ABSTRACT

The modern weld overlay applied by automatic gas-metal-arc welding (GMAW) process using Ni-Cr-Mo-Nb alloy 625 has been extremely successful in providing corrosion and erosion/corrosion protection for the waterwalls of waste-to-energy (WTE) boilers for over a decade. Without alloy 625 weld overlay protection, the carbon steel waterwall of a waste-to-energy boiler would be corroded through in a matter of months. The overlaid waterwalls for numerous WTE boilers have shown excellent performance results with services up to 10 years or more.

Welding Services Inc. has developed a patented process for manufacturing weld overlay bimetallic tubes involving GMAW/GTAW process. Unifuse® 625 overlay tubing with carbon steel substrate has been successfully used as screen tubes, superheater tubes and generating banks in the convection section. The overlay tubes have successfully replaced such corrosion protection methods as stainless steel tube shields and refractories.

INTRODUCTION

Municipal waste typically contains plastic materials, textile, leathers, batteries, food waste, and other miscellaneous materials. These constituents are the source of chlorine, sulfur, sodium, potassium, zinc, lead, and other heavy metals that form corrosive vapors of various chlorides and sulfates during combustion.
These chloride and sulfate vapors, along with fly ash, condense and deposit on the cooler surfaces, such as waterwalls, which surround the combustion zone, and heat exchanger surfaces in the convection path, such as screen tubes, superheater tubes and generating banks. These metallic components are subjected to accelerated chloride corrosion because many chlorides exhibit high vapor pressures and low melting points with some as low as 200 °C or lower. Corrosion problems in waste incineration are very well documented. [1-8]

In waste-to-energy boilers, the furnace waterwalls and tubes in the convection path, such as screen tubes, superheaters and generating banks, frequently suffer severe wastage problems. It is primarily due to corrosion by vapors and/or deposits of chlorides. Particulate impingement can further accelerate the wastage process by erosion/corrosion. Wastage rates of 1.3-2.0 mm/yr (50-80 mpy) or higher have been observed for carbon steel waterwalls, and of 2.5 mm/yr (100 mpy) and higher have been observed for carbon or Cr-Mo steel superheater tubes. Flame impingement, higher gas temperatures, and higher concentrations of chlorine and heavy metals in the feed will further contribute to increased wastage rates.

SOLUTION TO CORROSION PROBLEMS IN LOWER FURNACE

An innovative, engineering solution for solving corrosion or erosion/corrosion problems experienced by the waterwall is to apply an overlay of a corrosion-resistant alloy to carbon steel waterwalls on site using automatic welding machines. In 1984, WSI pioneered a field overlay technology by using automatic gas-metal-arc welding (GMAW) overlay machines applying a corrosion-resistant alloy to the waterwall on site in a waste-to-energy boiler in Lawrence, Massachusetts. The alloy selected for the overlay was alloy 625 (Ni-21.5Cr-9Mo-3.7Nb). It was an excellent alloy selection. The overlay had proved to be so successful in its performance in the Lawrence boiler that approximately 126,000 kg (280,000 lbs) of alloy 625 weld overlay metal had been applied by WSI from 1985 to 1990 for about 30 boilers. [9]

The GMAW overlay machine, which is fully automatic, deposits weld beads in a vertical down mode starting typically from the membrane and then moving to the tube section following a preprogrammed weld bead sequence to achieve a uniform coverage of the waterwall (i.e., membranes and tubes) in a boiler. Each weld bead is overlapped by subsequent weld bead to insure a full coverage with no missing spots, as shown schematically in Fig. 1. The thickness of the overlay applied to the waterwall in field is typically 1.78 mm (0.070") minimum. Figure 2 shows an overlay machine in the process of applying weld overlay to the waterwall in a boiler.

For overlay welding of the waterwall in the field, it is a common practice to use many welding machines, for example, 10 or more, at the same time in the boiler to complete the project during a maintenance shutdown. A modern machine can deliver a welding “speed” of approximately 0.14 to 0.19 m² (1.5 to 2.0 ft²) per hour. Thus, with 10 machines, a total area of about 16.7 to 22.3 m² (180 to 240 ft²) of the waterwall can be overlaid over a 12-hour shift. A waterwall area of about 280 m² (about 3000 ft²) can be routinely overlaid in seven days using a two 12-hour-shift-per-day schedule.

When the waterwall is damaged beyond repair on site, the damaged section can be removed and replaced with shop-fabricated overlay panels. Panels of sizes up to 1.2 m (4 ft) wide and 12 m (40 ft) long can be readily handled in the shop. Construction of an overlay panel consists of fabricating a panel of steel tubes and membranes, which is then followed by overlay welding of the panel on a stand using essentially the same techniques as field overlay.

Figure 1. Schematic showing the weld bead overlapping in overlay welding of the waterwall using automatic gas-metal-arc (GMAW) welding process.
Figure 2. Photograph showing an automatic GMAW machine in applying an alloy 625 overlay to the waterwall of a boiler.

Today, automatic GMAW applied overlay of alloy 625 has become a “standard” protection cladding for the waterwalls against corrosion or erosion/corrosion in most waste-to-energy boilers in the U.S. The alloy 625 overlay has proved to be successful in performance in both mass burning (MB) and refuse-derived fuel (RDF) units. In Europe, this weld overlay technology has been increasingly accepted as a reliable, long-term solution to the waterwall wastage problems for waste-to-energy boilers. Alloy 625 overlay has been applied to many boilers in the Netherlands, UK, France, Italy and other countries.

Figure 3 shows an alloy 625 overlaid waterwall sample obtained from a waste-to-energy boiler. The overlaid waterwall had been in service for 16 years. The cross-section of the overlay is shown in Figure 4, revealing very little corrosion attack. Another example is shown in Figure 5, which shows the alloy 625 overlay on the waterwall of a waste-to-energy boiler after 10 years of service. The figure shows an area near the grate exhibited some erosion/corrosion attack that required minor repair.

Figure 3. A sample of a 625 overlay waterwall sample obtained from an overlaid waterwall after 16 years of service in a Waste-To-Energy boiler.

Figure 4. Optical photomicrograph showing the full cross-section of the 625 overlay at the crown bead after 16 years of boiler operation in a waste-to-energy boiler. Magnification bar represents 0.5 mm (0.020 in).
Figure 5. Alloy 625 overlay on the waterwall of a waste-to-energy boiler after service for 10 years. An area near the grate exhibiting some erosion/corrosion attack required minor repair. Note that the area was ground prior to re-application of the overlay.

SOLUTION TO CORROSION PROBLEMS IN UPPER FURNACE

Unifuse® Overlay Tubing

As in the lower furnace, alloy 625 can also provide an adequate corrosion and erosion/corrosion protection in the convection section at the upper furnace. WSI has developed a welding process for manufacture of bimetallic tubing using GMAW process to deposit an alloy 625 overlay cladding on a ferritic steel tube, followed by a gas-tungsten-arc welding (GTAW) process to smooth the overlay surface and temper the heat-affected zone (HAZ) in the substrate steel. This patented GMAW/GTAW process produces bimetallic tubing with very smooth overlay surface and ductile overlaid microstructure. Figure 6 shows typical cross-section of a Unifuse® 625 overlay tube.

The overlay tube exhibits excellent ductility for forming and bending operations that are required for installation of the tube assembly in boilers. Figure 7 shows a Unifuse® 625 superheater tube bundle that was formed in the as-overlaid condition. The 625 overlay/SA210 A1 overlay tube can successfully pass a severe tube flattening test at a bend radius of \( \frac{3}{8} \) T (tube wall thickness) without cracking, as shown in Figure 8. On the other hand, a co-extruded alloy 625/carbon steel composite tube was found to show some microcracks developing at the interface while subjected to the same tube flattening test, as shown in Figure 9. Tensile tests were performed on the specimens of the 625 overlay/SA210 A1 tube sample in comparison with SA210 A1 tube sample, showing comparable ductility but significantly higher strengths due to the alloy 625 overlay. The test results are shown in Figures 10 and 11. The overlay specimens showed comparable ductility with the steel tube specimens at room temperature and 800 F. The steel tube specimens lost strength at 1000 and 1200 F, resulting in extensive elongation. The overlay specimens doubled the strength of carbon steel specimens at 800, 1000 and 1200 F. This additional strengthening by the overlay can help retain the tube integrity in cases when the tube bundle is under overheating conditions.
Figure 7. A Unifuse® 625 overlay superheater tube bundle that was bent and fabricated in the as-overlaid condition.

Figure 8. Unifuse 625/CS overlay tube in the as-overlaid condition was flattened at a bend radius of \( \frac{1}{2} \) T (tube wall thickness), showing no cracks at the bend area.

Figure 9. A co-extruded 625/CS composite tube was flattened at a bend radius of \( \frac{1}{2} \) T (tube wall thickness), showing cracks developing at the cladding interface while subjected to the tube flattening.

Figure 10. Tensile elongation of specimens of Unifuse® 625/SA210 Al overlay tube (black bars) in comparison with specimens of SA210 Al tube (white bars), tested at room and elevated temperatures. [10]

Figure 11. 0.2% yield strength of specimens of Unifuse® 625/SA210 Al overlay tube (black bars) in comparison with specimens of SA210 Al tube (white bars), tested at room and elevated temperatures. [10]
Screen Tubes

In some boilers, screen tubes have been used to lower the temperatures of the flue gas before entering into the superheaters in an effort to reduce the corrosion and erosion/corrosion rates for superheaters. The tube metal temperatures are quite similar to those of the waterwall. Carbon steel screen tubes could also suffer high wastage rates. Unifuse® 625 overlay tubes have been frequently used with great success. The overlay tubes can be expected to last in excess of 10 years.

Generating Bank (Boiler Bank)

The temperatures of flue gas stream are significantly lower after passing through superheaters before entering into the generating bank. Although the temperature of flue gas in the generating bank is much lower than that in the superheater, carbon steel tubes can still suffer erosion/corrosion attack. Furthermore, soot-blower erosion can pose another serious problem to carbon steel tubes. Typically, stainless steel tube shields are used to protect the tubes against soot-blower erosion. The stainless steel tube shields often suffer high-temperature corrosion, erosion/corrosion, and distortion, particularly at the attachment straps. As a result, shields drop off from the tubes with many being caught in the tube bundle impeding flue gas flow and adversely affecting heat transfer. Figure 12 shows a failed tube shield on a carbon steel tube. The tube shield provided protection from the back against soot-blower erosion. The straps used for holding the shield to the tube were badly corroded and distorted. The windward side of the tube, which was unprotected, suffered erosion/corrosion attack from the flue gas stream, causing tube wall thinning at about 50° angles on both sides. This is shown in Figure 13, which shows the cross-sections of the tube shield and the tube. Flue gas stream flowed from right to left, and the soot blower steam impinged from the back of the tube protected by the shield. The shields and the tube bundle had been in service for three years, and required tube replacement.

The use of Unifuse® 625 overlay tubes in the generating bank can not only resist erosion/corrosion from the flue gas stream but also resist soot-blower erosion attack. The generating bank can not only extend its life but also significantly improve its heat transfer because of the removal of the stainless steel tube shields.

Figure 12. A generating bank carbon steel tube with a stainless steel tube shield failed after three years of service.

Figure 13. Photograph showing the cross-sections of the tube shield and the tube from the sample in Figure 12. Flue gas stream flowed from the right to left causing erosion/corrosion attack on the carbon steel tube, resulting in severe tube wall thinning at approximately 50° angles on both sides. The tube shield suffered severe corrosion and distortion at the attachment straps (not shown in here).

Superheaters

High-temperature corrosion problems can be severe due to higher tube metal temperatures. This is particularly true for the finishing superheater, where the tube metal temperature is the highest. The leading tubes in the bundle can also suffer the worst attack due to the fact that those tubes in the front rows have received the most corrosive ash/salt deposits as the flue gas stream passes.
through the tube bundle. The flow velocity of the flue gas, if significantly high, can further accelerate corrosion attack via erosion/corrosion attack. Carbon or Cr-Mo steel superheater tubes, when unprotected, are susceptible to high wastage rates. Figure 14 shows a Cr-Mo steel superheater tube suffering severe tube wall wastage and leading to eventual tube rupture.

Common protection methods involve the use of stainless steel tube shields to provide corrosion and erosion/corrosion protection. The attachment of the tube shield to the tube typically involves a mechanical means and filler welds. Typical tube shield materials are stainless steels, such as Type 309 SS or Type 310 SS. Tube shields are generally exposed to the temperature of the flue gas that enters into the superheater bundles. The metal temperature of the tube shields is typically same as that of the flue gas, ranging from 1200 F to 1500 F, depending on individual boilers. Thus, tube shields suffer severe chloride attack and sulfidation at these high temperatures. Furthermore, stainless steels also suffer creep deformation and distortion due to high temperatures. Tube shields typically last for 18 months. Frequently, the remnant materials of the tube shields drop down to the bottom of the superheater bundle, blocking the flue gas flow through the superheater and adversely affecting heat transfer. Figure 15 shows the remnant of a Type 310 SS tube shield after service for about 18 months.

Another protection method involves the use of refractory on the superheater tubes. The operators, who have used this method of tube protection, have reported cracking problems with the refractory. Annual repair of the refractory is generally required to make sure the superheater tubes are protected. Furthermore, refractory reduces the heat transfer efficiency of the superheater.

The use of Unifuse® 625 overlay tubes for superheaters has become a preferred long-term solution in order to avoid the problems arising from frequent shutdowns for repairs and/or installation of refractories or metallic tube shields. Unifuse® 625 overlay tubes have been increasingly used for protection of superheaters in place of tube shields or refractories. An example of a superheater bundle constructed with Unifuse® 625 overlay tubes is shown in Figure 16.

An example of the performance difference between bare carbon steel tubes and Unifuse® 625 overlay tubes is given in below. The difference in performance was obtained from parallel tests between bare carbon steel tubes (SA178) and Unifuse® 625 overlay tubes in a waste-to-energy boiler in the State of New York. The results of a side-by-side test comparing bare SA179 carbon steel tubes with Unifuse 625 overlay tubes are summarized in Tables 1 and 2. Based on this set of performance data, the life for the Unifuse tubes is approximately 6 years and that of carbon steel tubes is
about 1-1/2 years. Thus, it would have required four times of tube replacements for the carbon steel tube bundle in addition to the down time required for tube replacement each time, thus causing loss revenue in power generation during each tube replacement. Therefore, there is a tremendous economic advantage to resort to Unifuse overlay tubes.

Table 1. Wastage Rates of Carbon Steel Tubes and Unifuse 625 Overlay Tubes in a Finishing Superheater in a Waste-To-Energy Boiler in New York. [10]

<table>
<thead>
<tr>
<th>Carbon Steel</th>
<th>Unifuse 625 Overlay</th>
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<tbody>
<tr>
<td>110 mpy</td>
<td>18.3 mpy</td>
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<tr>
<td>(2.8 mm/y)</td>
<td>(0.46 mm/y)</td>
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Table 2. Expected Replacement Interval for Carbon Steel Tubes and Unifuse 625 Tubes. [10]

<table>
<thead>
<tr>
<th>Carbon Steel Tube</th>
<th>Unifuse 625 Overlay Tube*</th>
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<tbody>
<tr>
<td>1.4 yr</td>
<td>5.8 yr</td>
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* Overlay (0.080" thick) + Steel Tube

Unifuse® 625 overlay tubes have been found to be successful in performance as primary, intermediate and finishing superheaters in many boilers. However, for some boilers, alloy 625 overlay was found to be inadequate for finishing superheater bundles due to much higher wastage rates possibly resulting from burning higher percentage of plastic material, or higher steam temperature and pressure, or higher inlet flue gas temperature, or the combination of the above. Efforts have been taken to find an overlay alloy that performs better than alloy 625 in these aggressive units. Other Ni-Cr-Mo alloys, such as C-276 (Ni-16Cr-16Mo-4W), 622 (Ni-22Cr-13Mo-3W), were tested in the field, showing no better than alloy 625. Furthermore, soot-blower erosion can significantly increase the wastage rate of alloy 625 overlay in superheaters.

In order to find an overlay alloy that would perform better than alloy 625 in some of the aggressive units as well as to resist soot-blower erosion in superheater areas, a laboratory chloridation test was performed on weld overlay samples at 1100 F for 2000 hours in Ar containing 20% O₂ and 4% Cl₂. The selection of this aggressive test environment was to determine the alloy’s intrinsic resistance to high-temperature chloridation attack. The results, as shown in Figure 17, indicated that Unifuse 30CrNi™ overlay was significantly more resistant to high-temperature chloride attack than either alloy 625 or 622 overlay. Field testing of Unifuse 30CrNi™ overlay tubes along with other proprietary alloys, such as 30CrNiAl™ and HF60™ overlay tubes, in boilers is currently underway.

30CrNi, 30CrNiAl and HF60 are trademarks of Welding Services Inc.

Figure 16. Finishing superheater bundle made of Unifuse 625/CS overlay tubes in a waste-to-energy boiler.

Figure 17. High-temperature chloride attack for three weld overlays tested at 1100 F for 2000 hours in Ar-20% O₂-4% Cl₂. [10]
SUMMARY

1. Automatic GMAW overlay of Alloy 625 applied on site has become an industry "standard" solution to mitigate waterwall corrosion problems in waste-to-energy boilers. Weld overlaid panels have also been adopted for construction of new units.

2. A bimetallic tube manufacturing method was developed and patented by WSI, which uses GMAW process to deposit alloy 625 weld overlay followed by GTAW process to smooth the overlay surface and temper the heat-affected zone in the ferritic steel tube. As a result, a ductile, formable overlay tubing, Unifuse® overlay tubing, is produced.

3. Unifuse® 625 overlay tubes perform well as screen tubes and in the generating bank, expecting a tube life in excess of 10 years.

4. The 625 overlay tubes have also been successful in primary, intermediate and finishing superheaters in replacing tube shields and refractory.

5. In some aggressive boilers due to burning more plastic material or higher steam temperature and pressure, or under soot-blower conditions, among other factors, the performance of Alloy 625 overlay was less than adequate. Testing of several proprietary overlay alloys, such as 30CrNi, 30CrNiAl and HF60, is underway.

REFERENCES