated to 50 mbar (0.05 atm) prior to detonation, eliminating the interstitial gas and atmospheric oxygen that cause the defects analysed in the remainder of this document. (A step-by-step description is given in the internal training document ‘Training explosive welding’, chapter 4.)

> **Key differentiator from the conventional process**
> *The elimination of interstitial gas between the plates prior to detonation distinguishes Vacuum Explosion Clad from all other methods. In atmosphere, the compressed gas generates an interstitial shock wave of up to 15.4 MPa that disrupts the process and produces pores and microcracks. Under vacuum, this pressure is reduced to 1.66 MPa — an 89% reduction. — Li et al. (2024).* ***1.66MPa is with 0.1atm, Shockwave uses an extreme 0.05 atm, hence reducing this number even further.***

2.2 Interface Quality — Evidence from Science and Production

2.2.1 Quantified Reduction in Hazardous Effects

Li et al. (2024) conducted the most comprehensive experimental study available in the literature on vacuum vs. atmospheric explosive welding, using calibrated pressure, vibration and noise sensors in CP-Ti/Q235 experiments in a spherical vacuum vessel:

Hazard Parameter	Atmosphere	Vacuum (0.1 atm)	Reduction
Peak shock wave overpressure	Reference	−69.27%	−69.27%
Specific shock wave impulse	Reference	−74.99%	−74.99%
Peak vessel vibration velocity	Reference	−74.46%	−74.46%
Ground vibration velocity	Reference	−29.45%	−29.45%
Maximum sound pressure level (SPL)	80–90 dB at 5 km	−45.31%	−45.31%
Interstitial gas shock wave — tail end	9.27 MPa	1.16 MPa	−87.5%

Source: Li, X. et al. (2024). Int. J. Adv. Manuf. Technol., 130, 3741–3754.

2.2.2 Microstructural Interface Quality, OM Photographic Evidence

Optical microscopy (OM) of specimens after processing under both conditions directly and visually demonstrates the difference in interfacial morphology. Fig. 1 shows the four experimental conditions: central zone and tail-end zone of the plate, in atmosphere and in vacuum.

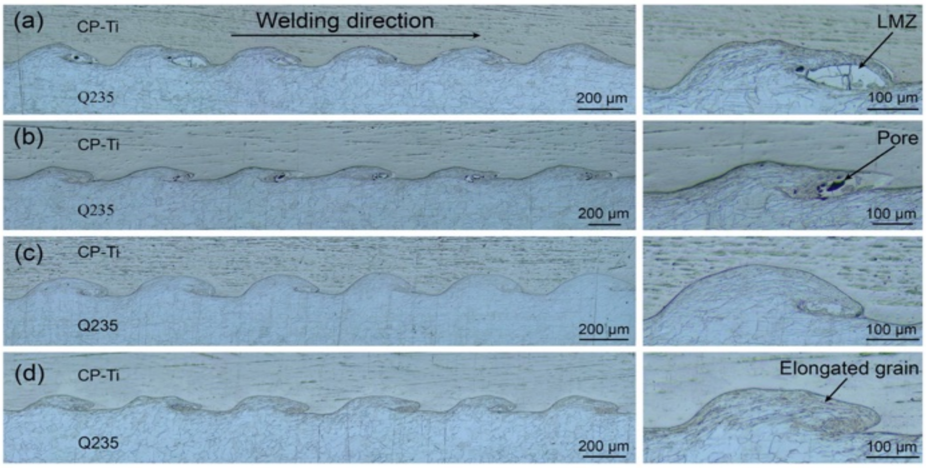

Figure 1: OM images of the CP-Ti/Q235 bonding interface: (a) central zone in atmosphere (regular waves with LMZ); (b) tail-end zone in atmosphere (flat waves, Pore visible); (c) central zone in vacuum (uniform waves); (d) tail-end zone in vacuum (stable waves, Elongated grain). Vacuum eliminates tail-end irregularity and suppresses pore formation. Source: Li et al. (2024).

Plate region	Condition	Velocity Vp (m/s)	Collision angleβ (°)	Assessment
Central zone	Atmosphere	806.0	16.69	Stable
Central zone	Vacuum	818.1	16.85	Stable
Tail-end zone	Atmosphere	655.5 (−18.7%)	19.95 (+20%)	⚠️ Irregular
Tail-end zone	Vacuum	771.6 (−5.7%)	17.21 (+2%)	✓ Stable

2.2.3 Wave Pattern Morphology, Laminar, Wavy and Turbulent Transitions

The shockwave generated during explosive welding can produce three distinct interface morphologies depending on the energy of the detonation: laminar, wavy, and turbulent. Understanding these transitions is essential to appreciating the quality advantage of the vacuum process.

A **laminar transition**, produced at lower explosive energy, is the most metallurgically ideal. The interface is clean, free of oxide inclusions, brittle intermetallic phases, and micro-cracks, and the mechanical properties of both metals remain virtually unchanged.

A **wavy transition** the characteristic sinusoidal morphology documented in the micrographs of this report, provides a robust bond while remaining free of entrapped oxides when wave amplitude is controlled.

A **turbulent transition** occurs when the wave peaks grow large enough to curl over, analogous to ocean waves breaking. In doing so, they trap portions of the oxide-laden jet as pockets within the wave crests. These oxide conglomerates are both porous and hygroscopic, and in corrosion-critical applications they provide a pathway for aggressive species to concentrate at the interface, accelerating localized attack. High-amplitude turbulent interfaces are also associated with micro-cracking at the wave peaks due to internal shear within the metal lattice, a risk particularly pronounced with less ductile metals such as titanium and zirconium.

Turbulent transitions occur primarily during atmospheric cladding because significantly more explosive energy is required to move the interstitial air, increasing shockwave intensity. The trapped oxides cause a weakening in the transition zone that becomes directly visible during the Hammer Bend Test (MIL-J-24445A): when a clad strip is bent 90° at the interface, oxide pockets open out visibly, a failure mode that does not occur with a clean laminar or wavy vacuum interface.

Vacuum Explosion Clad consistently produces laminar or mildly wavy transitions because the lower explosive charge required, no air to displace, keeps shockwave energy below the threshold for turbulent wave formation, practically eliminating oxide entrapment. Buijs, N.W. (2010). *Explosive Welding of Metals in a Vacuum Environment.* Stainless Steel World.

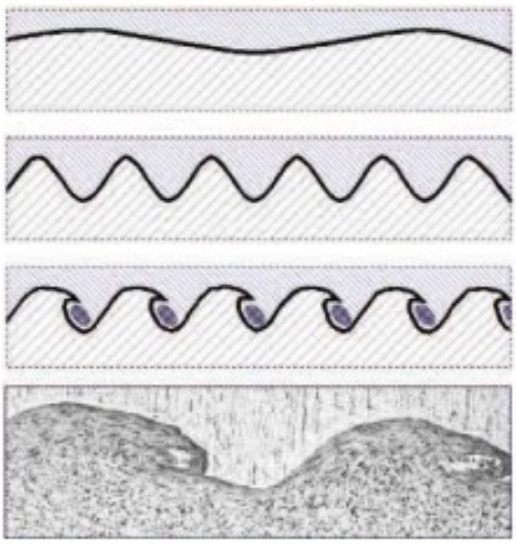

Figure 2: Three types of transitions resulting from explosion welding – laminar, wavy and turbulent.

2.2.4 Microstructural Interface Quality; Production Evidence Shockwave

The following micrographs are taken directly from Shockwave, documenting vacuum explosive cladding of UNS N06600 (Inconel 600) on P355GH carbon steel. Plates up to 8,000 × 2,000 mm, tested to ASME SA 578 Level B (100% UT) and EN 13445-2. All six plates passed every test, with shear strengths of 441–487 MPa against a minimum requirement of 140 MPa.

Figure 3: Macro cross-section of UNS N06600/P355GH vacuum explosive clad interface at 5× magnification (Adler etch). Clean, well-defined bond zone with characteristic wavy morphology. No porosity or cracking. Source: SMT Inspection Report, Shear strength 441–487 MPa (min. req. 140 MPa).

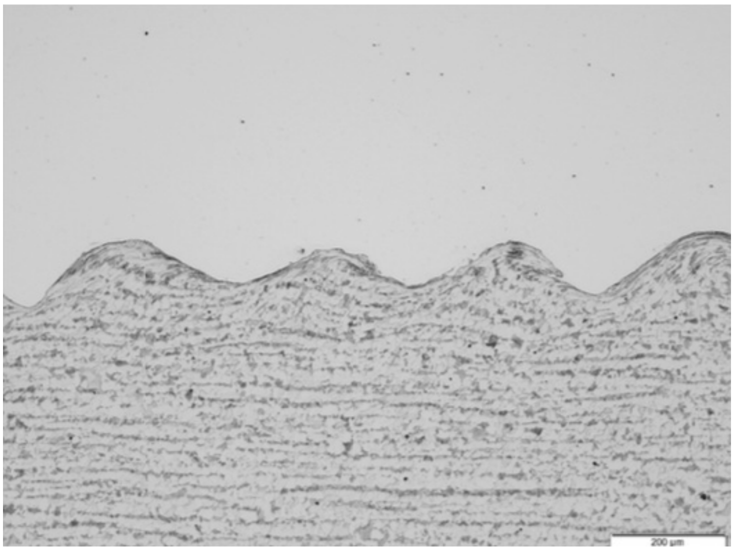

Figure 4: Optical micrograph of the vacuum explosive clad transition zone at 100× (3% nital etch). Wavy bonding interface with complete metallurgical continuity. "Good fusion was noted at the transition zone." Source: Shockwave, tested at an external laboratory; Element Breda under 3.2 LRQA

> **Interface quality conclusion**
> *Vacuum Explosion Clad is the only method that eliminates the root cause of gas-related interface defects, producing a uniform bonding interface across the entire plate, including the tail-end regions most prone to defects in atmospheric welding. The Shockwave production data above demonstrates that the vacuum process meets the most stringent quality criteria without post-treatment. Li et al. (2024); Shockwave IR-17267 (2018).*

2.3 Demonstrated Mechanical Properties

Rouzbeh et al. (2020) manufactured identical AA1050/Mg-AZ31B bilayers by both explosive welding and roll bonding under controlled conditions, providing the most direct available comparison of the two processes:

Mechanical Property	Explosive Welding	Roll-Bond	Advantage Explosive Welding
Tensile strength (MPa)	**270**	110	**+145%**
Elongation (%)	**13.5**	10.3	**+31%**
Work of fracture (MJ/m^3)	**28.6**	5.64	**+407%**
Failure mode	**Simultaneous — monolithic**	Layer-by-layer	Superior integrity

Source: Rouzbeh, A. et al. (2020). J. Mater. Eng. Perform. DOI: 10.1007/s11665-020-05126-9. Work of fracture is the energy absorbed per unit area before failure, the +407% advantage quantifies why explosive welded joints absorb five times more energy under shock, fatigue and thermal loading.

In Ti/steel systems, Cui et al. (2020) measured shear strengths exceeding 350 MPa with bending to 135° without delamination, well above ASTM B898 requirements. Shockwave production data demonstrates 441–487 MPa on UNS N06600/P355GH in industrial production.

Unique material capability

Explosive welding is the only solid-state process capable of bonding physically incompatible dissimilar metals: Ti/steel, Ti/SS, Cu/steel, Al/steel, Zr/steel, Inconel/steel. No other cladding method achieves this material versatility. Findik (2011); Sherpa et al. (2023); Kumar et al. (2025).

2.4 Corrosion Resistance, Mechanism and Evidence

2.4.1 Three Fundamental Advantages: Zero Dilution, No HAZ, No Oxidation

As a solid-state process with no fusion, Vacuum Explosion Clad preserves the full nominal composition of the CRA throughout its entire thickness. Three mechanisms explain its superiority over all fusion-based processes:

- **Zero dilution:** The bonding mechanism involves no melting. The CRA retains 100% of its nominal alloy composition down to the interface, including Cr, Mo, Ni and Nb. This is in direct contrast to weld overlay, where Fe from the substrate dilutes the CRA on every pass.
- **No heat-affected zone (HAZ):** Without thermal cycles, there is no sensitisation ($Cr_{23}C_6$ precipitation), no grain coarsening and no δ-ferrite formation, all of which degrade corrosion resistance in fusion processes.
- **No oxidation (vacuum-specific advantage):** In open-air/atmospheric explosive cladding, atmospheric oxygen contacts the hot collision zone for microseconds, sufficient to form brittle alpha-case in titanium and oxide inclusions in nickel alloys. Vacuum eliminates this entirely. Li et al. (2024) documented multiple cracks and fragmented metal in the solidified melt zones of atmospherically welded interfaces, with none present under vacuum (Fig. 5); Zeng et al. (2019) independently confirmed on titanium/steel plate that the gaseous medium in the standoff gap directly governs interfacial microstructure and mechanical properties.

2.4.2 SEM Evidence, Cracks and Pores vs. Clean Interface in Vacuum

Fig. 5 shows high-resolution SEM images of the interface under both process conditions. The difference is unequivocal: in atmosphere, the solidified melt zone harbours multiple microcracks and fragmented metal ("Broken metal"); in vacuum, the same interface zone shows none of these defects.

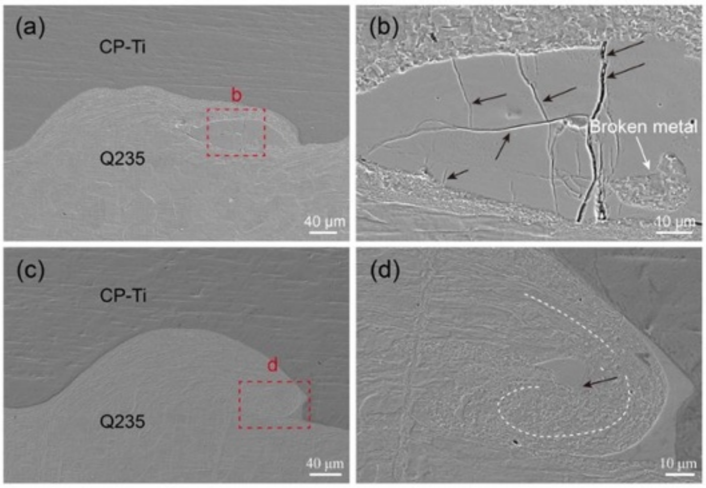

Figure 5: SEM images of the CP-Ti/Q235 interface: (a,b) atmospheric process, solidified melt zone with multiple cracks ("Crack") and fragmented metal ("Broken metal") clearly visible; (c,d) vacuum process, the same interface zone shows no cracks. Cracks in atmosphere are direct corrosion initiation sites. Source: Li et al. (2024)

Zhao et al. (2022) quantified the electrochemical behaviour through potentiodynamic polarisation tests: the corrosion potential (Ecorr) of the clad plate is significantly more positive than that of carbon steel, and the corrosion current density (icorr) is one order of magnitude lower.

2.4.3 Production Evidence of Interface Integrity

The optical micrograph below shows the Shockwave UNS N06600/P355GH interface unetched, the most demanding test for surface defects, as no chemical contrast is applied to mask defects that may be present. The interface shows no pores, no oxidation cracks and no melt-zone fragmentation.

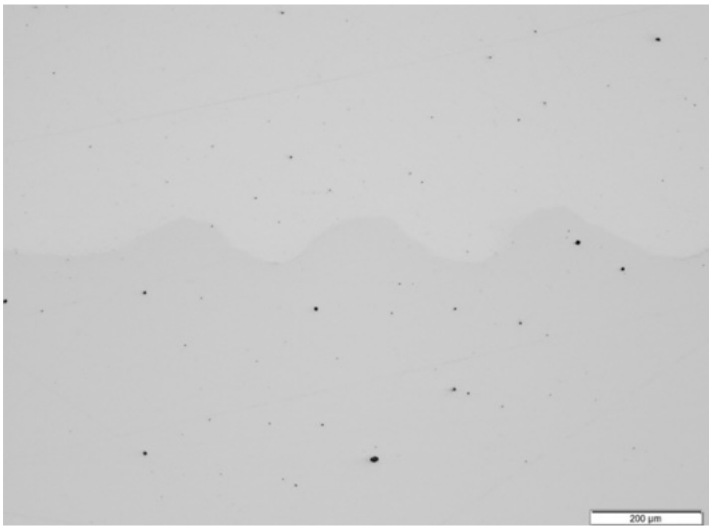

Figure 6: UNS N06600/P355GH Shockwave's vacuum explosive clad transition zone at 100× magnification, unetched polished section. Zero gas-entrapment pores, zero oxidation cracks, zero melt-zone defects. Source: Shockwave Inspection Report IR-17267 under 3.2 LRQA.

2.4.4 Three Localised Corrosion Failure Modes Eliminated

- **Crevice corrosion:** Pores at the interface create geometric crevices where Cl^- and SO_4^{2-} concentrate and oxygen depletes, driving self-accelerating corrosion. Vacuum bonding eliminates interface pores.
- **Stress corrosion cracking (SCC):** Microcracks act as stress concentrators. In H_2S, Cl^- or CO_2 environments, the combination of tensile stress and corrosive medium satisfies SCC initiation criteria. NACE MR0175/ISO 15156 identifies these sites as primary initiation points in sour service.
- **Galvanic disbonding:** A microcrack penetrating to the steel creates a galvanic cell between the noble CRA cathode and the active steel anode. The large cathode/anode area ratio severely accelerates steel corrosion, the opposite of the cladding's purpose.

2.4.5 PWHT and Intermetallic Compounds (IMC)

Post-Weld Heat Treatment (PWHT) above ~450°C activates thermally-driven diffusion that grows Intermetallic Compound (IMC) layers at the interface, brittle phases such as FeTi and Fe_2Ti that are mechanically weak, crack under load, and act as preferential intergranular corrosion pathways. The ASME PWHT requirement for carbon steel vessels (595–620°C) far exceeds this threshold, making PWHT management critical. Vacuum Explosion Clad provides the largest safety margin: by starting from an interface with fewer melt zones and no gas-induced defects, the IMC growth threshold takes longer to become critical.

2.4.6 KOH Environment, (Green) Hydrogen Applications

Alkaline electrolyser pressure vessels operate in KOH (potassium hydroxide, pH >13) with O_2 and H_2 under pressure. KOH is highly corrosive and penetrates any interface defect, triggering alkaline stress corrosion cracking (ASCC) in carbon steel. Additionally, O_2 accumulated in interface voids under pressure accelerates steel corrosion. Vacuum Explosion Clad eliminates both failure pathways at source by eliminating the defects that enable them.

2.4.7 IGC Test ASTM G28 Method A

The intergranular corrosion (IGC) test per ASTM G28 Method A (Huey test) is performed on SPWHT coupons to verify that the CRA layer is not sensitised after the vessel fabrication thermal cycles. For Vacuum Explosion Clad, the absence of a HAZ means the CRA layer is not pre-sensitised at manufacture.

2.5 Microcracks, Formation, Detection and Long-Term Consequences

2.5.1 What Microcracks Are and Why They Are Critical

Microcracks in explosion-bonded clad plates are sub-millimetre discontinuities, typically 0.03–0.2 mm, that form at the interface during the bonding process. They are invisible to the naked eye, routinely undetected by standard UT, and can determine whether a vessel lasts 30-40 years or fails prematurely.

The quantified consequence: in a tensile-instability model of explosion-welded steel/Al plate, validated against experiment (Huang et al., 2023), increasing interface crack length from **0.03 mm to 0.2 mm reduces uniform elongation by 92.52%**, a catastrophic drop from cracks completely invisible to the naked eye. This single data point explains why process selection is not a secondary specification detail: it determines whether the composite plate behaves as engineered.

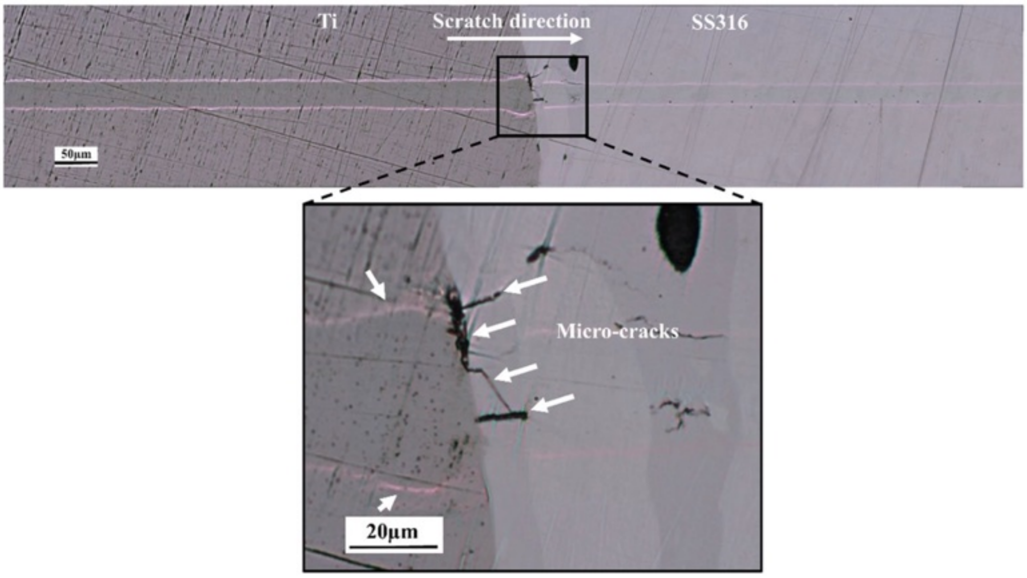

Figure 7: Optical micrograph of micro-cracks at the Ti/SS316 explosive weld interface (atmospheric process). Multiple cracks initiate at a wave-crest defect node and propagate into the transition zone. Source: Journal of Materials Research and Technology, 2023, Sherpa et al. (2023), ref [14].

2.5.2 Three Independent Formation Mechanisms

- **Gas-entrapment cracking:** Gas compressed in the standoff gap generates shock waves up to 15.4 MPa that destabilise the flyer plate trajectory, producing pores and associated cracks. Under vacuum at 0.1 atm this drops to 1.66 MPa, below the level at which pore formation is observed, no gas-entrapment pores were found in vacuum-welded specimens (Li et al., 2024); ELIMINATED at source. At Shockwave's 0.05 atm, the reduction is greater still.
- **Oxidation-induced embrittlement:** Contact with atmospheric oxygen during the microseconds of hot collision forms brittle alpha-case in titanium and oxide inclusions in nickel alloys. Oxide-related interfacial cracking is documented in atmospherically welded joints (Li et al., 2024; Zeng et al., 2019). Under vacuum; ELIMINATED.
- **Intermetallic melt-zone cracking:** Localised melting at wave crests forms brittle IMC (TiFe, $TiFe_2$, TiO_2, Fe_2O_3). Rapid solidification cracks the intermetallic material. Vacuum reduces melt zone size and hence crack density; REDUCED.

2.5.3 Real Microcracks, SEM-BSE Images (Cui et al., 2020)

Fig. 8 shows SEM-BSE images of the Ti/low-alloy steel interface after three-point bending test. The two microcrack types identified by Cui et al. (2020) are clearly visible: crack in the IMC region (red arrow) and crack in the 3 µm diffusion layer (green arrow). Subpanels (b) and (c) show the same zone before and after bending, confirming that microcracks pre-exist before testing and propagate under load.

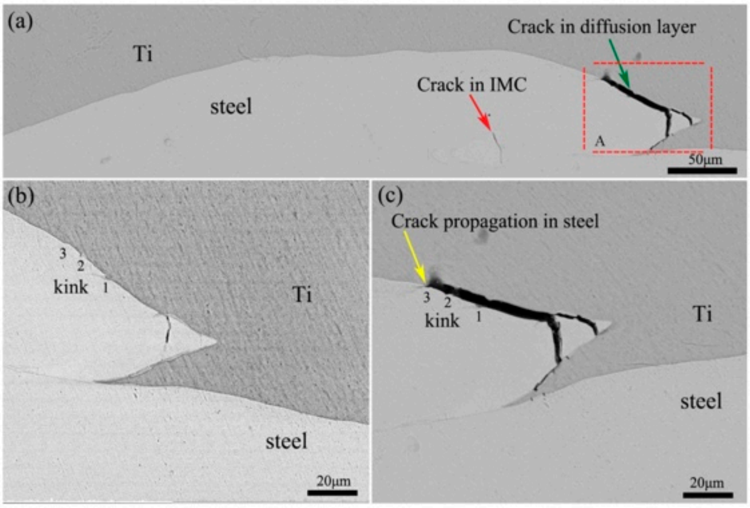

Figure 8: SEM-BSE images of microcracks at the Ti/low-alloy steel interface (atmospheric process): (a) general view after bending, "Crack in IMC" (red arrow) and "Crack in diffusion layer" (green arrow); (b) detail zone A before bending, pre-existing microcracks; (c) detail zone A after bending — significant microcrack propagation. Source: Cui et al. (2020), Fig. 11. Licence CC BY 4.0.

2.5.4 Long-Term Degradation Under Cyclic Loading

Microcracks do not remain static in service. Under cyclic pressure loading, inherent in every pressure vessel during start-up/shutdown cycles and operational fluctuations, pre-existing interface cracks grow according to Paris Law: **$da/dN = C \cdot \Delta K^n$**, where the crack growth rate per cycle is determined by the stress intensity factor range ΔK at the crack tip. **A smaller initial crack size (a_0) requires far more cycles to reach the critical size for failure.**

For atmospheric explosive cladding, gas-entrapment pores and oxidation cracks bypass the initiation phase, they are pre-existing fatigue nuclei from the moment of manufacture. Derda et al. (2023) showed that fatigue failures in Ti- and Zr-based heterostructured clad plates initiate at interfacial defect-like structures (melted zones, microcracks, shear bands). Karolczuk et al. (2020) tracked crack growth in Zr/Ti/steel composites and confirmed progressive disbonding as the life-limiting mechanism. Research by Karolczuk et al. (Metals, MDPI, 9(3):338, 2019) provides directly applicable fatigue crack growth rate data for clad plate qualification, including the influence of interface condition on threshold stress intensity and Paris exponent.

The practical implication: Vacuum Explosion Clad's reduced initial crack population (a_0 smaller by elimination of gas-entrapment and oxidation cracks) means the plate must accumulate far more service cycles before cracks reach critical size. This translates directly to longer inspection intervals, lower probability of progressive disbonding, and extended equipment service life, all with documented scientific justification.

2.5.5 Real life examples

The mechanisms described above are not laboratory curiosities. A field investigation published by Raymond Cordewener in the *Fugitive Emissions Journal* (22 January 2020) documents three pressure vessels in acid service, constructed from clad-steel plate (both roll-bonded and explosion-bonded), that suffered severe corrosion damage originating at locations where the CRA barrier was locally compromised:

- **Weld-seam dilution:** in a Hastelloy C-276 clad vessel, carbon-steel pick-up in the cladding restoration weld was not controlled at start/stop positions and local repairs. Acid attacked the diluted weld metal, corroded through the backing steel and ruptured the plate; the failure was detected only when fugitive-emission sensors raised an alarm. Seam restoration welds of this type are required in every clad vessel; however, vacuum-bonded plate sharply reduces the additional local clad repair welds needed to fix bond defects, each of which carries the same dilution risk shown here.
- **Brackets welded onto the clad layer:** local stresses beneath internal support brackets, combined with acid concentrating around the attachment, penetrated the 3 mm clad layer and consumed the carbon steel to a remaining wall of 1.8 mm out of 16 mm. Full penetration was estimated to be only days to weeks away at the time of inspection. The 100% dense, fully bonded interface of Vacuum Explosion Clad does not prevent this type of design-induced attack, but it does contain it: with no disbonds for the medium to migrate into, corrosion remains confined to the point of penetration rather than spreading laterally between the layers, as occurred in the sleeve case below.
- **Clad-sleeve repair:** a 3 mm cylindrical CRA sleeve welded inside an already-corroded clad vessel. Once the sleeve was locally penetrated, a pressurised swirling acid-gas stream circulated behind it, corroding the sleeve from both sides and eroding the interface between the layers. This failure is, in effect, a full-scale demonstration of an unbonded interface: wherever a gap exists between the CRA layer and the substrate, the medium that reaches it attacks from both sides, erodes the surfaces through flow and vibration, and progresses undetected. The metallurgically bonded, disbond-free interface of Vacuum Explosion Clad leaves no such gap anywhere in the vessel. Equally important, a clad barrier that retains its integrity in service (Section 2.5.4) does not force the operator into loose-liner repairs of this kind in the first place.

Case study by Raymond Cordewener, Fugitive Emissions Journal, January 22, 2020

The common denominator: every failure escalated from a small, locally compromised zone in the CRA barrier, invisible in normal operation and found only after major loss of pressure-retaining material, or after the leak itself. Interface microcracks belong to the same defect class: sub-visible discontinuities that concentrate stress, admit the process medium once breached, and grow under cyclic loading (Section 2.5.4). The field evidence reinforces the conclusion of Section 2.5.7: the integrity of a clad vessel cannot be inspected in afterwards, it must be manufactured in. Eliminating the defect population at source, through vacuum bonding and disciplined fabrication practice, is the only strategy that addresses the root cause.

2.5.6 Why Vacuum Eliminates Two of the Three Mechanisms

- **Gas-entrapment cracking → ELIMINATED:** Interstitial gas pressure reduced 89% at 0.1 atm, below the level at which pores form; further at Shockwave's 0.05 atm. Li et al. (2024).
- **Oxidation-induced embrittlement → ELIMINATED:** No atmospheric oxygen or nitrogen in the bonding chamber. Li et al. (2024); Zeng et al. (2019); Jáňa et al. (2014).
- **Intermetallic melt-zone cracking → REDUCED:** Smaller, more uniform melt zones from the more stable flyer plate trajectory under vacuum.

2.5.7 NDT Limitations; The Case for Prevention Over Detection

- **Conventional UT (ASTM A578 / EN 10160):** Acceptance criteria are defined by loss of back-wall reflection and by reference reflectors on the millimetre-to-centimetre scale. Orders of magnitude too coarse for 0.03–0.2 mm melt-zone microcracks.
- **45° shear transducer:** Can detect shear cracks, but only when oriented correctly relative to the detonation direction. End-on cracks are invisible.
- **SEM/metallographic examination:** Definitive, but destructive, applicable only to witness coupons. Representativeness decreases for atmospheric bonding where quality varies from centre to edge.
- **AUTO-UT:** Improved sensitivity through electronic beam steering. Full-area C-scan provides a statistical characterisation of interface quality across the full plate. The archived C-scan serves as a baseline for in-service comparison, changes in pattern indicate progressive disbonding. Recommended as standard for Clad qualification (see Section 2.7.5). This is the only way to accurately track the clad quality over the lifetime of a vessel.

The detection gap

No current NDT method guarantees detection of all sub-millimetre microcracks in production clad plate. A plate that passes all required NDT examinations can still harbour microcracks that degrade performance in service. Prevention through vacuum bonding is more reliable than any available post-production inspection method.

2.6 Safety, Environmental Impact and CO_2 Footprint

The vacuum process transforms the safety and environmental profile of explosive welding simultaneously.

2.6.1 Safety Quantified Hazard Reduction

- **45–75% reduction in all hazard parameters:** Shockwave, vibration and noise. Li et al. (2024).
- **Containment within a spherical vessel:** Eliminates dust and limits detonation product dispersal. Enables operation within established industrial facilities without remote sites or special permits.
- **Noise compliance:** 80–90 dB at 5 km reduced by 45.31%, compatible with noise regulations in densely populated industrial areas. Open-air detonation is incompatible with urban or densely occupied sites.

A further operational advantage is complete **Weather independence.** Open-air explosive welding (even when done inside a cave/mine) is directly dependent on weather conditions: wind, rain, humidity and temperature variations affect the consistency of the detonation wave and can force production to be halted or rescheduled. Since Vacuum Explosion Clad is performed entirely inside a sealed spherical vessel under controlled vacuum, the process is fully independent of external climate, enabling year-round production with consistent quality regardless of weather.

2.6.2 Environmental Impact, CO_2 Comparison by Process

A lifecycle CO_2 analysis across all four methods demonstrates a clear hierarchy. The comparison must account for both manufacturing energy and logistics emissions:

CO_2 Source	Vacuum Explosion Clad	Open-Air/Atmospheric Explosive	Roll-Bond	Weld Overlay
Manufacturing energy per m²	**Lowest (single detonation, no furnace)**	Low (detonation only)	High (rolling mill + multi-pass annealing)	Highest (multi-pass arc welding + PWHT energy)
Logistics transport CO_2	**Minimal (factory production)**	High (remote site transport of plates + explosives)	Low (factory production)	Low (factory production)
Site preparation/remediation	**None**	Significant (quarry/military range)	None	None
PWHT energy requirement	**Low (superior starting interface)**	Moderate	High (rolling temperatures 800–1000°C)	High (mandatory thermal cycles)
Rework/rejection CO_2	**Lowest (<0.1% rejection)**	Moderate (5–15% edge defects)	Moderate (3–8% IMC failures)	Highest (mandatory 2nd pass)
Overall CO_2 assessment	**✓ Lowest**	✗ High	Moderate	✗ Highest

Weld overlay demands the most energy of any cladding method: each pass deposits material at 200–450 A / 25–34 V, multiple passes are mandatory (the first pass typically exceeds API 582 Fe dilution limits and must be covered by a qualified second pass), and PWHT thermal cycles add further energy consumption. Roll bonding requires heating to 800–1000°C followed by multi-pass annealing, a continuous high-energy process incompatible with low-carbon manufacturing. Open-air explosive welding adds the unique liability of remote-site logistics: every production run requires transporting heavy plates, personnel and explosive materials to remote locations, each journey generating CO_2 that no 'process efficiency' metric captures. Vacuum cladding is done on the same location, no transportation required, additionally, vacuum cladding only uses about 1/3rd of the amount of explosive required in the open-air/atmospheric. Saving approx. 500 kilograms of explosives on an average 18m2 plate means a saving of approximately 750 kg of CO_2 per plate in detonation products alone.

> **Note**
> *Vacuum Explosion Clad is the only cladding process that simultaneously delivers the lowest CO_2 footprint, the lowest noise and vibration output, and the highest interface quality. For capital equipment procurement under ESG commitments, it is the only process that satisfies all three pillars without compromise.*

2.7 Proposed Qualification Test Programme

The following programme goes beyond minimum PED / ASME BPVC requirements. It is designed to document the long-term performance advantages of the vacuum process and to provide the data needed to justify specification of vacuum explosive cladding in EPC and owner-operator material specifications.

2.7.1 Shear Test Fracture Location Is the Critical Criterion

The shear test (ASTM SA 263/264/265, ASTM B432/B898, AD-W8, EN 13445-2 App. D, minimum 140 MPa) measures the resistance of the bond between the cladding and the base steel under sliding load, the dominant load mode at the interface in real service, generated by thermal expansion mismatch, pressure-induced bending, forming strains and welding residual stresses. **Where the specimen fractures is the decisive indicator of bond quality**, the numerical value alone is not sufficient.

- **Interface fracture = structurally weak bond:** If fracture initiates and propagates along the bonding interface, the interface is the structural weak point, regardless of whether the value exceeds 140 MPa. This bond will preferentially fail under service fatigue, thermal cycling and forming. An acceptable shear value with interface fracture should not pass.
- **Cladding layer fracture = genuinely strong bond:** Fracture within the CRA or base metal, away from the interface, confirms that the bond is stronger than either parent material. SMT IR-17267: 441–487 MPa with fracture in the cladding layer, the bond outlasted the material. This is not the exception, this is the rule. All shear-test carried out on Shockwave's vacuum cladded plates, shear in the clad-layer and not the bond itself.

Figure 9: Perfect shear-test.
Fracture in the flyer-material. 490Mpa, Alloy 625 clad

Specification requirement: (1) Shear strength ≥ minimum per applicable standard. (2) Fracture shall not initiate or propagate along the bonding interface. Fracture location shall be documented by metallographic examination of the fracture surface. Interface fracture is cause for rejection regardless of the numerical result.

2.7.2 Side Bend Test with Post-Bend Dye Penetrant Inspection (PT)

The side bend test bends a specimen 180° so that the interface runs through the full thickness of the bend, loading the bond simultaneously in tension, compression and shear across its entire extent, replicating the conditions of vessel head forming, tube expansion and cold fabrication. The guided side bend test (ISO 5173, 180°) shall be followed immediately by dye penetrant inspection (PT) of the bent surface. PT uses a liquid that penetrates any open surface discontinuity; after excess is removed, a developer makes cracks and disbonds visible. Visual examination alone is insufficient, subsurface delamination may not break through to the surface visibly but will propagate under service loading.

Acceptance criterion: No delamination indication detected by PT after bending to 180°. Any interface delamination indication, regardless of size, is cause for rejection.

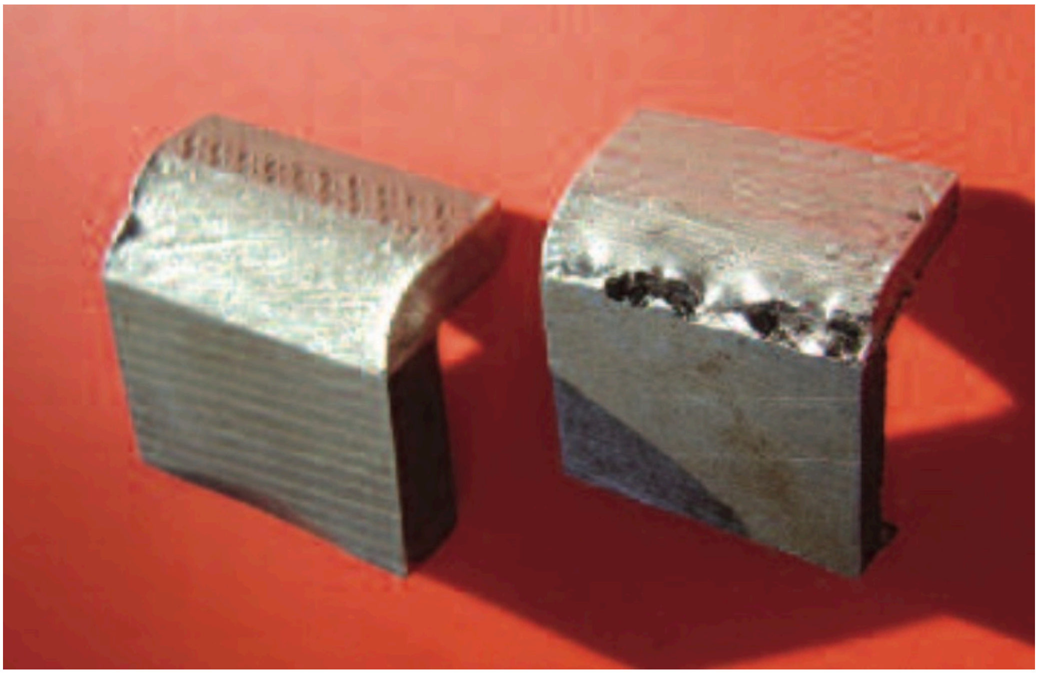

Figure 10: Vacuum cladding vs. open-air/atmospheric cladding hammer-bend-test.

Figure 11: Vacuum cladding vs. open-air/atmospheric cladding side-bend-test.

Figure 12: Vacuum cladding side-bend-test, various material combinations & thicknesses.

2.7.3 Metallographic Examination of the Bonding Interface

Metallographic examination is the only qualification method that shows the bond itself, rather than inferring its quality from a mechanical result or an ultrasonic response. Transverse cross-sections shall be taken from the qualification coupons, prepared to a polished and etched condition, and examined by optical microscopy at 50× to 500× magnification; SEM examination (including BSE imaging) shall be applied where melt zones or intermetallic phases require characterisation.

Acceptance criterion: a 100% dense and homogeneous interface over the full examined length. This means continuous metallic bonding with the characteristic wave morphology, no oxide inclusions or entrapped impurities, no porosity, and no microcracks either at the interface or in the adjacent parent materials. Localised melt pockets, where present, shall be isolated, discontinuous and crack-free; for titanium-clad plate the absence of alpha-case at the interface shall be verified. These criteria directly target the three defect-formation mechanisms of Section 2.5.2, which conventional UT cannot resolve (Section 2.5.7).

Figure 13 shows the practical difference. The vacuum-bonded interface presents a clean, dense transition free of oxides and microcracks; the open-air/atmospheric interface exhibits the oxide inclusions and melt-zone defects characteristic of atmospheric bonding. For vacuum explosive cladding, the centre-to-edge uniformity documented in Section 2.2 makes edge-cut coupons genuinely representative of the full plate, a representativeness that atmospheric bonding cannot claim.

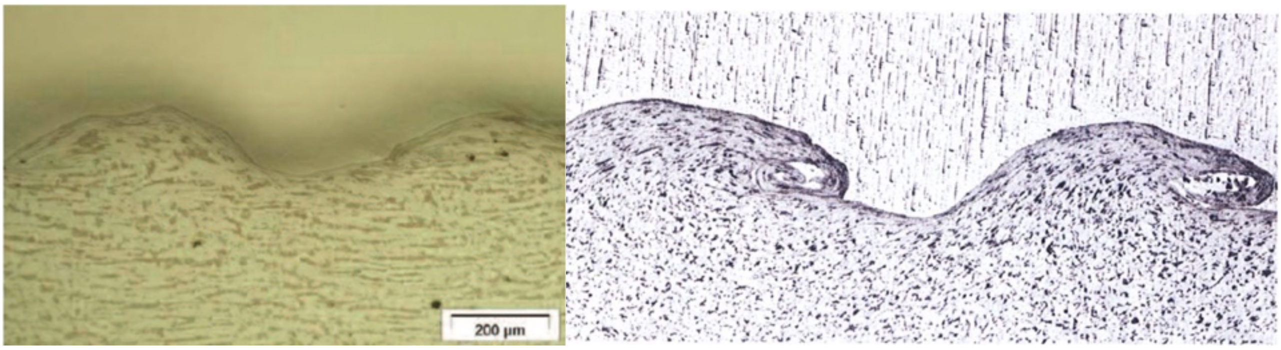

Figure 13: Vacuum cladding interface vs. open-air/atmospheric cladding interface

2.7.4 Fatigue Qualification, Measuring Bond Degradation Over Time

Standard qualification tests characterise the as-manufactured condition only. They do not assess how the interface degrades with accumulated service cycles. Fatigue testing specifically measures this, and the difference between vacuum and atmospheric bonded plates is most visible here.

For Vacuum Explosion Clad: the demonstrably lower initial crack population (gas-entrapment and oxidation cracks eliminated) means fatigue crack propagation begins from a smaller a_0. Paris Law integration from a smaller a_0 requires significantly more cycles to reach the critical crack size, directly translating to longer service life and longer inspection intervals. Karolczuk et al. (2019). Derda et al. (2023).

2.7.5 AUTO-UT

Standard UT is calibrated to detect disbonds orders of magnitude larger than the 0.03–0.2 mm melt-zone microcracks that determine clad plate long-term performance. Phased Array Automated UT (PA AUTO-UT) uses multiple transducer elements fired in programmed sequences to electronically steer and focus the beam in multiple directions, generating a full-area C-scan colour map of the complete bonding interface. This delivers capabilities that conventional UT cannot provide:

- **Full-plate statistical characterisation:** The C-scan provides a complete map of interface quality, not just pass/fail detection of large disbonds. Statistical analysis of C-scan data can quantify the difference in microcrack density between the different cladding methods.
- **Baseline for in-service comparison:** The archived C-scan enables direct comparison at future inspection intervals. Changes in the C-scan pattern, new indications or growth of existing ones, indicate progressive disbonding or fatigue crack growth before failure.
- **Objective process qualification data:** Systematic AUTO-UT comparison of bonded plates at the same material combination provides the objective technical data to justify inclusion of vacuum explosive cladding in owner-operator and EPC material specifications.

3. Open-Air/Atmospheric Explosion Clad, Limitations of the Conventional Process

Conventional open-air/atmospheric explosive welding shares the solid-state bonding mechanism and the ability to join dissimilar metals. However, the presence of interstitial gas between the plates introduces defects that are systematic, quantifiable, and unavoidable, they are not production imperfections but inherent consequences of the physics of atmospheric detonation.

Interface Defects, Systematic and Unavoidable

- **Gas-entrapment pores:** Gas compressed in the standoff gap produces pores distributed along the interfacial vortex. These cannot be eliminated by parameter optimisation, they require post-treatment (diffusion annealing or hot rolling) that introduces Intermetallic Compound (IMC).
- **Tail-end degradation:** Li et al. (2024) measured −18.7% velocity reduction and +20% angle increase at the plate tail end under atmospheric conditions. This produces systematically weaker tail-end zones that must be trimmed, adding material waste. Under vacuum, the same measurements show only −5.7% velocity and +2% angle change, near-uniform quality across the full plate.
- **Thicker diffusion layer and Intermetallic Compound (IMC):** Adiabatic gas compression increases heat accumulation at the collision point, promoting Intermetallic Compound IMC layer growth and reducing bond strength.
- **Oxidation cracks at reactive metal interfaces:** Titanium begins absorbing oxygen above ~400°C. The collision zone temperatures are orders of magnitude higher. The resulting oxygen-enriched alpha-case is brittle and serves as a primary crack initiation site in Ti-clad plates.

Operational and Environmental Limitations

- **Noise 80–90 dB at 5 km:** Incompatible with urban areas or densely occupied industrial zones.
- **Vibration and blast:** Affecting adjacent structures and equipment, requiring remote sites and extensive permits.
- **Remote-site logistics CO_2:** Every production run requires transport of heavy plates, personnel and explosives to quarries or military ranges, generating logistics CO_2 that does not appear in process comparisons.

> **Structural limitation of the atmospheric process**
>
> *The interstitial gas is not a controllable variable. Its presence is inevitable and its impact on interface morphology is systematic across the full plate, especially at the tail end. Process parameter optimisation cannot overcome this fundamental physical constraint. The only solution is to eliminate the gas, which requires vacuum. Li et al. (2024).*

4. Roll-Bond and Bang & Roll, Disqualifying Limitations

Roll bonding and its hybrid variant Bang & Roll present a combination of structural limitations that disqualify them from demanding applications. The analysis must distinguish clearly between the two processes:

4.1 Pure Roll Bonding, Material Incompatibility

Direct roll bonding cannot produce structurally sound Ti/steel or Zr/steel clad plate for pressure vessel applications. The rolling temperatures required to achieve bonding lie far above the ~450 °C threshold at which brittle FeTi and Fe_2Ti intermetallics form: the thermal cycle that creates the bond simultaneously creates the brittle phases that undermine it. Where roll-bonded Ti/steel plate is produced at all, it relies on vacuum rolling with interlayers and still carries the IMC penalty quantified by Luan et al. (2025).

For material systems where roll bonding is feasible, the mechanical properties are demonstrably inferior. Rouzbeh et al. (2020), AA1050/Mg AZ31B bilayers: tensile strength 110 vs 270 MPa (−59%; explosive welding +145% higher); work of fracture 5.64 vs 28.6 MJ/m^3 (−80%; explosive welding +407% higher); layer-by-layer failure mode confirming the interface as the structural weak point.

4.2 Bang & Roll, Compounded Limitations

The Bang & Roll process uses an open-air/atmospheric explosive welded thick slab as input to a rolling mill. It is marketed as combining the advantages of explosive bonding and rolling, in practice it combines the disadvantages of both:

- **Inherits all atmospheric explosive cladding defects:** Gas-entrapment pores, oxidation cracks and tail-end irregularities are present in the slab before rolling begins. Rolling cannot heal them.
- **Hot rolling actively grows IMC, unavoidably:** Rolling temperatures of 800–1000°C for Ti/steel are far above the 450°C IMC formation threshold. Luan et al. (2025) confirm that bond strength is inversely proportional to Intermetallic Compound IMC layer thickness, and that IMC layers >5 µm produce an abrupt mechanical discontinuity. The longer and hotter the rolling schedule, the more IMC grows, there is no parameter window to prevent this.
- **Pores become sharper fatigue cracks:** Hot rolling flattens spherical gas-entrapment pores into elongated, crack-like defects with higher stress intensity factors at the crack tips, potentially more damaging under cyclic loading than the original pore.
- **Grain refinement advantage lost:** The grain refinement at the interface produced by explosive bonding's high-strain-rate deformation is eliminated by recrystallisation during hot rolling, removing one of the key mechanical advantages of explosive cladding.
- **Split quality accountability:** The explosive bonding and rolling are typically performed by different companies. Final interface quality depends on both operations neither is fully transparent to the end user.

Property	Vacuum Explosion Clad (SMT)	Roll-Bond / Bang & Roll
Ti/steel pressure vessel capability	✓ **Full capability**	✗ Not possible (Roll-Bond) / Severely limited (Bang & Roll)
Interface defects at manufacture	**Gas and oxidation cracks eliminated**	Gas pores + oxidation cracks + IMC layer
IMC layer thickness	**< 3 µm (diffusion layer only)**	Grows to >5 µm during rolling — unavoidable
Mechanical properties	>350–650 MPa shear (material dependent) Fractures in weakest material	140–300 MPa (material dependent) Fractures on bonding interface
Work of fracture	**28.6 MJ/m^3**	5.64 MJ/m^3 (−407%)
Quality accountability	**Single supplier, full traceability**	Split: bonding + rolling (two companies)
CO_2 footprint	**Lowest**	High (rolling mill energy + annealing)

Fundamental limitation of Roll-Bond and Bang & Roll

Roll bonding cannot produce Ti/Zr steel clad plate. Bang & Roll inherits all open-air/atmospheric explosive cladding defects and adds thermodynamically unavoidable IMC growth during rolling. Neither process delivers the interface quality, material versatility or process traceability. Luan et al. (2025); Jiang et al. (2023); Li et al. (2024).

4.3 Published Fatigue and Bond-Strength Data, Roll-Bond vs. Explosion Bond

Jiang et al. (2023), ref [4], provide the most direct published comparison available: three commercial TA2 titanium / Q355B steel clad plates — two hot-rolled bonding grades and one atmospheric explosion-bonded plate (2 mm cladding on 8 mm substrate, structural grades per GB/T 8547) — tested for interface shear strength and high-cycle fatigue under identical protocols:

Interface condition	Interface shear strength	Fatigue strength at 2×10^6 cycles	Fatigue crack initiation
Hot-rolled, low bond grade	41.3 MPa avg (min 34.1) — below the 140 MPa code minimum	361.8 MPa	interface and substrate modes
Hot-rolled, high bond grade	218.3 MPa avg; scatter 148.8–271.1 MPa (SD 44.7)	401.9 MPa	three failure modes, incl. interface
Explosion-bonded (atmospheric)	147.3 MPa avg (one specimen at 133.5)	387.9 MPa	interface — 18 of 18 failed specimens
Shockwave Vacuum Explosion-bonded	Min 270 MPa & avg of 367 MPa	425 MPa	No interface failed specimens

Three conclusions follow. First, "roll bond" on a specification does not define interface quality: two commercial grades of the same process differ by a factor of five in bond strength, and the low grade ships below the 140 MPa minimum that pressure-vessel clad codes require. Second, even the high roll-bond grade shows the widest scatter of the three (standard deviation 44.7 MPa): bond quality is a per-plate outcome, not a process guarantee. Third, the atmospheric explosion-bonded plate — respectable on average — failed in fatigue at the interface in 18 of 18 failed specimens, a behaviour the authors attribute to interface imperfections introduced by the atmospheric explosion process. In every case the fatigue-limiting feature is the interface defect population: precisely the parameter that vacuum bonding controls at source (Section 2.5), and precisely where SMT vacuum production data separates from both alternatives and excels in demanding environments.

5. Weld Overlay: The Structural Problem of Dilution

Weld overlay cannot eliminate its fundamental limitation: the iron dilution of the cladding metal. This is not a manufacturing defect, it is a physical consequence of fusion welding. Every arc welding process deposits CRA metal into a pool that is partially molten substrate steel. Fe from the substrate is always incorporated.

5.1 Dilution: Six Consequences for Corrosion Resistance

- **Reduced Cr, Mo and Ni content:** Fe dilution directly reduces the alloying elements that provide corrosion resistance. Cunha et al. (2025) confirmed that Fe content in Inconel 625 overlay is the critical parameter limited by API 582. The first pass typically exceeds permissible Fe limits, a mandatory second pass is required, adding 35–50% to cost.
- **Sensitisation ($Cr_{23}C_6$ precipitation):** Carbon from the substrate diffuses into the CRA during high-heat welding, promoting chromium carbide formation at grain boundaries. The Cr-depleted zones are susceptible to intergranular corrosion, exactly the failure mode the cladding is designed to prevent.
- **δ-ferrite formation:** Higher δ-ferrite fraction in the weld microstructure results in lower pitting corrosion resistance. δ-ferrite content is difficult to control consistently across multiple passes and positions. Nunes et al. (2020).
- **Laves and sigma phases:** Picchi et al. (2023) revealed hot cracks, deleterious Laves and sigma phases, and microhardness up to 400 HV in ESC-deposited Inconel 625, equivalent to martensitic microstructure. These phases are both brittle and corrosion-susceptible.
- **Welding residual stresses:** Qin et al. (2020) documented significant tensile residual stresses in electroslag strip cladding. These stresses, combined with service loading, promote stress corrosion cracking, exactly the environment that CRA overlays are specified to resist.
- **Geometry incompatibility:** There is no viable arc welding process for depositing titanium, aluminum, zirconium etc. directly onto carbon steel. Weld overlay is completely excluded from all these applications, which represent the majority of high-value cladding in the chemical, nuclear and hydrogen industries.

5.2 Dilution by Process: Comparative Table

Process	Typical Fe dilution	Layers required	PWHT required	CO_2 intensity
SMAW	15–25%	≥2	Frequent	High
GTAW	5–15%	≥2	Occasional	High
GMAW	10–20%	≥2	Recommended	High
FCAW	10–25%	≥2	Recommended	High
SAW	10–20%	≥2	Frequent	Highest
ESSC	**3–8%**	1–2	Occasional	Highest

Intrinsic limitation of Weld Overlay

Iron dilution is a physical consequence of fusion welding, no arc process achieves zero dilution. The first pass typically exceeds API 582 Fe limits, mandating a second pass that adds 35–50% to cost. The PWHT required for vessel fabrication adds further risk of sensitisation and phase formation. Weld overlay is fully excluded from all Ti-clad applications. For any application where titanium is specified, weld overlay is not an option. Cunha et al. (2025); Picchi et al. (2023); Malhotra et al. (2020).

5.3 Overlay Economics at Vessel Scale

Overlay cost scales with area × passes: every square metre of shell requires arc time, filler consumption, inter-pass control and inspection for each deposited layer, and the dilution-driven second pass multiplies all of it — the 35–50% adder of Section 5.1 applies across the full clad area. Clad plate inverts this economics: the bond for an entire plate is created in a single detonation (SMT production: up to 40 m² per shot), and cost per m² falls as plate size grows. Overlay therefore retains a legitimate niche, nozzles, complex internals, local repairs, and small areas where plate cutting waste dominates, but for shell courses and large tubesheets, deposition man-hours dominate its cost long before interface quality enters the comparison.

Dilution also inflates CRA consumption itself. Because overlay chemistry must be verified at a prescribed depth below the finished surface, the deposit must be laid down thicker than the corrosion allowance nominally requires: diluted material is deposited, machined and inspected in order to guarantee a chemistry that a 3 mm explosion-clad layer provides as-manufactured, at full nominal composition, from the first micrometre (Section 2.4.1). Combined with PWHT sensitisation risk (Section 2.4.5) and residual-stress-driven SCC susceptibility (Qin et al., 2020), the result is the shortest inspection interval and the highest lifecycle cost of the four processes, as summarised in Section 6.3.

6. Cost Analysis, Initial Cost vs. Total Cost of Ownership

A cost comparison between cladding processes that shows only initial manufacturing cost is fundamentally misleading. The correct comparison is Total Cost of Ownership (TCO) over the design life of the equipment, typically 25–30 years for pressure vessels. The modest premium of vacuum explosive cladding over competing processes is consistently recovered within the first avoided maintenance event.

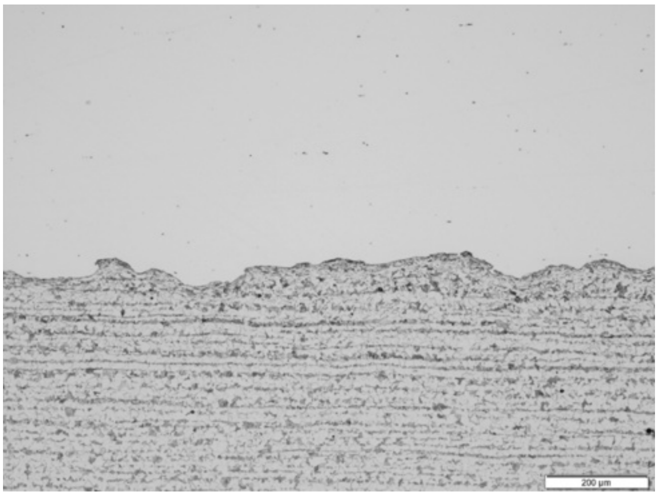

Figure 14: Full-plate cost analysis: initial cost vs. Total Cost of Ownership (TCO). The modest premium for vacuum explosive cladding over atmospheric or roll-bonded alternatives is typically recovered within a single avoided maintenance event. Source: own elaboration based on Ene & Scutelnicu (2012).

6.1 Material Economics, Clad vs. Solid CRA

The primary economic justification for all cladding is the ability to use the minimum quantity of CRA needed for corrosion protection, supported by a low-cost structural carbon steel substrate.

CRA Material	Typical CRA thickness	Savings vs. solid (25 mm base)
Titanium Gr. 1/2	3–5 mm	**~60-65%**
Zirconium 702	3–5 mm	**~80–85%**
Inconel 625 (UNS N06625)	3–5 mm	**~75–85%**
Incoloy 825 (UNS N08825)	3–5 mm	**~65–75%**
Incoloy 800 (UNS N08800)	3–5 mm	**~75–80%**
AISI 316L (UNS S31603)	3–5 mm	**~30–40%**
Duplex / Super-Duplex SS	3–5 mm	**~55–60%**

6.2 Initial Process Cost Comparison

Cost Factor	Vacuum Explosion Clad	Open-Air/Atmospheric Explosion Clad	Roll-Bond	Weld Overlay (ESSC)
CRA material efficiency	**100% — no dilution**	100% — no dilution	~95%	70–95% — dilution loss
Rejection rate	**<0.1%**	5–15% (edge defects)	3–8% (IMC failures)	5–15% (dilution, cracks)
Mandatory 2nd pass	**No**	No	No	Yes — API 582 Fe limits exceeded
Logistics cost	**Low — factory production**	High — remote site	Low — factory production	Low — factory production
Relative initial cost index	100	~100 (similar pricing)	**~85**	~120

(*) Roll-Bond lower initial cost reflects limited material capability — it cannot produce Ti/steel plates. Weld Overlay higher due to mandatory second pass. Vacuum Explosion Clad pricing at parity with open-air/atmospheric, with superior quality.

6.3 Total Cost of Ownership, Why Initial Cost Misleads

The scale of the underlying problem is documented at industry level. The NACE International IMPACT study estimates the global cost of corrosion at US$2.5 trillion per year, approximately 3.4% of global GDP, and concludes that applying available corrosion-control best practice would recover 15–35% of that cost, US$375–875 billion annually [25]. The study's central finding is that these savings are unlocked by changing how corrosion decisions are made at the design and procurement stage; the selection of the cladding process is precisely such a decision.

The downtime side is equally well quantified. Kimberlite's study of offshore oil and gas operators found average losses of US$38–49 million per operator per year from unplanned downtime, exceeding US$88 million for the worst performers, approximately US$1.4 million per lost production day [26]. Against numbers of this magnitude, the initial cost differential between cladding processes is noise; what matters is which process minimises the probability of the corrosion event that triggers the outage.

For pressure vessels in demanding service, the unplanned downtime cost of a single corrosion event, a cladding disbond, a liner repair, or a premature vessel replacement, easily exceeds 10–100 times the initial cost differential between cladding methods. The TCO comparison is the only economically valid basis for process selection:

TCO Component	Vacuum Explosion Clad	Open-Air/Atmospheric Explosion Clad	Roll-Bond	Weld Overlay
Initial bond quality	**✓ Highest — gas & oxidation cracks eliminated**	Moderate — gas cracks present	Low — IMC layer intrinsic	✗ Diluted CRA, HAZ, residual stress
In-service inspection interval	**✓ Longest — smaller a_0, slower crack growth**	Shorter	Medium	✗ Shortest — dilution & sensitisation
Corrosion maintenance cost	**✓ Lowest**	Moderate	Moderate — IMC corrosion pathways	✗ Highest — dilution + HAZ degradation
Unplanned downtime risk	**✓ Lowest**	Moderate	Moderate	✗ Highest — disbond risk
Regulatory/permit cost	**✓ Lowest — factory operation**	✗ Highest — remote site permits	**✓ Lowest — factory operation**	**✓ Lowest — factory operation**
CO_2 lifecycle cost	**✓ Lowest**	✗ High — logistics + 2-3 times more explosives	High — rolling energy	✗ Highest — multi-pass energy
Overall TCO assessment	**✓ Lowest lifecycle cost**	Moderate	Moderate	✗ Highest lifecycle cost

The TCO argument

The modest premium for Vacuum Explosion Clad over open-air/atmospheric explosive cladding or Roll-Bond is typically 0–15% on initial manufacturing cost. A single avoided liner repair in a chemical reactor or a single inspection interval extension covers this premium several times over. For weld overlay, the TCO comparison is not close: mandatory second passes, higher rejection rates, shorter inspection intervals and elevated maintenance costs make weld overlay the highest-lifecycle-cost option for any application where explosive cladding is feasible.

The arithmetic can be made concrete. The worked example below combines the cost structure of Section 6.2 with the published downtime figures above; the only internal assumption is the clad-plate share of total vessel cost.

Parameter	Value
Clad plate share of total fabricated vessel cost	20–50%
Cost of one unplanned corrosion outage	≈ US$7–14 million (5–10 days × ≈US$1.4 M/day)
Payback condition	one avoided or deferred corrosion outage over the 25–30-year design life repays the vessel-level premium by one to two orders of magnitude

The same logic drives inspection economics. Under risk-based inspection (API 580/581), inspection intervals are set by the expected defect population and its growth rate. The smaller initial crack population of vacuum-bonded plate (Section 2.5.4), combined with an archived AUTO-UT C-scan baseline (Section 2.7.5), gives the owner objective grounds to extend intervals and defer turnaround scope, a recurring saving over the vessel life that no initial-cost comparison captures.

7. Global Comparative Analysis

Technical Criterion	Vacuum Explosion Clad	Open-Air/Atmospheric Explosive	Roll-Bond	Weld Overlay
Interface free of gas/oxidation defects	**✓ Yes — both eliminated**	✗ No	~ Partial	✗ No (HAZ)
Full-plate interface uniformity, after removing the edge zones over the entire periphery.	**✓ Full plate**	~ Weak tail end	~ IMC-sensitive	✗ Variable
Zero CRA dilution	**✓ Yes**	✓ Yes	✓ Yes	✗ No (3–25%)
No HAZ	**✓ Yes**	✓ Yes	✓ Yes	✗ No
Ti/steel capability	**✓ Yes**	✓ Yes	✗ No	✗ No
Shear strength (MPa)	>350–650 MPa shear (material dependent) Fractures in weakest material	210–450 MPa (material dependent) Fractures on bonding interface	140–300 MPa (material dependent) Fractures on bonding interface	Variable
Work of fracture vs. Roll-Bond	**✓ +407%**	✓ +407%	Reference	N/A
Fatigue life (pre-existing cracks)	**✓ Longest — minimal a_0**	Reduced — gas/oxidation cracks	Reduced — IMC cracks	Reduced — HAZ
Noise and vibration	**✓ Minimal (−69% vs. atmosphere)**	✗ High	✓ Low	✓ Low
Industrial/urban feasibility	**✓ Yes — factory operation**	✗ No — remote site required	✓ Yes	✓ Yes
CO_2 lifecycle footprint	**✓ Lowest**	✗ High (logistics)	High (rolling energy)	✗ Highest (multi-pass)
Total lifecycle cost	**✓ Lowest**	Moderate	Moderate	✗ Highest

Sources: Li et al. (2024); Rouzbeh et al. (2020); Jiang et al. (2023); Luan et al. (2025); Nunes et al. (2020); Picchi et al. (2023); Findik (2011); Zhao et al. (2022); Cui et al. (2020); Cunha et al. (2025); Derda et al. (2023); SMT IR-17267 (2018).

FINAL SCIENTIFIC SYNTHESIS: Vacuum Explosion Clad delivers scientifically quantified superiority on every dimension that determines the value of clad plate in service: (1) maximum interface quality, gas and oxidation defects eliminated at source; (2) superior mechanical properties, no dilution, no IMC, no pre-existing fatigue nuclei; (3) fully preserved CRA corrosion resistance, nominal composition guaranteed throughout; (4) lowest CO_2 footprint and Total Cost of Ownership of any available cladding process. For end users and EPC engineers specifying cladding for critical applications, inclusion of vacuum explosive cladding as the required process, not just a permitted option, is the technically and economically responsible choice.

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All numerical data and technical claims in this document are directly traceable to primary sources indexed in Web of Science, Scopus or Google Scholar. DOI links are provided for direct access.

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