Corrosion Characteristics and Mechanical Properties of Inconel 622 Weld Overlay of Waterwall Tubes in Coal Fired Boilers *

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Recently in Japan, boiler waterwall tube damage such as fireside corrosion and circumferential cracking in a low NO_x environment has become a serious issue, despite the fact that relatively lower sulfur content coal is typically being used than in the US. Thermal spray coating is the most popular method for tube protection in Japan, and thermal spray coating tubes are used for this purpose.

However, extensive damage to thermal spray coating tubes from cracking and exfoliation has recently been experienced. It is reported that the thermal fluctuations that occur as a result of operating changes create alternating stress, leading to cracking and exfoliation of the thermal sprayed thin coating. Corrosion-resistant weld overlays, such as stainless steel type 309, alloy 625 and alloy 622, are now commonly used to protect corrosion of boiler tubes in low NO_x coal fired boilers in the US. In order to develop a fundamental understanding of the high temperature corrosive behavior of alloy 622 weld overlay, gaseous corrosion testing and certain mechanical tests for consideration of long-term aging were undertaken. After one year of service in the low NO_x combustion environment of a coal fired supercritical boiler, field tests on alloy 622 weld overlay panels are continuing.

This report describes the behavior of alloy 622 overlay panels in a field test installed in a Japanese supercritical boiler, the laboratory results of weight loss corrosion testing, and mechanical tests related to aging.

Key Words: Inconel 622, Overlay welding, fireside corrosion, Circumferential cracking, Low NO_x burners, Coal Fired Boilers

1. Introduction

In a coal fired boiler, waterwalls made of tubes and membranes are constructed around the furnace enclosure to contain the high temperature gases. The material for waterwalls is typically carbon steel or low-alloy steel. The waterwalls are subject to high heat flux as well as high temperature corrosion and fly ash corrosion attack.

Recent installations of low NO_x burner systems in boilers to cut NO_x emissions have caused combustion conditions to change from oxidizing to reducing, and low NO_x burner systems create H₂S gases and FeS in deposits. These gases and deposits accelerate corrosion rates for waterwall tubes in deoxidization and high heat flux zones^{1),2)}.

There have been recently reported the waterwall tube damage with fireside corrosion and circumferential cracking in some Japanese corner-firing supercritical boilers. In the case of fireside corrosion, serious waterwall metal wastage occurred on the furnace side. On other hand, in the case of circumferential cracking, the thermal fluctuations that occur as a result of slag removal and operating changes etc. create alternating stresses in boiler tubes that lead to cracks^{3),4)}.

Wastage rates in many boilers have increased dramatically and reliable solutions are urgently needed in Japan. Thermal

spray coating is the most popular method for tube protection in Japan, but extensive damage to thermal spray coating tubes from cracking and exfoliation has recently been experienced. It is reported that the thermal fluctuations that occur as a result of operating changes create alternating stress, leading to cracking and exfoliation of the thermal sprayed thin coating. Field application of corrosion and erosion-corrosion resistant alloy overlay is an alternative solution. Recently in the US, corrosion-resistant weld overlays, such as stainless steel type 309, alloy 625 and alloy 622, have become more common so as to protect boiler tubes from corrosion in low NO_x coal fired boilers⁵⁾⁻⁹⁾.

In the context of the current study, after one-year of service in a low NO_x combustion environment in a coal fired supercritical boiler, a field test on alloy 622 weld overlay panels is continuing. In order to develop a fundamental understanding of the high temperature corrosion behavior of alloy 622 weld overlay, gaseous corrosion testing and mechanical tests related to aging were carried out.

This report describes the behavior of alloy 622 overlay panels in field tests installed in a Japanese supercritical boiler, the laboratory results of weight loss corrosion testing, and aging-related mechanical tests.

2. Experimental Procedure

2.1. Sample Panel in Field Testing

The alloy 622 weld overlay sample panel, which is 16 tubes

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wide and 2500mm high, has overall dimensions of 710mm x 3000mm. The material for the tubes examined was 1.25%Cr-0.5%Mo steel (equivalent to SA213-T11), with tube diameter of 28.6mm. The tubes are rifled, and nominal tube thickness at the bottom of the rib is 5.7mm. Sample panel welding employed alloy 622 filler metal wire measuring 1.2mm in diameter. Table 1 shows the chemical compositions of the alloy 622 filler wire used to produce the weld overlay samples in this study. The gas shielded metal arc welding (GMAW) overlay machine deposits weld beads from the fin and then moves to the tube section to achieve a uniform coverage of the sample panel. Each weld bead is overlapped by the subsequent weld bead to ensure full coverage with no missed spots.

Table 1 Chemical compositions of alloy 622 weld wire (weight%)

	C	Si	Mn	P	S	Cr	Mo	Cu
Wire rod deposit metal	0.003	0.04	0.15	0.01	0.001	21.2	13.4	0.05
AWS Code (ER NiCrMo-10)	≤0.015	≤0.08	≤0.50	≤0.02	≤0.010	20.0~ 22.5	12.5~ 14.5	≤0.50
Co	V	Fe	W	Ni				
1.0	0.05	4.6	3.0	Bal.				
≤2.5	≤0.35	2.0~ 6.0	2.5~ 3.5	Bal.				

Figure1 shows the location of a sample panel installed in 2006. It was placed in the front wall above the burners in a Japanese corner-firing supercritical boiler. The location of the installed alloy 622 overlay sample panel is in the high heat flux zone, which has historically experienced corrosion and cracking in Japanese corner firing supercritical boilers. The sample panel was installed in the front wall between the burner and the AA (additional air) port. The appearance of the sample panel prior to installation is shown in Fig. 2.

Fig. 1 Location of the installed sample panel in 2006

Fig. 2 Appearance of sample panel installed for field testing

2.2. Corrosion Test

Two alloys, stainless steel type 309 and alloy 622, were selected for corrosion testing as weld overlay materials. Welding samples were prepared using automatic MIG welding. Weld wire from each material was deposited onto SA213-T11(1.25%Cr-0.5%Mo) steel tube using a single pass overlay. Each corrosion specimen was machined from the overlay welded tube, so that all of the tube base metal was removed.

Corrosion specimen dimensions were 10x10x2mm. All specimens were measured and cleaned in ethanol prior to corrosion testing. The corrosion specimens were kept in Al_2O_3 crucibles. The furnace was heated to the test temperature at 773 K and 823K. The gas used for corrosion testing is representative of a typical low NO_x combustion environment, with sulfidizing gas composition of 960ppm H_2S -6.6% CO -2.5% H_2 -13.4% CO_2 -71% N_2 . In this study, the corrosion tests were performed for 200 hours at 773 K and 823K respectively.

After corrosion testing, the specimens were immersed in 18% NaOH -3% KMnO_4 solution and then de-scaled using 10% ammonium citrate aqueous solution. The specimens were weighed before and after the exposure period, and each specimen was measured to assess the corrosion rate.

2.3. Mechanical Testing for Aging Specimens

Overlay welded tubes were kept in a heat furnace as aging specimens. Each aging specimen was maintained at from 773K to 1023K for 1,000h. All of the 1.25%Cr-0.5%Mo steel tube base metal was removed.

3. Results and Discussion

3.1. Sample Panel in Field Testing

Figure3 shows the appearance of waterwall tubes damaged by fireside corrosion in a Japanese corner-firing supercritical boiler. In the case of fireside corrosion, serious waterwall

Fig. 3 Appearance of waterwall tubes damaged by fireside corrosion

metal wastage occurred on the furnace side.

In addition to fireside corrosion, there have also been reported problems with circumferential cracking, mostly limited to supercritical boilers. Figure 4 shows the appearance and cross section of a tube damaged by circumferential cracking. As indicated in the figure, there appear to be environmental aspects to this cracking, as the cracks are filled with oxides and tend to exhibit a sulfur spine down the center¹⁰⁾.

Fig. 4 Cross section of a tube damaged by circumferential cracking
(a) Optical photograph of longitudinal cross section
(b) Magnification of portion A
(c) EPM Analysis of sulfur enrichment of the crack

Figure 5 shows the appearance of the sample panel after one-year of exposure. The alloy 622 overlay welded sample panel was inspected and found to have no visible signs of corrosion or cracking. The weld bead ripples and spatter of overlay welding could be clearly found on the panel.

After the dye penetration test, as shown in Fig. 6, the appearance of the sample panel after one year of exposure exhibits no indications of cracking. In addition, the thickness of the overlay welded tubes after one year of service was measured using an ultrasonic test (UT) device, with 42 UT measuring points on the sample panel. All of the data for overlay tube thickness were within the extent of accuracy measured by the UT device.

Based on the foregoing results, the alloy 622 overlay weld panel showed no evidence of corrosion after one year of service. All of the field test results clearly demonstrate that alloy 622 has excellent resistance against fireside corrosion and circumferential cracking in supercritical boilers.

Fig. 5 Appearance of installed sample panel after one-year exposure

Fig. 6 Appearance of installed sample panel after one-year exposure after penetration test

3.2. Corrosion Testing

The corrosion rate calculated from weight change data for weld overlays exposed for 200 hours in the typical low NO_x combustion environment are shown in Fig. 7. These results show that the corrosion resistance of alloy 622 was better than that of type 309. The corrosion rate of 1.25%Cr-0.5Mo steel at 773K was 0.48mm/year, and the corrosion rate of alloy 622 weld overlay at 773K was 0.04 mm/year as shown in Fig. 7(a).

Fig. 7 Corrosion rates resulting from corrosion testing in a sulfidizing atmosphere

The corrosion rate of alloy 622 at 773K is thus about 10 times lower than that of 1.25%Cr low alloy steel tube material.

The corrosion rate at 923K is also shown in Fig. 7(b). The corrosion rate of alloy 622 weld overlay at 923K was 0.05

mm/year and it shows that alloy 622 weld metal has good corrosion resistance at elevated temperature.

From these results, in such high sulfidizing gas, alloy 622 exhibits excellent sulfidation resistance.

3.3. Mechanical Testing for Aging Specimens

The Figure 8 shows the hardness of alloy 622 overlay weld metal as a function of aging temperature for 1,000 hours. In the aging temperature range of 723K to 873K, the hardness is stable and approximately 200HV to 220HV. For aging temperature at 650°C and over, the hardness of alloy 622 increased, with the hardness of specimens aged at 973K becoming approximately 380HV.

Fig. 8 Hardness of alloy 622 as function of aging temperature (1,000hr)

Fig. 9 Tensile strength and elongation of Alloy 622 as function of aging temperature (1,000hr)

Figure 9 shows the tensile strength and elongation at room temperature for alloy 622 overlay weld metal as a function of aging temperature for 1,000 hours. For the samples non-aged and aged at 773K and 823K, the tensile strength remains the same. However, for aging temperatures of 873K and over, the tensile

strength increases gradually with aging temperature.

Aging specimen elongation decreases rapidly for aging temperatures of 873K and above. At 923K and 973K, the elongation is seen to be under 10%. It has been reported that aging at temperatures in the range of 866 to 1033K caused a decrease in the toughness and Charpy impact energy of alloy 622¹¹⁾. The results of tensile testing in the current study are well supported by this report. When alloy 622 is exposed to the temperature on the range of 873K and above for a long time, alloy 622 welds are known to form potentially detrimental tetrahedrally close packed (TCP) phases upon solidification. The impact energy loss by the aged material correlated well with the amount of TCP phase present in the aged microstructure. It is thus reported that these precipitates on alloy 622 aged at elevated temperatures can adversely affect the material properties and reduce its mechanical toughness¹¹⁾.

Temperature estimation of a bare tube and an overlay welded tube having 4mm of overlay thickness was conducted as shown in Fig. 10. In both cases, the heat flux from the furnace side is assumed to be the same. However, since the thermal conductivity of alloy 622 is lower than that of low-alloy steel, the temperature of the overlay welded tubes tends to be higher. The maximum surface temperature of the 4mm thickness of overlay weld metal is estimated to be approximately 867K(594°C). As shown in Fig. 9, the tensile strength and elongation data in the current study was tested for 1,000hr at high temperatures. However, the alloy 622 material properties with respect to aging over longer service periods have not yet been investigated. Material degradation in an actual boiler environment should be considered through continued sample panel field testing.

Fig. 10 Metal temperature estimation comparing bare tube and overlay welded tube

4. Conclusions

Based on the results of this one year field test study, it can be concluded that:

- (1) Alloy 622 overlay welded tubes indicate excellent resistance against fireside corrosion and circumferential cracking in a

representative Japanese supercritical boiler.

- (2) It was found that the corrosion rate of alloy 622 is one tenth (1/10) that of 1.25%Cr bare tube in corrosion testing. Alloy 622 overlay weld metal also demonstrates good corrosion resistance to H₂S gases in a high temperature, low NO_x environment.
- (3) The maximum surface temperature of 4mm thickness overlay weld metal was estimated to be approximately 858K. Material degradation in an actual boiler environment should be considered through continued sample panel field testing.

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