Extending Autoclave Service Life Beyond the Third Decade

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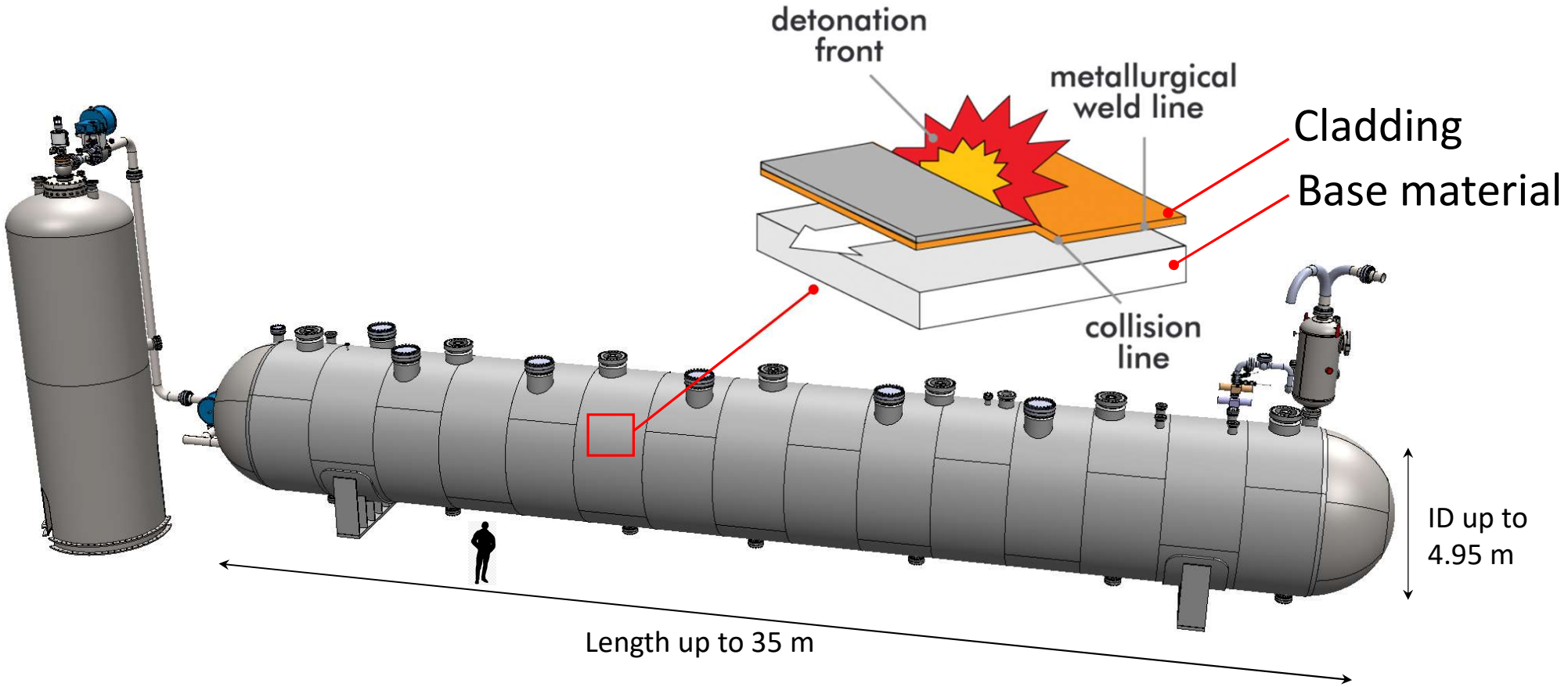
Autoclaves require maintenance and repair

Autoclaves are formed from Explosion-Bonded (EB) plates.



Explosion-Bonded plate material combinations

Carbon steel provides the pressure-containing envelope, while titanium cladding provides the corrosion envelope.

Clad layer
2-8mm thick

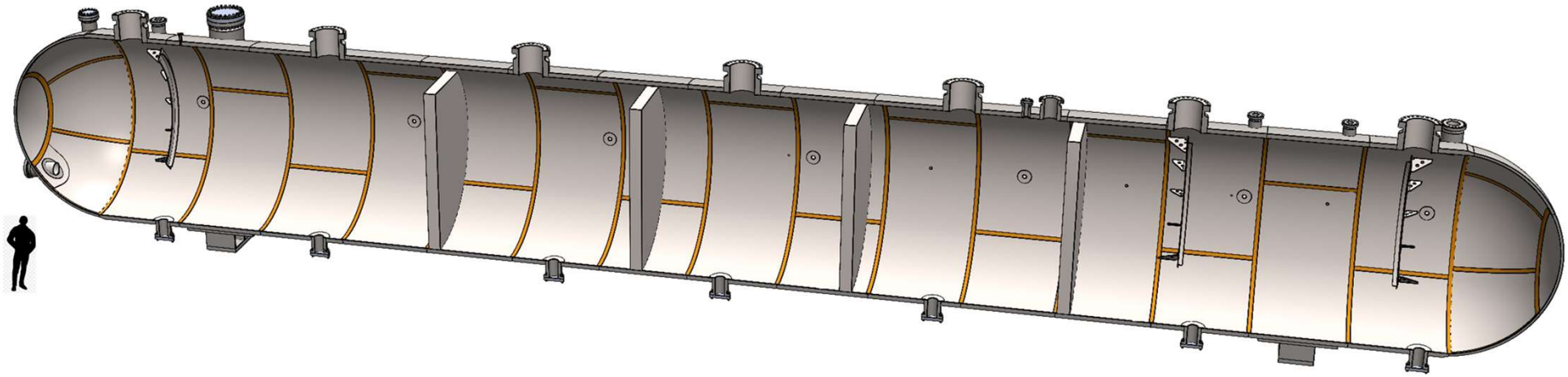
Base material
100-170 mm
thick

Typical interface profile:
"Cladding wave"

- Fused interface, free of oxide and impurities.
- Typically manufactured in compliance with ASTM B898 to ensure suitability for use.

The challenge of real life versus design

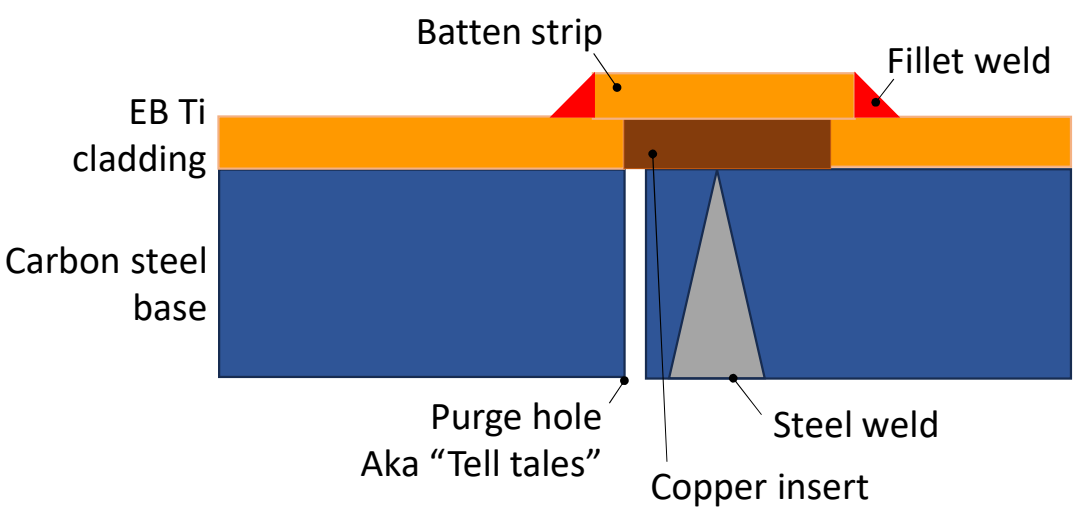
EB plates are connected by up to 2 km of batten strips welded to the Ti cladding.



Batten strips create the corrosion envelope

Various batten designs, each present advantages and disadvantages.

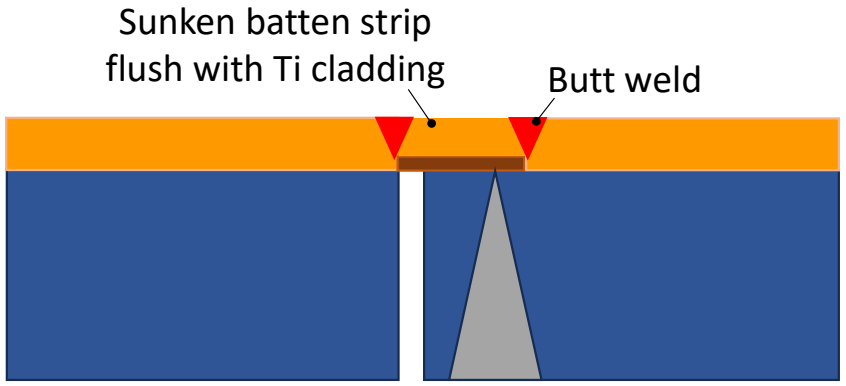
Conventional batten design



Notable issues:

- Cracking along the centerline of the fillet weld due to thermal expansion
- Stands proud makes it more susceptible to erosion.

Submerged batten design



Notable issues:

- Weld repair of batten will compromise the original Ti cladding.
- Lengthier to repair because butt welds require careful excavation.

Design versus the reality of inspection & repair

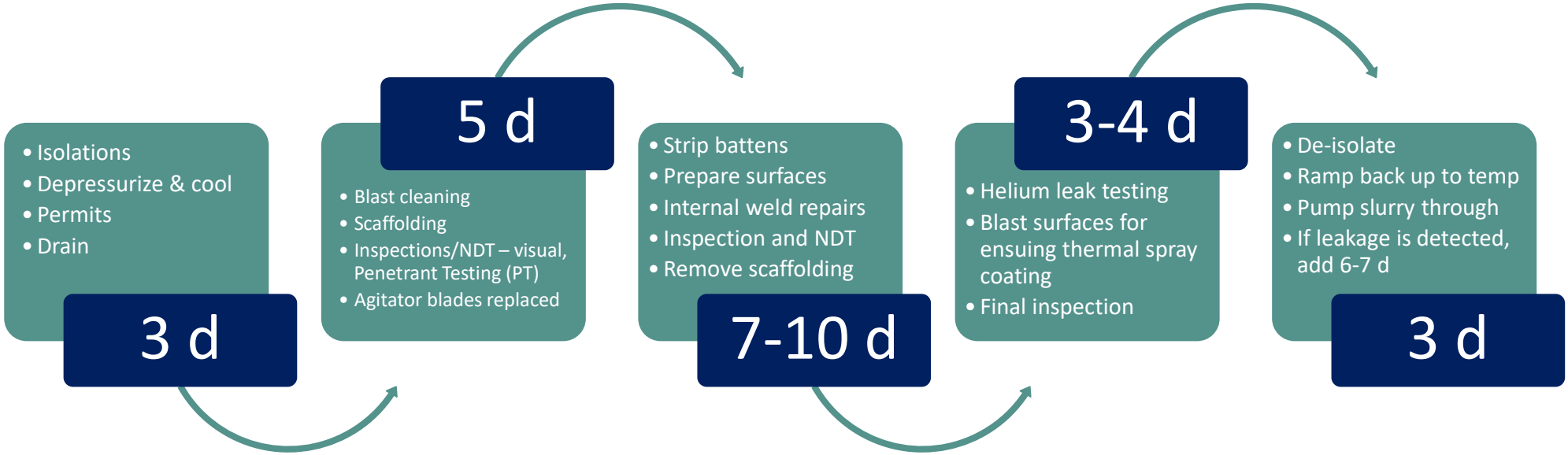
Repair of autoclave Ti cladding is challenging alongside the absence of an international weld repair standard.

- Confined space
  - Elevated temperature
  - Dim lighting
  - Complex geometry
- Specialized PPE requirements
  - Non-uniform surface profile
- Time constraints

- Absence of an industry standard.
- ASME VIII for vessel design, and ASME IX for qualifying welders and procedures but the Ti cladding is not considered part of the pressure envelope

Autoclave weld repair is up against the clock

Weld repair is limited to a defined window within a typical autoclave shutdown that scheduled for 21 days.



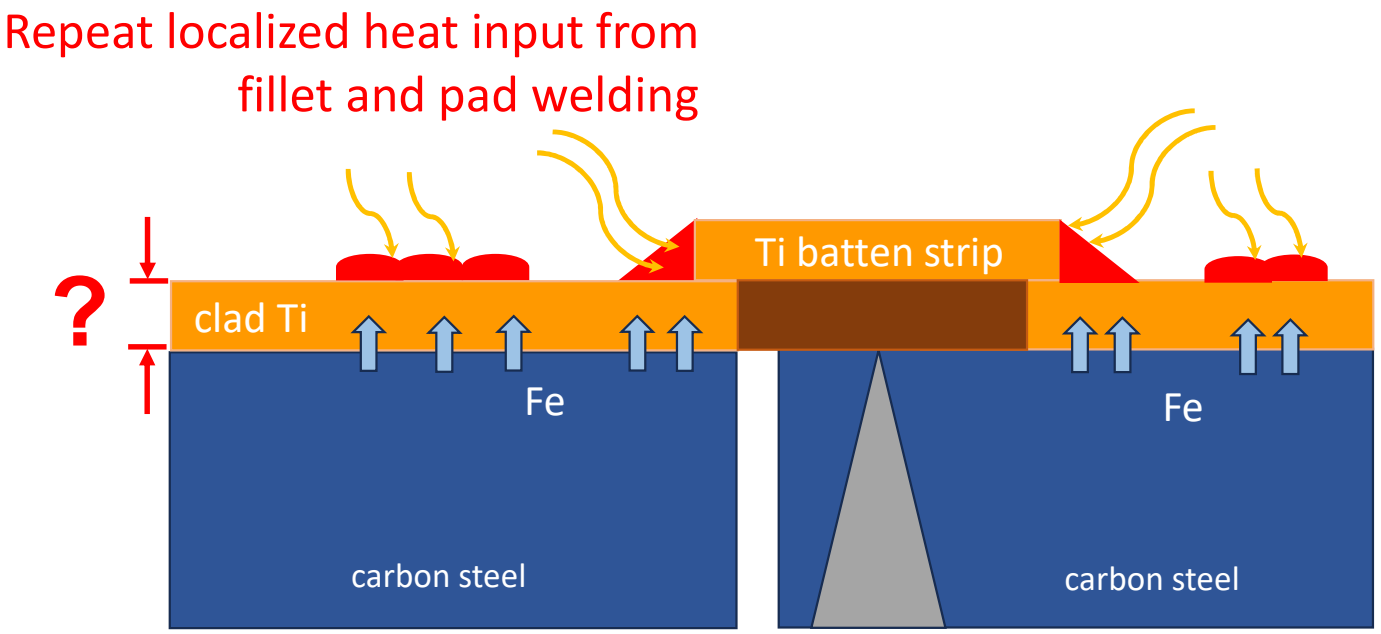
>1 week to gain access into the autoclave

>1 week to repair up to 80 locations per Comp

~ 1 week to bring the autoclave back online, if nothing goes wrong

How thin is too thin when welding clad Ti?

The focus of this study: What is the threshold Ti cladding thickness where Fe draw-through occurs?



Identifying the gap in knowledge

Defining the starting point for this study based on available data

The starting point says ≥1.98 mm is safe

Limited data is available concerning the risk presented by welding EB clad Ti on carbon steel.

Orr, A. (2019) from Tricor Metals claimed:

- It is risky to weld on anything less than 1.98 mm (0.078”).
- Even a thickness of 2.49 mm (0.098”) could provide too much heat input and contaminate the cladding.

This is a good starting point, but focusing on autoclave maintenance strategy, <u>what is the risk presented by repair welding</u>? i.e. repeated welding in the same location.

Final Results:

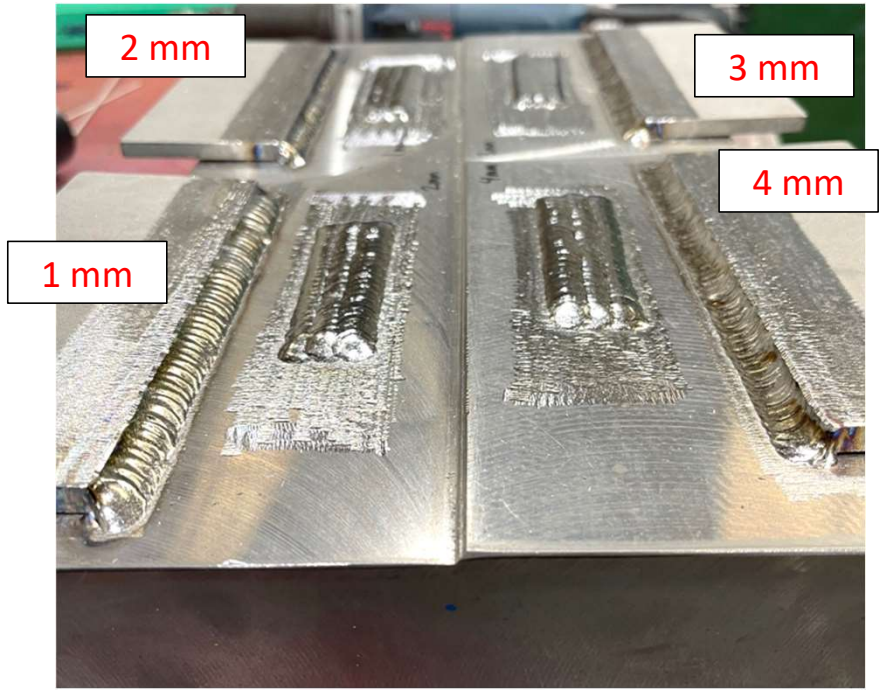
Table 3: Results Comparison

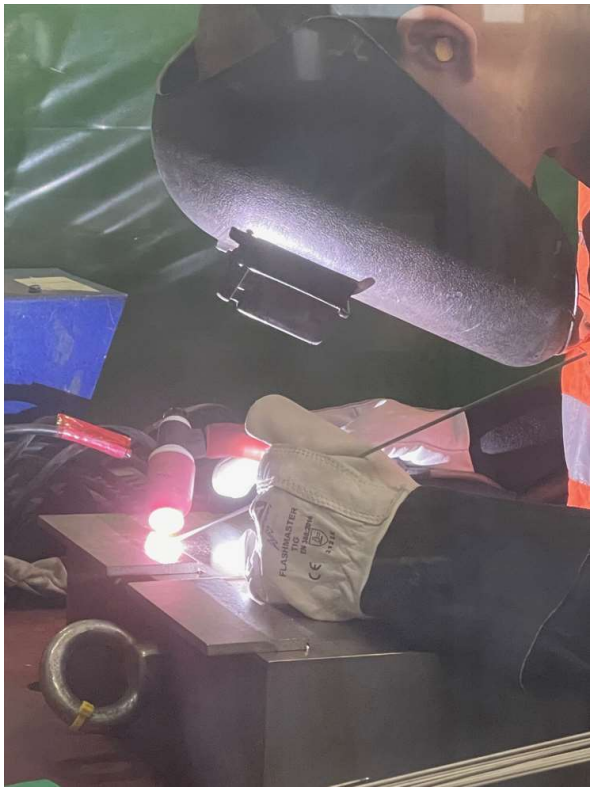
Thickness	Contamination	Intermetallics?	XRF PMI: Iron Detected?	Successful?
0.098"	No	No	No	Yes
0.088"	No	No	No	Yes
0.078"	No	No	No	Yes
0.068"	Possible	Questionable	No	Questionable
0.058"	Yes	Yes	No	Risky
0.048"	Yes	Yes	No	No
0.038"	Yes	Yes	Yes	No
0.028"	Yes	Yes	Yes	No

Orr, A. (2019). Clad metal repairs, how thin is too thin? NACE International Corrosion Conference & Expo March 24-28, Nashville, Tennessee. <https://cdn.ymaws.com/titanium.org/resource/resmgr/02_jens_folder/industrial_committee_webpage/map_proceedings/orralex2018_map_presentation.pdf>. Accessed 10 October 2023.

Experiment replicates clad Ti repair & inspection

Fillet and pad welding on a range of Ti cladding thicknesses, from 1 mm to 4 mm thickness.



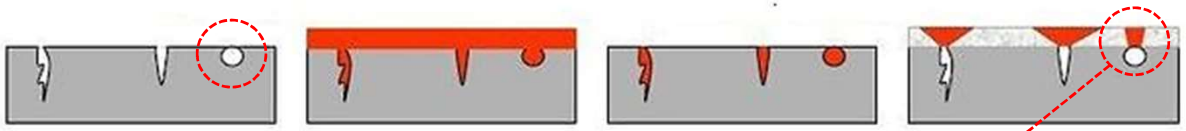


NDT: Penetrant Testing and visual inspection.

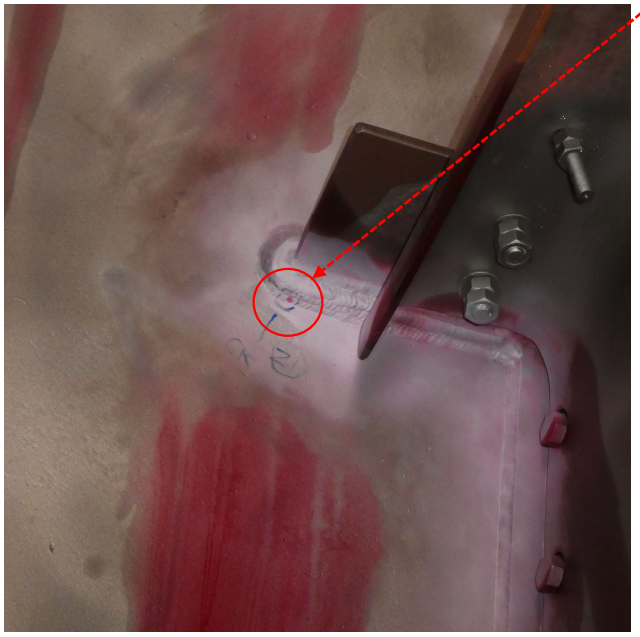
Result: NDT of welds showed no indications

Extensive use of Penetrant Testing (PT) and visual inspection in the autoclave to identify local areas for weld repair.

Sequence of actions when performing PT

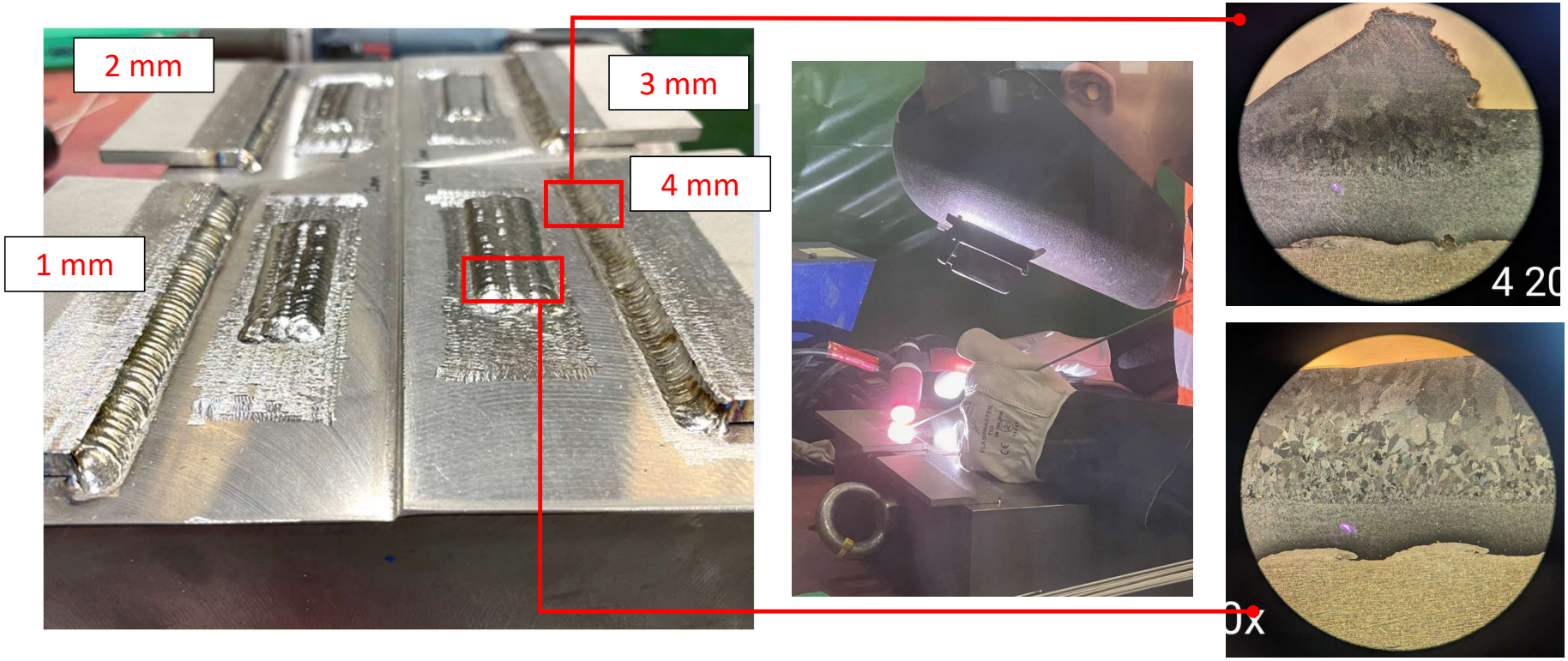


Surface cleaning ⇨ Cover surface with pink penetrant ⇨ Remove excess penetrant ⇨ Cover with developer and inspect for deviations



But what is occurring below the surface?

Fillet and pad welding on Ti cladding thicknesses, 1 – 4 mm, were characterized in cross-section.

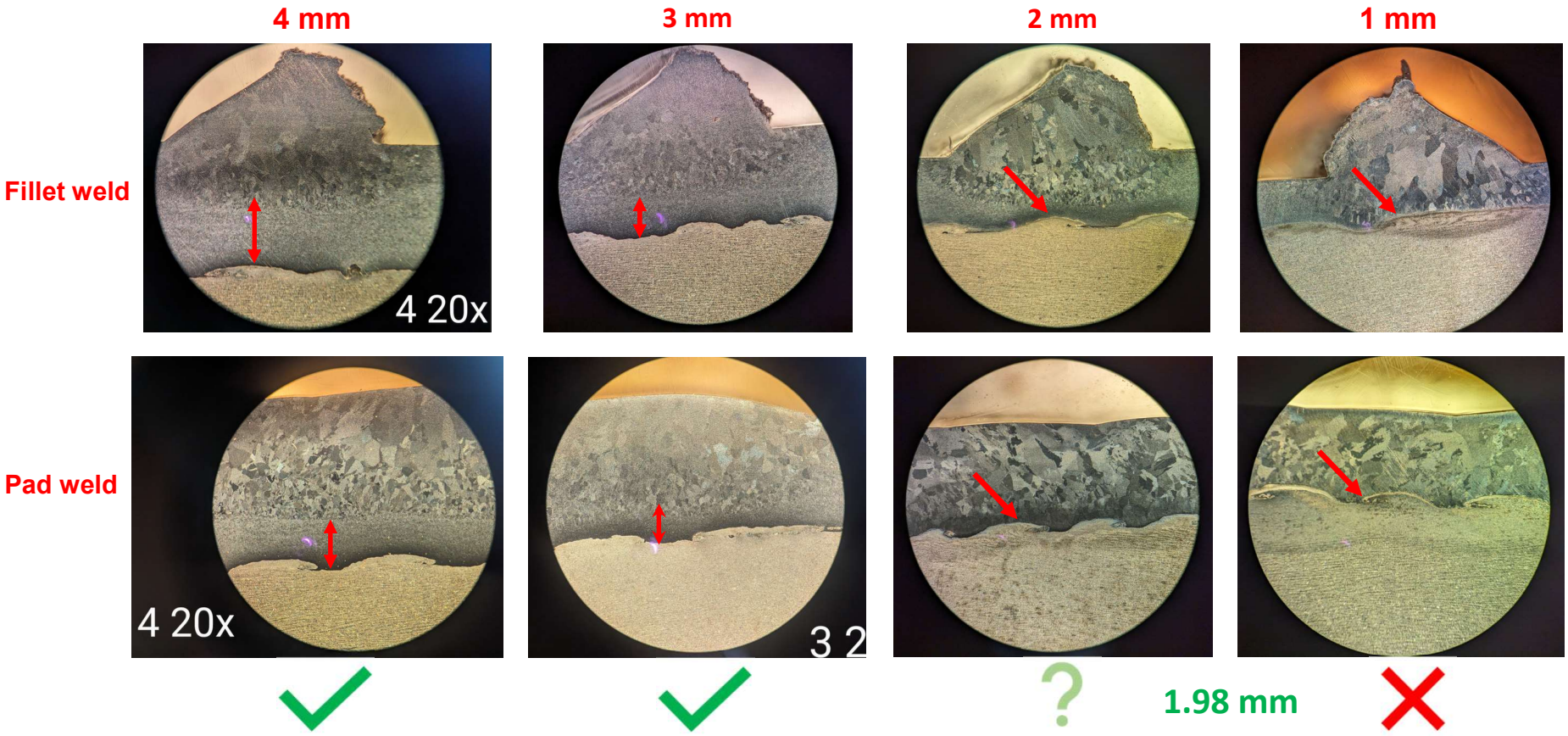


NDT Penetrant Testing and visual inspection

SEM and EDS mapping,
stereo and optical microscopy.

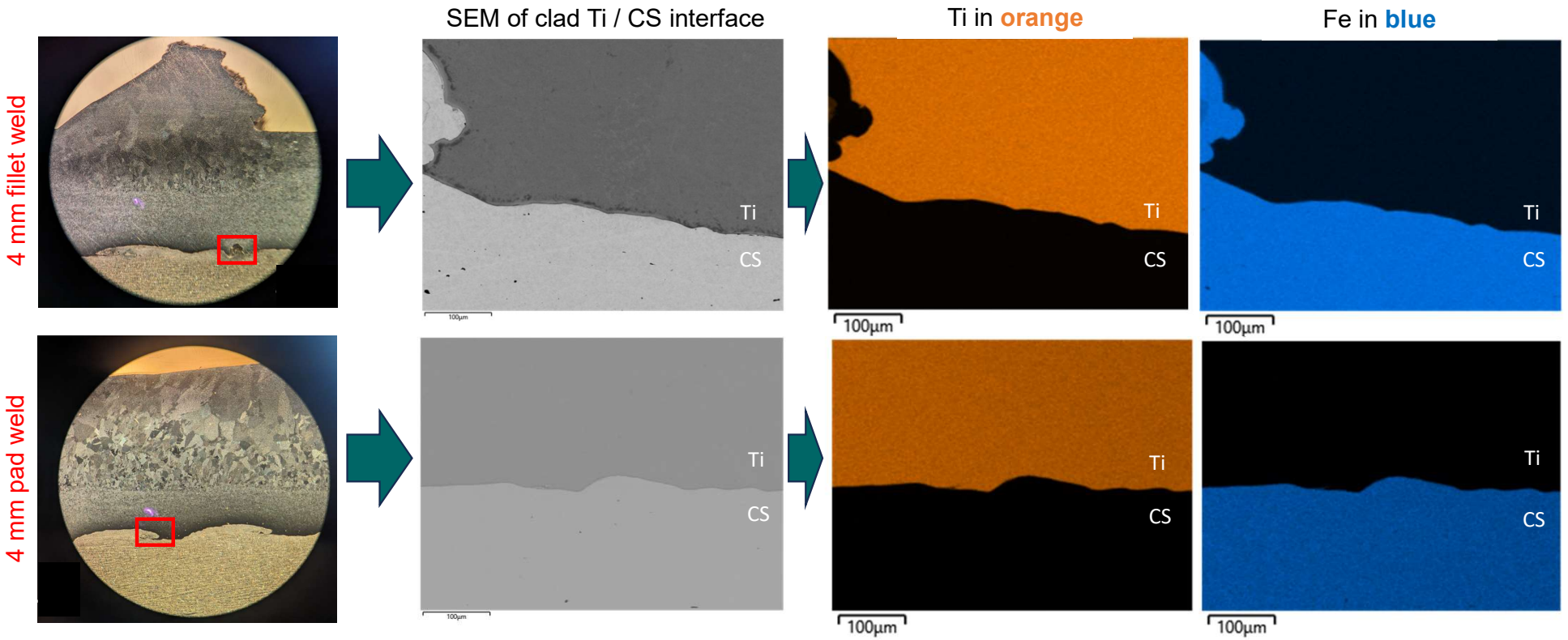
Results clad Ti / carbon steel interface

Visually, the clad Ti Heat Affected Zone (HAZ) appears to contact carbon steel when clad Ti is 2 mm or less.



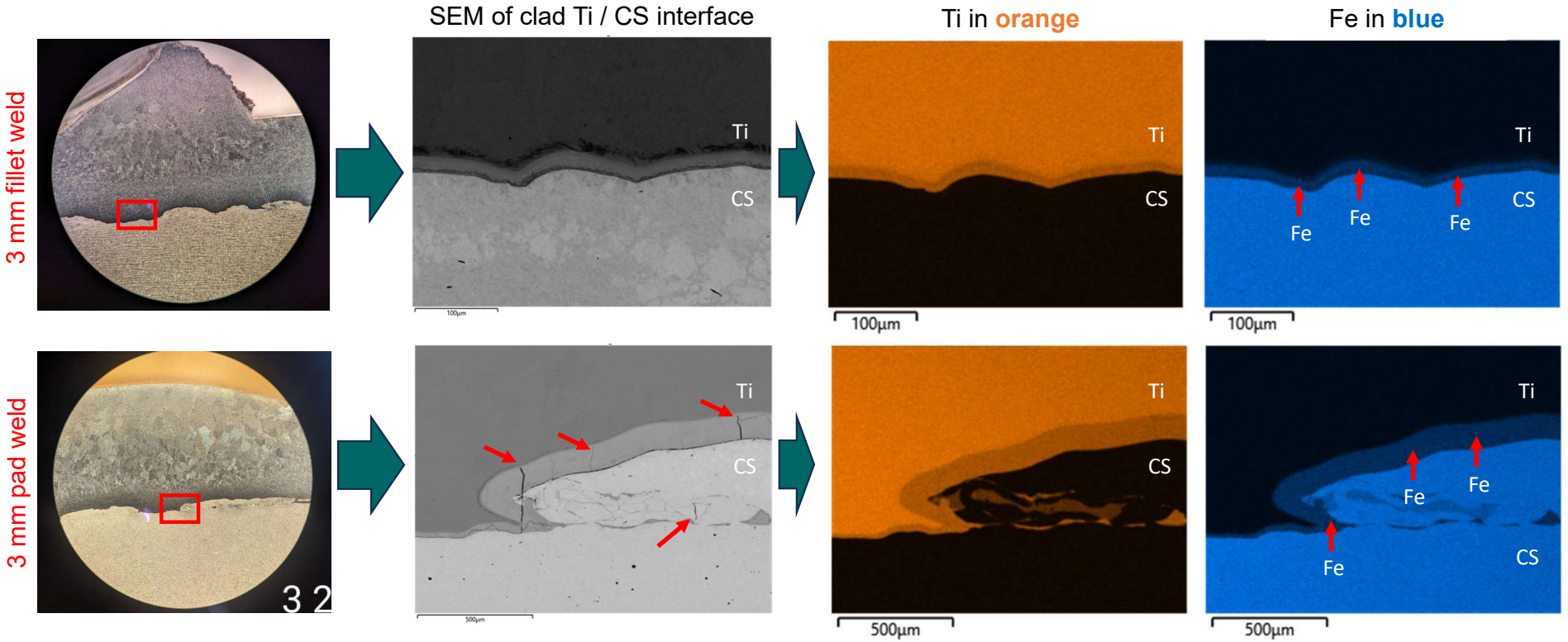
So, 4 mm clad Ti/carbon steel is safe to weld?

SEM/EDS mapping confirms there is no Fe in welded 4 mm clad Ti.



What about 3 mm clad Ti/carbon steel?

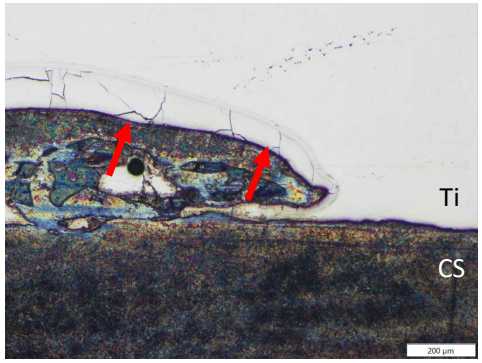
Confirmation there *is* Fe migrating into a welded 3 mm clad Ti, both fillet and pad weld. Cracks were also observed.

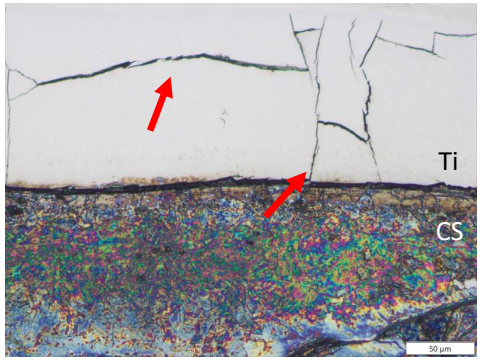


Extensive intermetallics seen at 1 mm clad Ti-CS

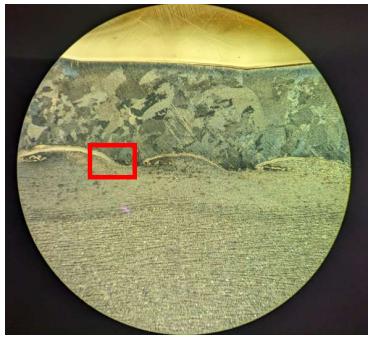
In optical micrographs, extensive formation of intermetallics containing cracks was observed at the clad Ti-carbon steel interface.

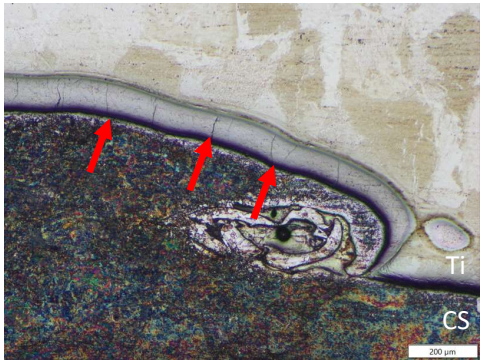
1 mm fillet weld

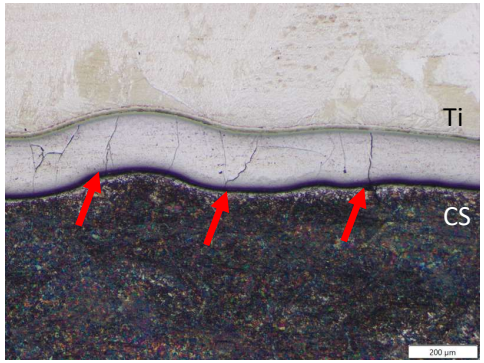


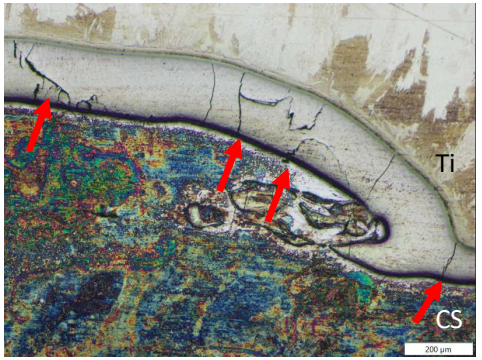


1 mm pad weld









Preliminary conclusions

Defining the go and no-go clad Ti thickness when weld repairing pressure vessels.

NDT, performed on clad Ti per autoclave shutdown activities, does not indicate what is occurring below the surface, i.e. migration of Fe into Ti.

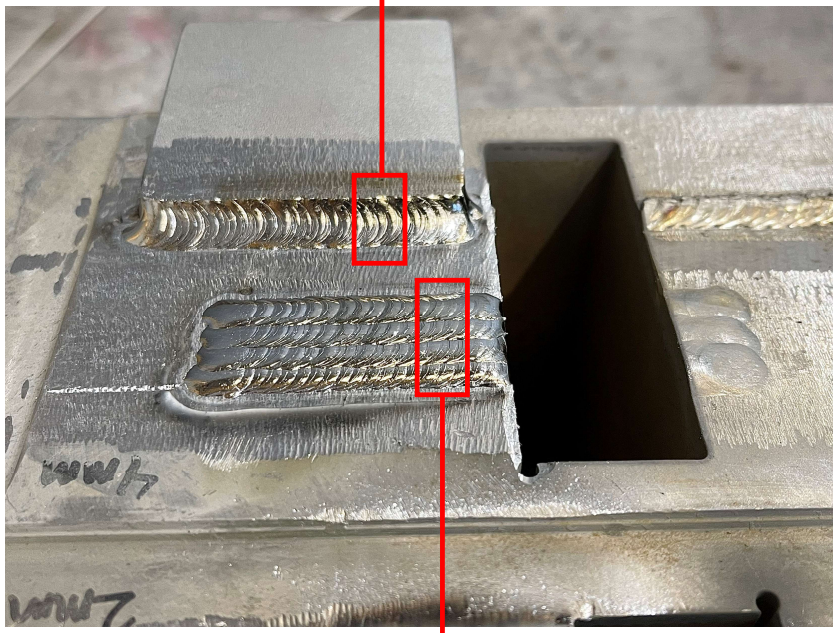
Iron migrating into clad Ti ≤3 mm plate thickness, where intermetallics containing cracks were observed along the clad Ti/carbon steel interface

Even more conservative thickness than what was reported by a previous study by Orr (2019).

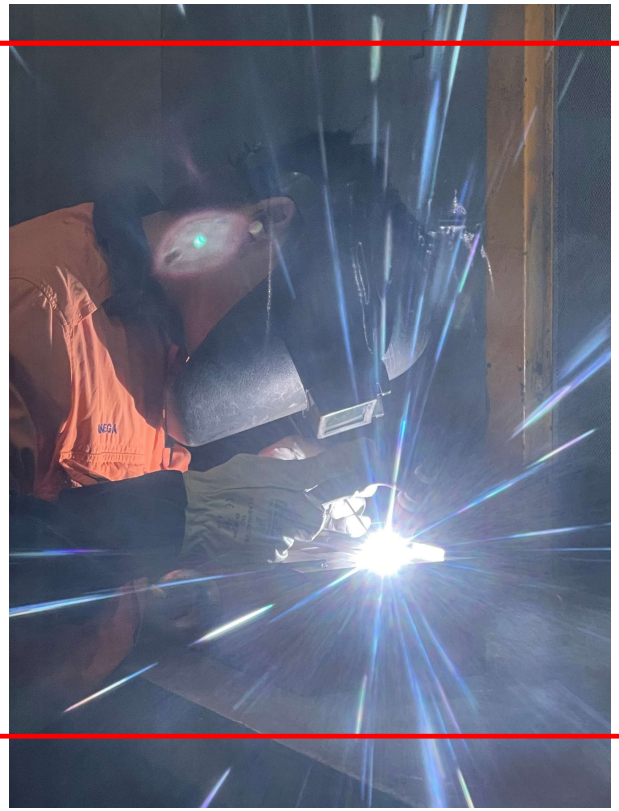
Next steps:
Mechanical testing of the interfaces per ASTM shear strength, adhesion, and bend tests.

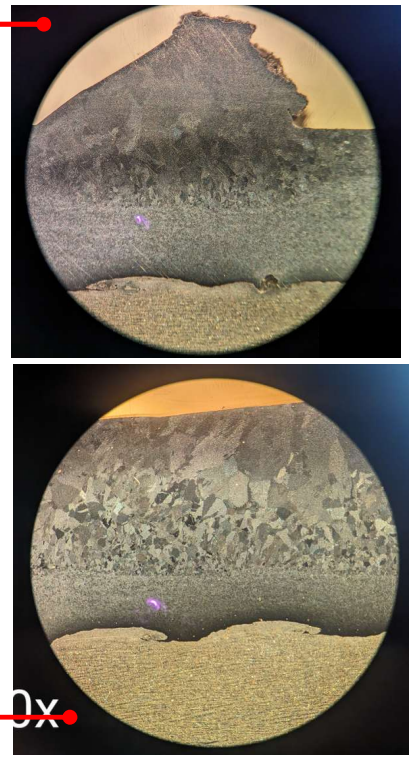
Repeat the experiment on top of the original

To simulate weld repair on Ti cladding that typically occurs over the same region.



NDT: Penetrant Testing, and visual inspection.

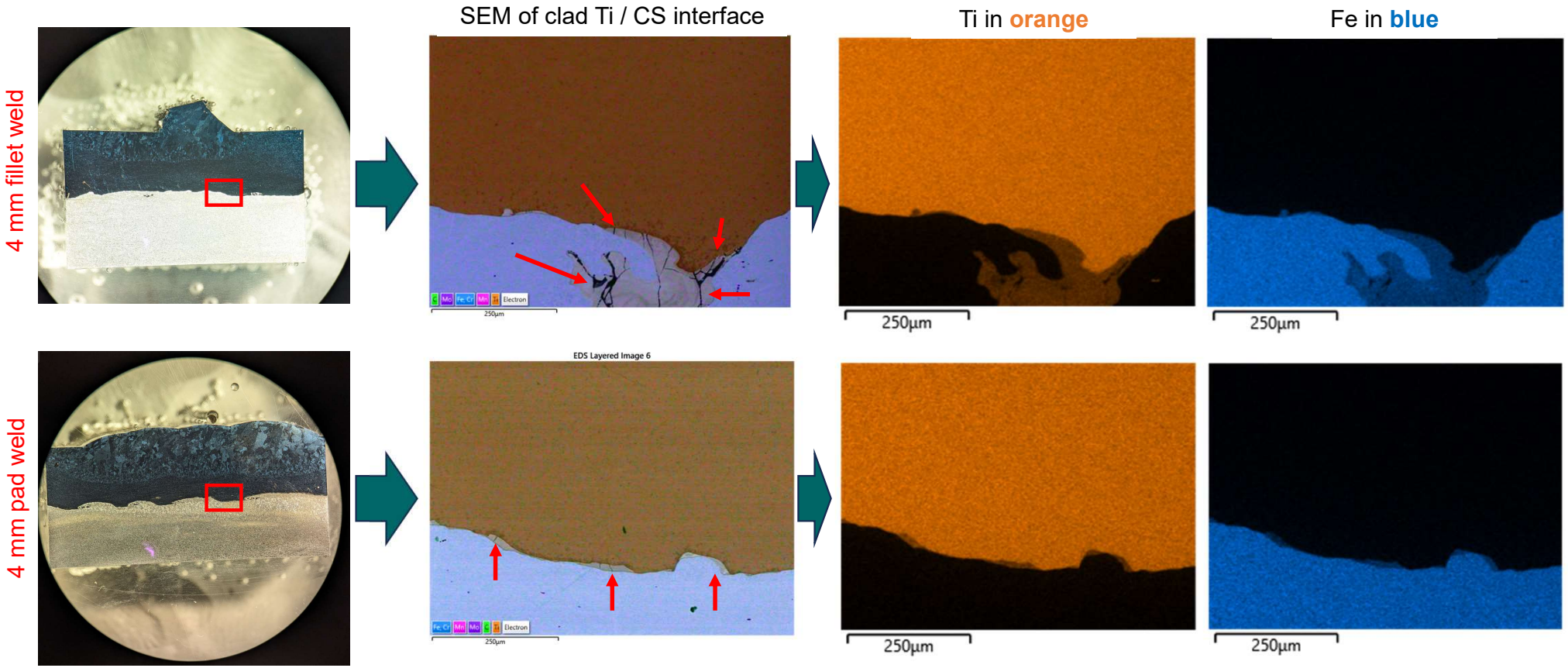




SEM and EDS mapping,
stereo and optical microscopy.

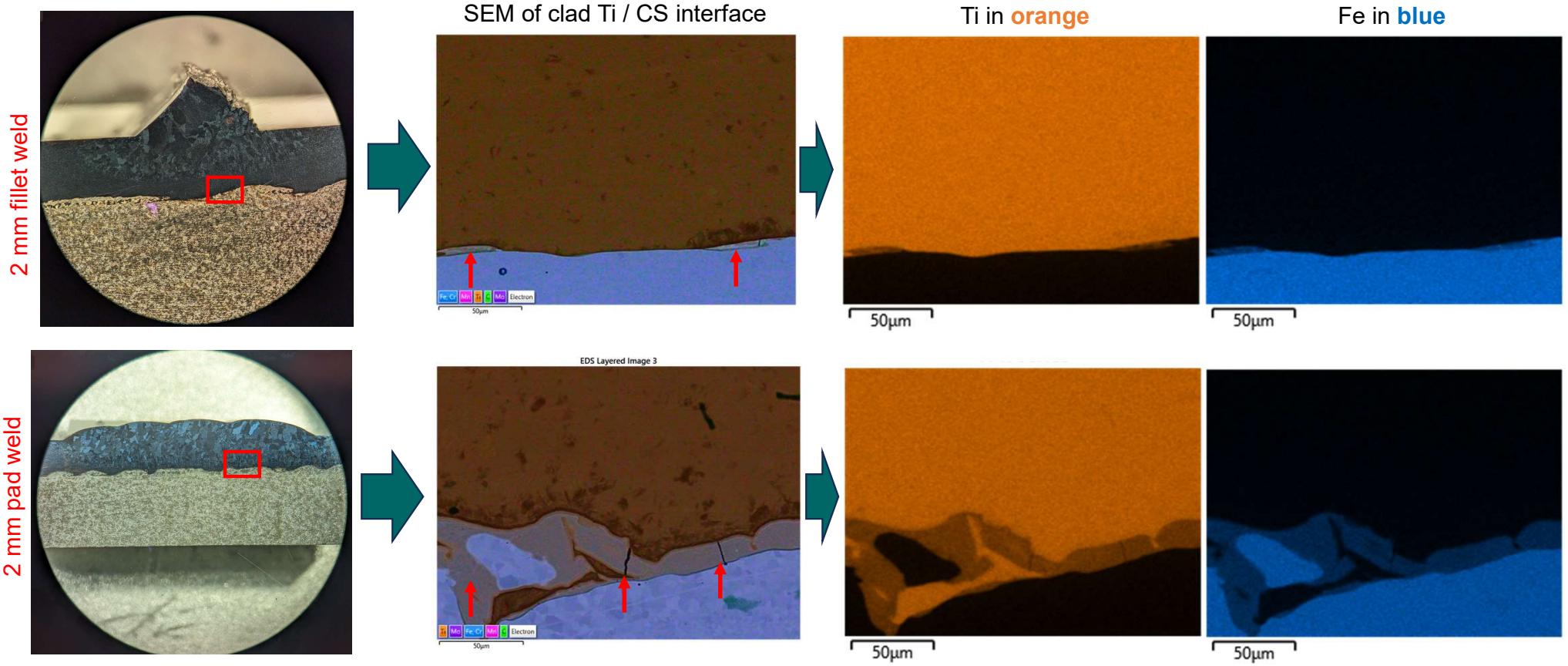
Intermetallics seen at 4 mm Ti clad weld repair

Intermetallics containing cracks were observed at 4 mm clad Ti thickness.



Extensive intermetallics at 2 mm weld repair

Intermetallics, which included cracks, formed continuously along the interface up to 20 mm in length.



Closing takeaways

Preliminary results are indicative of integrity issues in a repaired Ti clad pressure vessel. Study to continue.

1. Standard NDT is not indicative of the integrity of welded and repaired Ti cladding. Brittle intermetallics form at a 4 mm clad Ti thickness, contrary to a previous study that determined intermetallics formed at 1.98 mm.

2. Options exist to enhance the erosion resistance and service life of cladding, including thermal spray ceramic protective coating, nitriding, and wear plates. Determined on a case-by-case basis guided by experience.

3. Weigh the benefits of a short-term repair versus a long-term strategy because the continued risk of vessel breach is too high.