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UPDATED CASE STUDY OF FIRESIDE CORROSION MANAGEMENT IN AN RDF FIRED ENERGY-FROM-WASTE BOILER

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ABSTRACT

Fireside corrosion management in energy-from-waste (EfW) boilers is the leading cost of boiler maintenance. The combustion of refuse-derived fuel (RDF) processed from municipal solid waste in a boiler for power generation produces a very corrosive environment for boiler tube materials. Water wall corrosion has been greatly reduced by the use of Alloy 625 overlay in the highest corrosion areas. This paper will describe the progression of water wall corrosion up the boiler walls and novel attempts to reduce this problem. This paper presents an updated case study conducted at the Great River Energy plant in Elk River, MN from 2003-2009 on corrosion management. Areas to be addressed are protection of exposed carbon steel water wall tubes, management of Alloy 625 weld overlay on the water walls and corrosion in the high temperature superheat sections. Methods for testing and maintaining the corrosion resistant Alloy 625 cladding are reviewed. High temperature superheat material selection and shielding are reviewed with information leading to a cost effective solution that requires superheat replacement every three years with very few tube failures between replacements.

INTRODUCTION

Great River Energy's Elk River Station (ERS) Units 1 and 2 were constructed in 1951 and Unit 3 in 1959 and operated as base loaded coal plants. In 1989, all three units at Elk River Station were successfully converted from coal/natural gas to 100 percent RDF firing. The boilers are designed to run at 615 psig (4.2 MPa) and 750 ^{o}F (400 ^{o}C) with a furnace exit temperature of approximately 1600 ^{o}F (871 ^{o}C). Unit 3 runs at about double the output of Unit 1 or Unit 2. Refuse derived fuel (RDF) typically consists of chopped municipal solid waste that goes through a processing step. Processing recovers ferrous and aluminum materials and removes glass, grit, and other materials that are not combustible. The remaining material is classified as RDF. The Elk River Station burns approximately 1000 tons RDF/day.

Numerous modifications to the boilers were required to burn RDF. The principal modification increased the height of the furnace. At the time of the modification, it was thought the longer furnace would allow the exit gas temperatures to be reduced enough that high temperature superheat corrosion would not be a major problem. Initial operation on RDF was acceptable with spot UT readings on the water walls showing no large scale corrosion. Unfortunately, after less than one year, extensive thinning of the water walls was detected. The rapid corrosion was combated by weld overlaying a layer of Alloy 625 to the first 15 feet (4.7 m) of the furnace walls.

DISCUSSION OF HIGH CORROSION AREAS

At ERS, three areas have been identified as the highest cost maintenance areas of the boilers. The areas include the high temperature superheat elements, furnace water wall repairs and maintaining the protective Alloy 625 cladding on the furnace. This paper updates an earlier study at ERS.[1]

High Temperature Superheater Wear

High temperature superheat wear has become critical in boiler maintenance. The original set of high temperature superheat elements installed at ERS lasted approximately 7 years. The second superheater lasted about 3 years and the next about 2 years. Severe wall loss required that every year the first two tubes closest to the sootblower were replaced and a number of other tubes were pad welded or replaced. Reaction of the tube metal to molten slag is considered the driving mechanism for high temperature superheat corrosion. Slag deposits on the superheat elements commonly contain chlorides of Fe, Zn, Pb, K and Cd, as well as eutectic phases of chlorides of these elements which exhibit very low melting points. The kinetics of the reaction between a liquid and a metal are many times faster than the gas to metal reactions. The very aggressive attack in the sootblower lane is due to erosion/corrosion of the outer layer of the tube that is in contact with a low melting point slag and the high energy cleaning medium.

Tube wear can exceed 200 mpy (5 mm/y) in the sootblower lane and 80 mpy (2 mm/y) in the body of the main pendants. Tube wear in the sootblower lane was relatively independent of tube material with 310 SS only having about a 20% reduction in wear rates as compared to T-22 material. Tube shields operate at elevated temperatures relative to the tubes due to poor heat transfer to the tubes and even higher wear rates occur. Wear rates of shields in the sootblower lane exceed 300 mpy (7.5 mm/y) and are relatively independent of the shield material. Different materials have been tested for shields including 310 SS, RA 85H, RA 253, HR-160 and Haynes 556. Results varied slightly for each shield lasting from 3-5 months, but nothing lasting a 1 year outage cycle. Typical rolled shields that are 10 gage (3 mm) thick and are constructed of 310 SS material last less than 4 months in the sootblower lane.

Some tests have been done at ERS and other facilities using MgO to modify the slag on the boiler tubes and reduce its corrosive nature. Tests at ERS did not show a significant reduction in corrosion rates while treating with MgO although the slag was much more friable and easier to remove with sootblowers.

Furnace Water Wall Erosion and Corrosion

Wear to the furnace water walls is another major contributor to boiler maintenance costs. In 2004, Elk River Station suffered forced outages for 12 water wall leaks from all units. During 2003 massive wear on tubes in Unit 3 that were not overlaid caused a forced outage of almost 1 week.

Since the original Alloy 625 overlay was applied at the bottom of the boiler there has been a yearly progression of the wall thinning just above the Alloy 625 to carbon steel transition. Corrosion rates are highest within a few inches of the interface with values near 100 mpy (2.5 mm/y). Table 1 shows typical water wall corrosion for a section just above the Alloy 625 interface. The data begins at 34 feet above the grates because the area below this is covered with Alloy 625.

Small areas that do not have complete coverage of Alloy 625 can have very high corrosion rates in excess of 120 mpy (3 mm/y). The corrosion rate is consistent with other EfW plants across the country. No detailed analysis that documents the mechanism or prevention of the corrosion at the interface has been found in available literature. One possible mechanism in the acceleration of corrosion at the interface is a galvanic type reaction between the dissimilar metals.

The standard repair method to prevent tube failures is to overlay a new band of Alloy 625 cladding on the thin tubes between the old cladding and carbon steel tubing that has not seen significant wall loss. In following this yearly repair pattern, most of the furnace has been overlaid from the grates up to the roof.

Alloy 625 Corrosion Resistant Cladding

In order to prevent numerous tube failures, most EfW furnaces have been clad with Alloy 625 to provide corrosion protection. The Alloy 625 protective cladding has allowed much of the lower water walls of the furnace to remain in service with relatively few leaks and repairs. Although this layer is far more resistant to corrosion than carbon steel, it does experience wear over time. Alloy 625 wear rates of 5 mpy (0.125 mm/y) have been measured by ERS and others[2]. The original layer of Alloy 625 was applied in 1991 with a nominal thickness of 0.070-0.090 inches (1.8- 2.3 mm).

With the first application of Alloy 625 over 19 years ago ERS has spent significant amounts of time and resources maintaining this protective layer. Some areas of the original cladding have worn to less than 0.010 inches (0.25 mm) thick. As the cladding layer ages, its ability to protect the carbon steel under it decreases. Maintaining the integrity of the Alloy 625 cladding is critical, as any area where the cladding has spalled off and carbon steel is exposed experiences corrosion rates in excess of 120 mpy (3 mm/y).

MODIFICATIONS TO BOILER MAINTENANCE

High Temperature Superheater

Since the wear in the sootblower lane area is far greater than the general tube wear, shields were required that would last one year to allow them to be replaced during annual outage cycles. Wear rates require shields that exceed 0.300 inches (7.5 mm) thick to last in the highest wear areas. Cast tube shields were chosen because rolled shields are not available in this thickness. Cast shields made out of HD stainless cast in the shape of a "U" were selected and installed in 2003. HD stainless steel contains 27% chrome and 5% nickel with the remainder mostly iron. The shields shape allows it to protect the first two tubes. The shields are installed with heat transfer silicon carbide cement to increase cooling of the shield. The tube shields have proven to survive approximately twelve months of service. Figure 1 shows a typical high temperature superheater shield installation. The shields were replaced on all boilers from 2003 to 2009 on an approximately annual basis. In Units 1 & 2, the shields were mostly intact at the end of a one year cycle. The shields in Unit 3 lasted a full year in 2003 and 2004 but showed signs of increasing wear. By 2009 the shields in Unit 3 were providing adequate protection for only about 9 months.

In order to get a longer life in the body of the superheat pendant, tube material with a large corrosion allowance was selected. The original tubing installed in the high temperature superheater was made from SA-178 material with a 0.220 inch (5.5 mm) minimum wall thickness. Wear in areas not directly in the sootblower lanes can still experience corrosion rates of over 80 mpy (2 mm/y). By selecting the tubing thickness with an excessive corrosion allowance, it is possible to predict that the tubes will operate for 3 years without significant failures. Tubing made from SA-T22 with a 0.300 inch (7.5 mm) minimum wall thickness was selected and installed without measurable loss in boiler performance. Although the average wear rates in the superheater area for SA-178 and SA-T22 material are similar, SA-T22 showed fewer areas of localized accelerated corrosion. Tubing constructed of 310 stainless steel showed lower wear rates, but was not considered cost effective.

Reducing localized corrosion spots in the superheater pendants is critical to getting a predictable life for the entire bank. Typical sootblowers are run on a timing gear that operates the sootblower through the same cleaning pattern with every operation. This mode of operation can lead to localized erosion of the superheat tubes even deep into the bundle. A modification can be made to the sootblower carriage timing rack that skips a tooth after every cleaning cycle. The modification makes the sootblower travel in a non-repeating pattern. Wall thickness data on the superheaters from 2005 to 2009 indicate that the wear tended to average out with fewer high wear areas deep in the superheater pendants. Wear on the superheater pendants was reduced from over 80 mpy (2 mm/y) to less than 50 mpy (1.3 mm/y).

By making these modifications, it was anticipated that the high temperature superheater pendants would survive three years with minimal repairs. The superheater pendants in Unit 1 and Unit 2 actually lasted over four years and in Unit 3 lasted just under 3 years. Because the measures listed above offer significant corrosion protection, NDE inspections of the high temperature superheater were greatly reduced. Only spot checking the tubes in the sootblower lanes is required. In addition the labor intensive process of major replacement of tubes closest to the sootblowers has been eliminated. This allows the replacement cycle to follow the average wear of the entire superheater instead of numerous localized unpredictable wear areas. Additional benefits include the reduction of the number of field welds by more than 75%. Between 2003 and 2009 superheater leaks were almost eliminated. Unit 3 had a few premature leaks before the pendants were replaced in November of 2007. It is estimated that these modifications have saved the plant over $130,000 per year during this period.

Furnace Water Walls

The corrosion rates on the furnace walls are always highest on the steel closest to the transition from the Alloy 625 cladding. Areas far from the cladding line show no excessive wear. Because iron is very easily oxidized, it was theorized that if the furnace gas was allowed to contact non-pressure part, sacrificial iron before the carbon steel to Alloy 625 interface on the wall, the corrosion would occur on the sacrificial iron and not on the wall tubes. Wall thickness data was used to calculate that approximately 1000 lbs (454 kg) of iron was lost from the water wall adjacent to the Alloy 625 interface in one year.

During the 2003 annual outage, approximately 850 lbs (386 kg) of iron bars (1/2"x2"x24") were installed on the clad tubes just upstream from the carbon steel surface in Unit 3. Figure 2 shows the installed iron bars. During one year of operation, about 75% of the sacrificial bars were corroded away. Results have shown that corrosion is reduced around and downstream of the bars. On a furnace wall area that had lost up to 0.100 inches (2.3 – 2.5 mm) from 2002 to 2003, the largest loss was 0.025 inches (0.64 mm) from 2003 to 2004 and affected a smaller area. The sacrificial bars have been replaced on an annual basis to maintain this protection. From 2003 to 2009, only small areas of new Alloy 625 have been required to protect thinning tubes. The average loss of material during this period was approximately 10 mpy (0.4 mm/y). Few areas of accelerated localized corrosion have been recorded.

It was speculated that the available sacrificial steel was being oxidized by the chlorine in the gas so that the chlorine was not available to react with the carbon steel wall. This cannot be the primary method of protection because there is still a large excess of chlorine available.

$$Fe + 3Cl \rightarrow FeCl_3$$

RDF contains approximately 0.5% Cl. ERS Unit 3 burns 500 tons per day of RDF. If all the Cl were converted to $FeCl_3$, it would require about 110 lbs (50 kg) of iron per hour. It is apparent that the small amount of iron in the bars cannot affect the overall Cl concentration, but it does affect the localized corrosion downstream of the bars.

The selection of the boundaries of the Alloy 625 cladding is critical. The corrosion rate of carbon steel is very high if it is isolated in area of Alloy 625. The cladding must be applied in an even fashion with a uniform transition to unprotected carbon steel. This may require that areas larger than that designated by minimum wall thickness be overlaid to maintain a uniform transition. In addition, small areas of carbon steel that are below required minimum wall thickness need to be pad welded with carbon steel. This is because a pad weld of Alloy 625 on an area that is predominantly carbon steel will experience rapid corrosion of the carbon steel at the boundary of the pad weld.

Repair and Maintenance of the Alloy 625 Cladding

The integrity of the Alloy 625 cladding is critical to the reliable operation of the boiler. An area where the Alloy 625 is thin or has cracks or holes is very susceptible to accelerated corrosion. Until recently, visual inspection of the general integrity of the surface was the only inspection method widely used. UT probes cannot reliably measure the thickness of the cladding on top of carbon steel tubes.

At ERS, a detailed mapping and testing procedure has been initiated to maintain the cladding integrity. During scheduled annual outages the thickness of the Alloy 625 cladding is measured and recorded on a grid system. The grid is laid out on every tube at one foot elevation marks. Mapping is accomplished using an Elcometer 355 meter with a ferrous probe. This probe will measure the thickness of a non-ferrous metal over a ferrous base metal.

Detailed mapping can show wear areas of immediate concern that can be repaired and also long term wear patterns that may be able to be mitigated with process controls. Table 2 shows a typical cladding thickness grid on the furnace wall. Any areas showing less than 0.030 inches (0.76 mm) of Alloy 625 require immediate repair.

Cracking or spalling of the cladding can also lead to tube leaks. Inspection for cracks and spalled areas is accomplished by first sandblasting the entire clad area to a near white finish. Figure 3 shows typical pitting on the Alloy 625 surface. The cleaned area is then sprayed with a copper sulfate spray which rapidly oxidizes any exposed carbon steel. The oxidized areas show as a bright red finish and are shown in Figure 4 as the darker areas.

Where carbon steel is exposed, the surface is prepared with a grinder and Alloy 625 reapplied. If the base carbon steel tube has excessive metal loss, it is ground down to the carbon steel layer and repaired with carbon steel welding rod. The area is then prepared with a grinder and Alloy 625 is applied as a final layer. It is critical to repair every hole, as even very small exposed areas can lead to tube leaks during the year. In 2004, ERS applied over 1,100 lbs (500 kg) of Alloy 625 wire in one unit for cladding repair. From 2003 to 2009, water wall failures in the boiler have been greatly reduced because of the maintenance of the Alloy 625 protective layer.

CONCLUSION

There are still many questions about the exact corrosion mechanisms in EfW boilers. Current information does not explain the success of installing sacrificial iron bars to the furnace wall tubes in the boilers at Elk River Station. New alloys and weld overlay materials have not yet provided an economical answer to excessive high temperature superheat corrosion.

Although it is difficult to maintain an EfW boiler and keep a high availability factor, it is possible to use available technology to manage corrosion. The life of high temperature superheaters can be extended to last into an annual outage cycle utilizing cast tube shields and tube material with excess corrosion allowance. The life of carbon steel water walls can be greatly extended by the application of Alloy 625 and use of sacrificial iron bars at the Alloy 625 interface. Furnace water walls can be repaired and Alloy 625 can be maintained for over 20 years without significant water wall section replacement.

REFERENCES

1. Steve Vrchota, “Fireside Corrosion Management in RDF Waste-To-Energy Boilers”, Presented at NACE 2005, January 30 - February 2, 2005, San Diego, CA.

2. George I. Lai, “Corrosion Mechanisms and Alloy Performance in Waste-To-Energy Boiler Combustion Environments”, Presented at NAWTECH 12, May 17-19, 2004, Savannah, Georgia.

ANNEX

TABLE 1- TYPICAL CORROSION (INCHES) NEAR THE ALLOY 625 BOUNDARY AFTER 1 YEAR OF OPERATION WITHOUT SACRIFICAL IRON BARS AREAS OF HIGHEST CORROSION ARE SHADED

42	41	40	39	38	37	36	35	34	33
OBST	OBST	0.012	0.012	0.010	0.013	0.002	0.012	0.016	Clad
OBST	0.004	0.012	0.017	0.021	0.018	0.012	0.013	0.026	Clad
OBST	OBST	0.015	0.020	0.021	0.018	0.016	0.023	0.034	Clad
OBST	0.012	0.016	0.015	0.008	0.008	0.023	0.022	0.020	Clad
0.000	0.022	0.029	0.008	0.011	0.003	0.027	0.036	0.062	Clad
0.008	0.024	0.028	0.024	0.021	0.015	0.033	0.036	0.053	Clad
0.003	0.012	0.021	0.021	0.016	0.000	0.024	0.036	0.063	Clad
0.017	0.022	0.028	0.019	0.028	0.021	0.053	0.048	0.101	Clad
0.008	0.027	0.033	0.011	0.029	0.027	0.034	0.067	0.073	Clad
0.039	0.036	0.031	0.000	0.000	0.000	0.016	0.017	0.010	Clad
0.056	0.063	0.057	0.000	0.000	0.000	0.006	0.019	0.000	Clad
0.019	0.049	0.034	0.000	0.012	0.000	0.014	0.000	0.015	Clad
0.053	0.050	0.056	0.000	0.006	0.010	0.015	0.012	0.021	Clad
0.046	0.047	0.049	0.000	0.003	0.005	0.010	0.003	0.023	Clad
0.079	0.064	0.071	0.005	0.000	0.000	0.010	0.019	0.021	Clad
0.051	0.026	0.058	0.006	0.011	0.013	0.006	0.020	0.017	Clad
0.048	0.046	0.078	0.000	0.002	0.000	0.036	0.029	0.028	Clad
0.057	0.066	0.085	0.014	0.015	0.014	0.020	0.045	0.044	Clad
0.001	0.005	0.012	0.008	0.014	0.008	0.056	0.046	0.061	Clad
0.008	0.013	0.018	0.005	0.015	0.021	0.053	0.063	0.055	Clad
0.001	0.008	0.031	0.003	0.021	0.034	0.044	0.036	0.047	Clad
0.013	0.012	0.000	0.001	0.013	0.015	0.073	0.053	0.065	Clad
0.012	0.012	0.010	0.005	0.031	0.019	0.017	0.072	0.073	Clad
0.008	0.008	0.021	0.010	0.028	0.031	0.069	0.060	0.082	Clad
0.006	0.006	0.010	0.032	0.025	0.027	0.094	0.077	0.083	Clad
0.000	0.018	0.021	0.020	0.022	0.028	0.080	0.083	0.092	Clad
0.022	0.023	0.017	0.033	0.038	0.047	0.073	0.053	0.091	Clad
0.013	0.016	0.022	0.028	0.017	0.038	0.074	0.024	0.076	Clad
0.000	0.020	0.008	0.019	0.019	0.035	0.049	0.070	0.054	Clad
Clad	Clad	Clad	Clad	0.016	0.012	0.040	0.042	0.053	Clad
Clad	Clad	Clad	Clad	0.012	0.024	0.025	0.050	0.027	Clad
Clad	Clad	Clad	Clad	0.008	0.026	0.042	0.051	0.051	Clad
Clad	Clad	Clad	Clad	0.016	0.029	0.031	0.025	0.028	Clad
Clad	Clad	Clad	Clad	0.131	0.150	0.059	0.045	0.059	Clad
0.044	0.021	Clad	Clad	Clad	Clad	Clad	Clad	Clad	Clad
0.079	0.040	Clad	Clad	Clad	Clad	Clad	Clad	Clad	Clad

Tube

Elevation above grate level (ft)

TABLE 2- TYPICAL ALLOY 625 CLADDING THICKNESS (MILLS) AREAS WHERE CLADDING IS THINNEST ARE SHADED

15	14	13	12	11	10	9	8	7	6
27.4	97.2	56	46.2	55.6	58	71.6	49.4	56.4	45.4
49.4	87.8	48.4	44.8	65.4	47.4	64.2	71.8	64.2	56.4
55.2	143.6	104.2	69.2	36.8	94.8	65.4	107	159.2	38.4
136.6	150.4	21.2	22.4	33.6	99.4	47.4	165.4	92	57.6
163.6	92.4	37	49	49.6	94.8	60.6	65.6	45.2	145.2
94.6	78.6	67	72.6	123.8	76.6	110.4	68	69.4	140
47.2	93.6	54.2	60	50.2	109.8	71.4	51.6	125.8	139.4
54.2	52.4	16.3	33.2	42.6	56.4	26.4	44.2	86	119.2
55.2	85.2	33	32.2	48.6	96.2	93	47	150.2	112.8
38.6	31.6	34.2	26.4	34.6	198.6	99.2	59.4	53.2	49
63.6	85.8	18	46.8	38.8	200.2	179.4	115.4	130.8	45
61.6	46.8	44.2	11	13.1	82	139.4	57.2	110.6	24.2
45.8	73	52.4	38.8	60.2	86	49.8	58.2	128.6	98.8
67	69.4	32.2	26.6	39.4	62.2	29.2	58.6	181.2	129
94.2	51.8	35	25.2	41	90.4	34.2	65.6	70	64.6
72	93.6	32.6	24.2	27.6	43.2	18.1	22.2	100.8	47.4
76.2	55.2	55.8	44	27.6	75.2	35.6	30.6	41.8	22.4
79.4	70.8	86.6	90.2	63.6	89.6	109.6	44.2	38.4	48
80.2	92.2	85	64.2	67.2	109.2	104.6	66.2	73.2	61
101.8	105.2	82.2	44	49	86	91	58.2	80.4	91.6
67	69.8	110.2	56	32.2	67	75.8	56.6	72.6	63
91	120.4	73.4	56.6	39.8	40.4	132.2	57.6	72.8	71
72.6	100.2	49.4	32.6	30.2	14.8	85.4	76.6	76.4	95
67.2	77.2	52.6	45.4	57.8	124.6	74.4	140.6	131.6	90.4
88	104	86.6	65	61.6	188.6	149.8	135.4	114	142.4
124.6	101	79.8	56	54.4	131.6	66.6	114.2	132.2	109.4
95.8	104.8	104.4	44	86	181.6	67.4	132.4	92	36.4
86.4	69.8	59.4	29.6	33.8	161.2	184.2	74.8	149	41
116.4	51.8	66.6	79.6	65.6	53	70.8	55.8	100	69.4
121	44.6	17.9	37.6	62.8	114.4	38.4	53.2	108	107.2
94.8	71.6	61.8	33.6	45.8	132.4	99.6	37.2	68.8	57
111.2	40.4	74.8	42.6	48	32.4	91	46.2	166.4	46.8
175.8	110.2	110	102.2	104	81.8	65.8	107	74.8	41.2

Tube

Elevation above grate level (ft)

FIGURE 1- INSTALLED HIGH TEMPERATURE SUPERHEAT SHIELDS AFTER 1 YEAR OF OPERATION

FIGURE 2- INSTALLATION OF SACRIFICIAL IRON BARS

FIGURE 3- TYPICAL SURFACE PITTING OF ALLOY 625 SURFACE ON LOWER WATER WALL SECTIONS

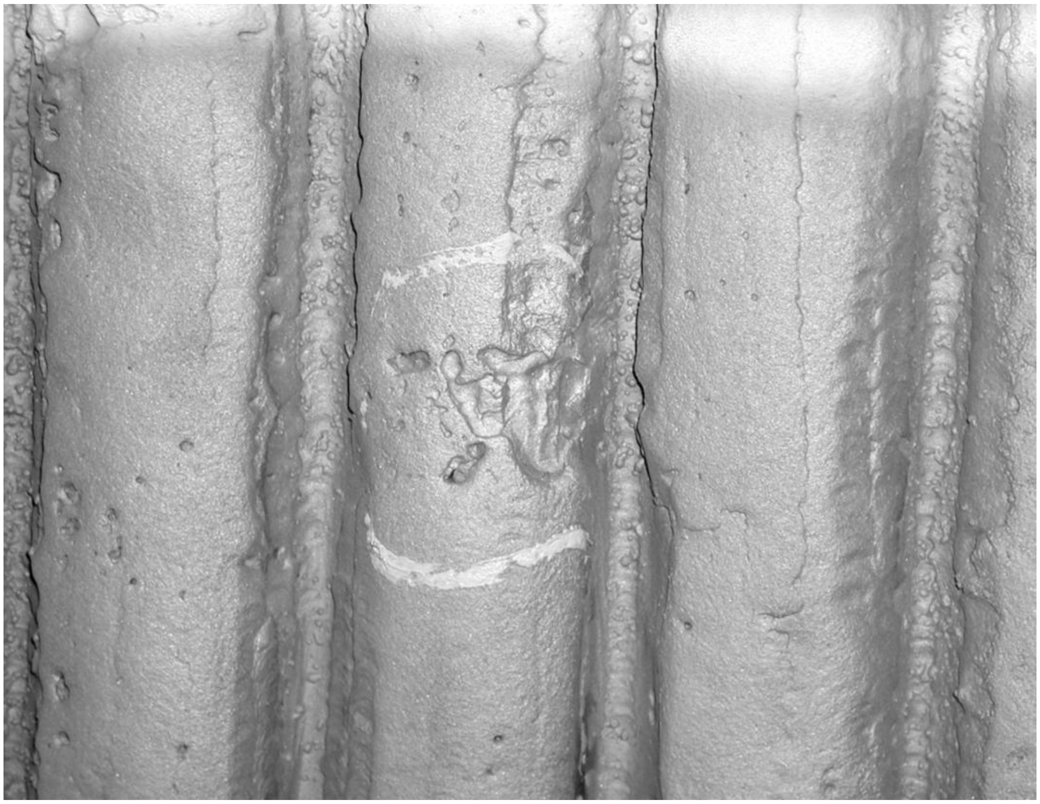

FIGURE 4- SURFACE TREATED WITH COPPER SULFATE