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Technical Note

Advanced Coatings on Furnace Wall Tubes

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Nickel-based self-fluxing alloy coating extends the service life of furnace wall tubes at waste incineration plants due to its excellent corrosion resistance and heat resistance. Fusing of such coatings by induction heating offers improved efficiency and reliability of products. Compared with conventional plasma, flame, and high-velocity oxy-fuel spraying thermal-sprayed coatings, induction-fused coatings provide a far stronger metallurgical bond at the interface, while minimizing the inclusion of pores. In addition, the tubes are less costly than those with welded coatings, and the process reduces the distortion of the products, facilitating easier final assembly. A successful experimental application of 11 units in a waste incinerator revealed virtually no corrosion on the exposed surfaces, and showed an improved water heating efficiency over that of the original tubes. Such units are now being employed in four incinerators in Taiwan, and continuing tests are showing great promise.

Keywords boiler plants, corrosion, heat treatment of coatings

1. Introduction

The conditions in the boilers of power generators at waste incineration plants contribute to severe corrosion of furnace wall tubes. This corrosion results in the cost and inconvenience of replacing boiler tubes as often as every 3 or 4 years (Ref 1). Even with treatments such as conventional plasma, flame, and high-velocity oxy-fuel spraying thermal-sprayed coatings, their mechanical bonds allow corrosive substances in combustion gases and ash to reach and corrode the base metal (Ref 2). This results in progressive disintegration of the tubes. In this research, the properties of induction-heated nickel-based self-fluxing alloy coatings were investigated in terms of microstructure, hardness, and corrosion resistance. An experimental application of one of these revealed virtually no corrosion on the exposed surfaces. A further application in an industrial setting is also showing promising results. Further, the induction fusing process is shown to provide stable quality, high productivity, and long service life.

2. Materials and Experimental Procedures

In the first experiment, the performance of nickel-based self-fluxing alloy sprayed coating on furnace wall tubes was investigated. The chemical compositions of the spraying powders are shown in Table 1. The base-metal specimens, carbon steel plates (ASTM: A36), in the test were 10 mm in width, 10 mm in length, and 5 mm in thickness. The specimens were blasted with steel grit and sprayed with nickel-based self-fluxing alloy using a Wall Colmonoy Spraywelder, J3™ (Madison Heights, Michigan, USA) flame spray system. Then the coated specimens were treated by induction heating to fuse the coatings. A stationary induction heating method, using a DHF HI-HEATER 4025 (Kawasaki, Japan) at 25 kW, was used for the heating operation and the heating temperature was controlled by on-off power regulation. Table 2 shows the flame spraying conditions and the conditions of induction heating. The properties of fused coatings were investigated in terms of microstructure, hardness, and corrosion resistance. High-Cr cast iron, SUS 304, and SUS 309 (chemical compositions shown in Table 1) were used as corrosion resistance specimens. The specimens were tested in either 50 vol% hydrochloric acid solution or 50 vol% sulfuric acid solution at 313 K for 72 h, and were then measured for weight loss.

In the second experiment, the aim was to research the experimental application at the furnace wall tubes in a waste incineration plant. The furnace wall tubes were set at position A, 20 m from the floor as shown in Fig. 1. Carbon steel tubes of 76.2 mm diameter × 6 mm thick × 990 mm long (ASME: SA192) were used as a base metal. The chemical composition of SA192 is shown in Table 3. They were assembled and welded as a unit of the furnace wall tubes as shown in Fig. 2. The unit was blasted by steel grit and was sprayed with powder A (shown in Table 1) using a J3 gun. The chemical compositions of the spraying powder are shown in Table 3, and the spraying conditions are shown in Table 4. Then the unit was heated by induction heating to fuse the coating. The conditions of the induction heating are shown in Table 4.

A further experiment was then conducted using a larger number of units, again in an industrial setting. Eleven units of furnace wall tubes were produced with the specifications shown in Fig. 3, and were sprayed with a nickel-based self-fluxing alloy under the conditions shown in Table 5. After flame spraying, they were treated by

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Table 1 Chemical compositions of powder and substrate

	Chemical compositions, wt.%					
	Ni	Cr	Si	B	Mo	W
Powder						
A	Balance	15	4.3	3.1	2.5	
B	Balance	18	4	3.5	16	
C	Balance	9.8	2.8	2	1.6	32.9
D	Balance	37.1	3.4	3.6	3	
E	Balance	15	4	3.2		
	Ni	Cr	Si	B	Mo	Fe
Substrate						
Cr cast		24.8				Balance
SUS 304	8.7	18.4	0.4			Balance
SUS 309	13.9	22.2	0.6			Balance

Table 2 Flame spraying and induction heating conditions (first experiment)

Flame spraying conditions		
Powders		A, B, C, D, E
Operation gas	O_2	0.2 MPa, 45 L/min
	C_2H_2	0.1 MPa, 28 L/min
Powder feed rate		70-80 g/min
Spraying distance		205 mm
Coating thickness		1.2-1.5 mm
Induction heating conditions		
Powders		A, B, C, D, E
Frequency		8-10 kHz
Input power		10-20 kW
Temperature		1273-1323 K
Holding time		30-40 s

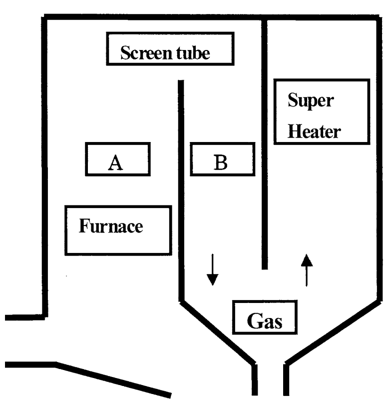


Fig. 1 Schematic diagram of furnace

Table 3 Chemical compositions of powder and substrate (wt%)

Powder	Ni	Cr	Si	B	Mo
Powder A	Balance	15	4.3	3.1	2.5
Substrate	Fe	C	Si	B	Mn
SA192	Balance	0.1	0.2		0.4

induction heating with a dynamic method (stationary units were treated by an induction coil passing along their lengths) under the conditions shown in Table 5. Figure 4

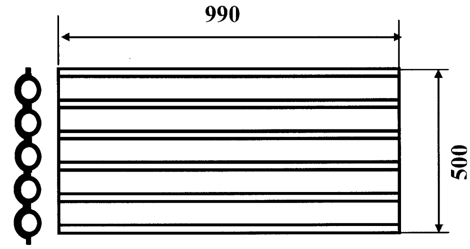


Fig. 2 Dimensions of test unit

Table 4 Flame spraying and induction heating conditions (second experiment)

Flame spraying conditions		
Operation gas	O_2	0.22 MPa, 45 L/min
	C_2H_2	0.10 MPa, 28 L/min
Powder feed rate		76 g/min
Spraying distance		205 mm
Coating thickness		1.5 mm
Induction heating conditions		
Frequency		2 kHz
Input power		145 kW
Temperature		1273-1323 K
Coil moving speed		1.5 mm/s

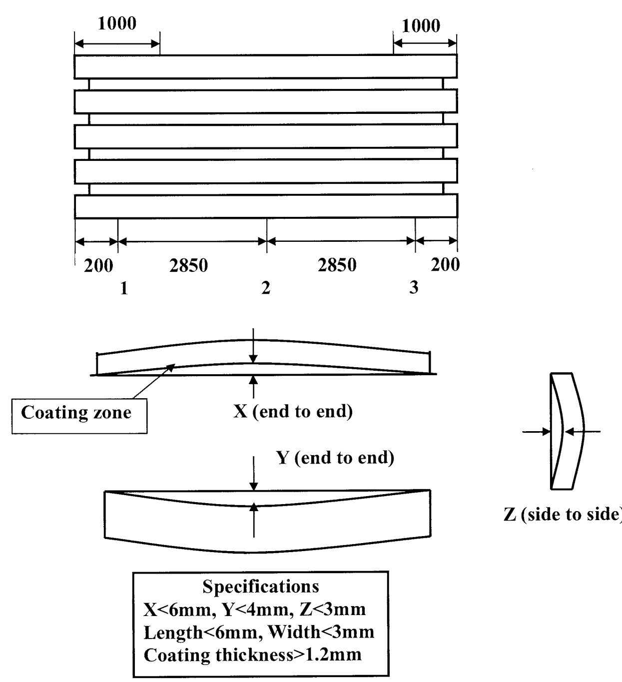


Fig. 3 Dimensions of furnace wall tubes

shows the appearance during induction heating. The surface temperature during induction heating was measured with a pyrometer, and was maintained between 1273 and 1323 K (Ref 3). The units were installed 20 m from the floor on the front wall at a waste incineration plant (capacity: 450 ton/day, max temperature: 1323 K, waste

Table 5 Flame spraying and induction heating conditions (third experiment)

Flame spraying conditions		
Operation gas	O_2	0.22 MPa, 45 L/min
	C_2H_2	0.10 MPa, 28 L/min
Powder feed rate		76 g/min
Spraying distance		205 mm
Coating thickness		1.2-1.5 mm
Induction heating conditions		
Frequency		2 kHz
Input power		150 kW
Temperature		1273-1323 K
Coil moving speed		1.5 mm/s

Fig. 4 Furnace tube unit undergoing induction heating

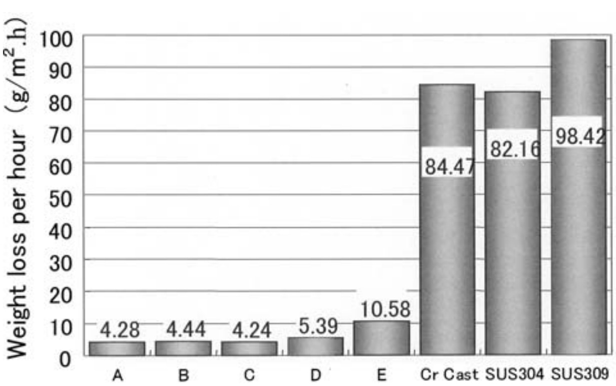


Fig. 5 Corrosion test results of 50 vol% HCl treatment

type: domestic garbage) replacing a portion of the original mortar coated tubes.

3. Results and Discussion

3.1 Corrosion Resistance of Sprayed Coatings

Figures 5 and 6 show the results of corrosion resistance with the sprayed coatings in 50 vol% hydrochloric acid

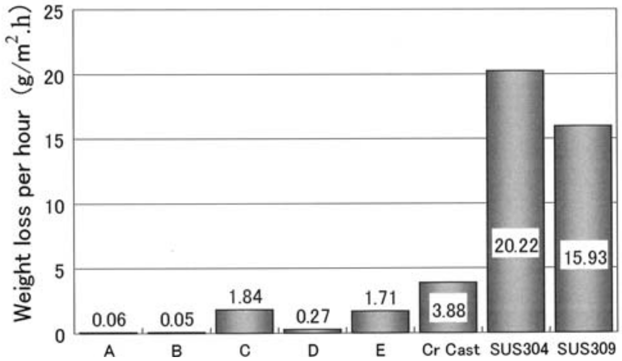


Fig. 6 Corrosion test results of 50 vol% H_2SO_4 treatment

solution and sulfuric acid solution at 313 K. Nickel-based self-fluxing alloy coatings were found to be less corroded than the high-chromium cast iron, SUS 304, and SUS 309 substrates, demonstrating that they can provide stable corrosion resistance coatings.

Powder A proved to be more economical and easier to apply than powders B, C, D, and E (Table 1), since its ingredients are less expensive, and the operation temperature required is lower, as shown in Table 6. Figure 7 shows the resulting coating microstructure to contain fine chromium boride particles throughout, and to have a hardness measurement of 810 Hv.

3.2 Experimental Application of Furnace Wall Tubes

Table 7 shows the burning conditions of the waste incinerator plant. Figure 8 shows the appearance of furnace wall tubes during experimental application testing after 24 months of use. The sprayed coating surfaces were found to show metal brightness and were free of corrosion. However, the carbon steel without the sprayed coating was found to contain oxides and was severely corroded. Figure 9 shows a cross section of the furnace wall tubes at the intersection of the treated and untreated areas. Table 8 shows the result of thickness measurements. The thickness of carbon steel without the sprayed coating was found to decrease as much as 1 mm.

Figure 10 shows the x-ray diffraction analysis result of the oxide remaining on the surface of the carbon wall tubes (Ref 4). $FeCl_2$ and Fe_2O_3 are found in the scale layer (Ref 5). During this sulfide reaction, chlorine gas is released as shown in Eq 1. The chlorine concentrates near the metal surface and reacts to form iron chloride as

Table 6 Relative costs and operation temperatures of induction-fused coatings

Powder	A	B	C	D	E
Relative cost	1	2	2	2.1	1.3
Operation temperature (K)	1313	1453	1373	1413	1313

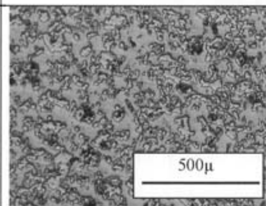
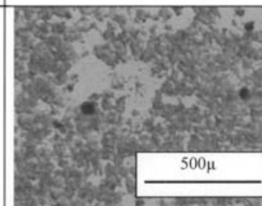
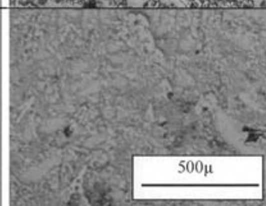
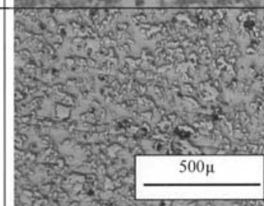
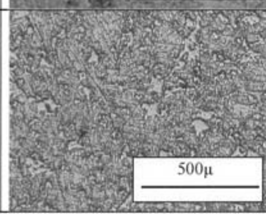
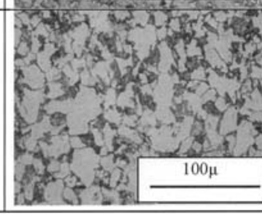
Powder	Average Hardness (Hv)	Microstructure	Powder	Average Hardness (Hv)	Microstructure
A	810		B	680	
C	970		D	875	
E	820		Base-metal Specimen	187	

Fig. 7 Hardness and microstructure of induction-fused coatings

Table 7 Incinerator conditions

Incinerator conditions	
Waste type	**Domestic garbage**
Furnace temperature	Max 1323 K
Tube pressure	5.0 MPa
Tube temperature (outer tube surface)	Max 623 K
Tube temperature (inner tube surface)	Max 533 K

Fig. 8 Appearance of furnace wall tubes after 24 months of service

shown in Eq 2. The iron chloride then reacts with oxygen and iron oxide, again releasing chlorine, as shown in Eq 3 and 4:

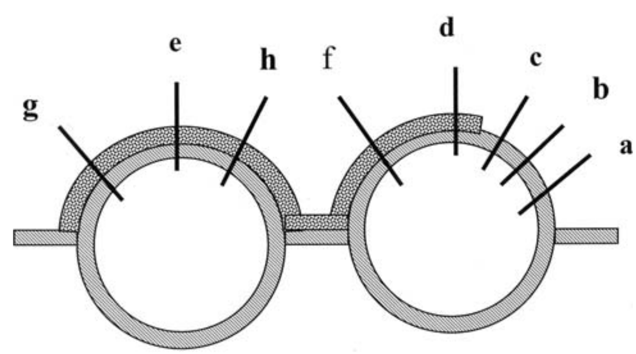


Fig. 9 Cross section of tubes at intersection of treated and untreated areas

$$\begin{aligned}&2\mathrm{Nacl} + \mathrm{SO_2} + \mathrm{O_2} = \mathrm{Na_2SO_4} + \mathrm{Cl_2}\\&2\mathrm{KCl} + \mathrm{SO_2} = \mathrm{K_2SO_4} + \mathrm{Cl_2}\quad \text{(Ash Layer)}\end{aligned} \qquad \text{(Eq 1)}$$

$$\mathrm{Fe} + \mathrm{Cl_2} = \mathrm{FeCl_2}\quad \text{(Metal Surface)} \qquad \text{(Eq 2)}$$

$$2\mathrm{FeCl_2} + 1.5\mathrm{O_2} = \mathrm{Fe_2O_3} + 2\mathrm{Cl_2}\quad \text{(Scale Layer)} \qquad \text{(Eq 3)}$$

$$\mathrm{FeCl_2} + \mathrm{O_2} + \mathrm{Fe_3O_4} = 2\mathrm{Fe_2O_3} + \mathrm{Cl_2}\quad \text{(Scale Layer)} \qquad \text{(Eq 4)}$$

In contrast to the untreated tubes, the thickness of the coated tubes showed a minimal decrease, between 0.0 and 0.2 mm, the microstructure of which is shown in Fig. 11.

Table 8 Thickness of furnace wall tubes after 24 months

	Untreated tubes		Treated tubes	
Thickness, mm	***a*, *b*, *c***	***d*, *e***	***f*, *g***	***h***
Before	5.4	6.9	7.2	7.2
After	4.4	6.9	7.0	7.1
Loss	−1.0	0	−0.2	−0.1

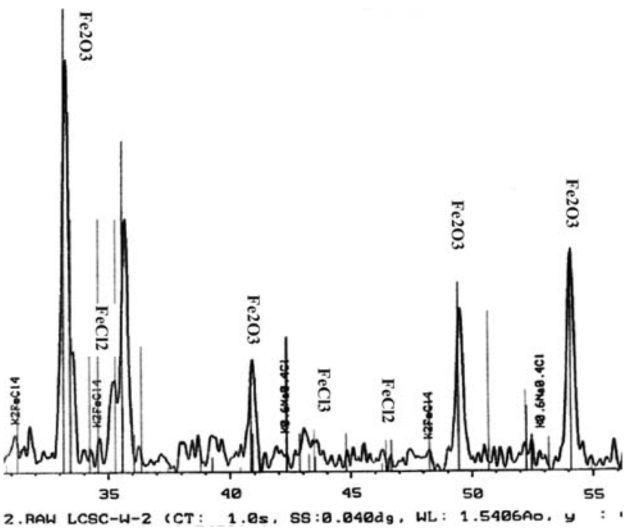


Fig. 10 Electron probe micro analyzer analysis of untreated tubes after service

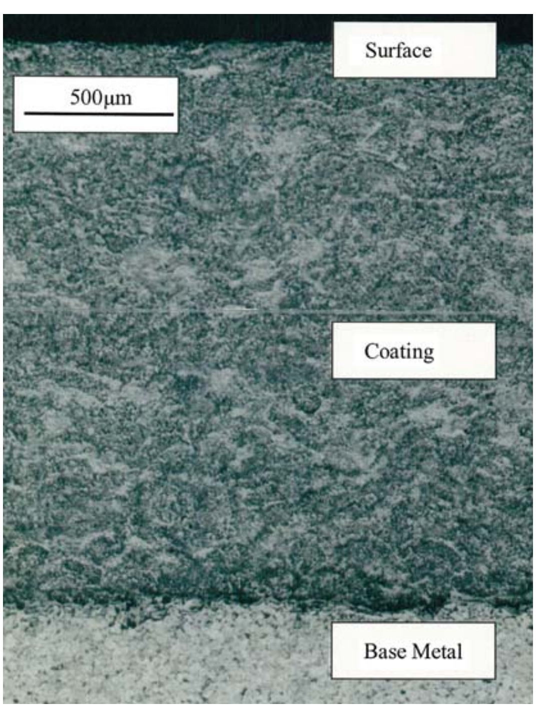


Fig. 11 Microstructure of treated tubes after service

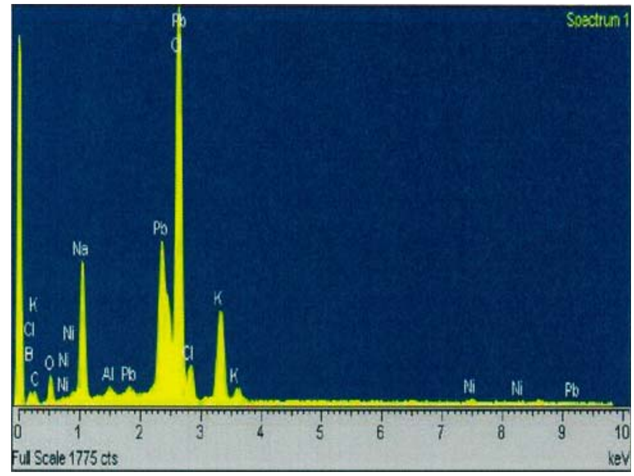


Fig. 12 Energy dispersive x-ray analysis of treated tubes after service

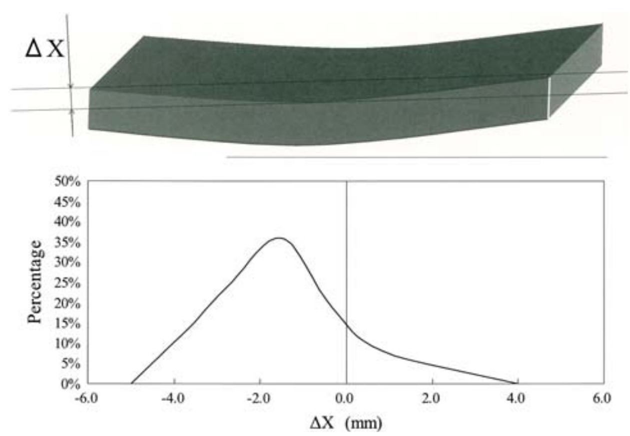


Fig. 13 Distortions of the units after induction heating (ΔX)

Analysis of the surface of the coated tubes showed no metal loss of the sprayed coating (Ref 6). Figure 12 shows the energy dispersive x-ray analysis results of the ash remaining on the surface of treated wall tubes. Negligible amounts of nickel and chromium were found, evidence that oxidation was not occurring.

3.3 Applications on Furnace Wall Tubes

Compared with gas or welded treatment, the induction heating method both reduces the process time and accurately maintains the optimum operating temperature, providing a product with minimum distortion. Figures 13 and 14 describe the lengthwise vertical (ΔX) and horizontal (ΔY) distortions, with a maximum of 4 mm for ΔX, and a maximum of 3 mm for ΔY after induction heating. Production of wall tubes by this method reduces the distortion of the products, facilitating easier final assembly.

Figure 15 represents the test units (Nos. 1-11) set 20 m from the incinerator floor, between the mortar-covered lower units and the untreated upper units (Nos. 21-31).

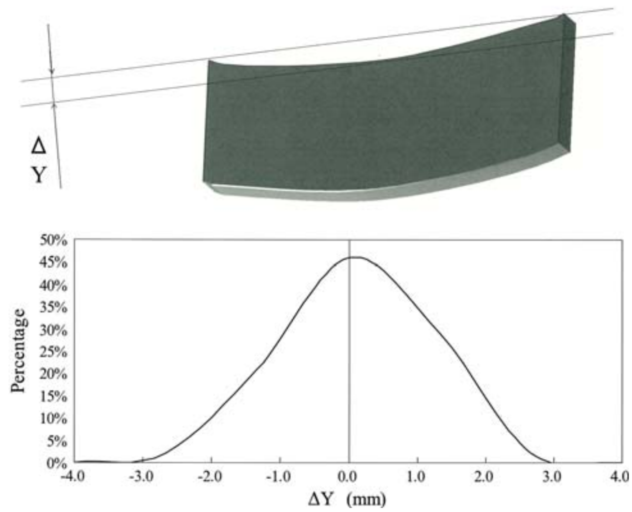


Fig. 14 Distortions of the units after induction heating (Δ*Y*)

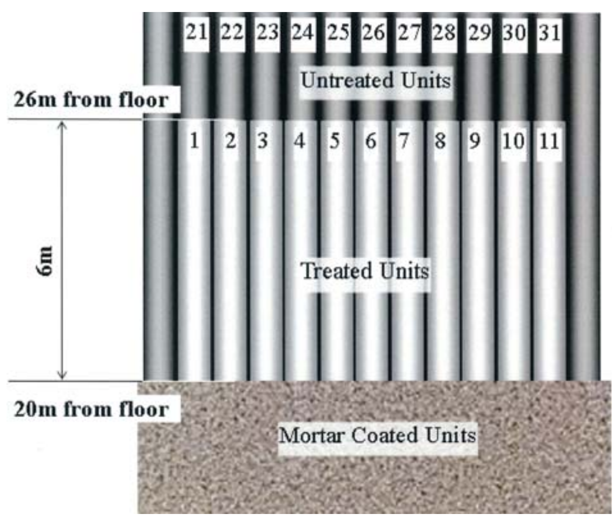


Fig. 15 Position of test units in furnace front wall (11 units)

Test units Nos. 1-3 and 21-31 were installed in April 2003, while units Nos. 4-11 were installed 1 year later. Under normal operating conditions, the wall thickness of the untreated tubes in the upper part of the combustion room decreased at the rate of about 1.5 mm per year, resulting in the need for replacement after 3 years as shown in Table 9. The thickness of the treated tubes shows no decrease after 3 years of normal use. The treated tubes after service contrast clearly with the untreated tubes, and were continuing to perform well three and a half years after installation.

Notably, with the introduction of the treated tubes to only a portion of the furnace wall (about 50 m^2 of the original 230 m^2 mortar coated units), the furnace operating temperature could be dropped from 1263 to 1193 K, with a corresponding drop in the operating temperature of the super-heater from 873 to 793 K, with no loss in the performance of the facility. This can be expected to result in the additional benefit of a longer operating life for the entire incinerator.

Table 9 Thickness of furnace wall tubes after service (mm)

	Unit numbers			
Inspection year	**21-23 Untreated units**	**1-3 Treated units**	**24-31 Untreated units**	**4-11 Treated units**
April 2003	6.7-6.9	8.2-8.4	6.8-6.9	
October 2003	5.6-5.9	8.2-8.3	5.9-6.3	
April 2004	5.0-5.4	8.1-8.4	5.2-5.5	8.7-9.0
October 2004	3.9-4.2	8.2-8.4	4.0-4.3	8.7-9.1
April 2005	2.9-3.2	8.2-8.3	3.2-3.6	8.7-9.0
October 2005	2.1-2.3	8.1-8.4	2.2-2.5	8.7-9.0
April 2006	Replaced	8.1-8.4	Replaced	8.6-8.9
October 2006	-	8.1-8.3	-	8.7-9.1

4. Conclusions

The results obtained are:

1. Nickel-based self-fluxing alloy coating extends the service life of furnace wall tubes at waste incineration plants due to its excellent corrosion resistance and heat resistance. IH treatment further enhances the qualities of such coatings due to the resulting metallurgical bond created.
2. The IHT process reduces the distortion of the products, facilitating easier final assembly.
3. No decrease in the thickness of treated furnace wall tubes was found after 24 months of use.
4. Lower operating temperatures in incinerators using the new product can be expected to result in a longer operating life.

Further testing is being conducted and units are being installed in five incinerators in Taiwan. In addition, we are looking into wider applications of this technology, such as in incinerator super-heater pipes, and in heat-exchanger pipes used in steel making processes.

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