Thermal Stress Analysis on the Inner Cover of Bell-Type Annealing Furnace of the Wire Rod Spheroidization Plant

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The inner cover of the wire rod spheroidization plant's annealing furnace suffered from frequent rupture and structural deformation due to elevated operating temperature. CFD and FEM were performed to explore such fluid-structure coupled behavior. The analysis reveals that the rupture of the welded joint outside of the channel would be eliminated if the cooling water channel of the bottom flange could be separated from the inner wall of the inner cover. However, the stress reduction around the inner side of the water channel is not acceptable. Thus, cracks and permanent deformation of the structure shall be inevitable after repeated thermal cycles. However, maximum stress on the inside of the channel would shift to the base metal instead of the weld if the geometry of the connection between the flange and the body is modified with a round corner. As a rule of thumb, the fatigue endurance of the base metal is always higher than that of the weld HAZ. Therefore, the weld joint is also recommended to be modified to double-sided groove welding to achieve better endurance. Besides, adopting a bigger wave shape of the inner cover is not recommended due to higher stress generated at the certain wave position.

Keywords: Thermal Stress, Inner Cover, Bell-type Annealing Furnace, Spheroidization Plant, CFD, FEM

1. INTRODUCTION

Some of the as-rolled coils (wire rods) need to be reprocessed and go through a pickling and annealing process to make the spheroidization products in the spheroidization plant. The annealing furnace of the spheroidization plant is a bell-type annealing furnace. The schematic diagram of the furnace body is shown in Figure 1. Bell annealing heats batches of the coil placed on a base assembly, enclosed by an inner cover and covered by the heating hood. An overhead crane loads the base and moves the suspended heating hood. The base assembly typically includes a recirculation fan to provide a source of convection to enhance the heat transfer to the charge. The inner cover contains the desired atmosphere (N_2) and protects the charge from the heating source. The coke oven gas is used as the fuel to heat the inner cover. After annealing, cooling is performed by removing the heating hood but leaving the inner cover in place to maintain the protective atmosphere. The forced cooler replaces the heating hood at the end of the heating cycle and circulates air to accelerate the cooling of the outside of the inner cover.

The inner cover comprises the head, the main body, and the bottom used as the sealing flange. The main body is a wavy cylinder manufactured by high-temperature resistant material SUS310S. The base metal material of the flange is SS400, and it is welded onto the SUS310S cylinder main body. The schematic diagram of the flange is shown in Figure 2.

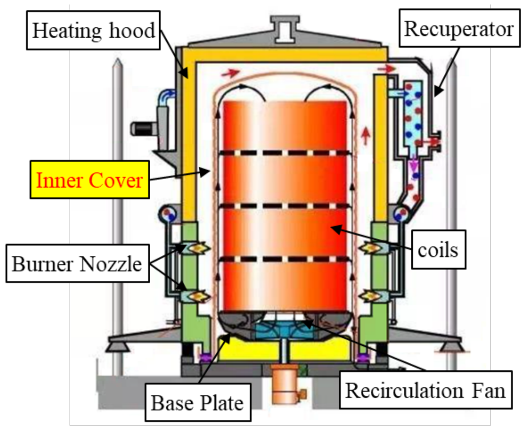


Fig.1. Schematic diagram of the bell annealing furnace.

The inner cover is installed on the furnace table with a rubber sealing ring embedded on the sealing plane. Thus, outside air is blocked into the inner cover to ensure that this bell-type annealing furnace is completely isolated. A cooling water channel is also equipped on the flange to prevent damage to the rubber sealing ring due to elevated temperature. The base of the heating hood placed on the water channel of the inner cover is designed as an annular sealing groove in which a heat-resistant sealing rope is installed. The inner layer of the sealing rope is filled with ceramic fiber, and the outer layer is filled with fireproof material. With the application of the sealing rope, the heating space can be isolated from the outside environment to improve thermal efficiency.

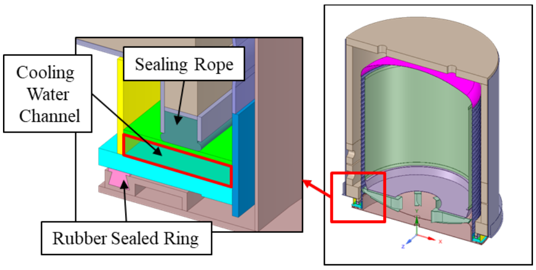


Fig.2. Schematic diagram of the inner cover flange.

After the inner cover had been used for about 1~2 years, the wavy steel plate of the main body deformed and expanded dramatically, causing the weld bead of the cooling water channel on the flange to rupture and leak, as shown in Figure 3. When the heating hood was pulled out of the furnace, interference might occur between the inner cover and the heating hood, resulting in damage to the furnace. Therefore, it was also requested to evaluate the appropriate wave shape of the main body of the inner cover.

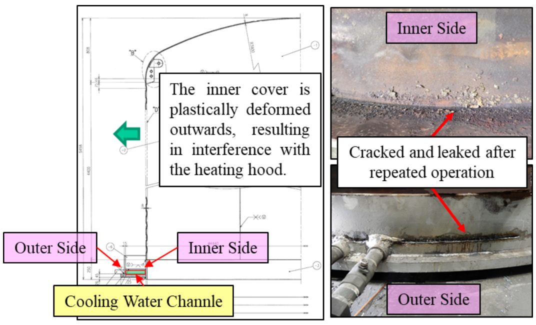


Fig.3. The rupture of the weld bead in the cooling water channel.

2. THERMAL IMAGING HOTOGRAPHING

It was suspected that the rupture of the cooling water channel of the flange could be attributed to thermal stress caused by a dramatic temperature gradient. In order to investigate the temperature distribution of the inner cover, thermal imaging photographing was performed, as shown in Figure 4. It was found that the maximum temperature of the wavy cylinder of the inner cover was about 550℃. However, the local temperature of the flange near the water channel dropped sharply to about 90℃. The location of the dramatic temperature gradient is consistent with that of inner cover rupture.

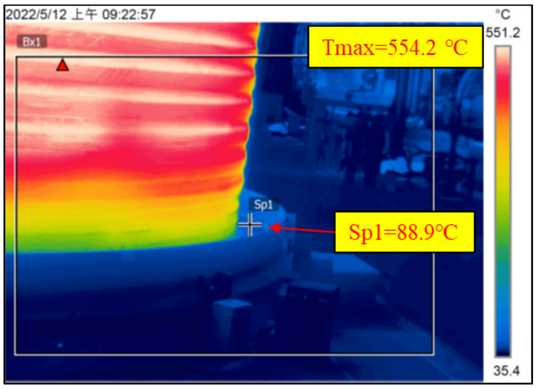


Fig.4. Thermal imaging photography of the inner cover.

Since the heating hood surrounds the inner cover, it is impossible to measure its temperature during production. Therefore, the above temperature measurement can only be executed during the instant of the heating hood removal. During the furnace's heating or soaking state, the inner cover's temperature will reach about 850℃. Therefore, great thermal stress is generated on the inner cover flange. Furthermore, since the wavy main body of the inner cover operated in the 850℃ environment, plastic deformation due to creep is inevitable.

3. STRESS EVALUATION FOR INNER COVER FLANGE

3.1 Ideas for improvement

Since the thermal stress of the flange of the inner cover originates from the rapid cooling effect, it can be improved by referring to the design of another annealing furnace. A schematic diagram of the improved concept is shown in Figure 5.

(1) Proposal #1 for implementation

The cooling water channel is separated from the inner cover body to reduce subsequent problems such as cracking of the weld bead caused by deformation of the inner cover after being heated.

(2) Proposal #2 for implementation

In addition to separating the flange cooling water channel from the inner cover body, the geometry of the connection between the flange and the body is suggested to be modified with a round corner. As a result, the high-stress area will shift to the base metal of the body with high fatigue resistance instead of the weld bead.

3.2 Analysis conditions

(1) Combustion exhaust gas and furnace atmosphere temperature

Typical gas and coil temperatures in the spheroidizing heat treatment process are shown in Figure 6. The maximum temperature appears at the end of the heating stage. This temperature is adopted for calculation. The furnace temperature is assumed to be the combustion exhaust gas temperature of 850°C, and the coil temperature is considered to be the furnace atmosphere temperature of 750°C.

(2) The flow rate of combustion exhaust gas

The fuel (coke oven gas) and air undergo a combustion reaction between the heating hood and the inner cover. The heating cover is heated by the energy generated from the above reaction. According to the operational data, the flow rate of the coke oven gas and the air are 181.9Nm^3/h and 838.5Nm^3/h, respectively, and the air-fuel ratio is 4.61. The analysis method of Huang Meijiao et al.[1] is employed to calculate the combustion reaction. The overall chemical reaction formula is as follows. The estimated flow rate of combustion exhaust gas is 1,573.41Nm^3/h.

$$0.5715H_2+ 0.2335CH_4+0.0705CO+ 0.0269C_2H_4+ (0.9681+0.0014)\ O_2+ (3.6401+0.074) N_2+0.0222CO_2 \rightarrow 1.0923H_2O+3.724CO_2+0.1008O_2 +3.714N_2$$

The molecular volume fraction of the exhaust gas is estimated according to the chemical reaction, which is used to calculate the physical properties of the exhaust gas, including specific heat, heat transfer rate, and viscosity coefficient.

(3) The flow rate of the furnace atmosphere

The furnace atmosphere is nitrogen. According to the original design, when the rated speed of the circulating fan is 1,200rpm, the flow rate is 27m^3/h. However, along with furnace temperature rise, the fan speed is reduced to 900rpm, and the fan flow rate can be estimated as 20.25 m^3/h.

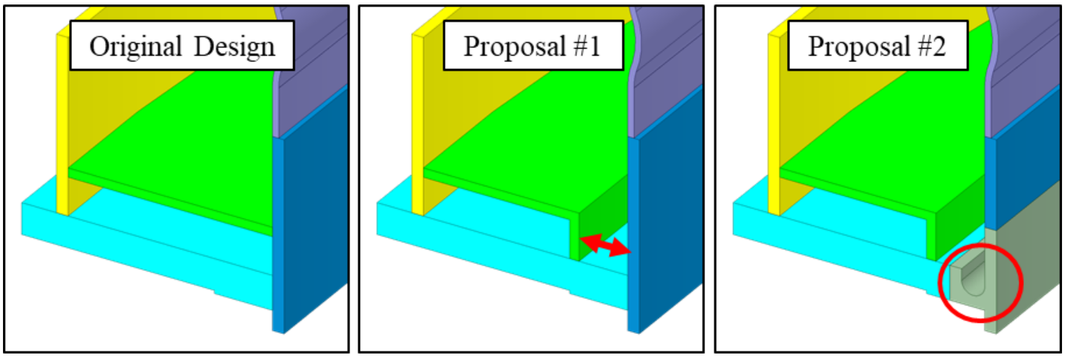


Fig.5. Schematic diagram of the improvement idea of the inner cover flange.

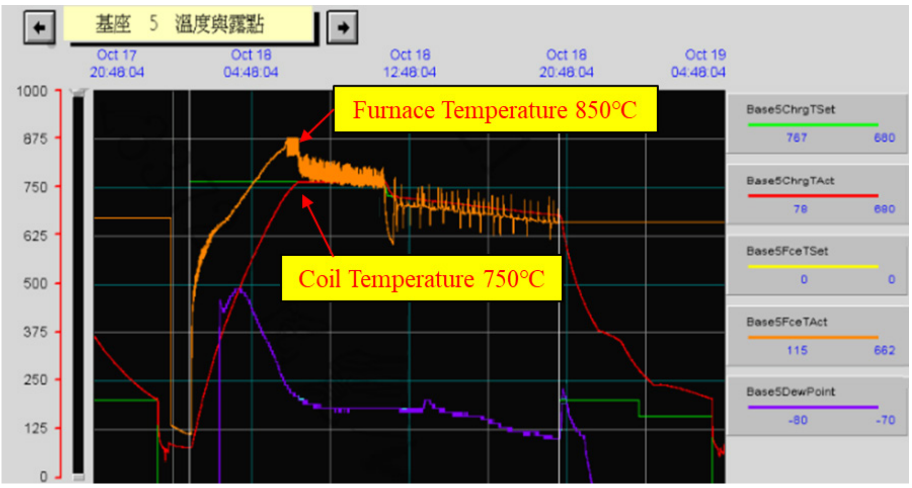


Fig.6. Typical furnace and coil temperatures in the spheroidizing heat treatment process.

(4) Heat transfer coefficient of cooling water

The heat transfer coefficient of the cooling water is adjusted repeatedly to make the temperature of the upper surface of the cooling water channel close to the measured data by the thermal image photography.

(5) Properties of the inner cover material

The main body of the inner cover is manufactured with high-temperature material SUS310S through welding. The base metal material of the bottom flange of the inner cover is SS400. The physical properties of the inner cover material are shown in Table 1, and the mechanical properties are shown in Table 2.(2)

(6)Axial displacement

The contact position between the cooling water channel and the rubber sealing ring is constrained in the x-direction.

3.3 Temperature distribution calculation

The temperature field of the inner cover must be calculated before performing thermal stress analysis. The software Fluent is applied with the standard k-ε turbulence model for incompressible flow to determine the temperature field. In addition, an axisymmetric model is used to simplify the complicated calculation.

The temperature distribution of the originally designed annealing furnace is shown in Figure 7. It is noted that the temperature in the junction between the bottom flange and the water channel drops dramatically to about 90°C, similar to the measured value.

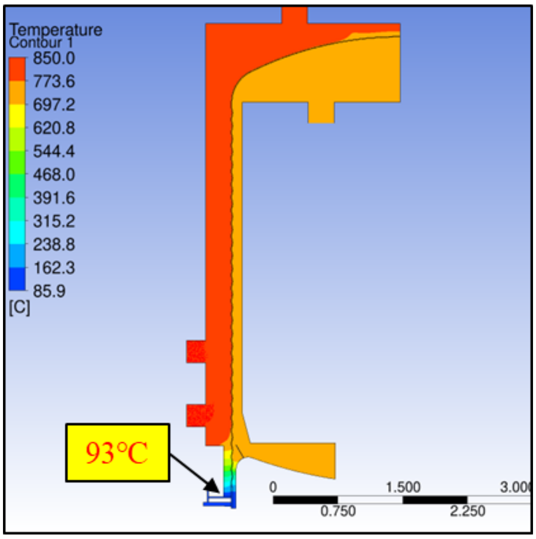


Fig.7. Temperature distribution of the original design spheroidization furnace.

3.4 Thermal stress calculation

A finite element software, Marc, was used to execute thermal stress analysis. An axisymmetric model

Table 1 Physical Properties of Inner Cover Material.

Material	Density(ρ) [kg/m³]	Heat Transfer Rate (k) [W/m°C]	Specific Heat (Cp) [J/kg°C]	Coefficient of Expansion (α) [×10⁻⁶/°C]
SS400	7,800	50	480	12
SUS310S	8,030	18.7	502	0~100°C→15.9 0~315°C→16.2 0~538°C→17.0 0~649°C→17.5 0~981°C→19.1

Table 2 Mechanical Properties of Inner Cover Material.

Material	Temperature [°C]	Yield Strength(Sy) [MPa]	Tensile Strength(Su) [MPa]	Young's modulus (E) [GPa]
SS400	27	245	400	210
SUS310S	27	314	624	200
	93	286	575	194
	204	254	533	185
	316	239	519	176
	427	209	508	167
	538	203	484	159
	649	178	393	150
	760	147	260	141
	871	111	155	132
	982	56	81	-
	1093	27	44	-

with quadrilateral elements was generated to perform the complex coupled thermal-stress analysis. The temperature field required for stress analysis was obtained from the analysis of CFD in 3.3.

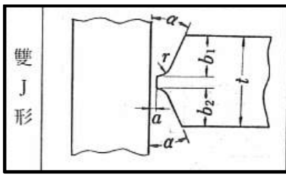
(1) Original design

The temperature and stress distribution of the bottom flange of the inner cover is shown in Figure 8. The maximum stress at the outer and inner water channels is 201MPa and 288MPa, respectively. Since these high-stress areas are located at the weld joint with lower fatigue resistance, rupture of the structure could not be prevented after long operation. Besides, the stress at the inner side of the water channel is 288MPa, which exceeded the yield strength. As a result, not only will fatigue occur, but permanent plastic deformation will occur, resulting in the subsequent interference between the inner cover and the heating hood.

(2) Proposal #1 for implementation

After the cooling water is separated from the inner wall of the inner cover, the stress at the weld joint of the outer water channel is reduced to 129MPa. Therefore, no crack will occur under such a low-stress level. However, the stress of the weld joint at the inside of the channel is only slightly reduced and still exceeds the yield stress. Therefore, yield and permeant plastic deformation will still occur.

Referring to Fujio Oguri et al.[3], it is recommended to modify the weld joint design from a fillet weld design to a double-sided groove weld to improve fatigue life, as shown in Figure 10.



t	α°	a	b_1	b_2	r
25	20～30	2	13	11	4
28	20～30	2	15	12	4
32	20～30	2	17	14	4
36	20～30	2	19	15	4
40	20～30	3	21	17	5
45	20～30	3	23	20	5
50	20～30	3	26	23	5

Fig.10. Weld Joint Design.

(3)Proposal #2 for implementation

The temperature and stress distribution of the flange are shown in Figure 11. The cooling water channel is separated from the inner wall of the inner cover, and the geometry of the connection between the flange and the body is modified with a round corner. As a result, the position of maximum stress shifts to the base metal in the vicinity of this round corner. Since the base metal possesses higher fatigue resistance than the weld joint, it

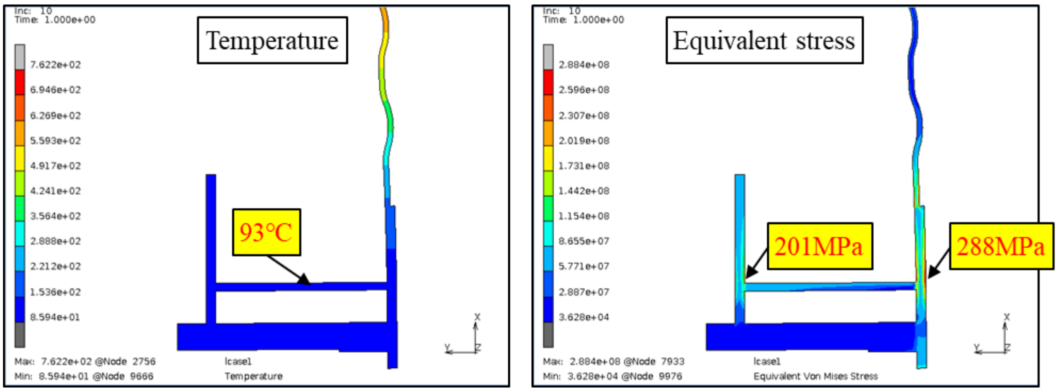


Fig.8. Temperature and stress distribution at the flange location of the original design.

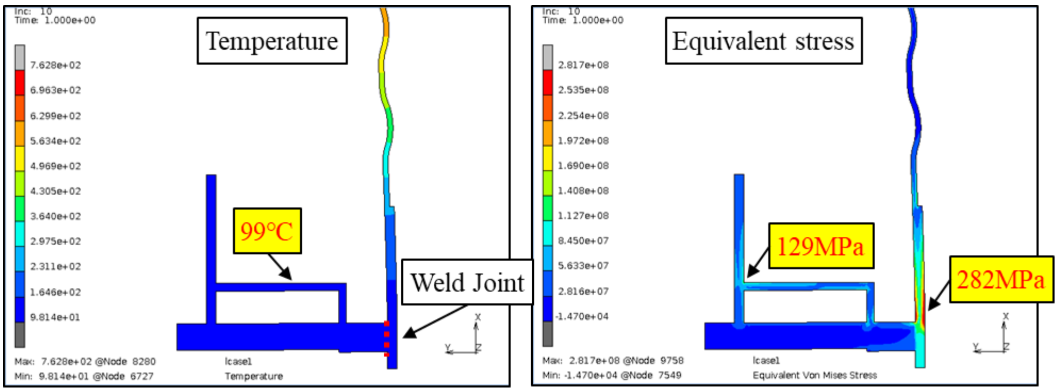


Fig.9. Temperature and stress distribution at flange position of Proposal #1.

will extend the operation life of the structure. The proposed weld joints are shown in Figure 12, and the double-sided groove welding can improve the fatigue life.

4. DETERMINATION OF THE APPROPRIATE WAVE SHAPE OF THE INNER COVER

4.1 Analysis model

The main body of the original inner cover is a wavy cylinder with 100mm radius waves. However, other factories have wavy cylinders with 40mm radius waves. The geometry difference is shown in Figure 13. Two models with different wave shapes were established, and coupled thermal-stress analyses were also executed to compare the strength of the wavy cylinders with different wave geometry.

4.2 Analysis conditions

(1) Temperature

The main purpose of the analysis is to compare the structure strength of the two different kinds of wave shapes. In order to simplify the calculation, the influence of cooling water is ignored, and it is assumed that the overall temperature of the inner cover rises to 850℃.

(2) Self-weight

The gravitational acceleration in the x direction is -9.81m/s^2.

(3) Baffle weight

The weight of the baffle is 1,595.1kg.

(4) Axial displacement

The contact position between the cooling water channel and the rubber sealing ring is constrained in the x-direction.

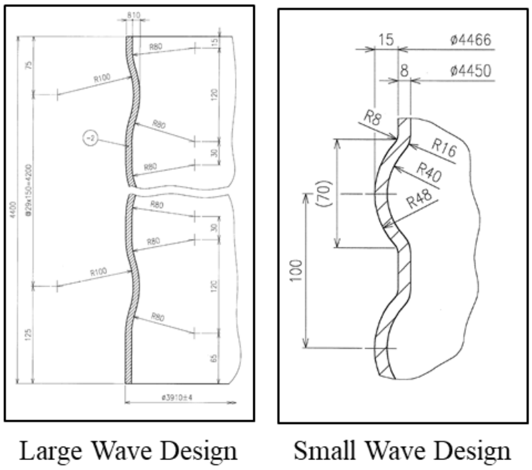


Fig.13. Wave shape comparison.

4.3 Analysis results

Figure 14 shows the stress variations of the two designs along the path in the elevation direction of the inner surface of the inner cover. It can be found that the stress level of a large wave design can be neglected at the wave position. On the other hand, the stress at the

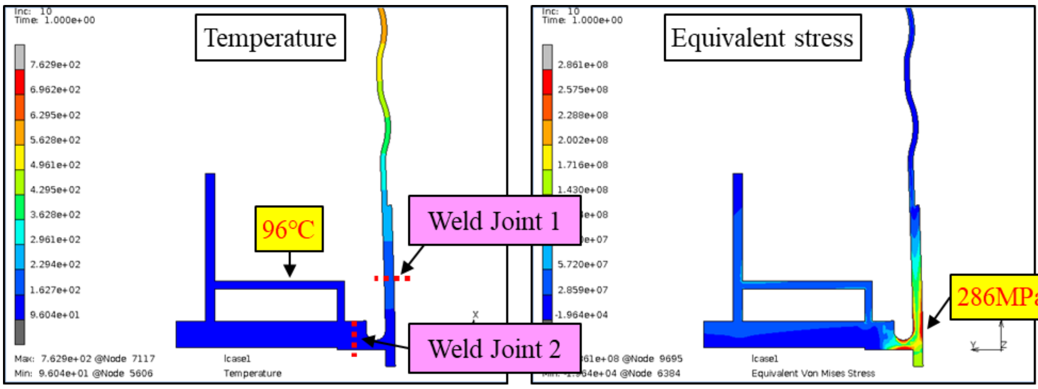
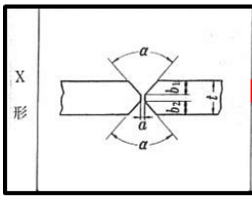
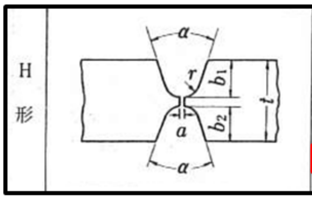


Fig.11. Temperature and stress distribution at flange position of Proposal #2.



t	α°	a	b_1	b_2
9	80~90	0~2	4	3
10	70~80	0~2	4	4
12	70~80	2	6	5
16	60~70	2	8	7
19	60~70	2	10	8
22	60~70	2	12	9
25	60~70	2	13	11
28	60~70	2	15	12
32	60~70	2	17	13

Weld Joint 1



t	α°	a	b_1	b_2	r
25	20~30	2	13	11	4
28	20~30	2	15	12	4
32	20~30	2	17	14	4
36	20~30	2	19	15	4
40	20~30	3	21	17	5
45	20~30	3	23	20	5
50	20~30	3	26	23	5

Weld Joint 2

Fig.12. Weld Joint Design.

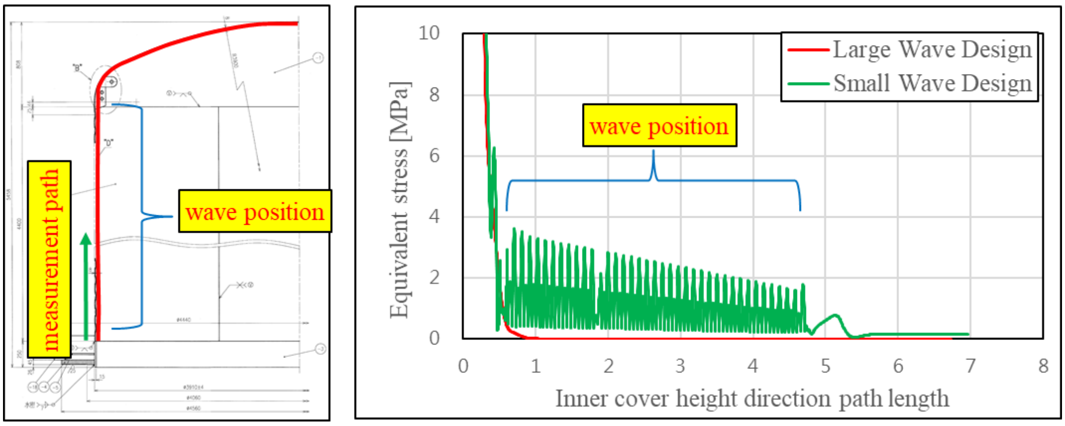


Fig.14. The stress distribution of the inner cover along the path in the elevation direction.

wave position is about 3MPa for the small wave design. Therefore, although the stress values are not high, the original big wave design appears to be better.

5. CONCLUSION

The thermal stress of the inner cover of the annealing furnace was carried out using the CFD-FEM fluid-structure coupled analysis. The analysis results show that if the cooling water channel of the bottom flange is separated from the inner wall of the inner cover, the rupture of the weld bead on the outside of the channel will be eliminated. However, the stress drop at the inner side of the water channel was not apparent. Thus, cracks and permanent plastic deformation of the structure are inevitable after multiple thermal cycles. It is suggested that the geometry of the connection between the flange and the body be modified with a round corner, so the maximum stress on the inside of the channel will shift to the base metal with high fatigue endurance instead of the weld bead. The weld joint is also recommended to be modified to double-sided groove welding for better fatigue endurance. Besides, if the inner cover of the original big wave shape is modified to the small wave design, higher stress will be generated at the wave position. Therefore, changing the inner cover's wave shape is not recommended.

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