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Qualification of Explosion-Bonded Ti-Ru Alloy Clad Steel Plate for Pressure Acid Leach Process Equipment

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ABSTRACT

The trend toward increasing acid and chloride levels in hydrometallurgical pressure leach processes, such as HPAL of nickel laterite ores, warrants selection of more resistant titanium alloys for equipment. Although the Ti-Pd alloys (Grades 7, 11, 16, and 17) are traditional, technically-viable candidates for preventing crevice corrosion and/or vapor phase acid attack in HPAL equipment, these alloys are costly due to the high and volatile price of palladium. The Ti-0.1% Ru alloys, Grades 26 and 27, represent lower-cost alternatives to Ti-Pd alloys with similar properties.

HPAL autoclaves are constructed of titanium-steel clad plates. Although one should expect the same explosion-bonding behavior as the unalloyed Ti and Ti-Pd alloys, Ti-Ru alloy plate bonding to steel had not previously been demonstrated. To formally qualify the clad product for HPAL process use, two explosion-bonding trials on 9 mm thick Grade 26 and Grade 27 Ti-Ru plates bonded to 50 mm A516GR70 steel backer plates were conducted. These clad plates were thoroughly metallurgically characterized via destructive and non-destructive examinations, and subsequently subjected to a typical hot head-forming operation to demonstrate vessel fabricability.

In addition to detailing results of these two bonding trials, this paper provides an overview of Ti-Ru alloy metallurgy and properties, and corresponding clad plate equipment cost implications and candidate HPAL applications.

BACKGROUND

Pressure acid leaching (PAL) ore in the presence of sulfuric acid at high temperatures and pressures provides a potentially low cost option for production of nickel metal. The process exhibits hot oxidizing conditions under which nearly all common metals and alloys perform poorly. Titanium is one of the only metals that has excellent corrosion resistance under the combined conditions of temperature, acid concentration, possible chlorides, and oxidizing ions present in these PAL autoclaves. However, the high pressure, temperature, and volume requirements for the autoclaves create conditions in which monolithic titanium equipment is not economically viable. Titanium clad steel offers

the corrosion performance of titanium at much lower cost. Fabrication and operation experience demonstrate that titanium clad steel is the preferred material of construction for PAL autoclaves for nickel production. Titanium-steel clad plate for PAL construction has been manufactured exclusively by the explosion cladding process.

AUTOCLAVE ENVIRONMENT

Autoclaves for PAL of nickel laterites operate around 250°C to 270°C (480°F to 510°F) and 5.0+ MPa (725+ psi), with a 5 to 7% sulfuric acid concentration. High concentrations of oxidizing metal ions, such as ferric and nickelous ions, are naturally present. Corrosion conditions in these facilities are frequently aggravated by high chloride concentrations in the available process water. Process economics demand that the autoclaves have large capacity and continuous process design. Consequently, the pressure vessels are typically large in diameter and length, and are of horizontal construction with a sequence of mechanically agitated chambers.

Six PAL autoclaves have been operating in nickel/cobalt ore leaching plants in Western Australia since 1999. The specific details regarding vessel size and material of construction are presented in Table 1. One of these autoclaves is pictured in Figure 1.

Table 1: Australian nickel laterite projects using PAL autoclaves.

Project	Owner	# Units	Size (m)	Titanium Cladding	Steel Backer Thickness (mm)
Bulong	Preston Resources	1	4.60 ID x 31 long	8mm Gr 17	100
Cawse	Centaur Gold	1	4.65 ID x 27 long	8mm Gr 11	102
Murin Murin	Anaconda Nickel	4	4.95 ID x 35 long	6mm Gr 1	110

MATERIAL OF CONSTRUCTION OPTIONS

The internal corrosive conditions in nickel leaching PAL autoclaves necessitate that vessel walls and internal components be either titanium (or related alloys) or acid brick. For a broad number of reasons, including temperature/pressure/cost considerations, neither acid brick nor solid titanium is a viable material of construction for the autoclave pressure containment body. Steel is the obvious structural material of choice. Consequently, the autoclave designer has two primary options for PAL autoclave



Figure 1: Titanium clad steel PAL autoclave at the Murin Murin Nickel Cobalt Project. (photograph provided by ASC Engineering)

construction; acid brick lined steel or titanium lined steel. Loose or mechanically fastened titanium linings in steel vessels are fraught with design and maintenance problems, especially where rapid depressurization is possible. Titanium clad steel, in which the titanium is metallurgically bonded to the steel over the total vessel interior surface, presents a viable solution. A review of capital and maintenance costs in nickel and gold PAL facilities over the past decade indicates that titanium clad steel is both lower initial capital cost and lower maintenance cost than brick lined steel construction⁽¹⁾.

The steel pressure containment body of the autoclaves has typically been fabricated from medium strength steel, such as ASTM A516 Grade 70 or international equivalents. These steels can be reliably manufactured, fabricated, and site repaired when needed. A516 Grade 70 is also an excellent choice for explosion cladding because of its good fracture toughness, good ductility, and yield strength level.⁽²⁾

A number of different titanium alloys are used in autoclave construction. The various titanium alloys have been tailored to offer improved strength and/or corrosion resistance in comparison to unalloyed titanium. Table 2 lists several standard titanium alloys and their relative performance features. The lower strength, higher ductility titanium alloys are preferable for explosion cladding to steel⁽³⁾. Consequently, several of the alloy compositions have two strength options; a medium strength alloy for monolithic titanium applications and a lower strength option for cladding. Grades 1 & 2 are the options in the unalloyed titanium family; whereas, Grades 7 & 11, 16 & 17, and 26 & 27, are the parallel more corrosion resistant alloy pairs discussed further in this paper.

In the absence of high chlorides or crevice conditions, unalloyed titanium has been shown to offer good corrosion resistance under nickel laterite PAL operation conditions. When high chlorides are present and/or when the design or operating conditions result in crevices, Grade 1 may be subject to localized attack and/or general corrosion⁽⁴⁾. The addition of small amounts of palladium or ruthenium has been demonstrated to

Table 2: Selected Titanium alloys and their Performance Features

ASTM Grade	Basic Alloy Content	Cost Ratio	Features/Motivation for Alloy
1	Ti (Chemically Pure)	1.1	Low cost + improved cladability
2	Ti (less pure)	1.0	Low cost + medium strength
3	Ti (less pure)	1.0	Low cost + higher strength
5	Ti+6Al+4V	1.7	High strength + erosion resistance
7	Ti (Gr2) +0.15Pd	3.5	Enhanced corrosion resistance
11	Ti (Gr1) + 0.15Pd	3.6	Enhanced corrosion resistance + improved cladability
12	Ti+0.3Mo+0.8 Ni	1.2	Strength + erosion resistance
16	Ti (Gr2) + 0.05Pd	2.0	Enhanced corrosion resistance + lower cost
17	Ti (Gr1) + 0.05Pd	2.1	Enhanced corrosion resistance + lower cost + improved cladability
26	Ti (Gr2) + 0.1Ru	1.6	Enhanced corrosion resistance + lower cost
27	Ti (Gr1) + 0.1Ru	1.7	Enhanced corrosion resistance + lower cost + improved cladability
NA	Ti-45Nb	8.0	Superior ignition resistance

prevent corrosion under similar conditions. The traditional alloy of this family, Grade 7, which nominally contains 0.15% Pd, has been used in the chemical process industry for over forty years. When this alloy was developed in the late 1950's, it was observed that only about 0.04% Pd was necessary to significantly improve corrosion performance⁽⁵⁾. However, palladium was relatively low cost, and setting the alloy composition well above the lower limit was considered prudent.

TITANIUM ALLOY COST CONSIDERATIONS

In recent years palladium has become a common alloy for use in a number of applications, the most prevalent being the catalytic converters in cars. The result has been a dramatic increase in palladium usage and price. Limited supply and world political conditions have resulted in dramatic price swings as well. Since 1995, palladium prices have ranged between \$200 and \$1,200 USD/troy oz. At present, palladium price is in the \$375 USD/t-oz range. In comparison, ruthenium price is currently in the \$75. USD/troy-oz range.

When the palladium price began to climb dramatically titanium producers, focused on development of the leaner palladium alloys and the titanium-ruthenium alloys^(6,7). Two new alloy groups have resulted from this work. The first to reach significant production levels were the two leaner Ti-Pd alloys, Grades 16 & 17, which have a nominal composition of 0.05% Pd (sometimes referred to as Pd-lite) . More recently the Ti-Ru alloys, Grades 26 & 27, which exhibit a nominal composition of 0.10% Ru have been commercialized (RMI tradename TIRU).

EXPLOSION CLADDING OF TITANIUM ALLOYS

Explosion clad plates of Ti-Pd Grade 11 and steel have been manufactured for the chemical process industry since the 1960's. The Bulong autoclave project was the first major commercial use of Ti Grade 17 clad steel. The first significant commercial applications of the Ti-Ru alloys, Grades 26 and 27, have occurred over the past two years. At this time, commercial use of Ti-Ru clad plates has been limited to some small heat exchanger tubesheet applications. The objective of the explosion cladding trial program discussed in this paper was to qualify the manufacture of large explosion clad plates of Ti Grade 27 bonded to steel, and to evaluate the suitability of these plates for fabrication into the heads and cylinders required for autoclave construction.

Ti-Ru ALLOY METALLURGY

The metallurgy of the Ti-Ru binary alloy system is fairly well defined. Established phase diagrams⁽⁸⁾ reveal that minor ruthenium additions act as strong beta phase stabilizers in titanium, such that as little as 0.05 wt.% Ru stabilizes a fine uniform dispersion of second (beta) phase within the alpha phase matrix, Figure 2. As such, the fine beta phase formed is enriched with ruthenium to levels on the order of 5-10 wt.%⁽⁶⁾. With a rather high solubility in beta titanium in excess of 30 wt.%, ruthenium remains in solid solution and does not form any intermetallic (e.g., Ti_xRu_y) compounds or additional phases in these alloys⁽⁶⁻⁸⁾.

Since the net amount of ruthenium addition to these Ti-Ru alloys is so meager (~0.12 wt.%), there is no significant solid solution strengthening and the mechanical and physical properties of Ti Grade 26 and 27 (Ti-Ru) alloys are equivalent to that of unalloyed Grades 2 and 1, respectively. As a result, strength values, design allowables, fabricability, and weldability of Ti-Ru and corresponding base chemically pure (C.P.) alloy mill products are generally similar. Since the ruthenium only forms a very small volume fraction (~2 vol.%) of uniformly dispersed beta phase which is metallurgically stable, Ti-Ru alloys are

thermally stable, and do not exhibit thermal or corrosion sensitization (e.g., weld/HAZ effects) or aging.



Figure 2: Typical Microstructure of Ti-Ru Alloy Sheet at 200X mag.

In addition to enhancing corrosion resistance, minor ruthenium additions to unalloyed titanium improve ductility and cold/warm formability in wrought mill products. This beneficial effect stems from a significantly finer microstructure (i.e., grain refinement) induced by Ru-stabilized beta phase particles, acting as nuclei and/or grain growth inhibitors during recrystallization. Therefore, Ti-Ru wrought products (e.g., plate or strip) can exhibit somewhat improved forming limits over equivalent low-iron C.P. titanium or Ti-Pd alloy products (i.e., with similar interstitial content, processing, and size) in such operations as brake-press forming, bending and warm head-forming.

EARLY ALLOY CHALLENGES

The development and qualification phases of the Grade 26 and 27 TiRu alloys by RMI Titanium Co. revealed two metallurgical challenges that needed to be overcome to successfully commercialize TiRu mill products. The first stems from pure ruthenium's elevated melting point compared to titanium (or palladium), which makes it difficult to VAR and, especially, EB hearth melt fully and homogeneously into titanium ingots. RMI Titanium Co. successfully addressed this concern through the development of a proprietary (patent-pending) master alloy which ensures total rapid assimilation and homogenization during the melting process.

The subsequent challenge involved the excessive directionality in strength values exhibited by TiRu plate products when processed via traditional routes used for C.P. titanium products. The refined grain structure from the Ru-stabilized beta phase magnified the typical basal transverse crystallographic texture in C.P. titanium plate; such that transverse direction yield strengths far exceeded maximum limits specified in ASTM B-265. This is of significant concern for Ti Grade 27 plate to be cladded, since low and similar yield strength (flow stress) values are required in all plate directions for optimum, successful explosion bonding to steel. RMI Titanium has since qualified a proprietary processing procedure which consistently achieves minimal L vs. T property directionality in all Grade 26 and 27 plate products, with strength values well within ASTM B-265 specification limits.

RMI Titanium Co. has U.S. trademarks for both Ti-Ru grade products: TIRU-26™ and TIRU-27™; which ensure that chemical homogeneity and minimal property directionality in plate mill products are consistently achieved. More stringent internal aims on minimum ruthenium content (0.1% Ru min.) and low iron limits for optimum corrosion resistance are also inherently designed into these trademarked alloys.

MECHANISM FOR Ti-Ru ALLOY CORROSION RESISTANCE

The mechanism for ruthenium enhancement of titanium corrosion resistance is basically the same as that of palladium and other platinum group metals, and involves alloy ennoblement. The fine ruthenium-enriched beta phase dispersed throughout the alpha grain matrix provide cathodic sites of low hydrogen overvoltage which facilitate hydrogen ion reduction kinetics^(9,10) in aqueous acidic media. This depolarization of the hydrogen ion reduction reaction, or "cathode modification" phenomenon, produces a substantial shift in the titanium alloy corrosion potential towards the noble (positive) direction where the protective surface oxide film (TiO_2) is stable, and full passivity can be achieved. It is, therefore, not surprising that Ti-Ru alloys exhibit very similar resistance to the Ti-Pd alloys in hot dilute reducing acid solutions as indicated in Figure 3. Similar behavior can be expected with weld and HAZ metal as shown. It is important to note that the use of Ti-Pd (ERTi-7) filler metal for welding Ti-Ru alloy components is recommended and preferred from both a corrosion resistance and commercial availability standpoint. This option in filler metal is allowed under Section IX of the ASME Pressure Code.

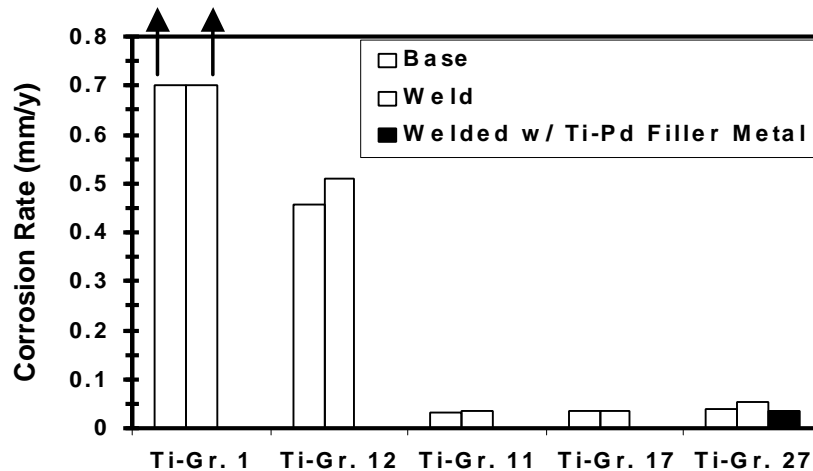


Figure 3: Comparison of Ti Alloy Base and Weld Metal Corrosion Resistance in Boiling 2% HCl Solution

These minor ruthenium alloy additions also effectively inhibit titanium crevice corrosion in hot halide and sulfate environments^(11,12,13). This enhanced crevice resistance stems from the same "cathode modification" mechanism discussed previously for reducing acid media. With time, the solution within a tight metal-to-metal, metal-to-gasket, or metal-to-salt deposit crevice exposed to hot salt solutions often becomes a more corrosive, deaerated reducing acid. Creviced surfaces are ennobled by the Ru-enriched beta phase, and local passivity is maintained within these acidic crevices. Therefore, as revealed in Figure 4, both Grade 26 and 27 (TiRu) alloys can be expected to provide superior crevice corrosion resistance which mimics that of the Ti-Pd alloys.

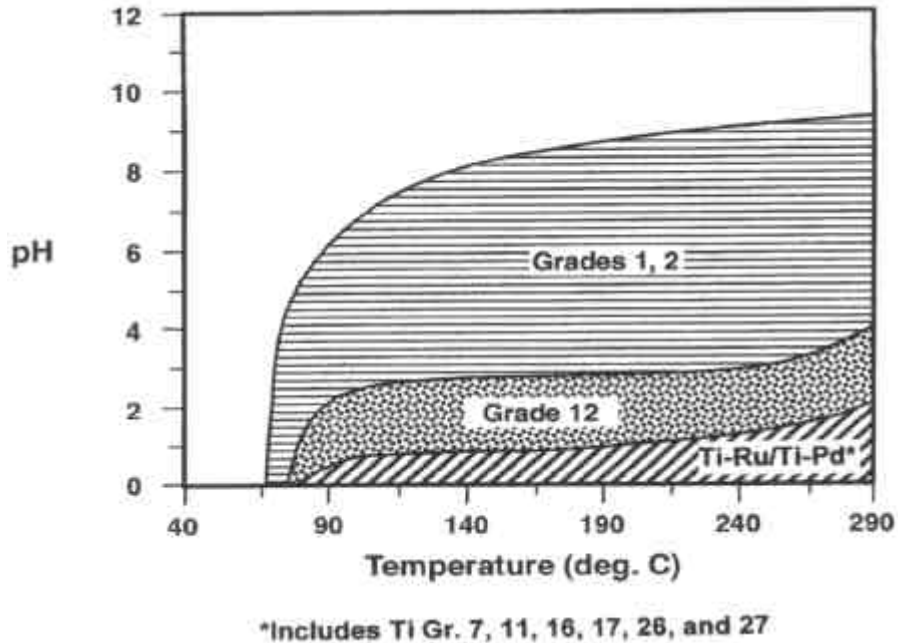


Figure 4. Temperature-pH Limits for Crevice Corrosion of Titanium Alloys in Naturally-Aerated NaCl-Rich Brines. (Shaded areas indicate alloy susceptibility to attack.)

EXPLOSION CLADDING OF TI-RU ALLOYS TO STEEL

Depending upon processing and heat chemistry, the Ti-Ru alloys may exhibit somewhat higher strength and ductility than their palladium equivalents. The increased strength presents a potential concern for explosion cladding, whereas the higher ductility should be beneficial. When explosion cladding titanium to steel, it is well accepted within the industry that superior bond strength and ductility is achieved when titanium exhibiting low strength and high ductility is clad to steel with similar properties. Explosion clad manufacturers typically restrict production of large clad plates to the lower strength family of alloys, Grades 1, 11 and 17. When the lower strength titanium alloys are not a technically acceptable option, and when clad plates are large, it is common to use an interlayer of Grade 1 between the higher strength titanium and steel plates^(3,14).

EXPLOSION CLADDING TRIALS

Two explosion cladding trials were performed with Ti Grade 26 and 27. The first, Test A, involved a small plate of Grade 26 to confirm basic explosion bonding parameters. The second, Test B, utilized a larger plate of Grade 27, simulating the size required for PAL autoclave vessel plates. The titanium for Test A exhibited mechanical properties that were somewhat higher than would normally be considered acceptable for cladding. The plate for Test B exhibited significantly lower strength in the longitudinal direction but only slightly lower yield strength in the transverse direction. The properties of these two titanium plates are presented in Table 3.

Table 3: Properties of titanium plates used in cladding trials.

Test	Ti Grade	Property	Longitudinal	Transverse	ASTM B265 Allowables
A	26	Ultimate Tensile Strength (MPa)	440	435	345 min.
		Yield Strength (MPa)	285	301	275-450
		Elongation (%)	30	28	20 min.
		Oxygen content	1300 ppm		2500 ppm max
B	27	Ultimate Tensile Strength (MPa)	386	386	240 min.
		Yield Strength (MPa)	228	289	170-310
		Elongation (%)	36	38	24 min.
		Oxygen content	700 ppm		1800 ppm max

TEST A

The clad plate produced in Test A was 1000 mm x 1000 mm consisting of 9 mm thick Ti Gr 26 clad to 50 mm thick carbon steel, A516 Gr 70 (yield strength 355 MPa.) Ultrasonic inspection of the clad plate, in accordance with the procedures of ASTM A578, indicated bonding over most of the clad surface, except for an area near the edge, approximately 150 x 100 mm and an unusually large area at the initiator, approximately 600 mm x 170 mm, as shown in Figure 5. The bond quality was measured by shear strength testing using the specimen design of ASTM B898 (the reactive metal clad specification). The test values presented in Table 4 indicate good bond shear strength in comparison to the minimum specified in ASTM B898 Side bend tests exhibited no indication of bond separation. A 700 mm diameter disc was cut from the plate for forming evaluation. The disc was warm formed into a dished-only head by Antonius. Ultrasonic inspection after forming confirmed that no disbonding had occurred during this operation. The clad bond mechanical properties of this plate were acceptable, but the non-bond areas were larger than could be tolerated in manufacture. A review of cladding parameters indicated that the initiator nonbond could be corrected by an explosive set-up modification. The edge non-bond is typical of problems which can result when cladding higher strength titanium.

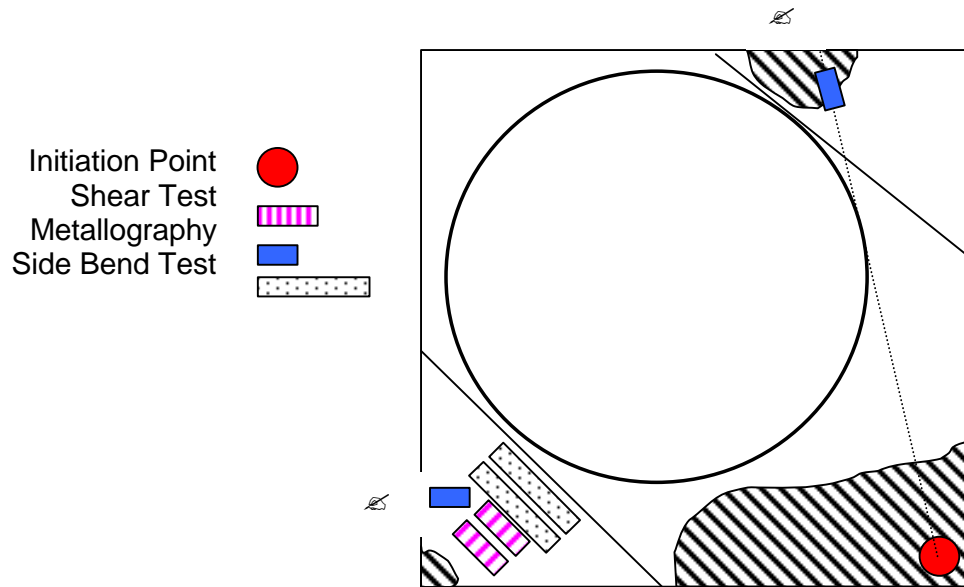


Figure 5: Inspection and test map of Test A. Cross hatched area is non-bond.

Table 4: Mechanical test results from trial clad plates.

Test	Location	Side Bend Test	Bond Shear Strength (MPa)*	
A	Corner	Acceptable	As-Clad	207 - 291
			Stress Relieved**	246 - 210
B	Corner -1	Acceptable	Stress Relieved**	184 - 170
	Corner -2	Not Performed	Stress Relieved**	160 - 184
Specification B898 Minimum		Not specified		137

* Shear tests design is as specified in ASTM B898

** Specimens were given a stress relief heat treatment of 2 hr at 605° C which is standard practice for titanium-steel clad plates ⁽²⁾

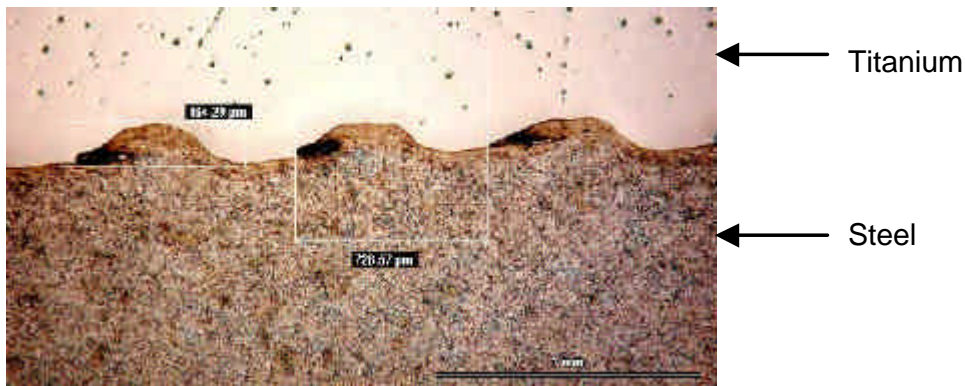


Figure 6: Metallographic observation of Test A bondzone (50X)

Figure 6 presents a metallographic cross section of the bond at the trailing end. The uniform wavesize, at 0.17 mm height and 0.7 mm length, and the absence of melt pockets along the tops of the waves, are indicative of a high quality, reliable explosion bond.

TEST B

Plate size is a key consideration in the explosion cladding process. Cladding becomes more difficult with increasing “run length” (the distance from the initiation point to the furthest point on the plate). In Test A, the run length was only 1.4 m. For a typical autoclave shell plate, it is 4 m. Test B was designed to evaluate the effect of increasing clad run length. The plate was 1.5m x 4.0m. The explosion bonding was initiated in a corner, providing a run length similar to that of a 2.5m x 8m clad plate (typical for autoclave manufacture.) ⁽¹⁵⁾ The steel was 50mm thick, A516 Gr 70 plate, yield strength 329 MPa . Titanium was 9.5 mm thick Gr 27 plate. Although the titanium cladding plate was manufactured as Gr 27 and both the ultimate strength and longitudinal yield strength were much lower than the Test A plate, the transverse yield strength was essentially the same, Table 3.

The Test B clad plate was ultrasonically inspected over 100% of the surface using the procedures of ASTM A578. Testing was performed by fully automated, computer aided,

equipment with precision of 5mm. The only non-bond indication observed was a 15mm x 40mm region beneath the initiator.

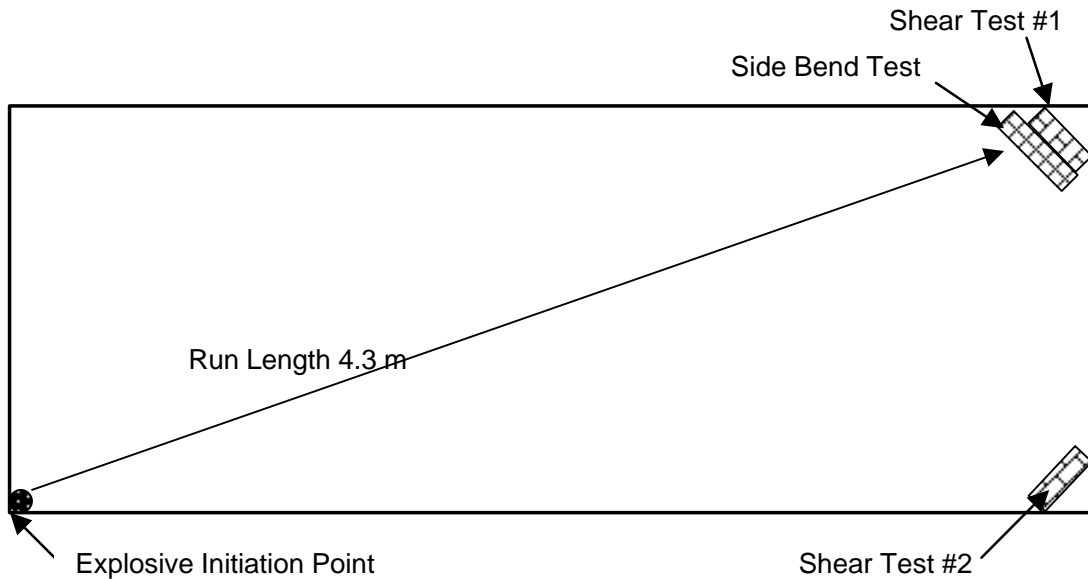


Figure 7: Layout of Test B. There were no non-bond indications except for a 15mm x 40mm defect beneath the initiator.

Figure 7 shows the layout of the Test B plate and the test specimen locations. Test specimens were taken from the corners that were furthest from the initiation. Bond shear strength test results are presented in Table 4. Side bend tests taken from the trailing end of the plate demonstrate good bond ductility and showed no indication of bond separation.

OBSERVATIONS

Overall evaluation of the Test B clad indicates that the Ti Gr 27 alloy can be reliably explosion bonded to A516 Gr 70 steel in sizes typically required for autoclave fabrication. The side bend tests of both trial clads and the head forming trail of Test A demonstrate that the clad product can be readily formed without cracking or bond separation.

The bond shear strengths for Test B are well above the minimum value of 137 MPa which is specified in ASTM B898. However, these values are noticeably below those which are typically observed for Grades 1, 11, and 17. The likely cause is the high transverse yield strength of the titanium cladder plate, 289 MPa, which is minimally but below the upper limit of 310MPa permitted in ASTM B265. The bond defects on Test A are also indicative of results expected from higher strength titanium. This result reinforces concerns about cladding the higher strength Grade 26 alloy direct to steel to steel. (DMC typically limits maximum yield strength to a value lower than specified in B265 when ordering titanium for cladding.)

ECONOMIC COMPARISON OF CLAD OPTIONS

Table 5 presents the comparative cost of titanium-steel explosion clad plates of the thickness typical for nickel PAL autoclaves. Gr 1 is the lowest cost followed by Gr 27, Gr 17, and lastly Gr 11, as would be expected from the comparative prices for ruthenium and palladium. As noted above, ruthenium is currently lower cost than palladium and has

been consistently lower cost in the past. Further, ruthenium has not been subject to the dramatic price swings common for palladium in recent years. However price changes in this family of elements are sometimes erratic and unexpected. Although there is no current indication of big changes in pricing behavior of these elements, it is possible. The materials selection engineer is encouraged to obtain updated pricing comparisons for these clad products before making hard cost decisions. Table 6 presents a list of PAL components for which TIRU should be considered.

Table 5: Comparative cost of titanium clad for autoclave construction.
(Based on plates of 8 mm thick Ti clad to 100 mm tk Steel, A516 Gr 70 N)

Titanium Grade	Cost Ratio*
1	1.0
11	2.2
17	1.5
27	1.3

* Cost comparison ratio to lowest cost alloy

Table 6: Potential Uses of Ti-Ru and Ti-Ru clad steel in PAL facilities.

Equipment/Component	Preferred Ti-Ru Alloy	Reason for Selection
? PAL Autoclave	TiRu-27 TM (for explosive cladding)	Overhead condensed acid vapor-phase attack, crevice attack in divider wall-vessel and wear plate-vessel fit up joints
? Splash/flash vessels solid titanium or clad	TiRu-26 TM (for solid wall) TiRu-27 TM (for explosive cladding)	Overhead condensed acid vapor phase attack, crevice attack
? Vessel compartment dividers and baffles	TiRu-26 TM	Overhead condensed acid vapor phase attack, crevice attack at attachment points
? Vessel nozzle liners	TiRu-26 TM or -27 TM	Crevice corrosion on gasketed flange faces
? Transfer piping and flanges	TiRu-26 TM	Crevice corrosion on gasketed flange faces, HCl acid condensation in flash overhead transfer lines
? Agitator shaft, hub, and/or blade shim plates and fasteners	TiRu-26 TM	Crevice corrosion on blade-hub mating surfaces and blade fasteners, condensed acid vapor phase attack
? Liquor/slurry heat exchangers	TiRu-27 TM (for clad tubesheets) TiRu-26 TM (for tubes)	Crevice corrosion on gasketed faces.

CONCLUSIONS

These cladding trials demonstrate that the titanium-ruthenium alloy, ASTM B265 Grade 27, can be reliably explosion clad to steel, A516 Grade 70. They further indicate that this

metal combination can be produced in plate sizes needed for cost effective PAL autoclave manufacture and that the clad plates can be formed into heads and cylinders without concern of metal cracking or bond separation. The data indicate that it is advisable to restrict mechanical properties and oxygen content more tightly than permitted in ASTM B265 Gr 27 to optimize clad bond quality. Ti-Ru alloy clad properties are similar to those of the Ti-Pd alloys, Grades 11 and 17, which have proven reliability in operating PAL autoclave service. In comparison to unalloyed titanium, the Ti-Ru and Ti-Pd alloy families offer enhanced resistance to corrosion in the hot oxidizing conditions present in nickel PAL autoclaves, particularly where crevices exist and/or chloride levels become significant. The Ti-Ru alloy, Grade 27, is lower cost than the Ti-Pd alloys, Grades 11 and 17; explosion clad steel plates of these alloys are similarly lower cost. Pricing for both palladium and ruthenium are potentially affected by supply/demand and political situations and may vary significantly and dramatically over relatively short periods. The PAL autoclave design engineer will benefit from having both alloy families available as clad options when seeking to reduce autoclave capital costs.

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