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ADVANCED EROSION PROTECTION TECHNOLOGY EXTENDS THE LIFE OF STEAM BOILER SUPERHEATER TUBES

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Abstract

The electric power generation industry is experiencing the most complex convergence of market pressures in history. Environmental regulations are more rigorous than ever, forcing producers to make substantial capital investments in emissions conformance. At the same time, deregulation, excess capacity, and reduced market demand are driving diminishing maintenance budgets. The threat of nonconformance penalties weighs heavily against the pressure to increase profits, and the decisions between capital expenditures, potential fines, and routine equipment maintenance become a precarious balancing act.

Plant operators employ an array of methods for managing effluents and operating efficiency, including the installation of low NO_x burners, over-fired air systems, and complex soot-blowing systems. These techniques, while contributing to the effective management of undesirable pollutants, significantly increase equipment wear rates, especially in waterwalls and boiler tubing.

Until recently, most wear-susceptible boiler tubing has been protected by weld cladding methods using various inconels, stainless steels, or chrome carbide composites. Infiltration brazed tungsten carbide cladding, a recent finalist for the 2003 Global Energy Awards, is an emerging boiler tube protection technology that has experienced success in high erosive, corrosive, and abrasive environments. This cladding, recently tested by EPRI at temperatures exceeding 1000 degrees Fahrenheit, lasted longer than virtually all other materials tested; and because the unique application process creates a true metallurgical bond between cladding and tubing, this material is not subject to chipping and spalling.

This paper will discuss the results of several comprehensive laboratory analyses, as well as real-world applications of advanced wear protection, including superheater tubes, burners, and other boiler components.

Convergence of Market Forces in Power Generation

Power production facilities are under escalating pressure to reduce production costs in order to remain competitive in an increasingly complex market environment. Failure to effectively reduce production and maintenance costs can result in decreased profits for each megawatt hour (MW-hr) sold, and may cause reduced dispatch load—a double jeopardy in a market plagued by over capacity. In this environment, unit availability has become one of the most important technical predictors of unit profitability.

Many operating variables threaten to reduce unit availability, including frequent switching of coal blends, which allows operators to take advantage of spot market fuel pricing. In addition, many units which were originally designed for base load operation are now frequently cycled to take advantage of peak power dispatch rates. These variables significantly contribute to the reduction of the useful life of boiler tubes, increasing tube distortion and misalignment, fatigue rates, and erosive wear. Further pressure is put on tube life by increased soot-blowing activity, which intensifies the concentration of ash in the flue gas. These variables jeopardize unit availability and, ultimately, capital asset productivity.

Asset productivity and overall profitability can be considerably improved through the use of advanced metallurgical technologies designed to reduce erosive wear of tubes at elevated temperatures.

Reconsidering Investments in Asset Availability

Boiler tube failures are a major cause of forced outages in the power production industry. As a means for improving asset availability, many power generation executives are making significant capital investments in new tube bundles. While full tube wall thickness may reduce the frequency of leaks, varying operating conditions can accelerate deterioration of the new tubes. New tubes made of commonly accepted materials, including carbon and stainless steels, are not necessarily designed to withstand the current operating variables of today's power generation industry.

The selection, installation, and operation of new tube bundles typically involves a large contingent of internal plant personnel, corporate engineers and asset teams, as well as numerous external contractors and subcontractors. Many external tube suppliers are primarily interested in establishing their products as the low cost solution. Advanced, value-added wear technologies, often perceived as having higher initial installation costs, are frequently overlooked. However, knowledgeable executives performing comprehensive profitability analyses recognize that advanced wear technologies offer higher long-term returns by extending capital equipment life.

Incremental replacement power costs, in the event of a tube leak, must be considered as an integral component of the investment analysis. Typically, the result of installing lower-cost tubing is an increased risk of unplanned downtime, and it is important to plan re-tubing projects in order to quantifiably reduce this risk. The financial benefit of this practice can outweigh the initial cost by several magnitudes. By considering the importance of long-range availability, savvy executives are able to convert smart investments into quantifiable returns. The initial commitment to use the most reliable technology will, in many cases, increase initial installation costs only nominally. Informed executives will seek out and explicitly specify such

technologies, protecting their overall investment against the cost-cutting measures employed by many contractors.

Understanding Wear, and the Material Characteristics Critical to Preventing It

It is important to differentiate between various modes of wear, and to understand which mode is the primary driver for tube failures in a given location. A material that withstands corrosive attack in a waterwall application may be a poor choice for protecting superheater tubes against fly ash entrained flue gas erosion. For example, 316 Stainless Steel may perform reasonably well at protecting against Nitric Acid attack, but does not provide notable protection against high velocity fly ash erosion. The same can be said for most weld overlay materials, which typically do not have a sufficient density of hard particles to qualify them as high performance erosion resistant materials.

Extreme temperatures, thermal shock, and the possibility of impact from clinkers are all factors confronting wear protection methods in a power generation steam boiler. A material must possess the following characteristics to defend against high velocity fly ash erosion in this severe environment:

1. Ultra high density of hard particles to withstand extreme ash particle impingement energies;
2. Extreme interparticle bond strength to ensure that the hard particles remain in place, even in the presence of corrosive agents;
3. Toughness to withstand large particle impact and extreme thermal shock;
4. Minimal impact on desired tube heat transfer characteristic.

Methods of Wear Protection

Several methods for protecting boiler tubes from the severe wear environment in a power generation steam boiler have been employed, with varying degrees of success. Each method offers certain benefits, but may add additional risks to asset availability.

Tube Shields

Virtually every boiler maintenance team is familiar with the use of shields for the protection of boiler tubes. Shields may be as simple as a sacrificial contoured plate of carbon steel welded in place, or as complex as a “hand-cuffed” superalloy with sophisticated spray coatings. While tube shields may reduce the frequency of tube leaks and the opportunity for collateral damage caused by high-velocity steam cutting, there are multiple issues that make tube shields a poor performing, if not risky, solution.

The objective of tube shields, to prevent hot gas from contacting the heat exchanger tubes of the boiler, it significantly reduces the efficiency of the unit by impeding heat transfer. This heat transfer degradation is caused not only by the increased material of the shield, but also by the shield’s tendency to entrap “dead” air between itself and the tube that it is protecting.

The additional area represented by the tube shield typically constricts gas flow through and between tubes in a zone that already may have a limited flow area. Most significantly, the affixing of tube shields is very difficult and unpredictable. Because of the severe operating environment in a steam boiler furnace, attaching a tube shield (either by bolting, welding, or other method) so that it will not come free is a tenuous task. Tube shields that come loose can block gas flow, which further reduces heat transfer efficiency and can be the source of flow

eddies that concentrate wear, accelerating tube failure. Tube shields that fall to the bottom of the furnace can lead to the reduced life of clinker grinders.

Spray Coatings

Protective spray coatings, including HVOF, plasma spray, laser, and others, have become very popular over the past two decades. While spray coatings have provided good wear resistance in some applications, their popularity has been primarily driven by the mystique of the technology, along with considerable marketing investments by OEMs and other large coating manufacturers. Though direct application of spray coatings alleviates some of the issues that plague tube shields, sprays have experienced limited success in protecting boiler tubes from fly ash erosion in severe environments.

The spray coating process, which typically utilizes a hot molten carrier material to move hard particles into place, tends to produce limited hard particle density in the resulting coating layer. The higher the density of hard particles, the more difficult it is to make and keep the carrier material fluid.

Spray coating is analogous to a painting process, albeit a very sophisticated one. Typically, multiple coats are applied atop one another to build up the material thickness. This process, which generally results in mechanical “sticky” bonding between particles and coating layers, can be susceptible to oxide and other contamination between layers (see figures 1 and 2). This limits the total available thickness, and may, in some cases, threaten the integrity of overall coating adhesion, resulting in spalling and chipping.

The bond issues described above can be particularly problematic in the severe environment of a power generation furnace. Frequent thermal shock, especially in soot blowing lanes, generates the rapid heating and cooling of dissimilar materials, causing differential expansion and contraction. This differential movement creates extreme stress in the coating bond zones.



Figure 1. Typical Flame Spray at 100 μm

(Note: maximum coating thickness approximately 15 mils)

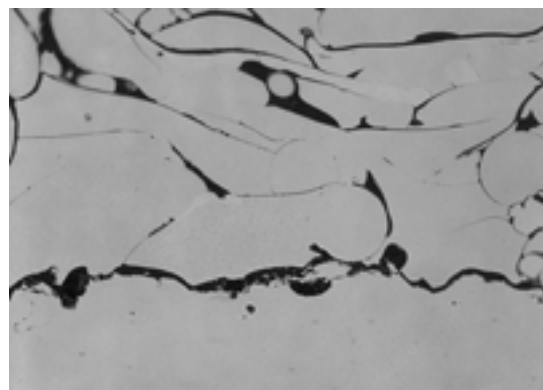


Figure 2. Typical Flame Spray at 10 μm

Weld Overlays

Weld overlay materials are available in a variety of compositions, including chrome carbide, vanadium carbide, tungsten carbide, inconnels, stainless steel, and other exotic materials. All weld overlays generally utilize the same approach to inhibiting wear, with varying compositions

selected depending upon environmental variables. In an environment where corrosion is a significant factor, a stainless steel overlay might provide adequate protection. Whereas, a tungsten carbide weld overlay may perform better when corrosion is nominal and the primary wear mode is erosion.

While their use in boiler tubes has been limited over the past several years, some weld overlay compositions have shown promise in protecting tubes against corrosive attack. This is particularly true of inconel weld overlays, which are becoming commonly used as protection against waterwall corrosive attack. While these, and other weld overlays, are often used for corrosive applications, their resistance to erosion is minimal when compared against more advanced erosion resistant materials.

Due to the relatively “low tech” nature of welding, many of the constraints related to spray coatings are even more relevant to weld overlays. Weld overlay procedures do not typically achieve the same temperatures or particle movement velocities as those attained with spray coating processes. This significantly limits the amount of hard particles that can be deposited for a given amount of carrier material. Typical hard particle volumetric densities for weld overlay materials rarely exceed 28% by volume, the remainder consisting of relatively soft carrier material. While there are many corrosion resistant carrier materials that can be used in the weld overlay process, the nature of such materials (which makes them useful as a carrier in the weld process) precludes them from withstanding high velocity particle erosion. Erosion resistance is directly proportional to the density of the material’s hard particles (see Figures 3 and 4).

High localized heating in the weld overlay process typically causes absorption of substrate carbon, known as “carbon dilution”, into the weld overlay material. This dilution of carbon causes a reduction in the material’s ability to withstand high velocity erosive attack. This extreme localized heating, combined with the difficulty in controlling cooling rates, also results in check cracking of the weld overlay material. This check cracking may propagate into the base tube material, leading to premature tube failure. Check cracking at the weld surface offers a path for high velocity erosive material to penetrate into the protective layer; a phenomenon known as “channeling”.

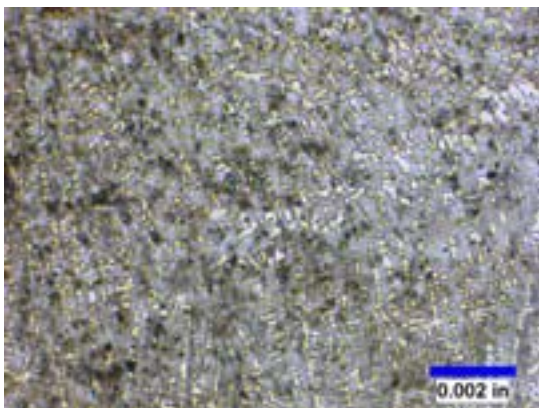


Figure 3. Typical Weld Overlay

(Note: Dark spots are chromium carbide particles)

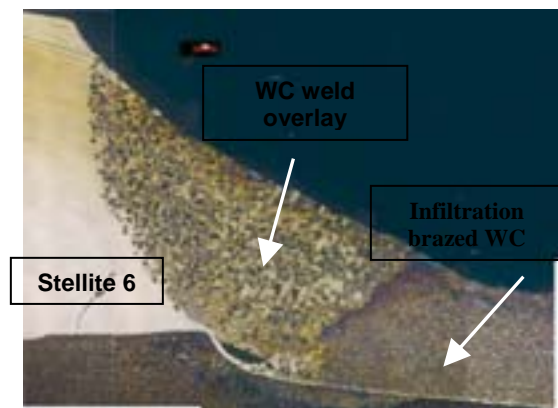


Figure 4. Comparison Mosaic

(Note visible variations in hard particle density)

Infiltration Brazed Tungsten Carbide Cladding

Infiltration brazed tungsten carbide cladding overcomes the constraints of tube shields, spray coatings, and weld overlay materials, as described below.

- Infiltration brazing does not require the movement of hard particles. Therefore, hard particle densities of more than 70%, by volume, can be achieved (see photomicrograph figure 5).
- Infiltration brazing creates a metallurgical bond between the hard particles, the carrier material, and the boiler tube to be protected, thus keeping the particles in place.
- Brazing precludes the introduction of contaminants and the development of oxides in the protective layer, ensuring consistent cladding integrity.
- Infiltration brazing does not allow for significant carbon dilution into the protective layer, ensuring uniform wear resistance from top to bottom.
- Infiltration brazing allows for a deposition thickness as high as 120 mils, providing extreme life extension when required.
- The metallurgical bond and high toughness of the carrier material enables infiltration brazed cladding to withstand extreme thermal shock and impact.
- Infiltration brazed tungsten carbide has a heat transfer coefficient similar in magnitude to common tube steels ($\sim 30 \text{ W}/(\text{m}^2\text{K})$), and the metallurgical bond ensures that there is no significant heat transfer impediment at the bond surface.
- Controlled application and cooling during infiltration brazing ensures that protection is virtually crack-free.

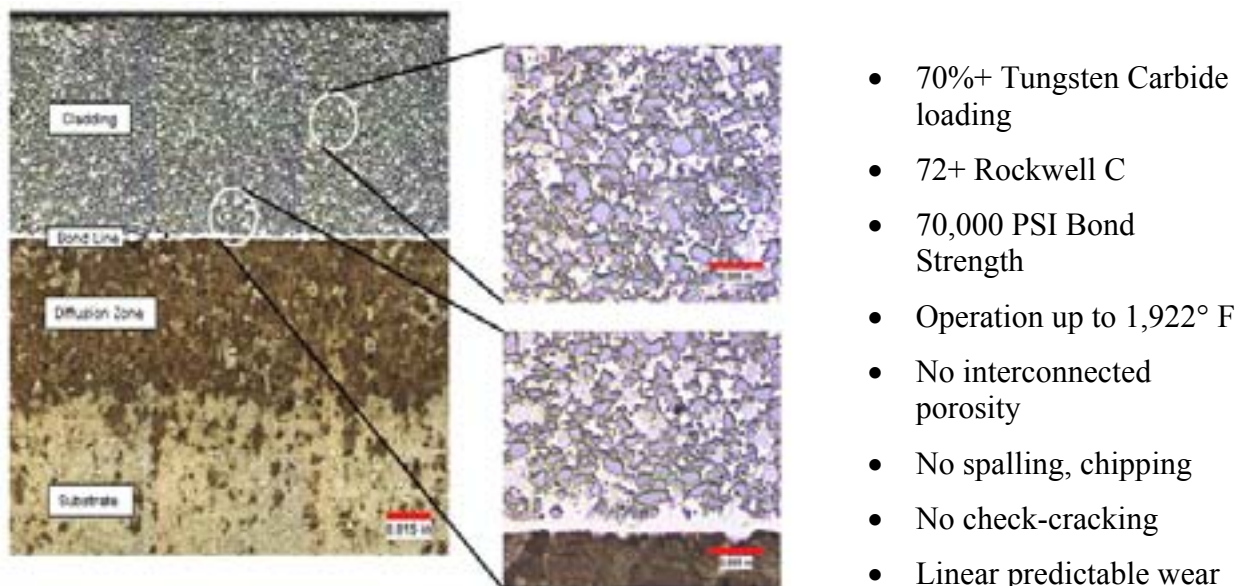


Figure 5. Infiltration Brazed Tungsten Carbide Cladding

Performance Comparisons

High Temperature Erosion Comparisons

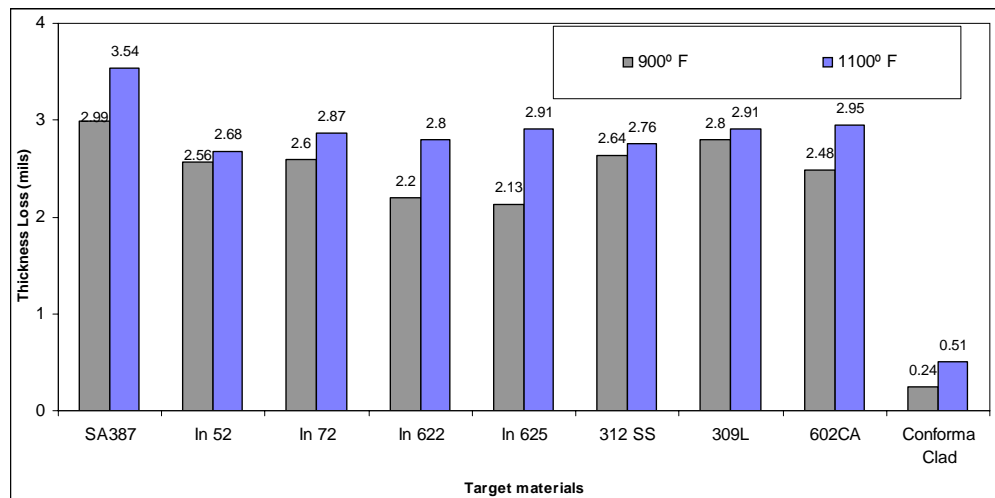
Multiple lab comparisons of infiltration brazed tungsten carbide cladding have been performed in order to benchmark its erosion protection capabilities against other, more commonly known, materials. In December 2003, the Electric Power Research Institute (EPRI) completed a hot erosion comparison utilizing ASTM G73 test methodology. The test, which used fluidized boiler bed ash as the erodent material, compared the following commonly accepted erosion “resistant” materials:

- SA387 steel
- Inconel 52 weld overlay
- Inconel 72 weld overlay
- Inconel 622 weld overlay
- Inconel 625 weld overlay
- 312 SS weld overlay
- 309L weld overlay
- Duocor[®] coating
- 602CA coating
- Conforma Clad[®] infiltration brazed tungsten carbide cladding



Figure 6. Erosion Testing Fixture

Figure 7 indicates that infiltration brazed tungsten carbide outperformed all of the alternative materials, by as much as a factor of ten, in a high temperature ash erosion environment.



Test Conditions
Particle velocity: 40 m/s
Temperature(s): 900, 1100 F
Impact Angle: 30 degrees
Test duration: 3 hours

Figure 7. EPRI Hot Erosion Comparison Results

Corrosion Resistance Comparisons

Corrosion is not typically the primary driver for failure of steam boiler tubes in the flue gas stream, such as primary superheater tubes. However, corrosion can play some role in accelerating other modes of failure, such as high velocity ash erosion. Therefore, corrosion resistance characteristics are of some interest.

ASTM specifies a standardized corrosion resistance test methodology referred to as G31. G31 testing exposes a material sample to a 10%, by weight, concentration of boiling corrosive material. ASTM classifies any material as a CLASS A corrosion resistant material if the amount of material lost over the period of one year is less than 0.002". Figure 8 is a graphical representation of the ASTM G31 test results, illustrating that all three primary formulations (WC200, WC210, WC219) of infiltration brazed tungsten carbide cladding are CLASS A corrosion resistant materials in Nitric and Sulphuric Acid environments. All infiltration brazed tungsten carbide claddings, except WC200, are CLASS A resistant to Hydrochloric Acid.

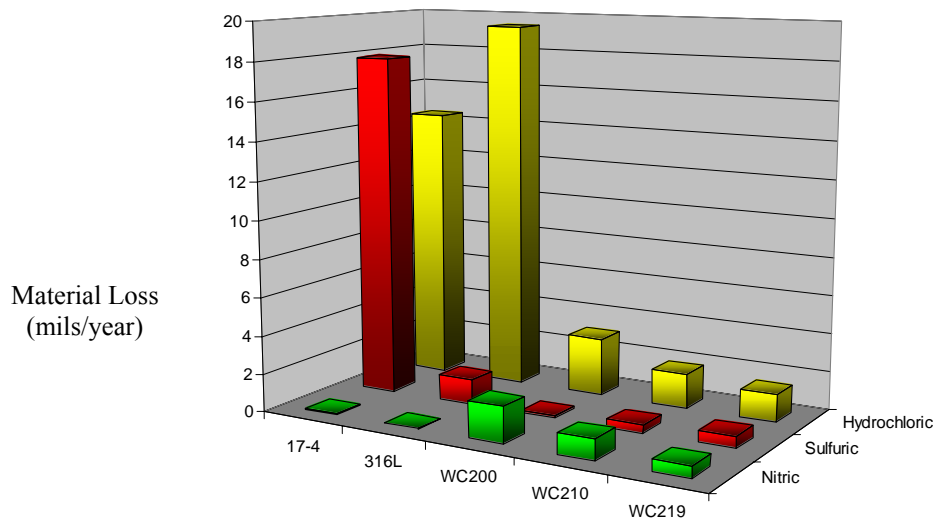


Figure 8. ASTM G31 Corrosion Resistance Results

Case Study

In an effort to reduce the risk of boiler tube leaks and increase unit availability, American Electric Power Company elected to perform a major retubing project on its Philip Sporn Unit number one. In order to achieve maximum predicted availability in its superheater tube sections, AEP elected to upgrade the protection of its primary superheater tube legs with infiltration brazed tungsten carbide cladding.

Philip Sporn unit 1 is a Babcock and Wilcox front-fired boiler with a nameplate rating of 153 MW, burning Bituminous coal. The unit, which went online in 1950, utilizes two elevations of burners supplied by five B&W E70 coal pulverizers. High velocity fly ash entrained in the flue gas causes severe erosive attack in several areas of the furnace. The erosive attack is exacerbated by increased fly ash concentration during periods of soot blowing activity. The flue gas temperature, in the area of primary superheat tubes, is approximately 700 degrees Fahrenheit during full-load operation. The steam conditions inside these tubes are 2450 PSIG and 550° F.

The primary superheat tube legs, made of SA210 Grade A-1 material, have an outside diameter (OD) of 2 ¾", with a 0.280" wall thickness. Tube sections have an "S" shaped double bend (see Figure 9), and are approximately 60" in length.

Due to frequent tube leaks, and the need for repeated patch weld repairs, the primary superheater tube inlet section in unit 1 was replaced with tube sections protected with infiltration brazed tungsten carbide cladding. Prior to this upgrade, the tube areas required pad weld repairs on an average of every two to four years.

Conforma Clad Inc. received tube sections from AEP, and applied a 0.030" thick layer of its WC219 cladding formulation along an approximately 40" section, centered along the length of the overall tube. It was determined that a thickness of 0.030" provided sufficient protection for the application. Greater thicknesses were evaluated and deemed unnecessary. The cladding layer covered only 200 degrees around the circumference of the pipe, on the upstream side facing the flue gas flow. Coverage on the downstream face was deemed unnecessary.



Figure 9. Clad Superheater Tube Leg

High Temperature Oxidation Test Results

Operating temperatures for this application were significantly below the oxidation onset temperature of infiltration brazed tungsten carbide cladding (1,922° F). Contact the author for specific oxidation test results.

Structural Integrity of Tube Materials

Infiltration brazing is a relatively high temperature process, which may have an annealing effect on some materials. Depending upon the material being brazed, this may affect the yield strength of the material. In many applications, a moderate reduction of a material's baseline yield strength is insignificant. However, for boiler tube applications, it is critical that a complete quantitative evaluation of mechanical integrity be performed to ensure the reliability and safety of the application.

ASTM material specifications require that SA 210 Class A-1 meets the following minimum criteria:

Tensile Strength:	60 ksi
Yield Strength:	37 ksi
Elongation:	30%

ASTM A 520 specifies that hydrostatic burst pressure shall be no less than 1.5 times design pressure; in this application 3,675 PSIG.

Destructive Testing Procedures

A twenty foot section of a SA 210 Class A-1 seamless boiler tube, with a 2 ¾" OD was procured from an approved supplier. A wall thickness of 0.280" was not readily available; therefore, a 0.240" minimum wall thickness tube was used. Several 12" and 18" test samples were cut from this single tube length.

Tensile Testing. Two 12-inch sections were processed through a typical infiltration brazing furnace cycle without the application of cladding material. One sample was subsequently

normalized at 1,675° F and rapidly cooled (specific rates are proprietary). A third 12-inch control sample was cut and left in its original state. All three 12-inch tube sections were then sent to an independent laboratory for ASTM E8 tensile testing. Three samples from each of the three 12-inch sections, for a total of nine samples, were tensile tested. The results are tabulated in Table 1.

Hydrostatic Burst Testing. Two 18-inch sections were clad with 0.030" WC 219 on the OD of 180 degrees circumference and processed through a typical infiltration brazing cycle. One sample was subsequently normalized at 1,675° F and rapidly cooled. A third 18-inch control sample was cut and left in its original state. All three 18-inch sections were sealed using a robotic welder, with plugs machined in-house, and were sent to an independent facility for hydrostatic burst testing. The results are reported in Table 2.

Destructive Testing Results

Tensile Testing. Results of Tensile Testing and calculated Yield Strength are tabulated below.

	Tensile Strength (ksi)	Yield Strength (ksi)	Elongation (%)
Control Sample 1	68.0	46.7	34.6
Control Sample 2	69.0	46.5	35.2
Control Sample 3	67.0	46.2	35.0
Average	68.0	46.5	34.9
Braze Cycle Sample 1	59.5	33.4	33.5
Braze Cycle Sample 2	60.5	33.1	32.9
Braze Cycle Sample 3	60.0	32.8	31.6
Average	60.0	33.1	34.9
Brazed and Normalized Sample 1	59.5	36.1	36.3
Brazed and Normalized Sample 2	60.5	37.7	38.0
Brazed and Normalized Sample 3	60.0	37.1	37.8
Average	60.0	37.0	34.9

Table 1. Tensile Test Results

Results shown in the center section of the table indicate that subjecting the tubes to a typical brazing cycle reduced the tensile strength of the material to its minimum allowable level of 60 ksi, and reduced the material yield strength to below its minimum allowable level of 37 ksi. The normalization heat treatment process, as shown in the bottom section of the table, increased the material yield strength to the minimum allowable level of 37 ksi.

Hydrostatic Burst Testing. Hydrostatic burst test results are tabulated in Table 2. Equation (1) was used to estimate burst pressures based on the tensile strength results shown in Table 1.

$$P = \frac{2\sigma t}{ID} \tag{1}$$

Where: P = Calculated burst pressure (psi)
 σ = Tensile strength (psi)
 t = Wall thickness (0.240 in.)
 ID = Inside diameter of pipe (2.510 in.)

	Calculated Burst Pressure (psi)	Actual Burst Pressure (psi)
Control	14,379	14,200
Braze Cycle	12,687	11,600
Braze Cycle and Normalized	12,687	12,900

Table 2. Hydrostatic Burst Test Results

Data in Table 2 indicates that actual burst pressure, following normalization heat treatment, exceeds the minimum allowable 3,675 PSIG by a factor 3.5X. The ruptured pipes are illustrated in Figure 10. Both of the clad specimens had axial cracks running the length of the cladding, and burst within the cladding.

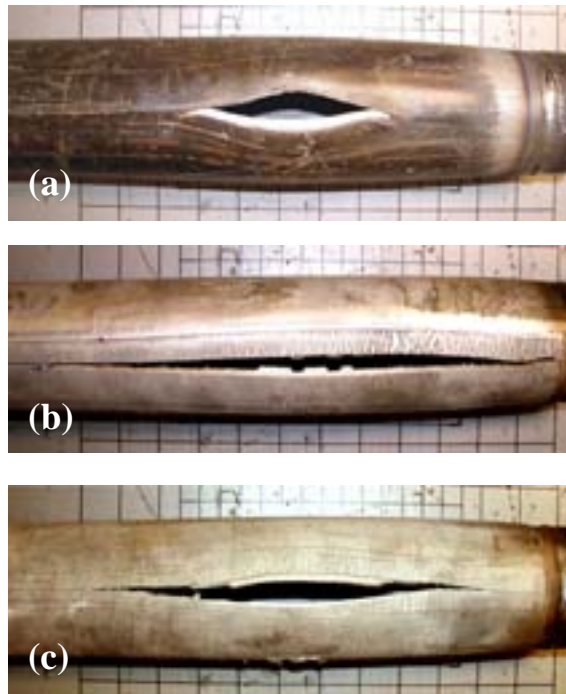


Figure 10. Boiler tube sections after hydrostatic burst test. (a) Control (b) As-brazed (c) Brazed and Normalized.

Results

Laboratory testing and the destructive evaluation of tubes indicates that the infiltration brazing of tungsten carbide cladding to boiler tubes, under high temperature and pressure, will not significantly alter the mechanical characteristics of the material. Proven erosion characteristics of this cladding indicate that this protective upgrade will provide significant reduction in the risk of tube failures.

The cladding application has performed as expected, after approximately 14 months of operation. Actual performance data has not been collected, due to the absence of an appropriate unit shutdown.

Conforma Clad Engineers will travel to AEP, equipped with portable eddy current cladding thickness gauges, and map the superheater tube inlet leg cladding thickness layers. Based upon the known initial cladding thickness and the fact that the cladding wears at a linear rate from top-to-bottom, Conforma Clad will provide a comprehensive report identifying the location of the most severe wear and extrapolating remaining life.

Conclusion

Power generation plant owners and maintenance teams are expected to use innovative methods to increase the availability and productivity of their steam boilers and other large capital assets. Infiltration brazed tungsten carbide is a proven technology available to provide substantial protection against the most common causes of aggressive equipment wear.

Infiltration brazed tungsten carbide, while not as well known as spray coatings and other older technologies, has proven its ability to simultaneously withstand extremes of thermal shock, erosion, abrasion, corrosion, and impact. Through the use of this ultra-high performance protection material, plant operators can significantly reduce the risk of boiler tube leaks, greatly increasing levels of unit availability and overall capital asset productivity.

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