Design Considerations in Attaching Pressure Vessel Internals: Welding to the Pressure Boundary or Welding to the Clad?

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ABSTRACT

Process equipment which employs a corrosion resistant alloy (CRA) layer cladded to steel is common in refineries and petrochemical plants. There are two regularly employed methods for welding attachments and internals to clad process vessels. One is to remove the CRA cladding and make the attachment to the base metal (steel). The other eliminates the step of removing the cladding, simplifying the attachment process. With the lack of data to support direct attachment, designers frequently demand the cladding be removed or allow only a conservatively low stress limit for what can be attached directly to the clad surface. It is well understood that eliminating the step of removing clad increases the simplicity, improves the lead-time, and reduces the cost of making these attachments for trays or other internals, but there are concerns about clad disbonding risks. So which method is better? Recently, a technical study, including significant testing, has been undertaken to verify the bond between clad material and the base steel is robust enough to withstand the heaviest attachments in the harshest conditions. The theory behind the technical study will be presented along with and the results of this study.

KEYWORDS

Clad, explosion welding, explosion clad, mechanical properties, tensile testing, shear testing, bond interface, bond strength, base metal, cladding metal, clad strip back, vessel internals, roll bond, direct attachment.

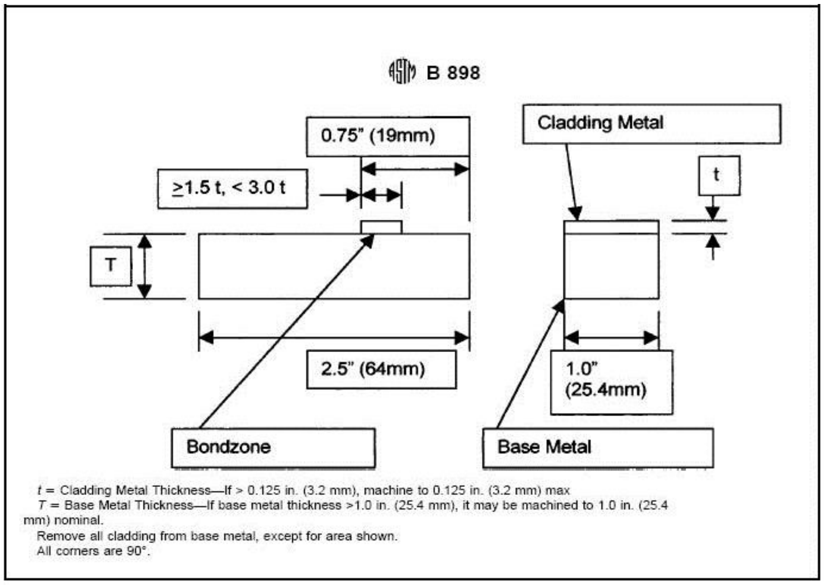
INTRODUCTION

Clad materials are employed in a wide range of applications, but one of the largest industrial applications is in the manufacture of large clad plates used for fabrication of pressure vessels and heat exchangers in the oil and gas, petrochemical, and chemical process industries. Depending on the CRA, the clad material is typically purchased in accordance with one of the internationally accepted clad specifications such as ASTM A263, A264, A265, B432, B898 or ASME SA-263, SA-264, SA-265. [1]

Most of the clad material discussed in this paper is governed by the ASTM A263, A264, or A265 specifications. Clad material produced to these specifications is either made by weld overlay, explosion welding (EXW) or by hot roll bonding. This paper focuses on the EXW and hot roll bond cladding methods. These standards define the required and optional nondestructive and mechanical testing evaluations that can be specified. The test that is specified to check for bond strength is a shear test. The shear test requirements are shown in Table 1, and the specimen geometry is shown in Figure 1. These limits are the minimum requirement and don't ensure the clad materials stay bonded together in the most aggressive conditions. These specifications do not define a through thickness clad tensile test to evaluate the strength of the bond in the through thickness direction. For most applications, the clad metal is simply too thin to produce a meaningful clad tensile specimen. Specification MIL-J-24445A for aluminum-steel bonded joints defines a "ram" tensile test specimen. [2] This design has been used for testing transition joint type products, such as Aluminum-to-Steel; but this specimen design has limited applicability. If the cladding metal is too thin, the ram will shear through the cladding metal without breaking the bond zone. In addition, because of the specimen geometry, the tensile strength measured is not equivalent to the tensile strength measured by an ASTM A370 specimen. [3]

Clad Specification	Materials	Minimum Shear Strength [MPa (ksi)]
ASTM A263, A264, A265 ASME SA-263, SA-264, SA-265	Stainless Steel and Nickel Alloys	140 (20)
ASTM B-432	Copper and Copper Alloys	85 (12)
ASTM B-898	Reactive Metals (Ti, Zr)	137.0 (20)

Table 1. Shear Strength Specification Requirements [4-11]



t = Cladding Metal Thickness—If > 0.125 in. (3.2 mm), machine to 0.125 in. (3.2 mm) max
T = Base Metal Thickness—If base metal thickness >1.0 in. (25.4 mm), it may be machined to 1.0 in. (25.4 mm) nominal.
Remove all cladding from base metal, except for area shown.
All corners are 90°.

Figure 1: Shear Test Specimen in Accordance with ASTM B898[4]

Because of the absence of specification requirements, and due to the practical testing difficulties, minimal data has been presented on the tensile strength of clad materials. Nevertheless, the tensile strength of a clad interface can be an important consideration when structural components are to be welded to the clad surface of process equipment. If tensile strength is known, then direct attachment of internals can be used. The more attachments welded to the clad in an application, the more benefit in cost and delivery that can be achieved. One such application is the crude distillation column as shown in Figure 2 where multiple internal support rings and other internals, as depicted in Figure 3, are attached to the column walls. Because of the lack of clad tensile data, the designer has minimal basis for designing non-pressure retaining components to be welded directly to the clad surface. This usually results in specifications requiring the removal of the cladding material, down to the base steel before welding the attachment. Some engineering and owner companies allow welding of tray support rings and other non-pressure bearing components directly to the clad surfaces, while others require clad removal and attachment to the base steel. In some specifications and designs, arbitrary limits have been set for allowable stress in direct attach welds, without a documented basis. It is generally accepted that the steps of removing the clad, making a dissimilar metal weld, and restoring the clad has implications of increased manufacturing time, increased cost and in some cases increased risk and reduced flexibility. However, without test data to support direct attachment, it seems engineers have determined strip back and welding to steel to be the norm, compared to direct attachment. Availability of clad tensile test data would strengthen the design analysis and may lead to extending the range of applications where direct attachment to clad is permitted. A testing program has been undertaken to fill this void and establish data on the interface tensile strength properties of EXW clad materials, including a comparison to hot roll bonded clad materials.

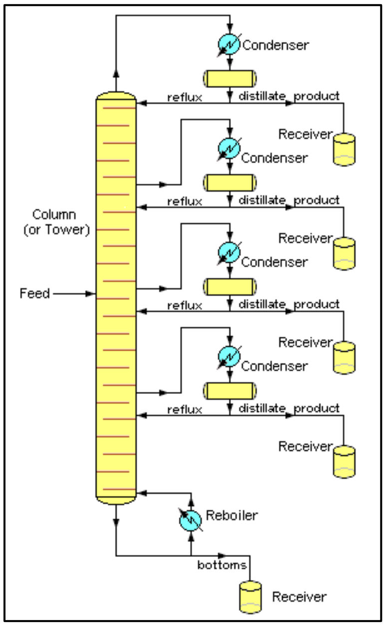


Figure 2: Schematic of Crude Distillation Column[13]

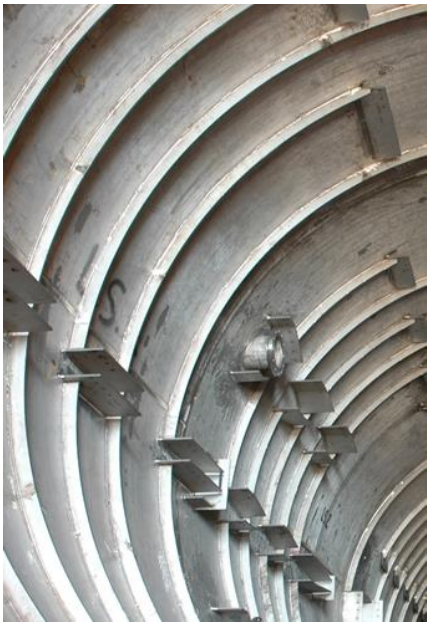


Figure 3: Tray internal Support Rings (Photo Courtesy Dacro Industries)

TESTING AND ANALYSIS OF EXPLOSION WELDED CLAD METAL

It was determined previously that shear testing of explosion welded clad material is a good indicator of the minimum tensile strength to be expected of the same clad system.[13] While this prior work was important to draw conclusions about the behavior of EXW clad metal, it did not take into account testing of coupons that simulate in-service conditions (welded coupons, SPWHT, elevated temperature testing, cantilever loading of welded attachment, etc.). In addition, the primary use of significant internals in pressure equipment is in the oil & gas industry. Therefore, stainless steel clad materials of construction, most closely associated with the oil & gas industry, were selected for further study.

The testing is focused on simulating in-service conditions on clad materials that are typical for oil & gas applications, and is based on feedback and comments from industrial partners, engineering companies and end users. Specifically, the test program was designed to address the following:

- Representative cladding metal thickness
- Additional representative base metal (SA-387-22-2)
- Multiple samples for each test condition
- Elevated temperature testing
- Heat input and stresses from welding
- Simulated Post Weld Heat Treatment, and step cooling heat treatments
- Cantilever loading of a direct weld attachment
- Simulated non-bond beneath an attachment weld

The explosion clad material combinations tested, shown in Table 3, were produced in accordance with NobelClad established explosion welding parameters and are fully representative of production materials.

Cladding Metals	Base Metals
SA240-317L SS, 4.8mm (0.188”)	SA 516-70 Carbon Steel 82.6mm (3.250”)
SA240-347 SS, 4.8mm (0.188”)	SA387-22-2 Q+T, 75.9 (2.990”)

Table 3: Clad Test Materials

All of the test coupons were machined from test blocks fabricated with an attachment welded on the explosion clad material as shown in Figure 4. The weld attachment was a 16mm x 76mm (0.625” x 3.00”) SS bar, beveled for a full penetration weld. The root pass was performed with GTAW, followed by completion of the joint with GMAW. The welding procedure and welder were qualified in accordance with Section IX of the ASME Code.

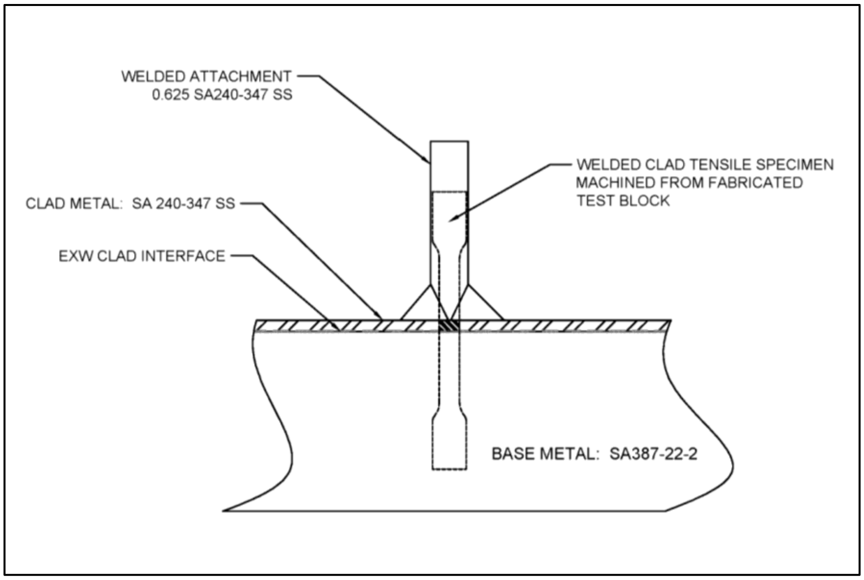
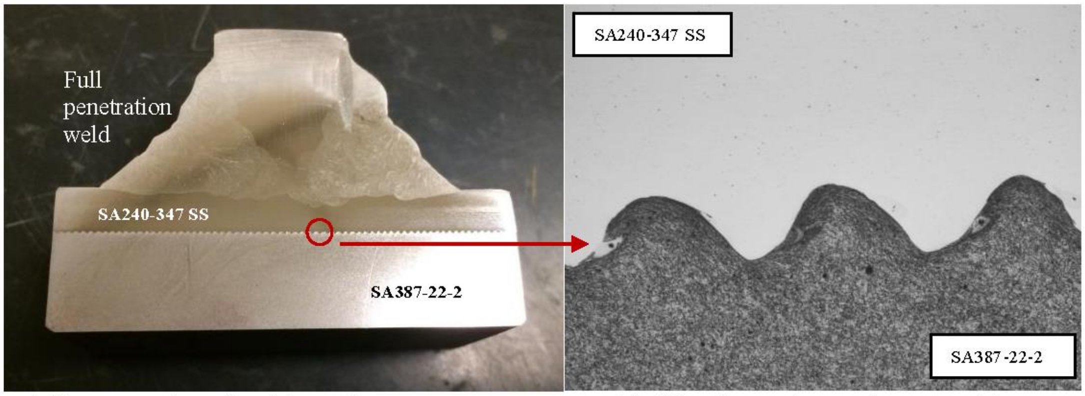


Figure 4: Fabricated Test Block with Attachment Welded to Explosion Clad Material

Figure 5a shows a macro section of a weld attachment. The full penetration fusion weld of the attachment on the cladding metal and the typical wavy interface of the explosion weld are evident. The weld fusion zone and HAZ did not extend into the base metal. Metallographic examination and microhardness testing across the interface confirm the base metal structure is unchanged. The Vickers microhardness in the base metal was ~ 200 HV500 at 1mm from the bond interface regardless of location relative to the attachment weld. A photomicrograph under the attachment weld is shown in Figure 5b.



a) Macro section of weld attachment
b) Micro beneath attachment weld

Figure 5: Macro and Micro Examination of Weld Attachment on EXW Clad

After welding, some of the test material was heat treated in an electric furnace with one or multiple cycles of simulated post weld heat treatment (SPWHT), and one test block was given an additional step-cooling heat treatment per ASME SA-387 following the SPWHT. Thermocouples were attached to each test block during heat treatment.

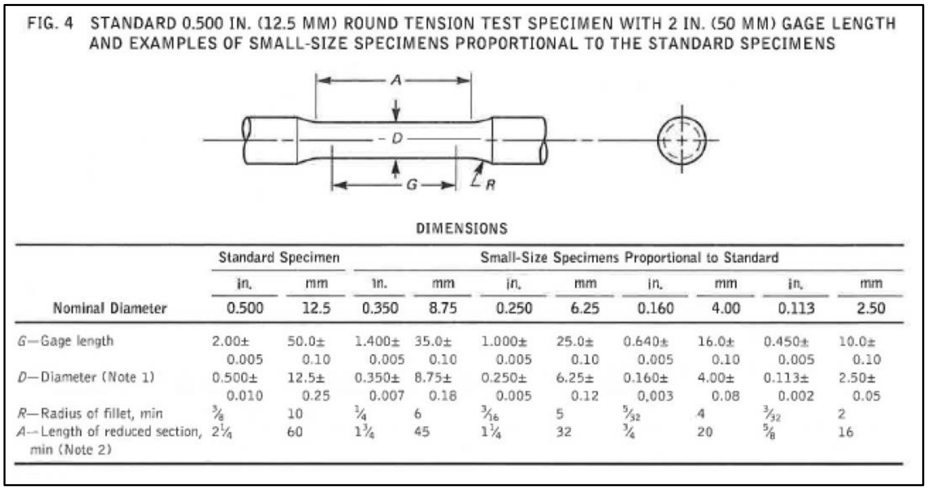


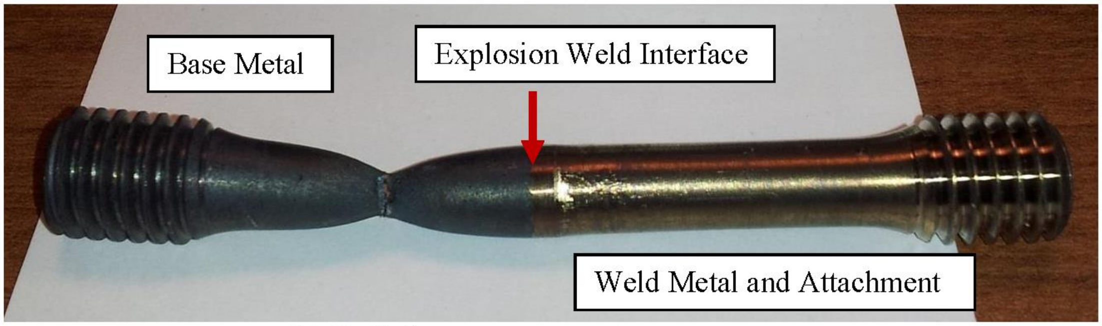
FIG. 4 STANDARD 0.500 IN. (12.5 MM) ROUND TENSION TEST SPECIMEN WITH 2 IN. (50 MM) GAGE LENGTH AND EXAMPLES OF SMALL-SIZE SPECIMENS PROPORTIONAL TO THE STANDARD SPECIMENS

DIMENSIONS

	Standard Specimen		Small-Size Specimens Proportional to Standard							
	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm
Nominal Diameter	0.500	12.5	0.350	8.75	0.250	6.25	0.160	4.00	0.113	2.50
G—Gage length	2.00± 0.005	50.0± 0.10	1.400± 0.005	35.0± 0.10	1.000± 0.005	25.0± 0.10	0.640± 0.005	16.0± 0.10	0.450± 0.005	10.0± 0.10
D—Diameter (Note 1)	0.500± 0.010	12.5± 0.25	0.350± 0.007	8.75± 0.18	0.250± 0.005	6.25± 0.12	0.160± 0,003	4.00± 0.08	0.113± 0.002	2.50± 0.05
R—Radius of fillet, min	3/8	10	1/4	6	3/16	5	5/32	4	3/32	2
A—Length of reduced section, min (Note 2)	2 1/4	60	1 3/4	45	1 1/4	32	3/4	20	5/8	16

Figure 6: Tensile Test Specimen in Accordance with ASME SA-370[3]

Following heat treatment, standard tensile specimens were prepared per ASME SA-370[3] as shown in Figure 6. The test coupons were machined such that the explosion weld interface was within the gauge length of each specimen as shown in Figure 7. Room temperature and elevated temperature testing was then conducted in accordance with ASTM E8[15] and ASTM E21[16].



Test Temperature: 454°C (850°F)

Figure 7: Explosion Welded Clad Tensile Test Specimen with Welded Attachment

TABLE 4. **BASE: SA516-70, 3.250" nom. Thickness**
CLAD: SA240-317L, 0.187" nom. thickness

Condition	Sample ID	Test Temp. (°F)	Tensile	Yield	% Elong.	% R.A.	Location of Fracture
As-Clad, As-Welded	**A1-1**	**RT**	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		64.4	33.7	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**	**RT**	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

TABLE 5. **BASE: SA387-22-2 Q+T, 2.990" nom. Thickness**
CLAD: SA240-347, 0.187 nom. thickness

Condition	Sample ID	Test Temp. (°F)	Tensile	Yield	% Elong.	% R.A.	Location of Fracture
As Clad + Post Clad SRHT 1175°F, 120 min. (HT performed on plate - no further HT required), As-Welded	C1-1	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				
+ 1 Cycle SPWHT 1274°F, 500 min. Heating and cooling rates per UCS 56	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	55.3	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
+ 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
+ 1 Cycle 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	26.0	30.6	90.4	base
	F2-3		37.3	30.9	28.6	90.7	base

TEST RESULTS AND DISCUSSION

Room temperature and elevated temperature tensile test results for each material and condition are shown Tables 4 and 5. The results were consistent with results reported in prior work [13] for stainless and nickel alloy clad, as all of the welded through thickness clad tensile specimen broke in the base metal except for specimen D4-2 and D4-3. Although these samples failed in the weld, the tensile and yield strength are consistent with D4-1 and other 650°C (1200°F) test results. Once again, the strength of the EXW exceeded the strength of the base metal, and all of the tests were essentially short transverse tensile tests of the base metal. One of the 454°C (850°F) test specimen is shown in Figure 14, and is indicative of all the tensile testing in this paper. Note that the composite test coupons did not elongate uniformly. In general the specimen exhibited limited elongation in the cladding metal, weld metal, and stainless steel attachment; and as can be seen in Figure 14, the necking and most of the deformation occurred in the base steel. As a result, the % elongation reported in Tables 4 and 5 is artificially low and should not be compared to base metal minimum elongation requirements.

In addition to the standard tensile testing reported above, specialized tests were designed to mock-up conditions that may be experienced in typical applications. One such test was the cantilever loading of a welded attachment that closely represents a tray support ring in a distillation column (Figure 8a). A bending moment was applied to the unsupported end of the cantilever attachment up to the 534 kN (120,000 lbf.) load capacity of the test frame. As can be seen in Figure 8b, the attachment was deformed and bent downward in excess of 12.5mm (0.50”). After loading, the EXW clad was UT inspected from the steel side and no indications were identified.

Figure 8 a) Test Article in Test Frame and b) After Application of 534kN: Cantilever Testing of Direct Attachment Welded to Explosion Clad Material

Subsequently, the cantilever test article was loaded to failure by employing a production press (applied load is unknown), and sectioned for examination of the explosion weld interface. Although the attachment was severely deformed, and cracking was initiated in the attachment weld, no disbond or clad separation was observed at the explosion weld interface. (Figure 9)

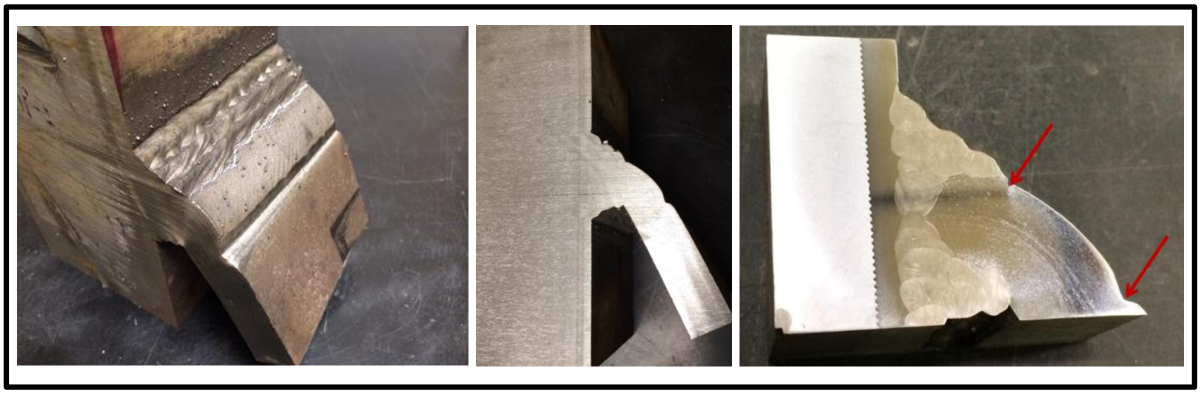


Figure 9: Cantilever Test Section Examination – Severe deformation of attachment and cracking observed in the attachment welds, but no clad separation at EXW interface.

A second mock-up test specimen was designed to simulate an allowable non-bond at the clad interface underneath a welded attachment as shown in Figure 10.

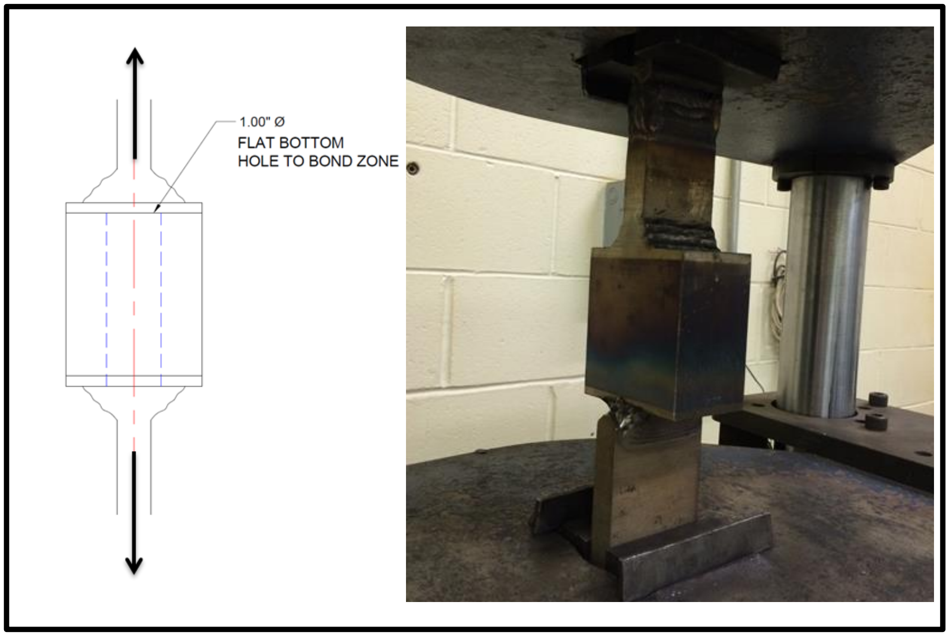


Figure 10: Tensile Testing of Welded Attachment with Simulated Non-Bond

ASME SA-263, SA-264, and SA-625 define ultrasonic examination Quality Level Class 1 as “No single unbonded area exceeding 1 in. (25mm) in its longest dimension with total unbonded area not to exceed 1% of the total cladded surface area.” To simulate the allowable unbonded area, a 25mm (1.00”) diameter flat bottom hole was drilled from the base steel side to the explosion weld interface. After drilling the hole, an additional bar was welded to the base steel and the specimen was loaded in tension.

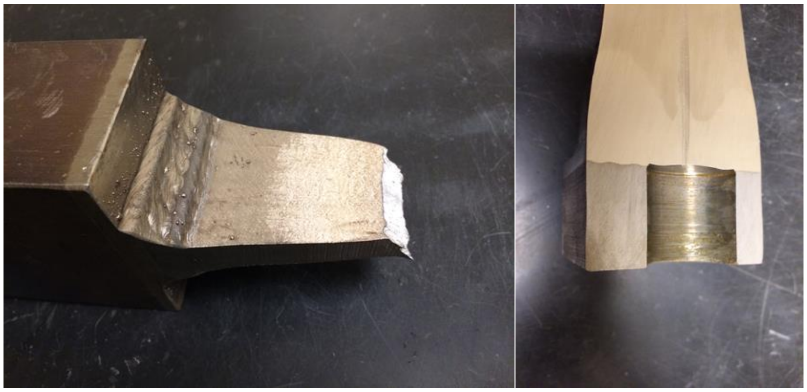


Figure 11: Examination of Simulated Non-Bond Test Specimen – No Clad Separation

The attachment bar failed at 652 MPa (94.6 ksi) at an applied tensile load of 526 kN (118,118 lbf). The average stress on the explosion weld around the simulated non-bond is relatively low, depending on how the stress area is estimated. However, this is representative of actual installations. In addition, the edge of the specimen and edges of the simulated non-bond represent sharp stress concentrations that generally will not be present in typical installations. After testing, the test article was sectioned and examined. No evidence of clad separation was observed under the weld; even at locations of stress concentration adjacent to the hole and at the edges of the test specimen (Figure 11).

COMPARISON WITH ROLL BONDED CLAD METAL

Hot Roll bond is a process of producing clad metal in a steel mill. Special packages of steel and stainless steel or nickel alloy are rolled together, under high pressure and high temperature, causing the two materials to bond together. It is generally accepted that the bond in hot rolled clad metal is not as strong as EXW clad. Recently, a major western producer of roll bonded clad metal released shear test data for their clad metal. The data was good and exceeded the minimum in ASTM A265 by a wide margin. However, when compared to explosion welded clad shear strength, in Figure 5, the discrepancy is clear. The result can be disastrous in certain aggressive forming operations and could lead to disbonding of clad subjected to the combined loading of a direct welded attachment.

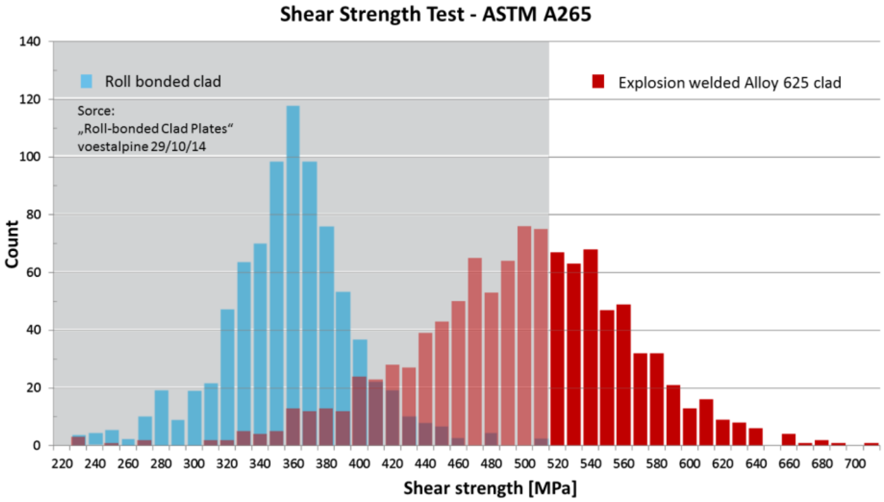


Figure 12: Comparing Shear Strength of EXW and Hot Roll Bond [17]

Figure 13 shows roll bond clad metal disbonding after forming. The clad plate (X65 35.6mm + Alloy 625 3.5mm) in this case passed basic UT and shear testing, by meeting the minimum requirement. After being formed into a 1 meter diameter, 90 degree, 5D induction bend, it is clear upon sectioning, the clad is separating from the steel. This type of disbonding of hot roll bonded plates during aggressive forming or service conditions is a primary driver for skepticism of all clad metal bond zones. To build a comprehensive comparison, it was necessary to examine how hot roll bond clad would perform in the same tensile tests performed on the EXW clad in the prior section.

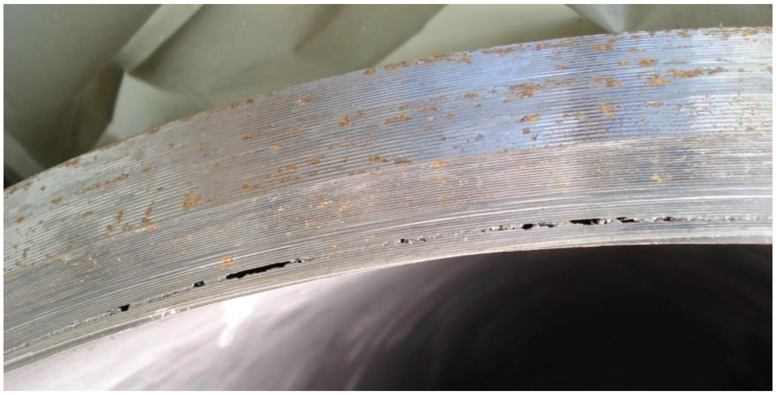


Figure 13: Hot Roll Bond, Disbonding after Forming

To further investigate roll bond clad, and to understand the response of this type of clad to tensile loading conditions, tensile specimens were fabricated by welding simulated attachments to the clad surface directly. The general arrangement of these specimens follows the same methodology demonstrated in the previous tests done of EXW clad metal (see Figure 6). The differences between these tests, and those above, are the materials used (516-70 + 316L clad) and an additional amount of steel was required to be welded to keep the bond zone in the gauge length of the tensile specimen. There also was no PWHT, elevated temperature testing, or PWHT performed. The results of the room temperature tensile tests are shown in Figure 14. Elongation was limited (Table 3) before the clad bond zone failed in a brittle manner, ending the tensile test. While roll bond meets the basic cladding specification for bond strength, it is proven to be unsuitable for the most aggressive loading conditions, like those experienced in critical pressure equipment.

Figure 14: Roll Bond Samples with Brittle Failure in the Bond Zone

	Sample 1	Sample 2	Sample 3
Elongation	2%	1.5%	3.1%

Table 3: Roll Bond Elongation in Tension

CONCLUSIONS

Test results were reported that extend the tensile test data for stainless steel explosion welded and hot roll bond clad materials. These tests were focused on materials that are typical for oil & gas applications and testing was performed to simulate in-service conditions (welded coupons, SPWHT, elevated temperature testing, cantilever loading of welded attachment).

These test results support the following conclusions:

- For explosion welded stainless steel and nickel alloy clad, the tensile strength of EXW clad produced by NobelClad
    - Exceeds the tensile strength of the steel base metal and
    - Meets the base metal minimum tensile strength requirement.

  This conclusion was maintained for welded coupons, at various heat treatment conditions, and over the range of service temperatures.

- For hot roll bonded stainless steel to carbon steel clad, the tensile strength of the bond zone
    - Was less than the strength of the base materials
    - Failure was observed as brittle failure after very little elongation

The clad tensile data reported herein provides the specifiers of clad with an improved basis for devising testing programs related to directly attaching internals to the clad surface in typical downstream oil & gas equipment. A through thickness welded tensile specimen could be required to fail in the base metal. This result would ensure a truly superior bond between the CRA and the steel. This data will also give designers a basis on which to plan for welds of non-pressure retaining components to be attached to the clad surface if the clad plate is produced to certain stringent criteria. Additionally, this data should extend the range of applications where direct attachment to EXW clad is permitted.

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