Extended Life of Boiler by Inconel Cladding

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Abstract:

The boiler is a facility that recovers waste heat of CO gas generated in the converter furnace and is installed in the upper part of the converter furnace. The converter furnace processes molten iron in batches per ladle. Therefore, the passage of exhaust gas and temperature rise/fall are also repeated in batches. For this reason, the deterioration of the boiler was mainly by wear due to dust and cracks due to thermal stress. However, since low-grade scrap was charged in the converter to reduce the mixing ratio of hot metal after 2006, wall thinning of tube due to corrosion became noticeable. Under this situation, as a countermeasure against corrosion, Inconel, which is a Ni-based alloy, is welded on the surface of boiler tubes. As a result, the life span of the boiler was extended from 5 to 10 years.

1. Introduction

The condition of converter furnace boilers deteriorates as a result of thermal cracks caused by the temperature amplitude due to the difference in thermal loading in the blowing and non-blowing periods, and wear and wall thinning of tubes caused by dust generated during blowing. If a water leak occurs due to a thermal crack or wall thinning, the equipment is stopped and repaired because of the heightened risk of a steam explosion in case of contact between the water and molten steel. Depending on the position and severity of the water leak, repairs sometimes take around 48 hours, and a long-term equipment shutdown becomes necessary. If deterioration has progressed to a point where recovery is not possible by repair, the equipment must be replaced, and in such cases, a shutdown of 20 days or more is required, depending on the boiler. Since an even longer equipment shutdown is necessary, boiler maintenance control and life extension are critical issues. At JFE Steel West Japan Works Fukuyama No. 3 Steelmaking Shop, the life of boilers was determined by wear and tube wall thinning due to dust cut. As a conventional countermeasure for wear, thermal spraying of a Ni-based self-fluxing alloy was performed. This made it possible to extend the life of the lower hood boiler, which is subjected to the highest thermal load among boilers, from 3 years to 5 years in comparison with only the conventional header. The main specification of the lower hood boiler is shown in **Table 1**. However, from the second half of 2006, the thickness reduction rate of water tubes where thermal spraying was not performed increased rapidly, from 0.04 mm/month to 0.22 mm/month, and water leaks occurred frequently. **Figure 1** shows the trend of thickness reduction. The cause of this abnormal thickness reduction of the water tubes was investigated, and an Inconel alloy cladding was applied by welding on the tube surface as a countermeasure.

Table 1 Specification of lower hood boiler

Size	Cooling method	Specification of tube	Evaporation
ϕ5.8 m× *H*2.3 m	Membrane water tube panel	STB410S ϕ38.1 mm×*t*4.0 mm	15.6 t/h

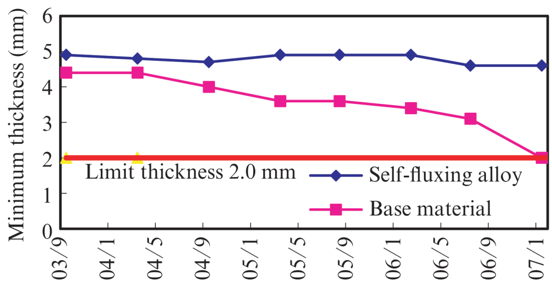

Fig. 1 Trend of thickness reduction

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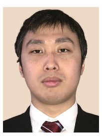

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2. Cause of Boiler Thickness Reduction

2.1 Condition of Water Tube Thickness Reduction

2.1.1 Microstructural images of water tubes

Microstructural observation of lower hood boiler water tubes with severe thickness reduction was carried out. An observation result is shown in **Fig. 2**. Because uneven erosion in one-crystal grain units was observed, we concluded that this was not wear due to dust cut, etc., and there was a high possibility of high temperature oxidation, corrosion, etc.

2.1.2 Analysis of dust

Next, an investigation was carried out to determine whether the dust in the exhaust gas contained substances that cause corrosion. **Table 2** shows the investigation results, which revealed that the dust had a high content of the element Cl. Based on this, we investigated the source of the element Cl, which has a correlation with corrosion.

2.2 Mechanism of Water Tube Thickness Reduction

2.2.1 Mechanism of water tube thickness reduction

At the converter furnace, scrap is charged into the furnace to reduce hot metal use. To further reduce the hot metal mixing ratio, use of low-grade scrap was increased from the second half of 2006, when the thickness reduction ratio increased. Since low-grade scrap has a high content of impurities, including Cl, it can be inferred that this was the source of the element Cl.

When hot metal is charged after charging scrap, impurities and paint that contain Cl form HCl gas. Air also enters the flue at this time, and the following reaction occurs between the HCl gas and O_2 in the air, with the Fe_2O_3 in the oxide film on the water tubes as a catalyst.

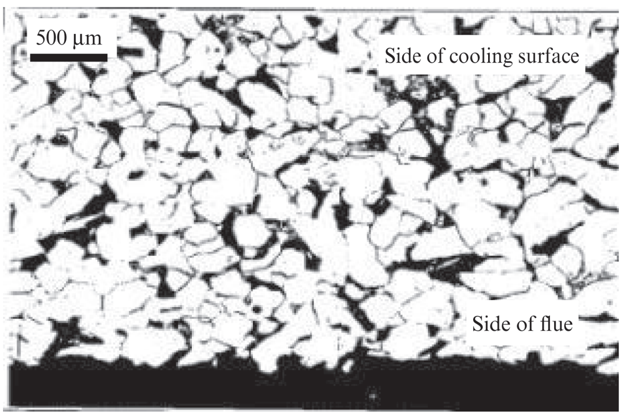

Fig. 2　Enlarged microstructure of tube

Table 2　Dust component

Component	C	Si	Fe	Zn	K	Cl
Content(%)	0.37	0.46	29.4	24.0	13.1	8.91

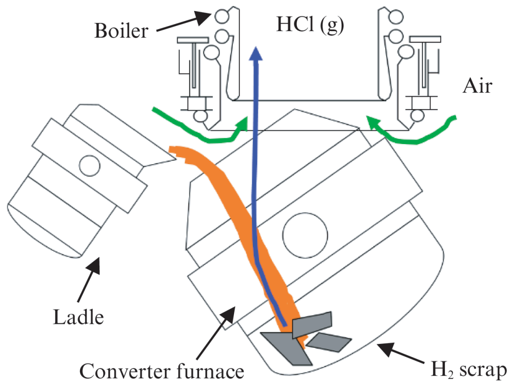

Fig. 3　Schematic diagram of corrosion reaction

$$4HCl + O_2(g) = 2Cl_2(g) + H_2O \quad \text{(1)}$$

Fe_2O_3 catalyst, reaction temperature 250 °C to 300 °C

The Fe_2O_3 oxide film is destroyed by the reaction shown in Eq. (1), exposing the base metal. In addition, because the oxidative power of Cl_2 is larger than that of O_2, the following reactions occur before a new oxide film can form on the surface of the base metal.

$$Fe + Cl_2 \Leftrightarrow FeCl_2 \quad \text{(2)}$$

Reaction temperature 25 °C to 677 °C

$$2FeCl_2(s) + Cl_2(g) \rightarrow (FeCl_3)_2(g) \quad \text{(3)}$$

It is thought that the base metal forms $(FeCl_3)_2$ by the mechanism described above, and corrosion occurs when this compound is vaporized. Moreover, the boiling point of $FeCl_3$ is approximately 300 °C, and the measured temperature of the boiler fin part was approximately 250 °C to 350 °C, which also supports the occurrence of corrosion. **Figure 3** shows a schematic diagram of the corrosion reaction.

2.2.2 EPMA analysis of water tubes

Next, **Fig. 4** shows the result of an EPMA analysis which was performed to investigate the cause of corrosion. This analysis showed that the boundary surface between the base metal and scale contained a large amount of the element Cl, which also supports the occurrence of corrosion.

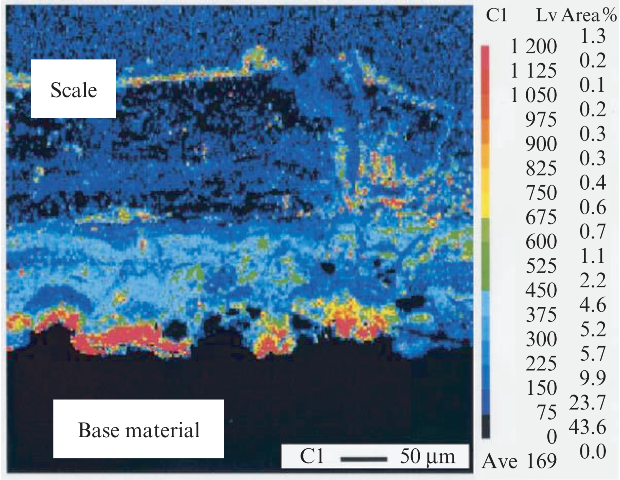

Fig. 4 Cl concentration analysis of tube

3. Countermeasures for Boiler Thickness Reduction

3.1 Offline Test of Boiler Flue Lining Material

3.1.1 Anticorrosion test

Use of a lining in the boiler flue to prevent the above-mentioned high temperature corrosion was studied. As lining materials, thermal spraying of a corrosion-resistant self-fluxing alloy ($SFNi_2$) and cladding with a Ni-based Inconel alloy were studied. The components of the base metal (STB410), the self-fluxing alloy and the Inconel alloy are shown in **Table 3**. As the lining materials are Ni-based and have high contents of Cr, both materials display excellent corrosion resistance.

An offline corrosion test was conducted with the cooperation of Fujico Corporation. The specimens were the base metal (ϕ38.1, t4.0), the self-fluxing alloy and the Inconel alloy. The self-fluxing alloy and Inconel alloy were bonded to the base metal by thermal spraying and welding on the surface, respectively. These specimens were placed in an electric kiln, and the test was performed under the conditions shown in **Table 4**. **Figures 5**, **6** and **7** show photographs of the respective specimens after the test. As the test results, although the base metal showed a maximum 2.0 mm thickness reduction due to corrosion, no corrosion was observed in the self-fluxing alloy and Inconel alloy. From this, it can be concluded that the corrosion resistance of the self-fluxing alloy and Inconel ally is equal or superior to that of the base metal.

Table 3 Component of lining

	Ni	Cr	Si	C	Fe
Base material	—	—	—	0.32	99
Self-fluxing alloy	69 ~ 83	9 ~ 11	2 ~ 3.5	<0.5	<4
Inconel alloy	57 ~ 63	20 ~ 23	<0.5	0.1	<5

Table 4 Condition of corrosion test

Surrounding condition			Corrosion condition		
Gas	Gas temperature	Specimen temperature	O_2 concentration	Surface coating	Heating time
CO	300°C	1 000°C	4%	50%HCl +NaCl	96 hr

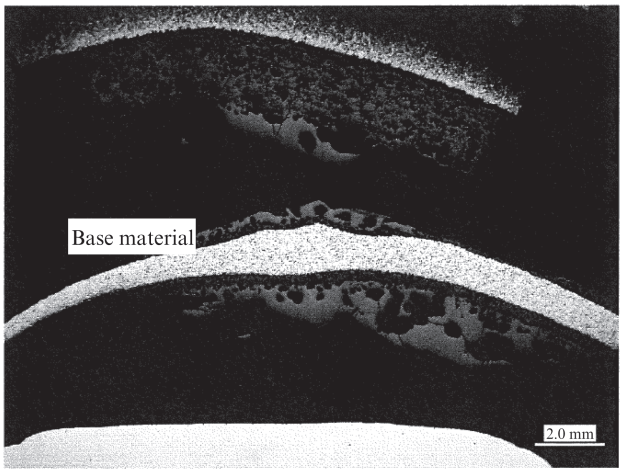

Fig. 5 Result of corrosion test (base material)

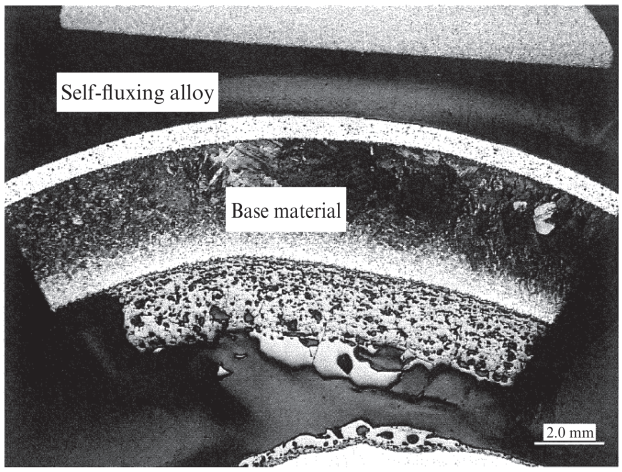

Fig. 6 Result of corrosion test (Self-fluxing alloy)

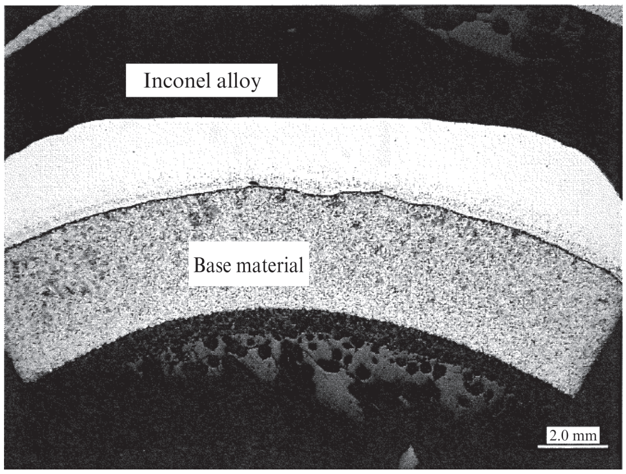

Fig. 7 Result of corrosion test (Inconel)

Table 5 Result of wear test[1)]

Material	Volume loss(cm^3)
Inconel	2.58×10^{-3}
Self-fluxing alloy	3.77×10^{-3}

3.1.2 Evaluation of wear resistance

It has been reported that the wear resistance of the Inconel alloy is approximately 1.5 times superior to that of the self-fluxing alloy[1)]. **Table 5** shows the results of the wear test in that report.

3.1.3 Crack resistance test

Crack resistance was also compared by conducting a test of the Inconel alloy, self-fluxing alloy and base metal[1)]. The test was carried out by repeatedly heating and quenching the respective materials and measuring the number of cycles until cracking occurred. As a result, in comparison with the self-fluxing alloy and the base metal, the Inconel alloy displayed the highest crack resistance. **Table 6** shows the test results. The above-mentioned results also revealed that cladding with the Inconel alloy is the most effective countermeasure for corrosion, wear and cracks, which are the deterioration modes of boilers.

3.1.4 Trial introduction of Inconel alloy

Based on the test results presented above, the Inconel alloy was introduced in actual equipment on a trial basis. The equipment where it was introduced was not a converter furnace boiler, but the OG skirt of ladle desiliconizing equipment, which is exposed to high thermal loads by injection. Since the OG skirt also has a membrane panel structure like that of the converter furnace boiler, the deterioration problem is similar. Cladding with the Inconel alloy was limited to the bottom of the OG skirt, where the thermal loads are particularly high. However, as shown in **Fig. 8**, many cracks originating from the level difference between the cladding part and non-cladding part were observed, indicating that good surface quality after cladding and elimination of stress concentrations at discontinuities are necessary for life extension.

Table 6 Result of crack test

Materials	Test cycle						
	1	100	200	300	400	1 000	5 000
Inconel alloy	○	○	○	○	○	○	○
Self-fluxing alloy	○	○	○	○	×		
Base material	○	○	○	○	×		

○ No crack × Crack

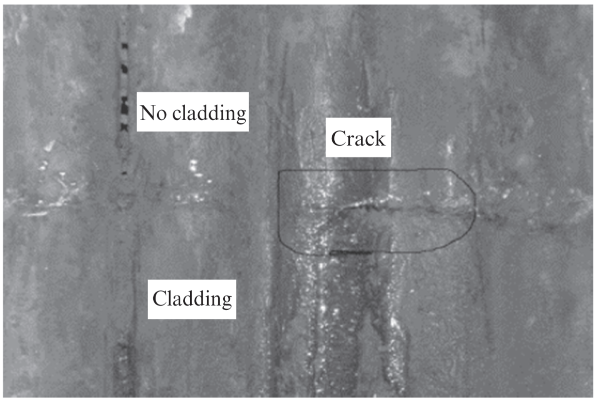

Fig. 8 Trial of inconel (De-Si system)

Fig. 9 Properties of surface after cladding

Fig. 10 Properties of surface after smoothing

3.1.5 Surface quality of Inconel alloy

The actual equipment test revealed that stress concentrates in the bead overlap area, and this shortens cracking life. Therefore, flat plate specimens with two types of Inconel alloy cladding having different surface qualities were prepared, and a thermal shock test was conducted[1)]. The results showed that life extension is possible by performing conditioning to smooth the surface. Based on this, when the Inconel alloy was introduced in the actual equipment, smoothing was performed with a grinder after cladding with the Inconel alloy. **Figure 9** shows the surface quality after cladding but before smoothing, and **Fig. 10** shows the surface quality after smoothing.

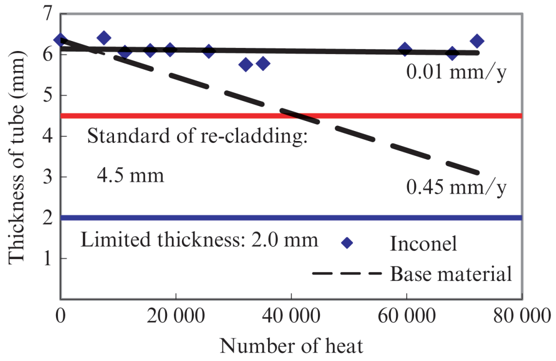

Fig. 11 Trend of inconel reduction

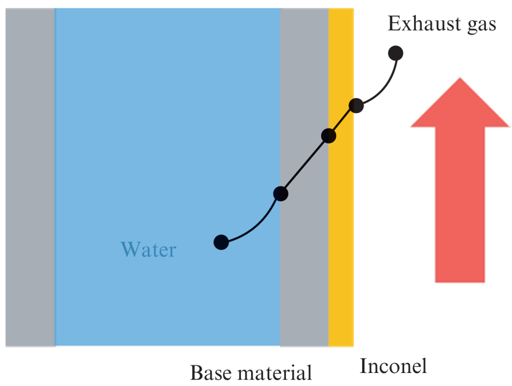

Fig. 13 Schematic diagram of heat conduction

4. Condition of Thickness Reduction and Cracking after Introduction in Actual Equipment

4.1 Condition of Thickness Reduction after Introduction in Actual Equipment

A boiler with Inconel alloy cladding was introduced in 2007. The change in the tube thickness after introduction is shown in **Fig. 11**. The thickness reduction rate after introduction was 0.01 mm/10 000 ch. With the Inconel alloy cladding, the thickness reduction rate was reduced to 1/45 of that of the base metal without cladding.

4.2 Condition of Cracking after Introduction in Actual Equipment

4.2.1 Condition of crack occurrence

The cumulative number of water leaks of the converter furnace boiler after introduction of the Inconel alloy in 2007 is shown in **Fig. 12**. The first water leak originating from a crack occurred in 2013. Similar water leaks occurred frequently from 2016, and in 2017, replacement was necessary. Thus, cladding with the Inconel alloy made it possible to achieve a life extension of the converter furnace boiler from the conventional 5 years to 10 years.

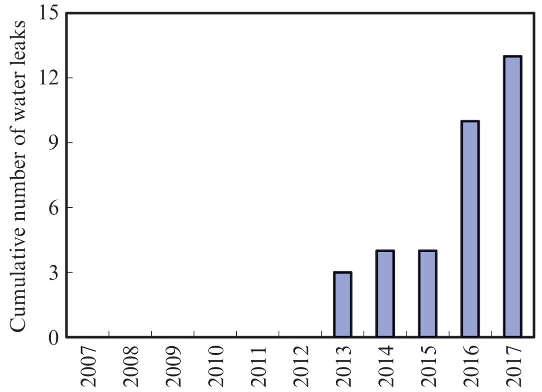

Fig. 12 Cumulative number of water leaks

4.2.2 Change of generated stress depending on Inconel alloy thickness

To realize a further extension of boiler life in the future, it will be necessary to extend cracking life. Because cracking life varies depending on the thickness of the Inconel alloy, the generated stress was calculated with different thicknesses. First, the temperature distribution was calculated assuming the 1D steady heat transfer shown in **Fig. 13**. The following equation was used in these calculations.

$$h_g(T_g - T_i) = \frac{k_i}{L_i}(T_i - T_b) = \frac{k_s}{L_s}(T_b - T_s) = h_w(T_s - T_w) \quad \cdots\cdots (4)$$

where, h_g: heat transfer coefficient of flue gas (W/m^{2}K), T_g: temperature of flue gas (°C), T_i: temperature of Inconel alloy (°C), k_i: heat conduction rate of Inconel alloy (W/mK), L_i: thickness of Inconel alloy (mm), T_b: temperature of boundary surface (°C), k_s: heat conduction rate of base metal (W/mK), L_s: thickness of base metal (mm), T_s: temperature on water-cooling side of base metal (°C), h_w: heat transfer coefficient of boiler water (W/m^{2}K), T_w: temperature of boiler water (°C)

After calculating the temperature distribution with Eq. (4), the thermal stress in the circumferential direction of a boiler tube was calculated by using Eq. (5). In Eq. (5), A and B are the functions shown in Eq. (6) and (7). Considering temperature dependency, Eq. (8) and (9) were used for the linear expansion coefficients of the base metal and the Inconel alloy, respectively. The temperature dependency of Young's modulus of the base metal and the Inconel alloy was considered as shown in Eq. (10) and (11), respectively.

$$\sigma_\theta = \frac{1}{1-\nu}\frac{E}{r^2}\left\{\frac{r^2+a^2}{c^2-a^2}(A+B)+A+B-\alpha T(r)\ r^2\right\} \quad \cdots\cdots (5)$$

$$A = \alpha_s \int_a^b T_s r dr \quad \cdots (6) \qquad B = \alpha_i \int_b^c T_i r dr \quad \cdots (7)$$

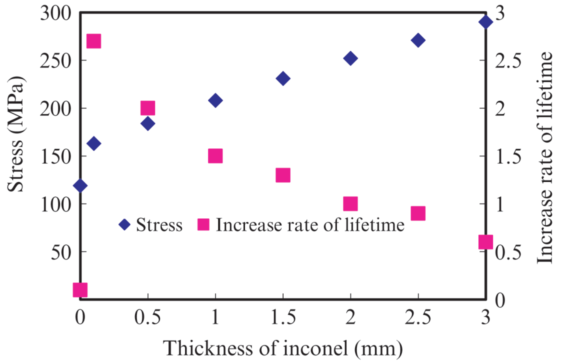

Fig. 14 Relationship between thickness of inconel and stress, and lifetime

$$\alpha_s = \left(4.5\times10^{-3}\times T(r)+11.9\right)\times10^{-6} \quad \text{(8)}$$

$$\alpha_i = \left(4.1\times10^{-3}\times T(r)+12.7\right)\times10^{-6} \quad \text{(9)}$$

$$E_s = \left[203-\left(2\times\{T(r)\}^2+7.9\times T(r)\right)\times10^{-4}\right] \quad \text{(10)}$$

$$E_i = \left[213-\left(0.1\times\{T(r)\}^2-610\times T(r)\right)\times10^{-4}\right] \quad \text{(11)}$$

where, υ: Poisson's ratio, E_s: Young's modulus of base metal (GPa), E_i: Young's modulus of Inconel alloy (GPa), $T(r)$: temperature distribution (°C), r: distance from center of tube (mm), a: inner radius of tube (mm), b: outer radius of base metal, c: outer radius of tube (mm), α_s: linear expansion coefficient of base metal (1/°C), α_i: linear expansion coefficient of Inconel alloy (1/°C)

The calculation results are shown in **Fig. 14**. As the thickness of the Inconel alloy increases, the generated stress also increases. Based on these results, the lifetime increase rate was calculated by calculating the number of cycles to crack initiation from the SN diagram of the Inconel alloy, and then dividing that value by the number of cycles to crack initiation for an Inconel alloy thickness of 2.0 mm (existing specification). The calculated results of the lifetime increase rate are also shown in Fig. 14.

When the thickness of the cladding is decreased, generated stress also decreases. If the thickness is decreased to 0.1 mm, it was found that extended life 2.7 times longer that of the existing 2.0 mm specification can be achieved. On the other hand, in the case of no cladding (Inconel alloy thickness: 0 mm), the strength of the base metal is low, and life is approximately 1/10 of that with the existing specification. Based on this, thinner cladding thicknesses are superior, but since there is also a limit to the cladding thickness reduction that is possible in cladding welding, the cladding thickness is currently set at 1.75±0.25 mm. In the future, it will be necessary to study welding methods for realizing a thinner cladding thickness.

5. Conclusion

Inconel alloy cladding was introduced in the bottom hood boiler of a converter furnace. The following results were obtained.

(1) The equipment life of the converter furnace boiler was extended from the conventional 5 years to 10 years, achieving a long lifetime.
(2) Thickness reduction of the water tubes was reduced to 1/45 compared to that before introduction.
(3) The results confirmed that thinner Inconel alloy cladding thicknesses are effective for further life extension.

Reference

1) Sonoda, A.; Kang, H.; Nagayoshi, H.; Kawamura, T. Characteristics Evaluation of Surface Hardfacing Materials for Reduction in Environmental Loading. tsukuru FUJICO Technical Report. 2007, no. 15, p. 61–67.