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APPLICATION OF TITANIUM LININGS IN FLUE GAS DESULFURIZATION SYSTEMS

1 - INTRODUCTION

Wet scrubbing of boiler flue gas is currently the primary method for successfully controlling sulfur dioxide emissions from coal-fired power plants. Past operational experience with these wet FGD scrubbers, however, has shown that highly corrosive conditions often develop in inlet quench, absorber, outlet, and stack zones of these systems. These aggressive zones are generally the result of wet/dry interfaces, hot oxidizing, acidic condensates, and flyash-laden duct wall deposits which are enriched in chloride and fluoride species. These conditions have contributed to numerous cases of accelerated localized corrosion failure of steel, stainless steels, and nickel alloy linings and various steel coatings reported in these systems. (1-5)

Based on extensive field (6-9) and laboratory (10-11) corrosion testing since 1981, titanium has become qualified as a prime corrosion-resistant material for inlet quench, outlet duct, and stack linings of wet FGD scrubbers. The in situ test exposures, along with service experience from a number of full-size power plant scrubber lining installations in the U.S., have confirmed titanium’s superior performance despite wide variations in scrubber chloride levels and other operating parameters. Other attributes of titanium as a durable and practical liner material include its favourable strength and ductility, excellent abrasion resistance, relatively low density (light-weight) and coefficient of expansion (reduced thermal stresses), and its reasonable shop and field fabricability and weldability.

Furthermore, it is readily available in mill-quantity sheet and strip forms, and has an attractive cost (on a per unit surface area basis) which falls between the common stainless steels and high nickel alloys.

Despite all of these favourable attributes, experience has shown that cost effective application of titanium linings in FGD systems is highly dependent on installation methodology. This paper compares the current methods for installing liners, and identifies the most practical method via cost analysis. Details on titanium liner installation and quality assurance are reviewed along with several examples of full-size power plant lining installations in the U.S.

2 - TITANIUM LINING METHODS

Titanium sheet linings are applied to FGD systems via three commercially-available and proven methodologies:

1) Fastened-on loose sheet lining,
2) Titanium explosion-clad steel plate construction,
3) Resista-Clad Plate lining and construction.

2.1 - Fastened-On-Sheet

The traditional method for lining steel ducting or vessels with thin (1.5-2 mm thick) titanium sheets involves fastener attachment (12). Fastening is achieved by titanium or steel bolts (typically 6.3 or 9.5 mm dia.) threaded into the drilled and tapped steel substrate wall, or fastened with a nut from the steel backside surface when accessible; or by a threaded steel stud resistance-welded to the steel wall surface onto which a steel nut is fastened. Aligned holes in the titanium sheet facilitate sheet attachment with these fasteners. A metal seal at fastener sites is achieved by circumferentially filet-welding titanium bolt heads to the sheet, or filet-welding a small titanium sheet cap or cover over the steel fastener sites. Filet-welding of overlapping adjoining titanium sheets permits a total liner seal.

Although applicable for either retrofit lining or new construction, this method is very labour intensive and time consuming due to the drilling, tapping and extra seal welding required at fastened sites. As a result, mechanically-fastened titanium linings have been found to be approximately 30-40% more costly than nickel alloy "wallpapers" which are plug-welded to steel walls.

2.2 - Explosions-Clad Construction

Titanium sheets down to 2 mm can be 100% pre-bonded to a thick ($\geq$ 9.5 mm) steel backer plate via explosive welding. However, due to its relatively thick steel backer, this product is more practical for new duct or vessel construction rather than retrofit linings. Standard fabrication methods involve butt-welding steel backer plates together, followed by filet-welding a titanium sheet batten strip over the welded plate joint. Since rather thin (typically 6-8 mm) duct walls are involved in FGD systems, the relatively high cost of titanium explosion-clad plate (about USD 100/ft^2 or USD 1080/m^2) results in an installed cost approximately 20% higher than fastened sheet liner methods.

2.3 - Resista-Clad Plate

Titanium sheet of virtually any thickness which is selectively pre-bonded to any thickness steel plate or sheet is commercially available as Resista-Clad Plate (13).

This patented resistance-braze seam process produces 6.3mm wide bond seams, exhibiting typical shear and peel strength values of 44 ksi (303 MPa) and 835 lb/in (15 kg/mm), respectively, which can be spaced or locally pre-applied per service requirements (14). Due to the flexibility in plate sizes (up to 12 ft (3.7m) wide x unlimited length) and thicknesses available, this clad product is applicable for retrofit linings (typically 1.6 mm Ti/1.6 mm steel) as well as new duct and vessel construction (typically 1.6 mm Ti/6-9 mm steel). Furthermore, Resista-Clad Plate can be manufactured with the titanium sheet offset in two directions from the steel backer to facilitate retrofit lining installation via overlap of adjoining plates (similar to roof "shingling", see Fig. 1). Similarly, the titanium sheet can be recessed from the steel backer on all sides to facilitate steel backer butt-welding and titanium batten strip seal welding in new construction (Fig. 2) .

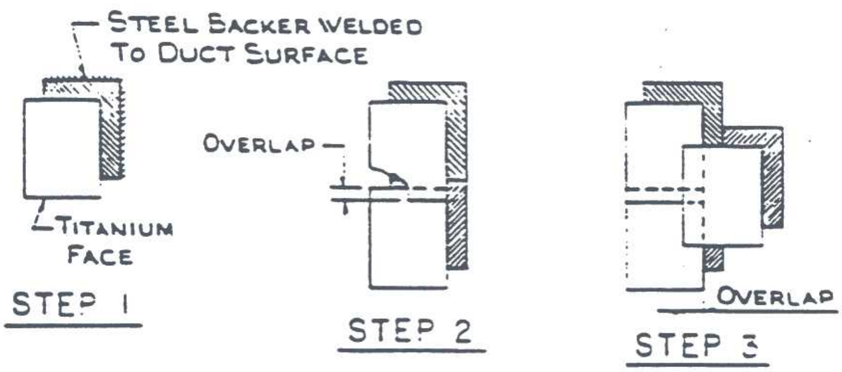

Fig. 1 - Typical pattern of steel wall attachment and overlap of titanium Resista-Clad Plates for retrofit linings.

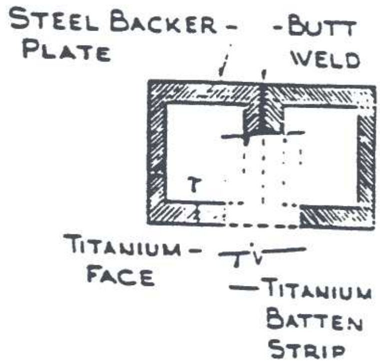

Fig. 2 - Typical titanium Resista-Clad Plate construction for new or total duct/vessel wall construction

The virtue of pre-bonding titanium to steel precludes the need for costly mechanical fastening while minimizing seal welding. For retrofit lining, plate to wall attachment is reduced to simple and inexpensive steel plate backer-to-steel wall filet welding. After Resista-Clad Plate attachment, a total retrofit liner seal is achieved by filet-welding of overlapping plates. These labor and time saving benefits afforded by the relatively inexpensive seam bonding process results in an installed cost of Resista-Clad Plate ~50% and 60% that of explosion-clad and fastened-on titanium liners, respectively, in new construction; and ~50% that of fastened-on sheet liners in retrofit lining jobs. Titanium Resista-Clad Plate retrofit installation costs are approximately 25-30% below those of nickel alloy wallpapers, while circumventing the cost and reliability problems associated with nickel alloy "wallpaper" plug-welding.

2.4 - Conclusion From Comparison of Available Methodologies

It can be concluded from the prior overview of current cornrnercially-available titanium lining methods that the Resista-Clad Plate approach has significant installed cost advantages over other lining options, while practical and reliable in actual field installations. Therefore, the balance of this paper will limit its scope to aspects of Ti Resista-Clad Plate linings for utility FGD systems.

3 - EFFECTIVE ANNUAL COST COMPARISON FOR FGD LININGS

A discounted cash flow (or net present value) analysis was conducted to calculate the effective annual cost of various FGD retrofit lining options. The assumptions for initial installed cost, annual maintenance, and lining life are outlined in Table 1 for each lining type. Rate of return was assumed to be 10% and an effective tax rate of 36%. Despite the conservative life assumed for titanium, the Ti Resista-Clad Plate lining is most attractive economically (Table 1).

Lining Material	Total Installed Cost		Annual Maintenance		Lining Life	Annual Cost	
	$/ft^2	($/m^2)	$/ft^2	($/m^2)	(yr)	$/ft^2	($/m^2)
Ti Resista-Clad Plate	33	(355)	0.50	(5.40)	20	-3.60	(-38.70)
C-276/C-22 Wallpaper	47	(506)	0.50	(5.40)	20	-4.99	(-53.70)
Flaked Glass Vinylester	25	(269)	2.00	(21.50)	3	-8.33	(-89.63)
Borosilicate Glass Block	40	(430)	1.00	(10.80)	10	-5.71	(-61.44)

Table 1: Discounted cash flow analysis of various FGD system lining options

4 - FGD SYSTEMS LINING REQUIREMENTS

In addition to resisting the harsh chemical environment, FGD wet scrubber system linings must accommodate various design and operating stresses. These include internal gas pressure, thermally-induced stresses (370°C max. temperature), shear and/or tensile gravity-induced (hanging) stresses, physical impact or bending from duct maintenance activities, and various forms of vibratory stresses induced from flue gas flow, rotating equipment, and external blowing winds. With the exception of internal gas pressure and physical abuse, all other stresses listed are calculated to be on the order of a few ksi or less (<15 MPa) and are, thus, generally not limiting for Resista-plate liners. A good metal liner fit-up to within 1.3cm of the duct surface will minimize bending and physical damage.

Based on typical FGD duct pressures ranging from -13 to +25 cm H_2O and -25 to +50 cm H_2O during upsets, negative internal duct pressure is often the most critical design parameter in these systems.

Designing with a safety factor of 3, the combined stress on Resista-Clad plate is maintained below 15 ksi (103 MPa) under upset condition negative pressures by a maximum bond seam spacing of 12-18 in (30-46 cm) and a maximum plate width of 4 ft (1.2m). For retrofit installations, clad steel plate to steel duct filet welds on two sides of each plate should also be continuous or no less than a 8 cm long on 15 cm center stitch (Fig. 1).

5 - LINING INSTALLATION PROCEDURES

Figures 1 and 2 schematically depict how Resista-Clad Plates are installed as retrofit linings and for new construction, respectively. The retrofit method is best described as a "shingling" process in which the lining is applied at an approximate rate of 3000 ft^2/wk (280 m^2/wk) in FGD ducting. On the other hand, the new construction method is similar to the batten strip weld joint procedure commonly utilized in explosion-clad construction.

The basic steps for applying retrofit Resista-Clad lining include:

1) Remove existing duct, stack, or absorber wall coating(s).

2) Thoroughly clean steel substrate surface with a commercial blast (SSPC-SP6) or white metal blast (SSPC-SP5).

3) Per Figure 1 pattern, tack up two sides of each Resista-Clad Plate (steel backer) onto cleaned steel surface using coated stick carbon steel electrodes. If possible, attach plates from top to bottom on horizontal Walls.

4) Apply continuous or stitch (8 cm long on 15 cm centers) carbon steel weld seams along the two tacked up sides of each plate backer using coated stick electrodes. E-7018 electrodes are preferred for white metal blast surfaces for strength reasons. E-60XX electrodes with continuous weld seams are suitable for commercial blast surfaces.

5) Clean dirt, debris, grease, and oxide films off of titanium sheet surfaces ~4 cm around seam weld joint via stainless steel wire brushing to silver metal, followed by a clean acetone wipe just prior to welding.

6) Achieve good overlapping titanium sheet fit-up (<1.5mm) using fit-up or cheater bars, and spot weld (tack) titanium seams via hand-fed TIG at 2.5-5.0 cm intervals.

7) Using hand-fed wire TIG, spot weld prefabricated and performed titanium sheet joint covers, corner pieces, transition pieces, or flanges into place onto titanium sheet surfaces.

8) Remove lightly oxidized spot weld surfaces by stainless steel wire brushing and reclean joints with acetone wipe. Grind out any heavily contaminated spot welds, clean up joint surface, acetone wipe clean, and reweld.

9) Filet weld all overlapping titanium sheet joints via hand-fed wire TIG to achieve a total lining seal.

10) Final inspection of titanium weld seams.

6 - WELDING REQUIREMENTS

Basic parameters for hand-fed wire GTA (TIG) welding of titanium sheet overlap seams are presented in Table 2. Quality titanium seam welds require totally clean and oxide-free joint surfaces, and complete face and trailing inert gas shielding as indicated. To limit air contamination both gas shields should be purged prior to welding, and weldments post-purged with argon 30 seconds or until metal temperatures tall below 370°C. Aluminium foil skirts attached to trailing shields further minimize contamination from air drafts. Drafts should be stifled by isolating work areas using dampers or temporary barriers. Titanium filler wire surfaces must be clean and air-contaminated ends cut off. High frequency arc starting and sharp tungsten stingers help minimize localized weld defects as well.

- No Preheat (10°C Min.)
- D.C. Straight Polarity
- 75 - 100 Amps
- 10 - 14 Volts
- 2.4mm Dia. 2% Thoriated-Tungsten Stinger
- 1.6 or 2.4mm Dia. Filler Wire
- ER Ti-1 (Preferred) or ER Ti-2 Wire; or ER Ti-7 for Gr. 7 Ti Linings
- Air Cooled GTAW Torch with Remote Amperage Control
- High Frequency Arc Starting
- 99.999% Argon Shield Gas
- 12.7 or 19.2mm Dia. Ceramic Gas Cup (Seal Welding)
- 25.4mm Dia. Ceramic Gas Cup (Tack Welding)
- 0.4 - 0.9 m^3/hr. Torch Gas Flow
- 1.4 - 1.7 m^3/hr. Trailing Shield Gas Flow
- Weld Joint Backshielding Not Required

Table 2: Details for GTA filet-welding of 1.6mm titanium sheet overlap seams in field installations.

Using these parameters, a titanium seam weld rate of 2-5 in/min (5-13 cm/min) can be anticipated depending on joint fit-up and position. An estimated total welding rate which includes surface preparation, tack welding. and seam weld-out is 10 ft/hr (3 m/hr). Lining bowing and distortion can be minimized by tack and seal welding the top and bottom (or opposing sides) of titanium plates simultaneously to balance weld-induced stresses.

Assessment of titanium tack or seam weld quality in the field is achieved through four basic methods: close visual inspection, weld surface colour, tungsten scratch testing, and liquid dye penetrant inspection. Silver, straw, gold or light blue coloured single-pass welds are generally considered to be acceptable.
However, dark-blue, iridescent, gray or white coloured titanium weldments are probably heavily contaminated and must be rejected. If local weld areas are of questionable quality relative to colour, tungsten rod scratching to compare the relative hardness of weld surfaces to adjacent base metal may further discern quality. If the weld does not scratch easily or at all compared to base metal, poor weld quality is indicated. Close visual inspection and final dye penetrant inspection are useful for detecting gross weld defects, voids, and cracks. Any titanium welds not meeting the prior quality tests must be

ground-out and rewelded after the joint has been re-cleaned and wiped with acetone.

Welders should be qualified in GTA-welding titanium in accordance with ASME Pressure Vessel Code Section IX guidelines. Qualification criteria can include weld colour, tungsten scratch hardness, and sample weld joint bend tests. The longitudinal weld bend sample should pass a 5T bend radius criteria when the filet-weld face is on the bend O.D. surface.

7 - TITANIUM LINING INTERFACES

Installation of titanium linings in FGD systems often requires a transition of the lining to other components or dissimilar linings. Although titanium cannot be successfully welded to ferrous or nickel alloys, several practical options are available. These methods involve mechanical seals, organic coating or sealant overlap, and total metal seals. Mechanical seal strategies include prefabricated integral titanium sheet flanges sealed into gasketed expansion joints (preferred whenever possible), or thin titanium plate strip flanges fastened down at the titanium lining periphery and incorporating an elastometric gasket (e. g. Viton) or sealant to effect a seal. Effective organic coating or sealant overlap transitions from coated steel surfaces require proper titanium surface preparation for maximum coating adherence. This is achieved by local sandblasting and subsequent cleaning of peripheral titanium surfaces to be coated prior to coating application.

Explosion-clad transition strips and Resista-Clad bond seams both provide total metal seals for titanium lining to duct/vessel wall interfaces. Either option offers wide flexibility in titanium to dissimilar metal transition combinations available, so that transition strips of titanium to steel, stainless steel, or nickel alloys can be used. Transition strip widths on the order of 8 cm permit titanium to titanium lining seal welds and dissimilar metal to duct wall filet-welds to be made. The Resista-Clad transitions are generally more cost-effective and can readily bond titanium sheet to nickel alloy (i.e. 625 or C-276) sheet for more corrosion-resistant peripheral seals.

8 - UTILITY FGD INSTALLATIONS

Table 3 describes installed full-size titanium linings currently in service in U.S. utility wet FGD systems. Corrosion-and trouble-free performance of these linings have been reported to date.

Utility/Plant (Location)	Lining Location	Alloy	Lining Surface Area X Thickness Sq. Meters X mm (Sq. Ft. X In.)	Install. Date	Liner Attachment Method
Texas Electric Martin Lake 3 (Tatum, TX)	Inlet Quench Wet/Dry Interface Zone of the 3AT300 Tower	Ti Gr. 2&7	28 X 2 (300 X 0.078)	12/84	Through-Wall Ti Bolts & Nuts, with Seal-Welded Bolt Heads
Mononghela Power - Pleasants 1 (Willow Is., W. VA)	Lower Section of Stack at 25 Ft. Level	Ti Gr. 2&7	15 X 2 (160 X 0.078)	9/85	Ti Bolts Threaded into Tapped Holes in the Steel Flue
Louisville G&E Millcreek 4 (Louisville, KY)	Inlet Quench Section of One Module	Ti Gr. 7	79 X 2 (850 X 0.078)	5/87	Steel Studs Resistance-Welded to Duct Wall Covered by Ti Sheet Caps Seal-Welded to Liner
PEPCO-Dickerson	Outlet Common Header Duct Floor	Ti Gr. 2	163 X 1.6 (1750 X 0.063)	10/86	Ti Bolts Threaded into Tapped Holes in Steel Ducting
	Outlet Floor Section	Ti Gr. 2	6 X 1.6 (67 X 0.063)	10/86	
PEPCO-Dickerson	Outlet Common Header Duct Floor	Ti Gr. 2	186 X 1.6 (2,000 X 0.063)	10/87	Ti-Resista-Clad Plate
N. Dakota CPA Coal Creek 1	Outlet Mixing Zone Section	Ti Gr. 2	510 X 1.6 (5,500 X 0.063)	11/87	Ti-Resista-Clad Plate
Big Rivers Electric RD Green 1	Full Stack Flue Liner	Ti Gr. 2	1300 X 1.6 (14,000 X 0.063)	1/88	Ti-Resista-Clad Plate

Table 3: Full-size titanium lining installations in utility FGD systems.

9 - SUMMARY

A review of commercially-available titanium lining methodologies for utility FGD systems indicate that titanium Resista-Clad Plate offers significant economic and practical advantages for both retrofit and new construction of lined FGD systems. Since titanium sheet is pre-bonded to steel plates by this method, the high cost of mechanical fastening, related seal welding, and the plug-welding of nickel alloy "wallpapers" is circumvented. As a result, titanium Resista-Clad Plate offers initial installed cost and/or life cycle cost advantages over many other FGD lining materials. Procedures for field welding, installation, and quality assurance of titanium Resista-Clad Plate linings have been established and are outlined in the paper. Examples of successful FGD system lining applications in U.S. power plants are cited as well.

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