Duplex and ferritic stainless steel sheet linings versus weld overlay and other metallic corrosion-resistant barriers

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ABSTRACT: Sheet linings made from stainless steel can protect carbon steel substrates at lower initial direct cost for installation and subsequent direct inspection than weld overlay and thermal sprayed coating. Closely matched thermal expansion coefficients of ferritic and duplex stainless steel grades with carbon steel allow large "tile pieces" in reliable, leak-proof linings compared to linings from austenitic grades, simplifying and speeding installation. Sheet linings with ferritic and duplex grades typically have lower unit costs than weld overlay and thermal sprayed coatings. Ferritic and lean duplex grades resist corrosion and stress corrosion cracking in most alkaline pulping and liquor recovery environments. Super-duplex grades can replace acid-resistant brick linings in D-stage bleaching equipment, including pre-retention tubes and towers. Carefully specified sheet linings of ferritic and duplex stainless steels, professionally installed in accordance with longstanding industry standards, are reliable and economical protective barriers, especially compared with weld overlay, in many applications in modern pulp and paper mills.

Application: Mill maintenance departments can increase the reliability of fixed equipment at substantially lower cost by following recommendations in this review.

Duplex stainless steel grades, because of their hybrid (duplex) austenite-and-ferrite microstructure, have higher strength and hardness, higher fatigue strength, and markedly superior resistance to chloride stress corrosion cracking than "workhorse" austenitic grades such as 304 and 316 stainless steel. Because of this range of superior properties, because duplex grades resist corrosion as well as any austenitic grade commonly specified for most applications in a pulp and paper mill [1], and because they cost less (per kilogram than austenitic grades) with comparable resistance to localized corrosion, duplex grades economically solve almost every corrosion and wear problem in fixed equipment in the woodyard, in pulping, bleaching, chemical recovery and power generation areas, in wet and dry ends of the pulp or paper machine, and in bleaching chemical preparation and water and wastewater treatment areas.

Decades of industry experience have shown the most affordable stainless steel grades, including weldable 12Cr ferritic grade (UNS S41003) [2], and lean duplex grades, including S32001, S32101, S32304, S32102, and S32002, resist alkaline environments in pulping, screening, brown stock, bleach extraction, and liquor recovery processes. Ferritic and austenitic grades with more than 12Cr resist high temperature and reducing (sulfidic) and oxidizing environments in recovery and power boilers.

In acid bleach stage equipment, including D-stage retention tubes and towers, super-duplex grades exhibit better resistance to localized corrosion than do traditional 6Mo superaustenitic grades [3]. All stainless steel grades resist corrosion by fresh water, aerated or not, and by hot, treated boiler feed water. Duplex and austenitic grades with moderate molybdenum content resist localized corrosion in near-neutral pulp and paper machine environments.

A practical impediment to wider industry use of these superior grades is that, with capital spending on new equipment severely constrained in North American pulp and paper mills in the last decade, little newly constructed equipment is made from these alloys. Substantial opportunities exist for using these alloys as a corrosion barrier for carbon steel and for lower grade stainless steels.

Because duplex and ferritic stainless steel grades are available in sheet form ("sheet" being of gauge dimension), and because duplex and ferritic grades have thermal expansion coefficients close to that of carbon steel, it makes good engineering and economic sense to protect carbon steel with these stainless steels.

Stainless steel corrosion barriers (for steel substrates) come in four basic forms:

1. Metallurgically bonded, clad layer added to steel plate or tube when it is manufactured.
2. Fusion-bonded weld overlay installed in the shop or field (abrasive wear-resistant layers are an example).
3. Physically bonded thermal spray coating installed in the

shop and field, using the right spray process.
4. Sheet lining welded or bolted to the substrate, always installed in the field.

A protective barrier can be any reasonable thickness, typically designed with the corrosion rate of the barrier alloy in mind and thick enough to resist mechanical damage from normal handling and installation. Thermal sprayed coatings seldom are thicker than 1 mm (0.040 in.). The protected surface can be almost any shape or curvature for all four types of barrier.

A major difference between these barriers is how they are attached to the steel substrate. Because a clad layer and weld overlay are each metallurgically bonded over 100% of the interface, with bond strength close to the strength of the weaker metal in the combination, they are mechanically robust and durable. A big disadvantage for weld overlay is the time required to "paint" the barrier on each square centimeter of the surface, and the time often required to make a corroded substrate smooth enough to weld an overlay of acceptable quality.

A thermal spray coating physically bonds 100% to a properly prepared steel surface with a bond strength of 10% to 20% of the substrate strength, typically between 4000-10000 psi, depending greatly on which thermal spray process is used. Thermal sprayed coatings typically are <1.0 mm (0.040 in.), are installed fairly rapidly, depending on the surface roughness, and remain bonded to the substrate unless mechanical damage deforms the substrate. TAPPI TIP 0402-32 "Guidelines for applying thermal spray coatings to protect pulp mill process equipment from corrosion" is an industry guideline for this topic.

A sheet lining typically is attached to a substrate by welding the sheet to the substrate around the edge with welds, sometimes augmented with strategically located plug or slot welds elsewhere in the sheet [4].

For any protective barrier, and especially those protecting steel in a pulp and paper mill, consider these three questions:

1. How reliable is it (will it come off)?
2. What will happen if process solution does get behind it?
3. How is it repaired?

Most traditional and continuing choices of weld overlay for a corrosion-resistant lining probably are primarily based on its low risk for coming off. Indeed, weld overlay and a clad layer, effectively, can be considered integral with the substrate from a strength point of view under certain circumstances, according to Section VIII, Division 1 of the ASME Boiler and Pressure Vessel Code [5]. This type of barrier also has no interface gap to worry about fluid getting behind the barrier. This is moot if the barrier's primary purpose is to physically shield the substrate from passive film removal by fluid flow, as, for example, with most alkaline liquor applications. Furthermore, local and general corrosion of weld overlay and a clad layer are straightforward to repair by weld overlaying.

A properly installed thermal sprayed coating barrier typically fails (comes off) where a coated substrate deforms more than the coating's elongation limit, or if pores or coating defects allow corrosive fluid to penetrate the coating and corrode the substrate. Repair prospects depend on the type of thermal spray process used to install the coating, which affects the coating's density and porosity. For example, dense coatings – high velocity oxygen fuel (HVOF) coatings are densest – can be more reliably repaired because of less gas permeation than arc-sprayed coatings.

Information in the rest of this paper is intended to increase understanding and promote wider application of properly designed and installed barriers made from duplex and ferritic stainless steel sheet to protect steel substrates in a wide variety of mill processes. The linings are reliable; it is simple to seal them to prevent substances getting behind, in cases where that poses a risk; and inspection and repair are far simpler than for the other barriers discussed in this paper.

SHEET LINING INSTALLATION STANDARDS

Sections 2 and 3 of NACE International Standard Practice (SP) 0292-2012, "Installation of thin metallic wallpaper lining in air pollution control and other process equipment," describe practices and procedures for installing a sheet lining ("wallpaper") in a process vessel, tank, or other fixed equipment, such as a stack. The basic concept involves attaching thin alloy sheets, in a manner similar to attaching shingles, over the steel substrate using fillet welds. Weld design objectives are to firmly install the sheet in contact with the substrate, support the sheet's weight, and resist shear or other forces acting on it. (A liquid, by definition, exerts no shear force.)

The space behind the lining is carefully sealed if the consequences of process liquor or other liquid entering the gap are harmful. For example, black liquor getting behind a stable sheet lining in a continuous digester, flash tank, or evaporator typically has no harmful consequence because the curved lining is very stable. In contrast, green liquor behind a stainless steel sheet lining in a dissolving tank can corrode the steel as a result of hydraulic pumping effects caused by continual hydraulic pulsing action of the lining from smelt "banging." (This is more likely with an austenitic grade lining that "pillows out" because of its higher expansion coefficient than a ferritic or duplex grade.) D-stage bleaching filtrate with pH <5 should not get behind a 2507 super-duplex sheet lining in a steel bleach tower, especially if the liquid behind the lining is continuously replenished. (The same mechanism corrodes steel behind a chemical-resistant brick lining.)

Sheet linings typically are 2-3 mm thick to obtain a good practical and economic combination of robustness, especially for shaped sheets; ease of handling because of low weight; low risk of welding burn-through; and low material cost. Most sheet lining alloys are specified to have no corrosion, avoiding the need for a corrosion allowance.

Appendix F, *Suggested Good Practice Regarding Linings*, in Section VIII of the ASME Boiler and Pressure Vessel Code [5], has simple guidance regarding the amount of additional steel thickness for corrosion allowance, depending on the lining's corrosion resistance. The estimated life of the lining should be "at least twice the length of the initial inspection period…," and "application of the material is such as to preclude any possibility of contact between the corrosive agent and the steel shell by infiltration or seepage through or past the lining." This author fundamentally accepts these points, with a clarification that where stagnant alkaline pulping liquor is not corrosive to steel it can be permitted to infiltrate through the lining.

WELDING CONSIDERATIONS FOR DUPLEX STAINLESS STEEL SHEET LININGS

Lining sheets typically are joined to each other with a welded lap joint, as described in SP 0292. This limits welding to fillet welds and ensures that welds contacted by the process liquid have a predictable microstructure, because there is no weld dilution by the steel substrate. Welds attaching the sheet edges to the steel substrate are moderately diluted, but are only required to be as corrosion resistant as the steel substrate and to have acceptable strength, which is never a question with regular, 309, and 312 filler metals used for this purpose.

Three welding processes are used in applying corrosion-resistant sheet linings in process equipment:

- Gas metal arc welding, both short-circuiting and pulsing-arc transfer mode
- Gas tungsten arc welding
- Shielded metal arc (manual, "stick") welding

Advantages and limitations of each process are discussed in Appendix E of SP 0292.

A number of factors influence selection of the welding process, including the shape and extent of surfaces to be lined, the installer's experience with the welding process, and welder skill. Often the installer qualifies more than one process and uses the one most suited for a particular area of the lining.

SHEET LINING VERSUS WELD OVERLAY

Considering that sheet linings are widely used in refining, chemical, power generation, and other industries in applications with very corrosive process environments, it is logical to wonder why sheet linings are so underused in the pulp and paper industry and weld overlay tends to be the default form of corrosion and wear-resistant barrier.

Political considerations

The author's subjective "political" explanations for the serious underuse of sheet linings on pulp and paper mill equipment include "tradition" (i.e., lack of user experience and confidence in the pulp and paper industry) and relative scarcity of contractors specializing in sheet lining installation, even though it is simpler to install than other types of barriers.

Technical considerations

Lining properties

As mentioned previously, a clear technical difference between a sheet lining and a weld overlay is that the latter is uniformly bonded to the substrate with a metallurgical bond as strong as the substrate. However, the greater mechanical robustness this gives the barrier mostly only matters in applications where the barrier is subjected to substantial physical or mechanical forces, which are not feasible for a corrosion resistant barrier in aqueous service.

Thermal cycling always raises concerns about lining reliability. As discussed previously, the close match between thermal expansion coefficients of duplex and ferritic stainless steels and of carbon steel, and the fairly high thermal conductivity of these grades, limit the tendency of a sheet lining to "pillow" on a steel substrate. Less pillowing minimizes bending stress at the fillet welds at the lining edges and makes cyclic stress induced by thermal or other cycling inconsequential. Weld overlay clearly avoids these concerns, irrespective of what weld alloy is used.

Less desirable aspects of weld overlays include their physical roughness, the likely presence of weld flaws, and uneven barrier thickness, even if the overlay meets the requirements of TAPPI TIP 0402-03 "Guidelines for corrosion resistant weld metal overlay of digester vessels in alkaline pulping service." These features complicate inspection of an overlay and compromise its durability, compared with the simplicity of inspecting smooth, wrought sheet and small fillet seal welds exposed to the process fluid.

Installation methods and speed

Installing a sheet lining is simpler and faster than overlaying the same surface. The "paint on" aspect of weld overlay is inherently slow. The surface must be thoroughly clean, fairly smooth, and crack-free and cavity-free to achieve high quality overlay. Even with robotic welding, it can take >20 days to overlay 150 m^2 (1500 ft^2) of continuous digester shell, depending how long it takes to remove sharp grooves, corners, edges, and pits.

In comparison, surface preparation for a sheet lining is limited to ensuring the substrate is clean and smooth enough so that the fillet stitch welds attaching the sheet to the substrate are of acceptable quality and the sheet fits snuggly against the substrate. Even if the substrate is corroded, 200 m^2 of 11-12 gauge, lean duplex or ferritic stainless steel sheet can be installed in <10 days total time, depending on the size of sheets that can be maneuvered into the vessel or tank.

A 3 m × 1.5 m (approximately 10 ft × 5 ft) 11 gauge stainless steel sheet weighs about 100 kg (220 lb), allowing easy handling. Even if only six or eight sheets this size were installed in a day, 200 m^2 will be lined in 6 days. It is good practice to roll or shape the sheet to a slightly smaller radius than the substrate's curvature to ensure good contact between the sheet lining and a curved substrate. (NACE SP 0292 shows how to avoid welding in corners.)

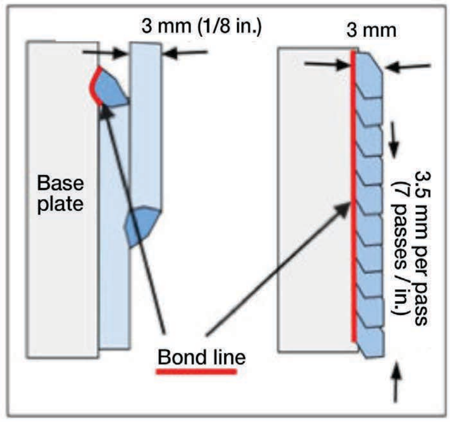
Welding considerations

Because larger sheet "tiles" require less welding length for installation, experienced lining contractors find ways to install the largest practical tiles, rather than small "mosaic" pieces, to minimize the amount of welding and time required. Because

Amount of welding in overlay vs. sheet lining.

Welds for 50 m^2 (500 ft^2), 3 mm (1/8 in.) barrier in 5 m dia. x 3 m ht. cylinder:

- **Sheet lining** has twelve sheets (90 kg); each sheet has 9 m (28 ft) of 1/8 in. fillet weld - 0.4 kg (0.8 lb) filler, so **lining uses < 5 kg** (10 lb) filler.
- **Overlay** has 40,000 ft (13 km) of overlapping 1/8 in. weld, so **overlay uses > 1,000 kg** (2,200 lb) filler.



1. Illustration of relative amounts of welding required for a sheet lining and a weld overlay corrosion barrier.

lining sheets and their welds typically are subjected to very low loads from contact with liquid vessel or tank contents, welds joining the sheet to the substrate typically need only support the sheet's weight and firmly position it on the substrate. In practice, 100 kg of a 3 m (10 ft) × 1.5 m (5 ft) × 11 gauge sheet piece is readily supported by < 25 mm (1 in.) of 1.5 mm (0.060 in.) fillet weld with > 480 MPa (70 ksi) strength because 25 mm of 1.5 mm fillet weld supports 2000 kg. **Figure 1** shows why a sheet lining requires substantially less welding filler metal and correspondingly less labor to deposit it than a weld overlay corrosion barrier.

The primary function for welds in a sheet lining is to stabilize the lining against the substrate and seal the lapped edges if the lining must be leak-tight. As stated earlier, not all linings in pulp mill equipment must be leak-tight. A sheet lining installed to physically shield a steel surface from impingement or erosion corrosion in a flash tank, evaporator body, or the top separator "doghouse" of a continuous digester can be left unsealed along the bottom. Because stagnant alkaline liquors do not corrode carbon steel, a stainless steel sheet lining in brown stock and black, green, and white liquor tanks can be installed with the bottom edge unsealed to prevent liquid pressure or liquor deposit growth behind the lining.

As mentioned in the previous section on "Welding Considerations for Duplex Stainless Steel Sheet Linings," welds to install any stainless steel grade lining over carbon steel typically are made with 309 or 312 stainless steel filler metal, using a welding process to minimize the likelihood of burning through the lining. Conveniently, 309L and 312 welds resist alkaline corrosion as well as any other stainless steel.

Following good practice and TAPPI TIP 0402-26 "Guidelines for welding and inspection of stainless alloy piping" regarding upgrading the filler metal in welds with added metal used in acidic, chloride-containing environments (e.g., D-stage bleaching, in which localized corrosion is the "enemy"), seal fillet welds for the lining must have a higher pitting resistance equivalent number (PREN) than the sheet lining alloy.

Recommended practice is for the weld filler's PREN to be at least 5 points higher than that of the base metal. Post-weld cleaning also is important to optimize the weld zone's resistance to localized corrosion resistance in neutral and acidic, chloride-containing environments. These issues do not apply when the process environment pH exceeds 10, even with chlorides present.

Code approval and quality considerations

In the National Board Inspection Code [6], installing corrosion-resistant weld overlay is designated as a *Routine Repair* for areas <0.06 m^2 (100 $in.^2$), and as a *Repair* for larger areas. Installation of a strip lining (presumably all sheet linings) is a *Repair*. Therefore, the overlay contractor and lining installer must have an R stamp and prepare an R-1 form.

Installation quality requirements differ for weld overlay and sheet lining. A weld overlay must be free of weld flaws, including those that could allow corrosive fluid to pass through the barrier and corrode the substrate; must be acceptably thick (controlled by the number of weld passes and degree of overlap); and must have the correct metallurgical and corrosion properties. As mentioned earlier, TAPPI TIP 0402-03

Property/Issue	Sheet Lining	Weld Overlay	Clad Plate
Range of alloys	10	10	5
Ease/speed of installation	10	5	5[a]
Inspection and repair	10	5	10
Code strength credit	0	10[b]	10
Relative unit cost[c]	10	2	5
Relative total cost[c]	10	5	5

[a] Clad plate is inserted in flush patch or replace a vessel or tank course; [b] Overlay welding procedure must be qualified by tensile testing; [c] Lower cost gets higher rating/score.

I. Author's subjective comparison ratings for solid metal corrosion-resistant barriers in pulp and paper mill applications (10 is highest rating).

has useful guidelines for weld overlay quality specifications.

A sheet lining has minimal quality requirements: there shall be enough sheet-to-substrate stitch welds of acceptable length to attach the sheet firmly to the substrate; sheet-to-sheet lap joints shall overlap by no less than 12 mm (0.5 in.); fillet seal welds exposed to a corrosive environment shall be free of acceptable size and free of cracks and pores that compromise their sealing function; and the completed lining shall be clean and smooth except for the fillet seal welds. NACE SP 0292 has quality requirements and tests.

Economic considerations

In general, direct costs (in 2014 U.S. dollars) for installing a duplex stainless steel sheet lining include material cost (typically \$80-\$100/m² for ferritic and lean duplex grades, up to \$150/m² for super-duplex), installation cost around \$240/m², welding consumables around \$25/m², and quality control and testing around \$40/m², producing a unit cost (excluding crew mobilization costs) of \$380-\$450/m².

Weld overlay with regular surface preparation typically costs \$800-\$1000/m² for a good sized area. Indirect costs, including lost production from time needed to install the lining, and subsequent costs for periodically inspecting both types of lining, are typically significantly lower for sheet linings than for weld overlay. **Table I** rates properties of three types of metallic corrosion barrier used in pulp and paper mill equipment, according to the author's subjective scale, based on decades of experience specifying, supervising installation, inspecting, and managing repairs of these types of barriers.

CONCLUSIONS

1. Duplex stainless steel sheet linings should be more widely used as a corrosion-resistant barrier. They can be used instead of weld overlay in a wide variety of fixed equipment in pulp and paper mill processes, especially considering their technical advantages, simpler and faster installation, and ease of inspection, all leading to substantial initial and long-term cost savings compared to both weld overlay and thermal sprayed coatings.
2. Because its thermal expansion coefficient is close to carbon steel, a duplex stainless steel sheet lining can be as stable and reliable to weld overlay. NACE SP 0292 is a well-proven standard specification for installing corrosion-resistant sheet linings in pulp and paper mill equipment. **TJ**

ABOUT THE AUTHORS

This paper recommends using a proven method of protecting steel from corrosion that is less costly than other methods. Cost savings from using the method described in the paper are greater than initially estimated because substantially less production time is lost. By following these recommendations, mill maintenance departments can increase the reliability of fixed equipment at substantially lower cost.

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