Comparative Tensile and Shear Strength of Explosion Clad Materials

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TOPICS

- Background – Motivation for Test Program
- Experimental Design and Test Results
- Conclusions

Comparative Tensile and Shear Strength of Explosion Clad Materials

Background – Motivation for test program

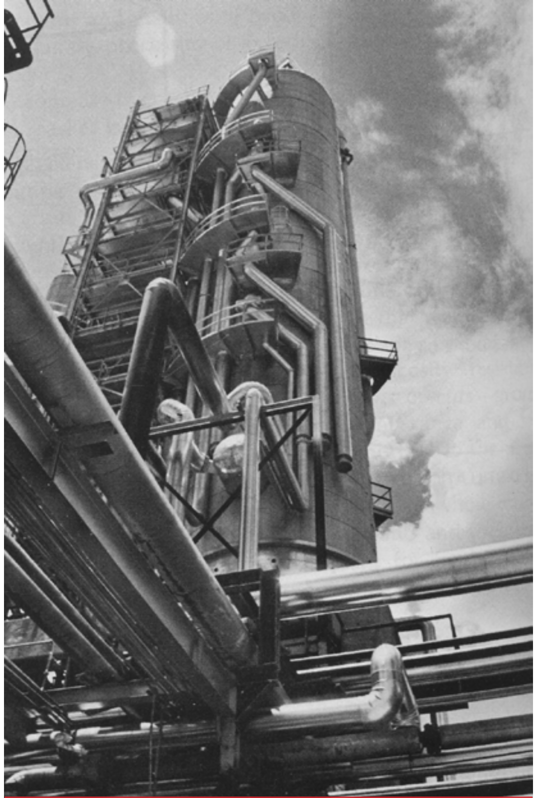
BACKGROUND – MOTIVATION FOR TEST PROGRAM

- Cladding metal thickness typically too thin for tensile test coupon
- Clad specifications do not require clad tensile testing or identify minimum strength requirements
- Shear testing is common, but clad tensile strength data limited

Shear Strength Specification Requirements		
Clad Specification	**Materials**	**Minimum Shear Strength (Mpa)**
ASTM/ASME A263, A264, A265	Stainless Steel and Nickel Alloys	140
ASTM B-432	Copper and Copper Alloy	85
ASTM B-898	Reactive Metals (Ti, Zr)	137.9

WELD INTERNALS DIRECT

- Direct Welding Attachment of Internals
  - In clad vessels, internal attachments to the vessel wall are frequently required
  - Many companies require clad strip-back (especially for “heavy” internals)
    - Lack of data to support design
    - Concerns with clad separation



CRUDE DISTILLATION COLUMN

1. Bond Quality

Disbonding of **Roll Bonded Clad Plates**
after forming and welding

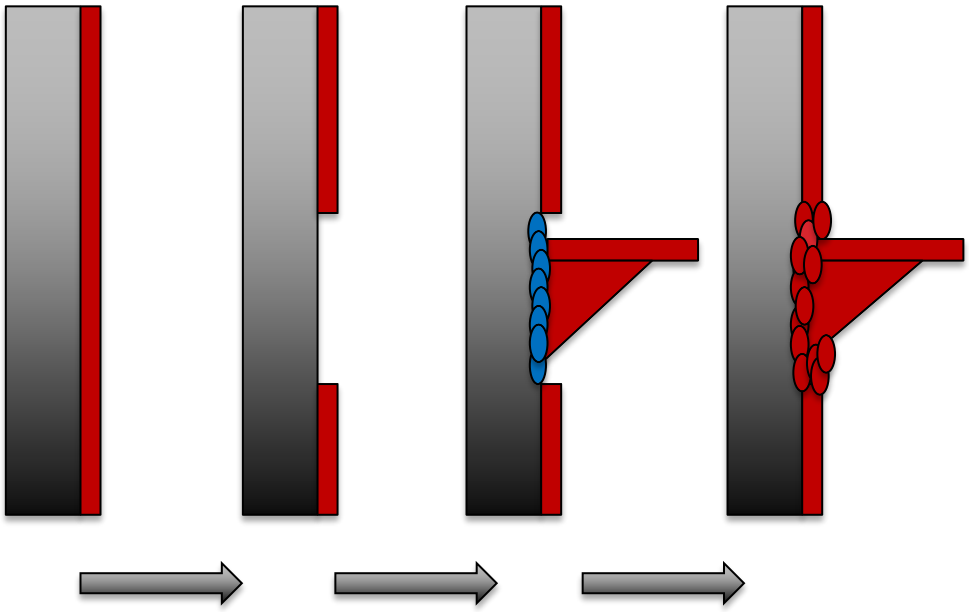
X65Q 35.6 mm + Alloy 625 3.5 mm
OD 39“, 90°/5D induction bend

X65Q 31.1 mm + Alloy 625 3.1 mm
OD 53“ (caisson)

Attachment with Clad Strip-back

Process Steps:

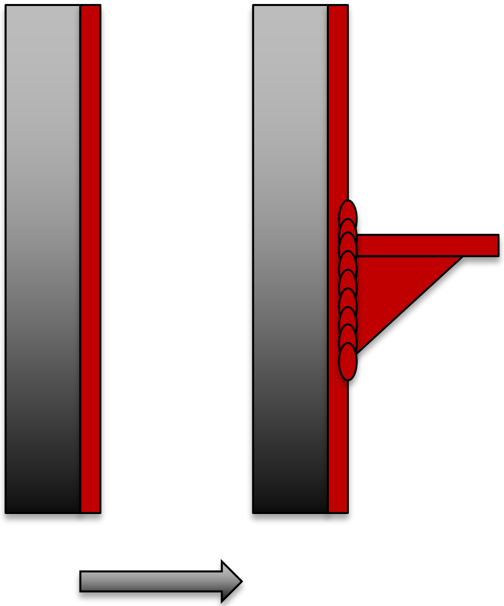
1) Strip back cladding
2) Inspect
3) Weld attachment to steel base metal (dissimilar metal weld)
4) Inspect
5) Complete CRA weld overlay
6) Inspect



Direct Attachment with NobelClad EXW Clad

Process Steps:

1) Weld attachment directly to cladding metal
2) Inspect

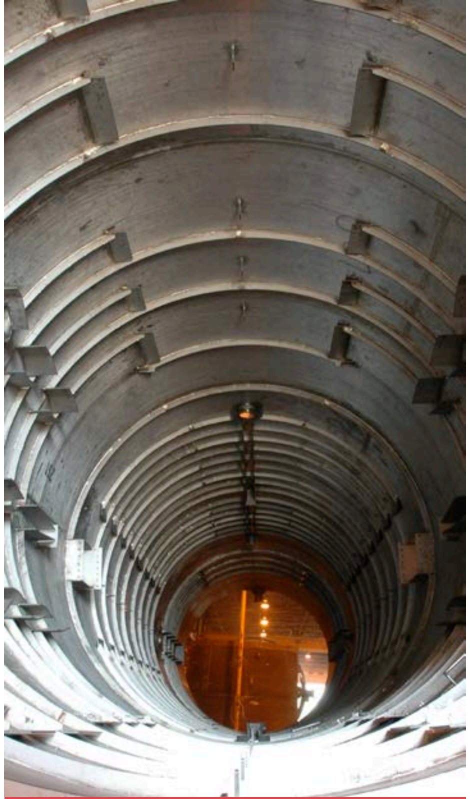


Direct Attachment

- Reduces cost $$$
- Less time in shop
- No dilution or dissimilar metal welding
- Improves design flexibility

WELD INTERNALS DIRECT

- Direct Welding Attachment of Internals
  - Requires reliable, high strength cladding
  - Testing program initiated by NobelClad to investigate clad tensile strength



CRUDE DISTILLATION COLUMN
(Photo courtesy of Dacro Industries)

Comparative Tensile and Shear Strength of Explosion Clad Materials

Experimental Design and Test Results

EXPERIMENTAL DESIGN AND TEST RESULTS

- **Phase I**
  - Testing of a broad range of explosion clad production materials
  - Clad tensile strength is compared to the shear strength, and the cladding and base metal properties.
- **Phase II** describes a second series of tests focused on
  - Materials that are typical for oil & gas applications
  - Covers testing of coupons that simulate in-service conditions (welded coupons, SPWHT, elevated temperature testing, cantilever loading of welded attachment).

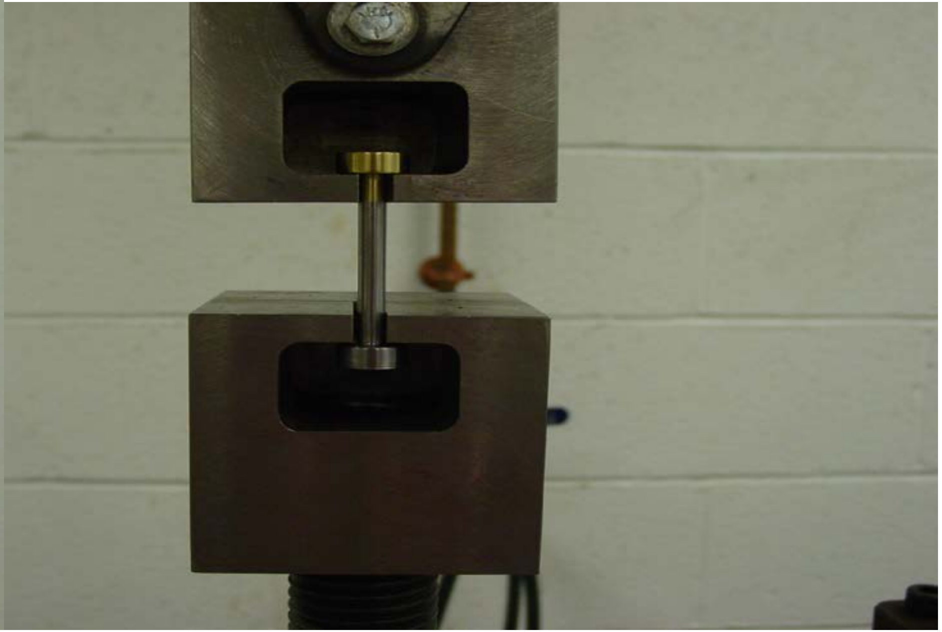
EXPERIMENTAL DESIGN AND TEST RESULTS – PHASE I

- Test material selected from NobelClad production plates
  - Cladding metal thickness>= 9.5mm
  - Heat treatment = production plate HT
- Tests machined from the same test block for direct comparison
  - Shear
  - Sub-size Clad Tensile (6.4mm gauge diameter)
  - Base Metal Tensile

EXPERIMENTAL DESIGN AND TEST RESULTS – PHASE I

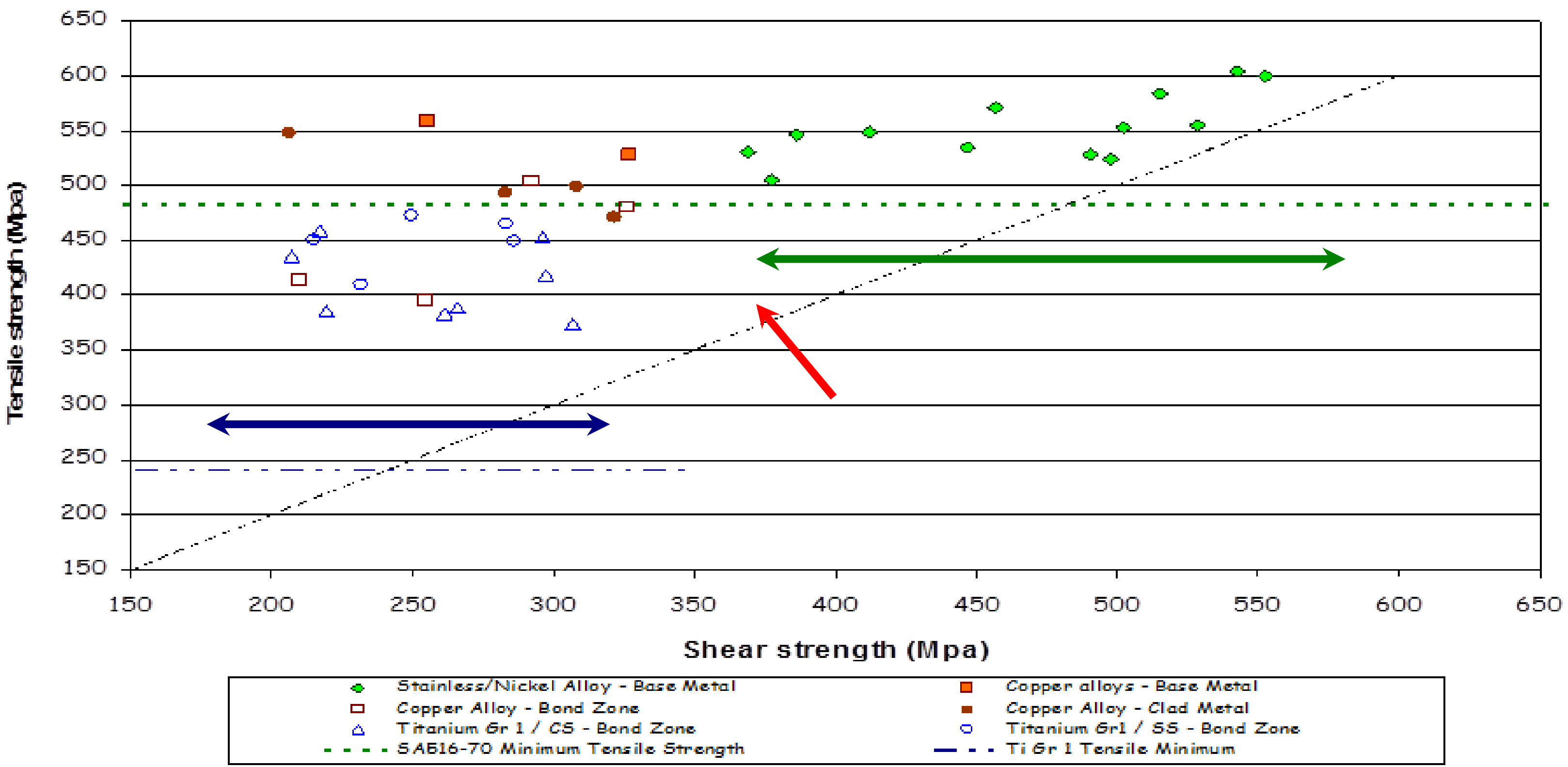
Clad Test Materials	
Cladding Metals	**Base Metals**
Stainless Steels / Nickel Alloys: 304L, 316L, 410S, Alloy 400, 2205, 2507 Duplex SS	SA 516-70 Carbon Steel
Copper Alloys: Naval Brass, 70-30 CuNi	SA 516-70 Carbon Steel
Titanium: Grade 1, 11, 17	SA 516-70 Carbon Steel SA 266-4 Carbon Steel Forging SA 240-304L and 316L SS

EXPERIMENTAL DESIGN AND TEST RESULTS – PHASE I

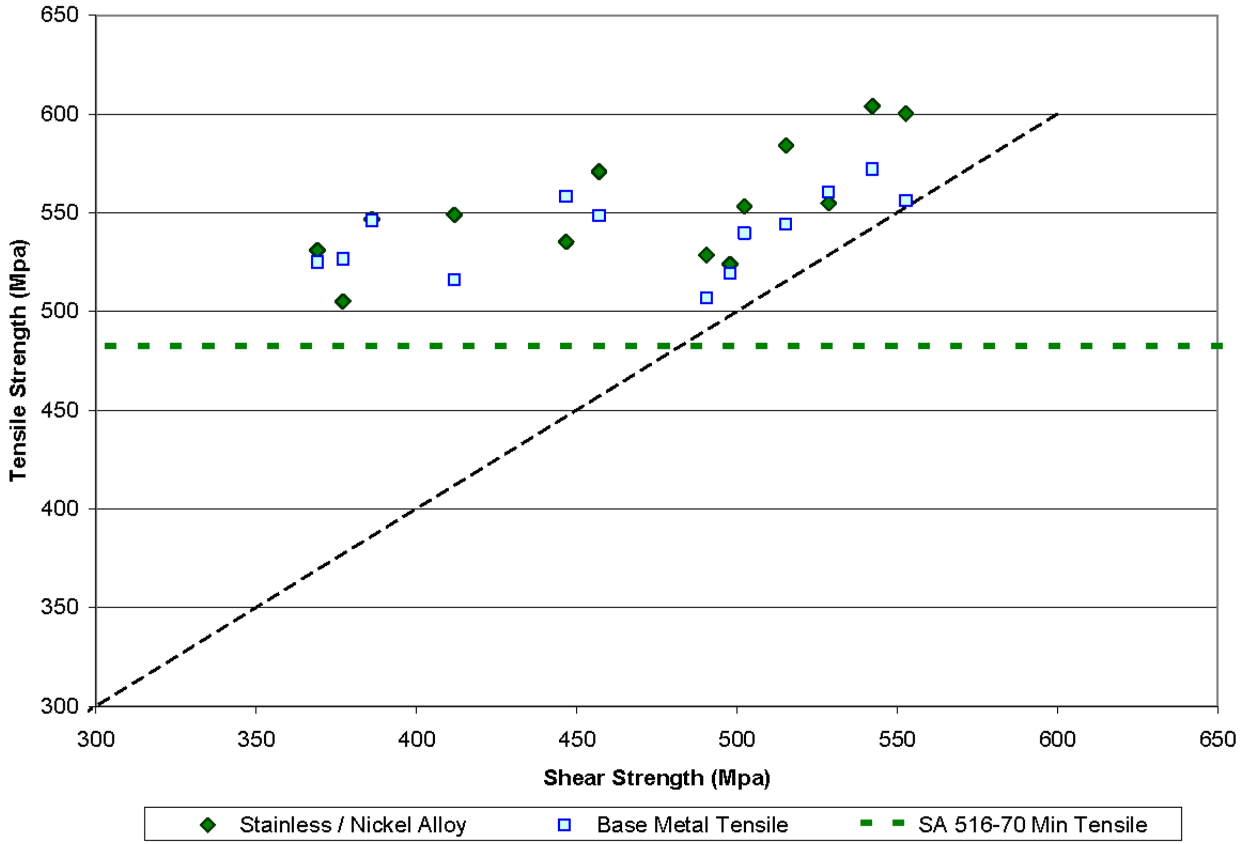


EXPERIMENTAL DESIGN AND TEST RESULTS – PHASE I

SHEAR STRENGTH VS. TENSILE STRENGTH



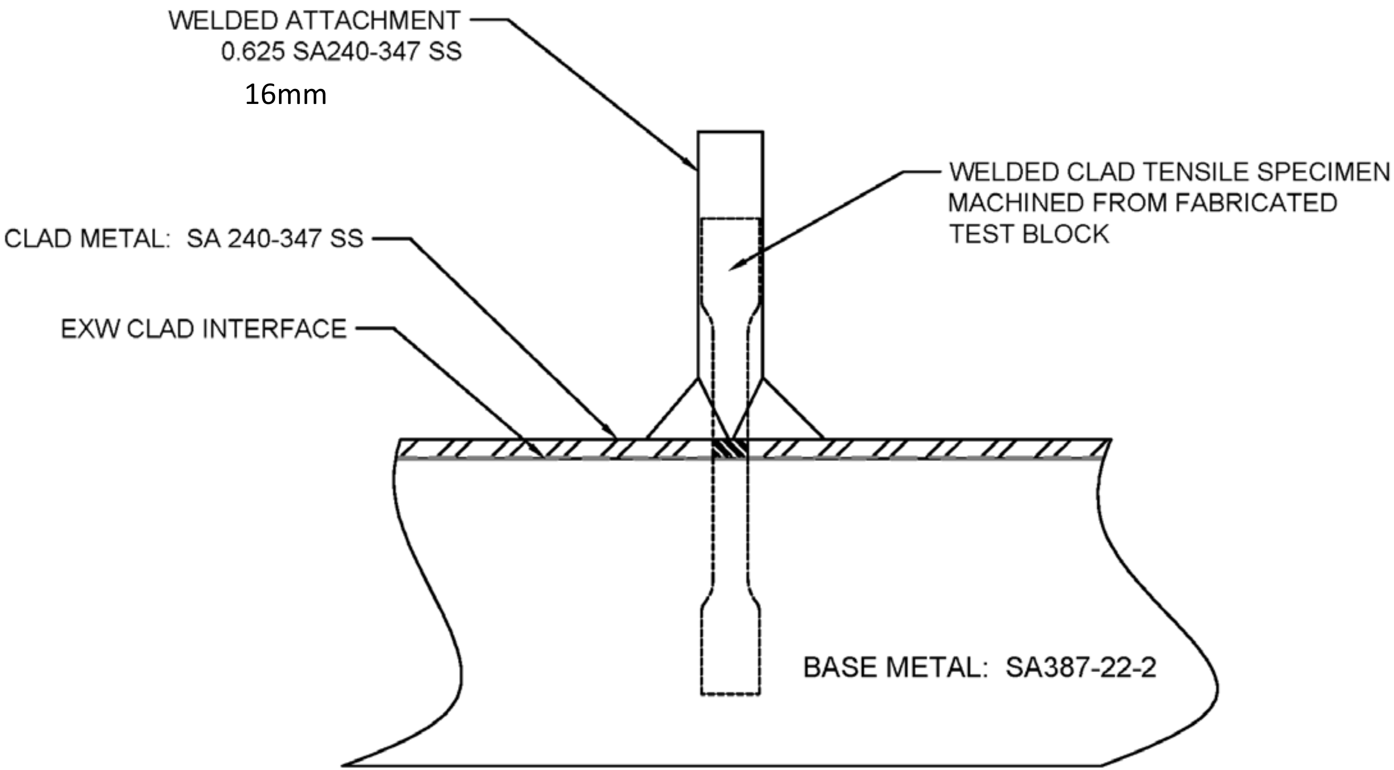
EXPERIMENTAL DESIGN AND TEST RESULTS – PHASE I



EXPERIMENTAL DESIGN AND TEST RESULTS – PHASE II

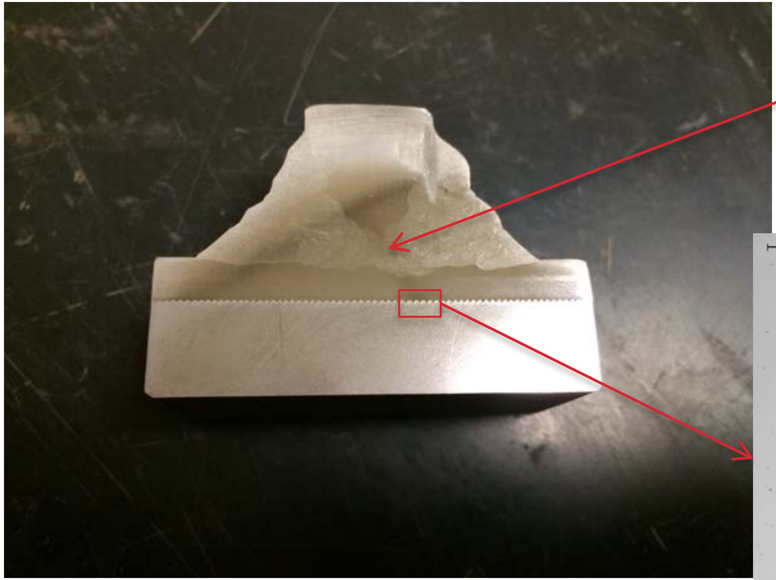
- Covers testing focused on typical oil & gas materials and conditions
- Clad Tensile Testing
  - SA387-22-2, SA516-70 base metal
  - SA240-317L, -347 clad metals
  - 4.8mm cladding metal and welded test coupons
  - Elevated temperature testing (RT to 650°C)
  - Multiple cycles of SPWHT, step cooling heat treatments
  - Evaluation of Tensile Strength and HAZ with reduced cladder thickness
- Cantilever loading of welded attachment
- Tensile testing with simulated non-bond

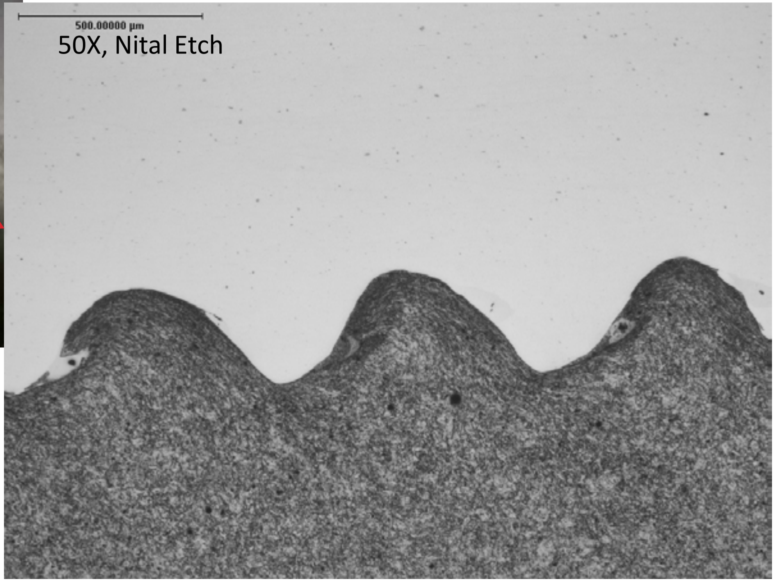
EXPERIMENTAL DESIGN AND TEST RESULTS – PHASE II



Full penetration weld of attachment

No change in steel structure at bond interface

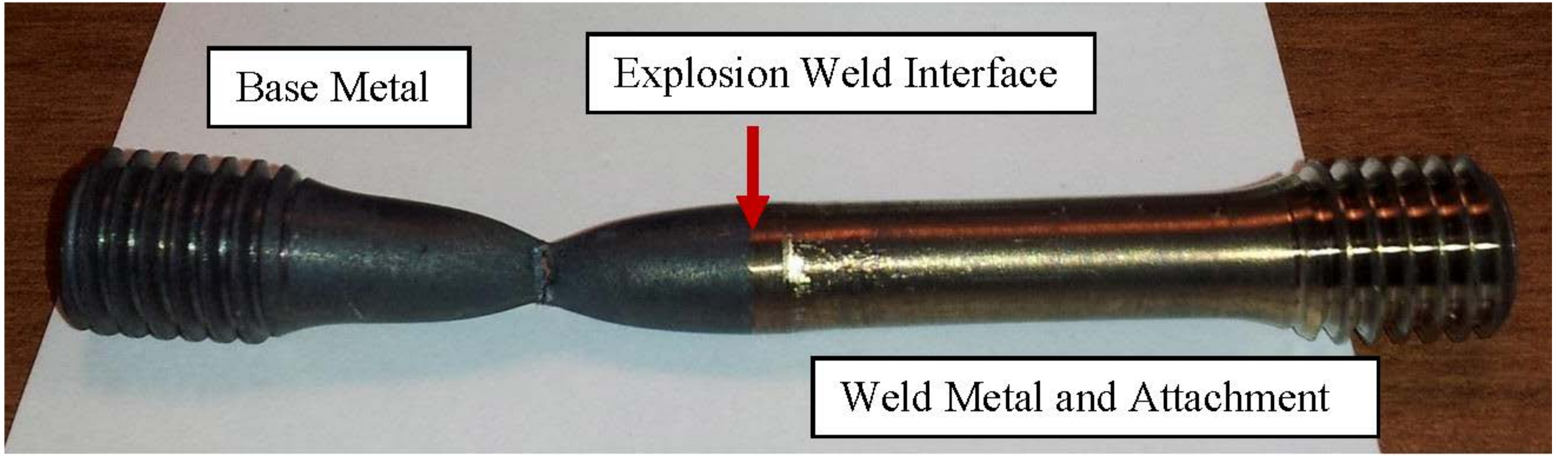




SA240-347 Clad
SA387-22-2 Base

EXPERIMENTAL DESIGN AND TEST RESULTS – PHASE II

- Clad tensile testing
  - Fractures in base metal



Test Temperature: 454°C (850°F)

Clad Tensile Testing (Welded Test Coupons)

RD13-0018

Base	Clad	Condition	Sample ID	Test Temperature (°F)	Tensile	Yield	% Elong	%R.A.	Location of Fracture
SA516-70, 3.250" nom. thickness	SA 240-317L, 0.187" nom. thickness	As-Clad, As-Welded	A1-1	Room Temperature	78.1	48.6	15.0	35.1	base
			A1-2		76.7	50.2	17.0	39.9	base
			A1-3		77.7	49.3	14.4	33.6	base
			A2-1	500	64.5	32.1	24.1	79.1	base
			A2-2		64.9	32.3	25.4	79.6	base
			A2-3		64	34	25.5	79.8	base
			A3-1	850	56.5	31.1	19.7	49.1	base
			A3-2		56.9	28.8	18.3	50.1	base
			A3-3		56.5	35.0	17.6	44.9	base
			A4-1	1000	42.0	27.0	16.2	43.3	base
			A4-2		42.3	26.8	17.9	44.6	base
			A4-3		42.2	27.3	15.7	41.9	base
		As Clad + SPWHT 1100°F, 120 min. Heating and cooling rates per UCS 56	B1-1	Room Temperature	76.6	51.0	17.7	40.4	base
			B1-2		77.3	48.0	17.7	36.1	base
			B1-3		76.5	47.1	17.0	34.4	base
			B2-1	850	55.6	26.7	19.7	45.0	base
			B2-2		55.4	29.5	20.4	46.0	base
			B2-3		56.9	31.1	19.6	43.6	base
			B3-1	1000	40.9	26.4	19.6	44.0	base
			B3-2		41.2	26.2	20.1	43.6	base
			B3-3		41.4	27.4	19.6	42.7	base

Clad Tensile Testing (Welded Test Coupons)

RD13-0018

Base	Clad	Condition	Sample ID	Test Temperature ('F)	Tensile	Yield	%Elong	%R.A.	Location of Fracture
SA387-22-2 Q+T, 2.990" nom. Thickness	SA240-347, 0.187nom. thickness	As Clad + Post Clad SR HT 1175F, 120 min. (HT performed on plate - no further HT required), As-Welded	CI-1	Room Temperature	79.8	57.6	23.6	80.3	base
			C1-2		80.1	56.7	23.1	79.6	base
			C1-3		80.1	57.8	23.5	79.6	base
			C2-1	850	62.3	42.4	22.2	77.5	base
			C2-2		62.4	41.7	22.9	77.7	base
			C2-3		62.4	40.4	22.8	78.9	base
			C3-1	1000	54.5	39.0	22.6	83.5	base
			C3-2		54.6	39.0	22.4	82.9	base
			C3-3		54.3	42.5	22.9	83.3	base
			C4-1	1200	39.3	33.2	29.0	89.9	base
			C4-2		39.4	31.7	28.8	90.3	base
			C4-3		sample damaged during preparation - not tested				

Clad Tensile Testing (Welded Test Coupons)

RD13-0018

Base	Clad	Condition	Sample ID	Test Temperature (°F)	Tensile	Yield	%Elong	%R.A.	Location of Fracture
SA387-22-2 Q+T, 2.990" nom. Thickness	SA240-347, 0.187nom. thickness	+ 1Cycle SPWHT 1274°F, 500 min. Heating and cooling rates per UCS56	D1-1	Room Temperature	78.4	55.6	24.0	79.7	base
			D1-2		78.5	55.3	23.8	78.8	base
			D1-3		78.5	56.3	24.6	79.5	base
			D2-1	850	60.5	39.0	21.1	77.0	base
			D2-2		60.4	40.1	21.7	77.9	base
			D2-3		61.1	40.0	21.8	78.1	base
			D3-1	1000	52.1	39.9	22.9	82.4	base
			D3-2		52.4	38.2	23.9	82.7	base
			D3-3		52.4	40.4	23.6	83.3	base
			D4-1	1200	37.6	31.6	29.6	90.4	base
			D4-2		37.7	31.2	11.6	29.1	weld
			D4-3		37.5	31.0	17.8	41.9	weld

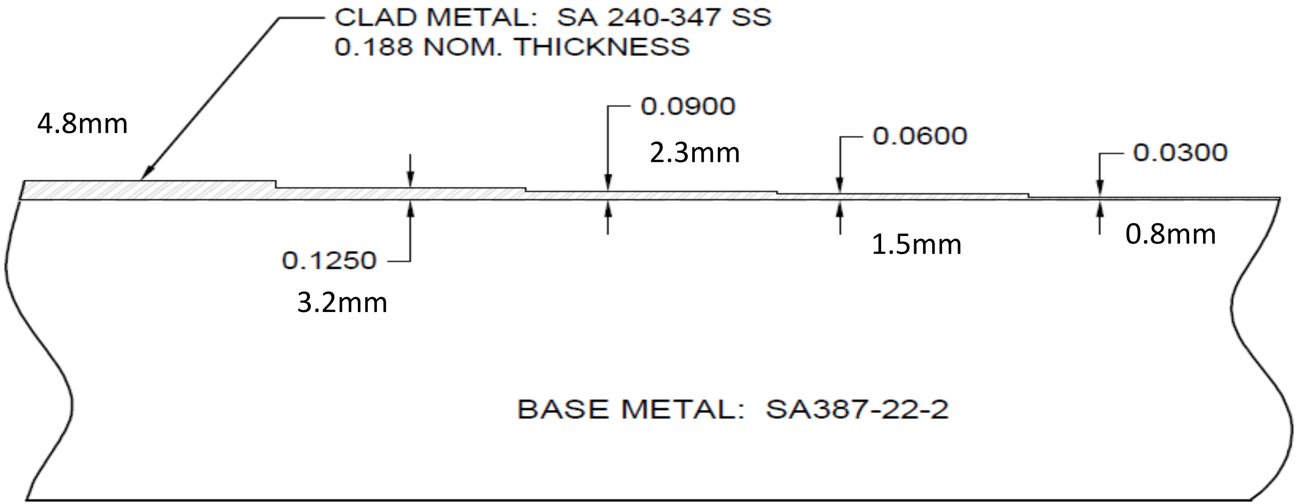
Clad Tensile Testing (Welded Test Coupons)

RD13-0018

Base	Clad	Condition	Sample ID	Test Temperature (°F)	Tensile	Yield	%Elong	%R.A.	Location of Fracture
SA387-22-2 Q+T, 2.990" nom. Thickness	SA240-347, 0.187nom. thickness	+3 Cycle SPWHT 1274°F, 500 min. (1500 min. total) Heating and cooling rates per UCS 56	E1-1	850	60.0	39.3	21.0	78.1	base
			E1-2		60.0	36.7	20.9	77.7	base
			E1-3		60.1	37.4	20.5	77.3	base
			E2-1	1200	36.3	29.1	28.4	91.0	base
			E2-2		36.5	29.0	29.1	88.8	base
			E2-3		36.5	29.7	28.7	90.6	base
		+ 1Cycle SPWHT 1274°F, 500 min. Heating and cooling rates per UCS 56 +SA-387 S63.2 Step Cooling	F1-1	850	58.2	38.4	20.9	78.0	base
			F1-2		58.5	43.1	22.3	78.7	base
			F1-3		57.9	38.5	20.3	78.0	base
			F2-1	1200	37.1	31.3	29.9	90.9	base
			F2-2		35.3	26	30.6	90.4	base
			F2-3		37.3	30.9	28.6	90.7	base

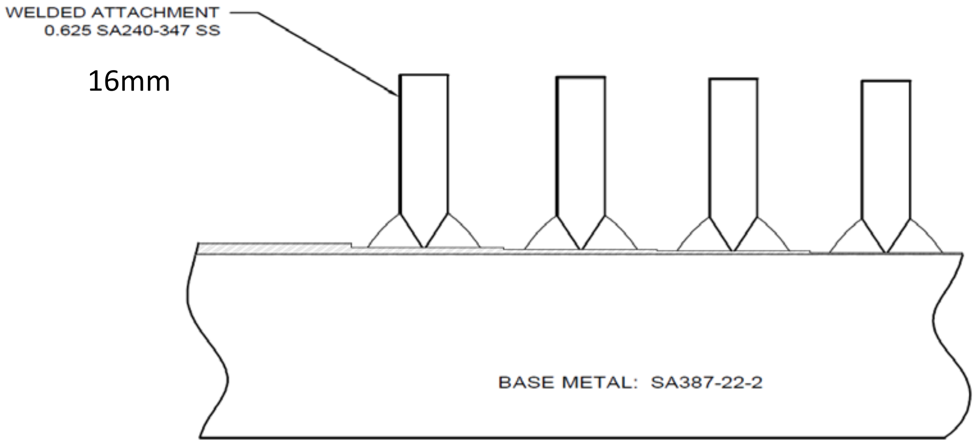
EVALUATION OF TENSILE STRENGTH AND HAZ WITH REDUCED CLADDER THICKNESS

- Evaluate minimum clad thickness required for direct attachment welding without affecting the base metal
- Demonstrate tensile properties without PWHT



TEST SET UP AND TENSILE RESULTS

- 4.8mm Clad: 593 MPa
- 3.2mm Clad: 589 MPa
- 2.3mm Clad: 598 MPa
- 1.5mm Clad: 590 MPa
- 0.8mm Clad: 610 MPa

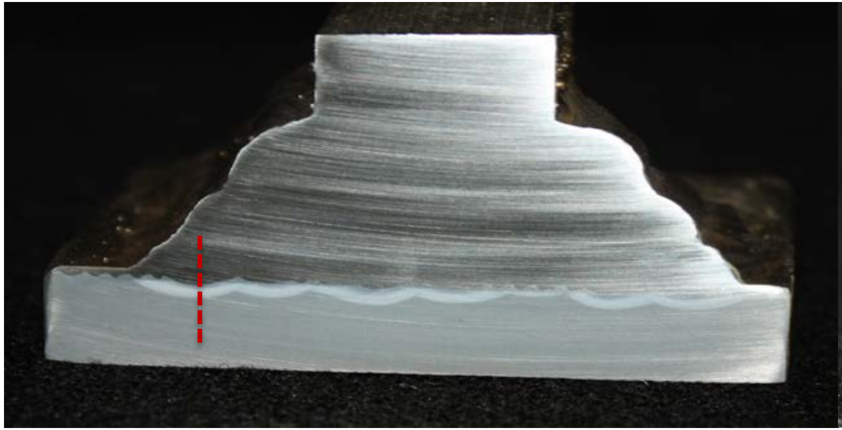


- All failure locations were in the SA 387-22-2 base metal

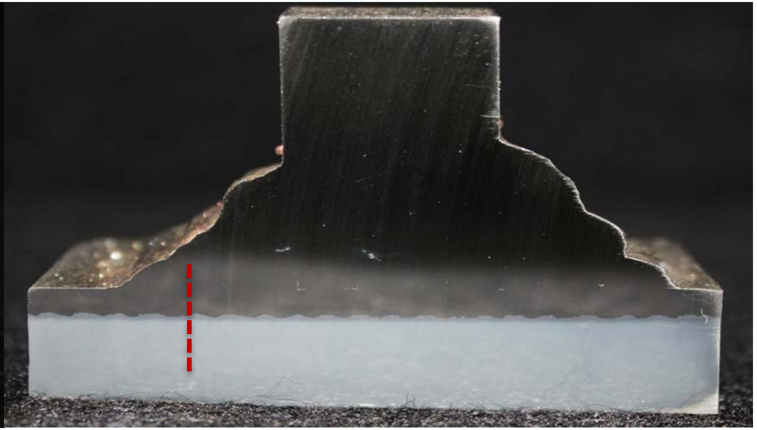
WELDING PARAMETERS

- Process: GMAW
- Shielding Gas: 90% He, 7.5% Ar, 2.5% Co2
- Filler Metal: ER347
- Current: 181 Amps
- Voltage: 21 Volts
- Travel Speed: 10 IPM
- Wire Feed Speed: 350 IPM
- Heat Input: 22,806 Joules per inch

EVALUATION OF HAZ

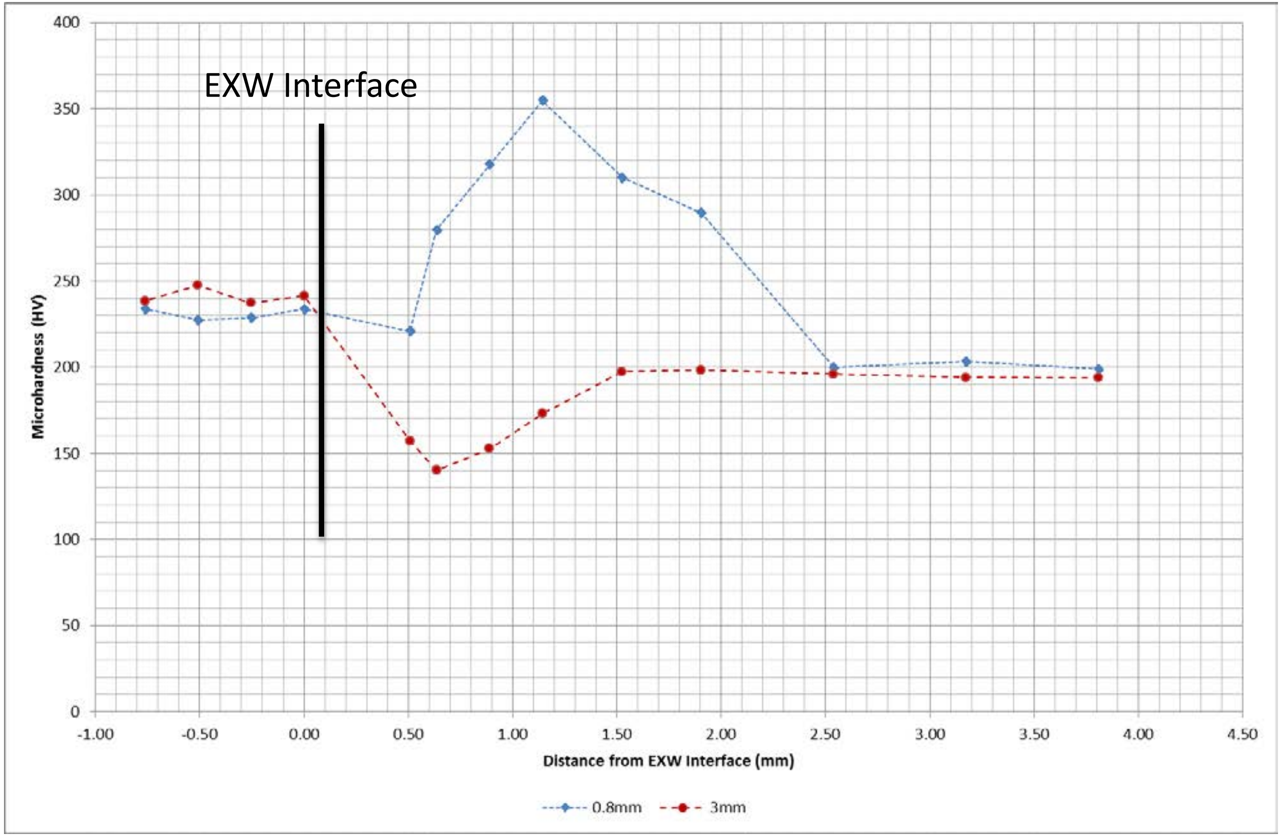


0.8mm Clad Thickness



3.2mm Clad Thickness

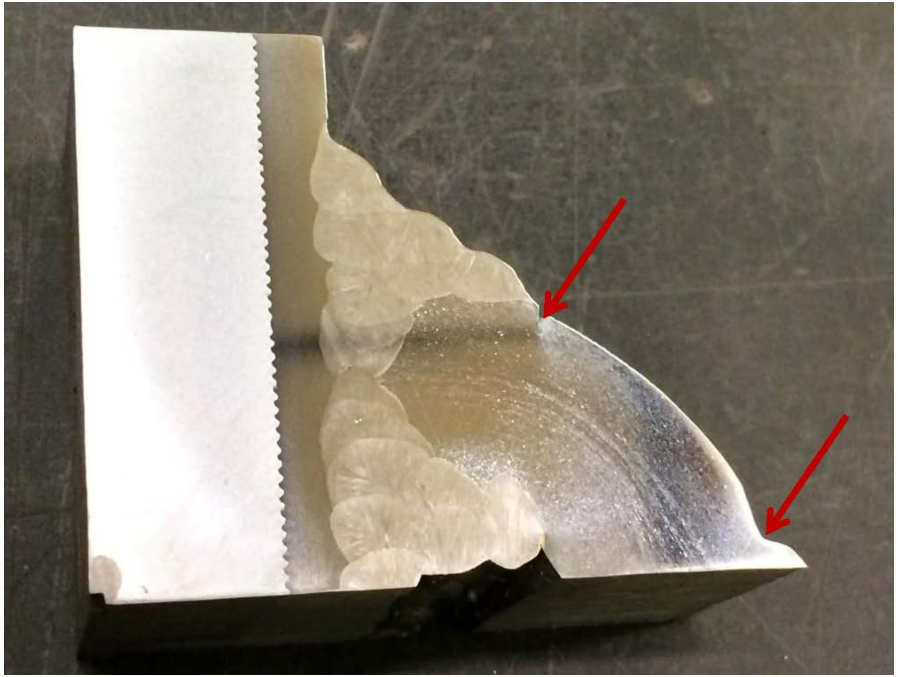
EVALUATION OF HAZ



CANTILEVER LOADING OF WELDED ATTACHMENT

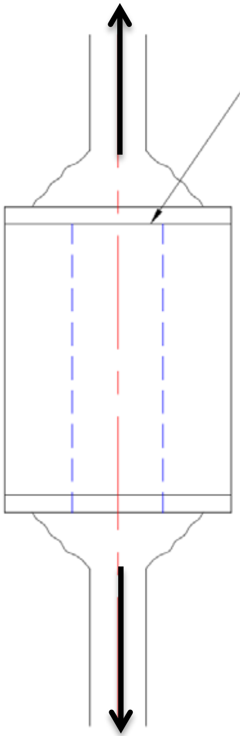
- Application mock-up testing
  - Bending moment on a welded attachment.
  - Loaded to failure on the production press.
  - After loading , samples cut for metallographic examination and evaluation.

CANTILEVER LOADING OF WELDED ATTACHMENT



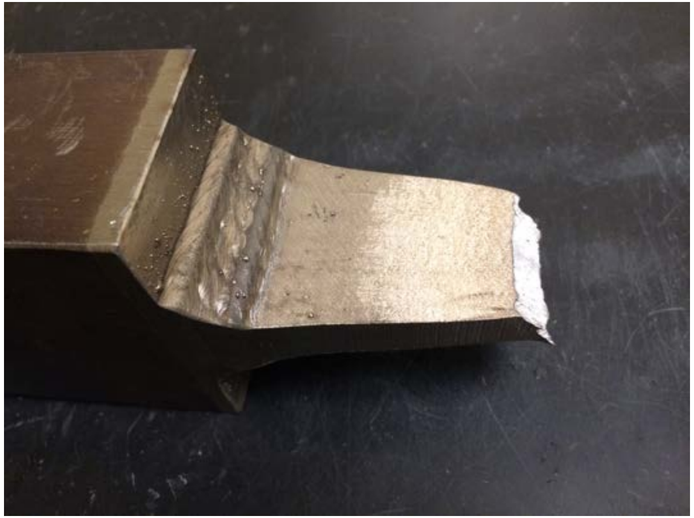
TENSILE TESTING WITH SIMULATED NON-BOND IN CLADDING

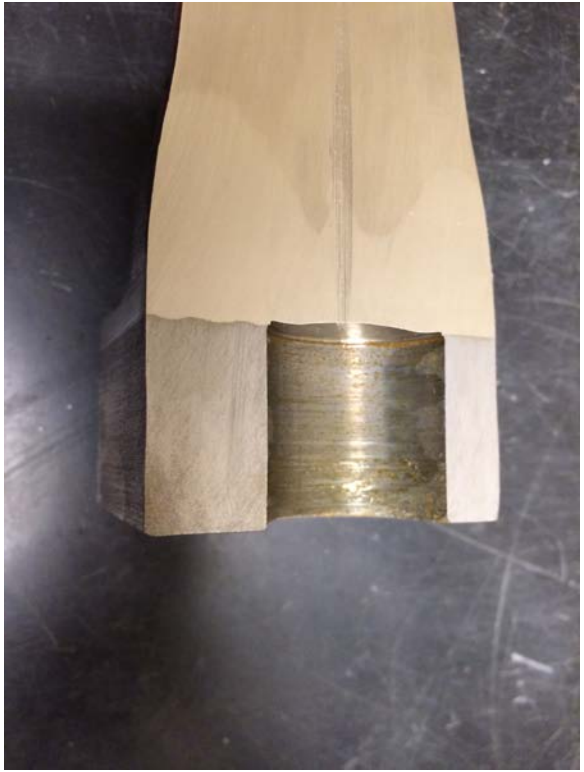
- Application mock-up testing
  - 25mm flat bottom hole drilled to the interface to simulate a 25mm non-bond.



TENSILE TESTING WITH SIMULATED NON-BOND IN CLADDING

Load at Break = 525 kN
No disbond at simulated non-bond





COMPARATIVE TENSILE AND SHEAR STRENGTH OF EXPLOSION CLAD MATERIALS

Conclusions

- The clad tensile strength exceeded the shear strength for 100% of the materials tested
- The through thickness tensile strength of explosion welded titanium alloy and copper alloy clad are well above the cladding metal minimum tensile strengths
- For explosion welded stainless steel and nickel alloy clad, the tensile strength of explosion weld
  - Exceeded the tensile strength of the steel base metal and
  - Meets the base metal minimum tensile strength requirement.
  - Tensile strength maintained for thinner cladding metal, welded test coupons, with various heat treatment conditions, and at elevated temperature
  - Mock-up testing did not produce any clad separation or disbonding

Conclusions

- Tensile strength data of NobelClad EXW material supports direct attachment to the clad surface

NobelClad

Thank you

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