Application Study on Thin Wall Ferritic Stainless Steel Tubing for Sea Water Cooled Condensers in Thermal Power Plant

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Aluminum brass tubing which is highly cost-effective and has a high heat transfer property has been widely used for seawater cooled condenser in Japan. However, the tubing suffers from erosion and corrosion on the inner surface in spite of ferric-ion injection and cathodic protection. Ammonia also attacks the outer surface after long years of service. Periodic replacement with new tubing has been performed. Titanium tubing which has high corrosion resistance, has been used in new condensers and for the air removal zone of the condenser. However, its service has been restricted due to higher cost and lower elastic modulus. As a countermeasure, we have developed a high performance ferritic stainless steel tubing called "Super Stainless: FS10" which has excellent corrosion resistance and is highly cost-effective. First, the tubings were used experimentally in our Buzen thermal power station, Unit 2 condenser in 1993, and various investigations have been performed on the extracted tubing and tube sheet every year. Ammonia attack on the outer surface, corrosion and erosion on the inner surface, crevice corrosion between the tube and the tube-sheet, H_2 absorption and degradation of properties was not observed. Based on these results, 1,006 pieces of FS10 were installed in Buzen thermal power station, Unit 1 condenser in 1996. The tubing has been used in seawater without any corrosion problems.

***Keywords** : thin wall ferritic stainless steel tubing, thermal power plant, seawater cooled condenser*

1. Introduction

Highly cost-effective aluminum brass tubing, which has a superior heat transfer property, is widely used for seawater cooled condensers in Japan. However, long years of service accelerate erosion and corrosion on the inner surface of the tubing, and in addition, ammonia attacks the outer surface. Periodic replacement with new tubes has conventionally been performed. While titanium (Ti) tubing, with high corrosion resistance against seawater and ammonia, has been used for newly installed condensers, its service has been restricted to the replacement of damaged aluminum brass tubes because of its lower elastic modulus. As a countermeasure for these situations, the authors have succeeded in putting into practical use a high performance ferritic stainless steel tubing with a 0.5 mm thin wall. The tubing has been used for seawater cooled condensers in thermal power plants. Field tests for our proposed ferritic stainless steel tubes and their operating states are reported herein.

2. Selection of the proposed tubing material

A corrosion resistance test, for natural and artificial seawater, was executed for different classifications of stainless steel. The results led to the selection of a high performance ferritic stainless steel tube, 29Cr-4Mo-2Ni (FS10 = ASTM A268 UNSS44800), having excellent corrosion resistance, strength and ductility, as well as the advantage of high cost-effectiveness.

2.1 Study on the application of the tube material to seawater cooled condensers

The characteristics were compared with aluminum brass tube and Ti tube, referring to previous experiments and references. The comparison study revealed that FS10 had a satisfactory capability, a high heat transfer property and a high corrosion resistance, and was equivalent to pure

Ti in this respect. FS10 was considered preferable to Ti in its application to seawater cooled condensers because of its strength and coefficient of elasticity, as well as the advantage of high cost-effectiveness. Further, in compa rison with aluminum brass, FS10 had a lower heat transfer property but high corrosion resistance, and was approximately the same price. (Table 1 and 2, and Fig. 1)

Table 1. Comparative specific performance of commercialized condenser tubes

Item \ Material		FS10	Aluminum Brass	Ti
Heat transfer efficiency		○	◎	○
Vibration resistance		○	○	△
Corrosion Resistance	Erosion	○	×	○
	Deposit attack	○	×	○
	Ammonium attack	○	×	○
	Polluted sea water	○	×	○
Fe-ion injection		No use	Use	No use
condenser cleaning equipment		○	△	○
Cost		○	○	△

Excellent ◎ 〉 ○ 〉 △ 〉 ×

Table 2. Physical and mechanical properties of Condenser tube material

	Density (g/mm^3)	Themal Conductivity (20~100℃) (W/℃)	Themal Expansion Coefficient (20~100℃) (10^6/℃)	Elastic Modulus (20℃) ($\times 10^4$MPa)	Yield Strength (MPa)	Tensile Strengt (MPa)
FS10	7.7	17	9	205	415	550
Ti	4.5	16	9	105	275	345
Aluminum Brass	8.3	90	18	110	125	345

Potential (Vvs.SCE)	FS10tube Naval brass	FS10tube SUS316L	Ti tube Naval brass
		I	
-0.4	I		I
-0.5			
-0.6	II	II	II
-0.7			
-0.8			
-0.9	III	III	III
-1.0			

I : General corrosion on tube sheet
II : Proper potential range
III : Hydrogen embrittlement

Fig. 1. Range of proper cathodic protective potential for tube-tube sheet combinations

2.2 Features and characteristics of FS10

FS10 is high strength ferritic stainless steel, 29Cr-4Mo-2Ni, and has excellent ductility despite its high strength. Since the pitting index of Cr + 3Mo is 40, there is no need to worry about pitting corrosion and crevice corrosion. An applicable standard is ASTM A268/A268M UNS44800. (Table 3 and 4, and Fig. 2)

Table 3. Chemical composition of FS10

(%)

	C	Si	Mn	P	S	Cu	Cr	Mo	Ni	N	C+N
Example	0.007	0.130	0.150	0.020	0.002	0.030	28.900	3.800	2.200	0.008	0.015
Specification	≦0.010	≦0.200	≦0.300	≦0.025	≦0.020	≦0.150	28.0~30.0	3.5~4.2	2.0~2.5	≦0.020	≦0.025

Table 4. Mechanical properties of FS10

	Tensile properties			Hardness(Hv)			
	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Base metal 1	Base metal 2	Base metal 3	Welded metal
Example	653	586	29	206	207	206	216
Specification	≥415	≥550	≥20	≥260			

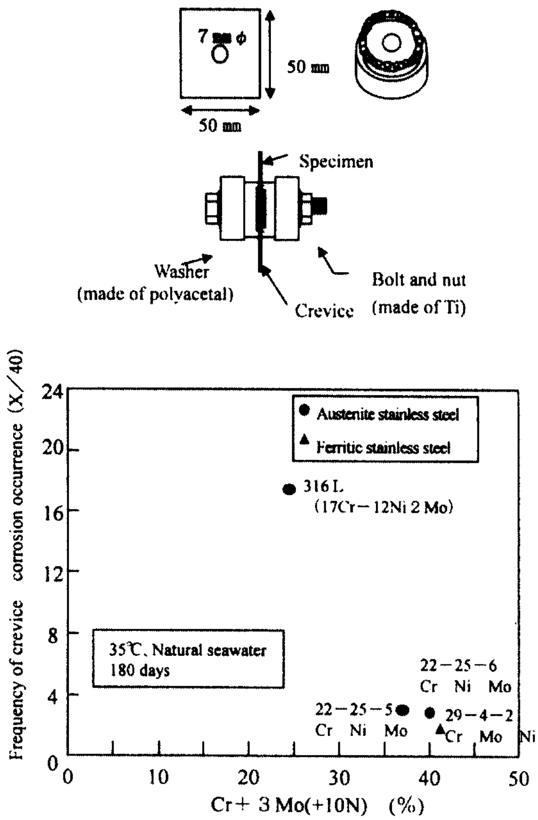


Fig. 2. Effect of alloying elements on crevice corrosion resistance

Table 5. Conditions of condensers in Buzen Thermal Power Station, Unit 2

	Unit 2
Cooling water	· Seawater · Circulating water flow:1,114m^3/min, · Circulating water temperature (entry/exit) 〔22℃(design criteria)/entry temperature+7℃〕
Cleanliness factor	75%
Electro-chemical protection	· Cathodic protection (Zn sacrificial anode) -500～-600mV(vs.SCE)
Tube material	· Aluminum brass 25.4mm^{OD}×1.2mm^t×16,000mm^L: 21,664pcs · Ti 25.4mm^{OD}×0.5mm^t×16,000mm^L:1,634pcs · FS10 25.4mm^{OD}×0.5mm^t×16,000mm^L: 40pcs
Tube sheet	Naval brass 28 mm^t
Chemical injection	· $FeSO_4$:0.4ppm×1.5h(twice/week)

3. Discussion regarding the application of FS10 to the tubing for seawater cooled condensers

There is a long track record for the use of high performance ferritic stainless steel tubing in the USA. In Japan, however, there have been only a few cases of tubing tests for practical use in small-sized condensers and commercial condensers. Therefore various application tests were performed with respect to practical-use, replacement with new tubes and new installations. For the purpose of replacing damaged aluminum brass tubes, studies have been initiated mainly to clarify the relationship between the corrosion resistance of the tube against seawater and the adhesion between the tube and currently used naval brass tube sheet. A long-term field test to examine the serviceability of the proposed tube was started in 1993 with the installation of 40 tubes with dimensions of 25.4$^{\varnothing}$mm×0.5^{t}mm into the seawater cooled condenser at Buzen Thermal Power Station, Unit 2 (output of 500MW). Table 5 shows the service conditions of the test.

3.1 Evaluation of an extracted tube

After 18 months, one of the tested tubes was extracted for the evaluation. No corrosion was observed on the surface of the tubes or tube sheet. A detailed survey on the extracted tube showed no corrosion and no degradation of its properties. It was estimated that the lower heat transfer coefficient of FS10 had no adverse effect on the heat transfer performance of the condenser.

3.2 Expansion joint properties of FS10 tube with naval brass tube sheet

The airtight performance and joint strength were investigated by jointing FS10 tube with 0.5 mm wall thickness to naval brass tube sheet for the purpose of practically using FS10 tube in newly installed or existing condensers assuming the same cost of conventional aluminum brass tube. Naval brass tube sheet of 28 mm thickness having mock tube holes was used. Tube expansion was performed by roll expander (three rolls) and expansion length was set to 25 mm, which was the same as for the existing aluminum brass tube. After sealing one end of the tube having a minimum of 7 % expansion rate with a plug, and reducing pressure to 730 mmHg in the FS10 tube by absorbing using a vacuum pump from the tube sheet surface side, the airtight performance was confirmed that there was no leakage after holding for five minutes. The joint strength of FS10 tube after expansion increases in proportion to expansion rate, and at the practical expansion rate of 7-30%, the joint strength is 400-600 kgf, which is higher than the joint strength of a Ti tube of 0.5 mm wall thickness, namely 300 kgf (a value at 7% expansion rate).

$$\varepsilon = \{1 - (D_k - d) / 2t\} \times 100 \ (\%)$$

ε : expansion rate,
D_k : inside diameter of hole of tube sheet (mm)
d : inside diameter of tube after expansion (mm)
t : wall thickness of tube before expansion (mm)

3.3 Improvement of expansion tube joint strength with use of anaerobic sealant

For the purpose of improving the joint strength of FS10 tube of 0.5 mm-wall thickness to 800-1,200 kgf, which is the value of an aluminum brass tube, anaerobic sealant was used on the FS10 tube. The relationship between the joint strength and the expansion rate was investigated in the case of a 25 mm expansion length. After using the sealant, the joint strength of the FS10 tube indicated a peak of 2,300 kgf at the expansion rate of about 12%. The joint strength decreased to 1,600 kgf at an expansion rate of 30%, and the strength then increased gradually. Further in the range of a 7-45% expansion rate, the joint strength of the FS10 tube is higher than the strength of the aluminum brass tube, and 3 to 4 times higher than that when no sealant was used on the FS10 tube. Also, it is very helpful to seal the joint between the tube and tube sheet, especially if the tube sheet hole is damaged

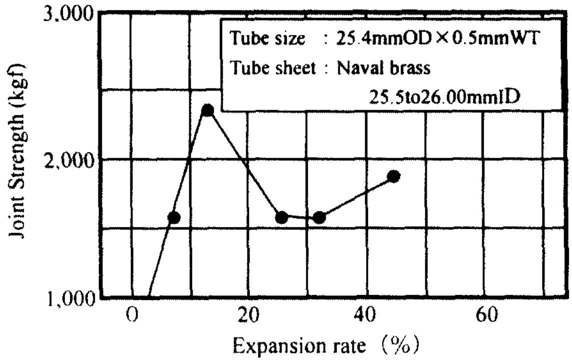


Fig. 3. Effect of expansion rate on joint strength when using a sealant between tube and tube sheet

or has a rough surface. It was confirmed that the use of the anaerobic sealant is necessary when the condenser tubes are replaced.

3.4 Material strength of expanded tube wall

In replacing the tube, the diameter of the tube sheet hole tends to be some what larger than the original. This may lead to a large expansion rate causing problems during expansion. Therefore the effect of the expansion rate of FS10 tubes with 0.5 mm WT was investigated using a simulated tube sheet. Both the tensile properties of thin wall sections of an expanded tube and the occurrence of cracks were evaluated. Crack inspection of the expanded tubes was performed using PT on all tubes with expansion rate in the range 7-81%, and no cracks were observed. The tensile strengths of non-expanded and expanded tubes with 81% expansion rate were 71.0 kgf/mm^2 and 92.6 kgf/mm^2 respectively. The tensile strength increased as the expansion rate increased. Apparently expansion results in a higher tensile strength compared to a non-expanded tube. On the other hand, elongation of non-expanded and expanded tubes with 81% expansion rate were 24.8% and 6% respectively. Elongation of the tubes decreased with an increasing expansion rate. Dimple patterns were identified on the fractured surface after tensile test on the tube with 81% expansion rate, which suggested a feature of ductile steel.

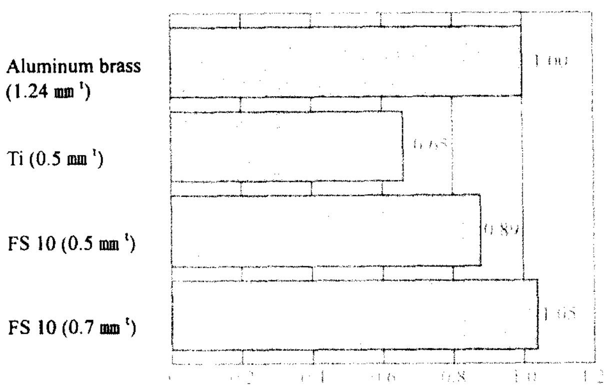
3.5 Vibration resistance of FS10 tube in an existing condenser

Thin and light FS tubes are effective from the point of view of good heat transfer properties and lower cost, but since the sectional secondary moment becomes smaller, the stream elasticity vibration due to steam flow increases. The stream elasticity vibration of a condenser becomes $V_{crit} \propto (E\ I)_{0.5}$, the critical steam velocity for vibration, proposed by Peake et al. Thereby by calculating the relative value of an FS tube and a Ti tube based on the V_{crit} of aluminum brass tube, studies were carried out on the application of FS tubes in an existing condenser unit without changing the span length between tube support plates. As a consequence, the relative V_{crit} of 0.5 mm WT FS tube is 0.89, which is smaller than that of aluminum brass tube and larger than that of Ti tube. Therefore 0.5 mm WT FS tube can be applied to both the ACZ where Ti tubes are currently used and in the center of the main condenser body where the steam velocity is lower than at the outer zone of the condenser. Further the relative V_{crit} of 0.7 mmWT FS tube is 1.05, which is nearly equal to that of aluminum brass tube. This would indicate that the 0.7 mmWT FS tube can be applied to other zones of the ACZ.

4. Field test

4.1 Selection of plant for field test

The field test was performed to prove the reliability, corrosion resistance and fouling performance at Buzen



$$V\,c\,(m/s) = \frac{K\lambda^2}{2\pi L^2}\left(\frac{a\,E\,I\,g}{\sigma}\right)^{0.5}$$

K, λ, a : Constant
E : Elastic modulus (kgf/m^2)
I : Secondary moment of inertia (m^4)
g : Gravity (m/s^2)
L : Span length between tube support plates (m)
σ : Steam density (kgf/m^3)

Fig. 4. Relative critical steam velocity affecting vibration resistance of commercialized condenser tubes

Thermal Power Station Unit 2, which is the same type of station located adjacent to the above-mentioned Buzen Thermal Power Station Unit 1.

4.2 Installation of FS tube

40 FS tubes with 0.5 mm WT thin were installed in the sub-ACZ (lower part of ACZ), where a greater than 50% decrease in wall thickness due to corrosion was observed. Tubes were expanded at expansion length of 25 mm and expansion rate of $20 \pm 5\%$ after sealing with anaerobic sealant. Prevention of galvanic corrosion of the naval brass tube sheet was achieved by a single brush coating of tar epoxy resin on the surface of the tube sheet without the ground coating. Further the electrical anti-corrosive potential difference was set with a constant voltage of -660mV(vs SCE).

4.3 Test results

4.3.1 Macro and micro structures

After 18 months, a tube was extracted to examine its condition. No pitting or inter-granular corrosion was found on the macro structure after removing scale and cross-ectional micro structure.

4.3.2 Galvanic corrosion of the part of installing FS tube

At the 12 monthly midpoint inspection, the isolation of painting films due to verdigris occurring under anti-corrosion paintings was identified. As a countermeasure against this, after ground treating using a wire brush, primer, second painting and final painting (two times) were performed. After that, no problems were found with the anti-corrosion painting.

4.3.3 Fouling property of tube inner surface

After 18 months (6,500 hours of operation), the deposits on the FS tube inner surface were 0.8-1.2 mg/cm^2. These values were lower than the values of our aluminum brass condenser tube (2-7 mg/cm^2 after cleaning with a brush). On the other hand the deposits on the aluminum brass tube at the previous B plant were 1.5-1.8 mg/cm^2 (9,380 hours of operation). Considering the difference in operation time for the condenser, no significant difference in deposits is found between FS and aluminum brass tubes.

4.3.4 Comparison of heat transfer coefficient of used tube

After 18 months, the heat transfer performances of the FS tube and aluminum brass tube were investigated on the extracted FS tube and adjacent aluminum brass tube before and after brush cleaning. The method of cleaning tubes by pushing out a nylon type brush by pressurized water, is the same as that actually used in commercial condensers. Before cleaning, the heat transfer coefficient of the FS tube and aluminum brass tube were 2,560 W/m^{2}K and 2,430 W/m^{2}K respectively. Compared with a new tube, the former was decreased to 80%, while the later was 67%. On the other hand, after cleaning with a brush, the heat transfer coefficient of the FS tube recovered to 3000, which was 95% compared to a new tube. On the other hand, the heat transfer coefficient of the aluminum brass tube only recovered to 2,730, which was 75% compared with a new tube. The recovery of the aluminum brass tube was evidently worse than that of the FS tube. After cleaning with a brush and being split open, the aluminum brass tubes were checked. It was found out that the cleaning with a brush on aluminum brass tube was not sufficient to remove hardened scale produced by corrosion.

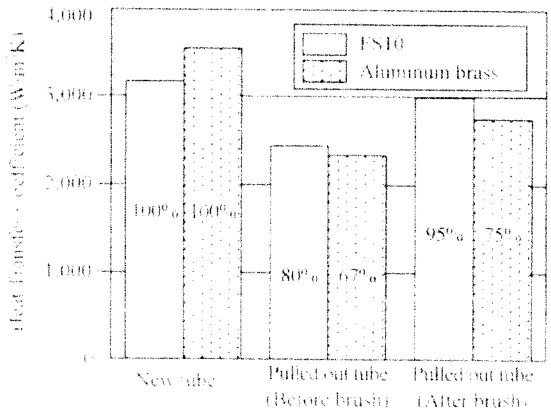


Fig. 5. Decreasing ratio of heat transfer coefficient compared to new tube

5. Conclusions

It is confirmed that the high performance ferritic stainless steel (FS10) tubes have almost the same anti-fouling and heat transfer properties as the aluminum brass tubes, and have much better corrosion resistance. Higher joint strength was also obtained for the FS tube than that of the aluminum brass tube, by using anaerobic sealant. Higher applicability to existing condensers was revealed since the FS tube had higher vibration resistance. Based on these results, 1,005 pieces of aluminum brass tube were replaced with the same number of FS tubes in December 1996 at the same station Unit 1 (output of 500MW), and the condenser is now in a good service condition.

One tube was extracted for sampling in May 1997 (3.5 years after installation), and a different tube was also extracted in June 1999 (5.5 years after installation, 15,514 hours of operation) from the remaining units in the original 40-tube continuous field test. The inner surface of tube was covered with slime and iron. However, once these were removed, the original state of the inner surface at installation emerged. No sign of corrosion was visible. Mechanical properties, as well as serviceability, remained as they were. No hydrogen absorption occurred during service. This showed that the FS10 tube is more advantageous than aluminum brass tube when service time becomes longer. The evaluation includes periodic inspection of an eddy current test (ECT) on the inner surface of 100 typical tubes.

Currently, 648 tubes have been replaced at Shinkokura thermal power station, Unit 3 (output of 600MW) as of January 1996. FS tubes have been concluded to be a most preferable material for replacement of aluminum brass tubes in the existing condenser.

References

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