New Design and Fabrication Technology Applied in Mercury Target Vessel #8 of J-PARC

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A mercury target vessel for the spallation neutron source at the J-PARC, which has the triple-walled structure, was improved to promote its robustness and reliability with conducting structural integrity simulations and mockup tests to confirm the suitable fabrication and inspection procedures. A monolithic structure fabricated by the wire electric discharge machining was adopted to reduce a number of welding lines. The total length of welding lines at the fore part of the mercury target vessel decreased drastically to approximately 53%. After the weld, an immersion ultrasonic testing which could detect small defects of more than 0.2 mm was adopted as a nondestructive inspection method. Stable beam operation at the beam power of 500 kW has been achieved and experienced the maximum beam power of 1 MW for an hour during a beam experiment.

KEYWORDS: spallation neutron source, mercury target, wire electric discharge machining, welding, nondestructive inspect, immersion ultrasonic testing

1. Introduction

A spallation neutron source has been installed at the Materials and Life Science Experimental Facility (MLF) of the Japan Proton Accelerator Research Complex (J-PARC) to promote material and life science studies [1]. A mercury target vessel, which is composed of 316L stainless steel, is designed with a triple-walled structure consisting of a mercury vessel and a double-walled water shroud to prevent the leakage of the radioactive mercury and other radioactive product to the circumference in the event of a failure of the mercury vessel. The water shroud is fixed together with the mercury vessel by many bolts.

When pulsed proton beams with 1μs pulse-width impinge upon the mercury target at a repetition rate of 25 Hz, the abrupt energy deposition results in a rapid increase in the temperatures of the mercury target vessel and mercury. The mercury target vessel exposes a large number of repeated loads owing to proton beam-induced pressure waves [2, 3]. The mercury target vessel is also exposed to repeated thermal load owing to the beam trip. During the beam operation at 500 kW, the water leakage from a small crack near the welding line of the water shroud was detected [4]. The water shroud was composed of external and internal vessels. The external vessel was fixed on ribs of the
internal vessel by means of a diffusion bonding and a tungsten inert gas (TIG) welding. Through experimental and numerical verifications, we concluded that the fatigue crack grew from the welding defect by repeated thermal loads.

Ultrasonic testing (UT) was added to nondestructive inspection items for welding lines. An ultrasonic method described in the Japan Industrial Standards (JIS) applies for thick plates with thicknesses more than 6 mm [5]. It was necessary to find an ultrasonic method which could detect small defects in the water shroud with thickness of 3 mm.

In this paper, we provide an improvement of design and fabrication process to achieve a stable operation with a beam power with 500 kW. The design with fewer welding and good welding inspection are essential to prevent failures of the mercury target vessel. In the fore part which suffers the high thermal load, we investigated the new design without the use of the diffusion bonding and TIG welding at the connection of vessels. Ultrasonic method which could detect welding defects with the allowable size of 0.4 mm in the water shroud was investigated.

2. Technical specifications

Figure 1 shows a schematic drawing of the mercury target vessel. The length, flange diameter, and total weight of the mercury target vessel are approximately 2.0 m, 1.2 m, and 1600 kg, respectively. The mercury vessel is covered with the double-walled water shroud which has water flow channels for cooling itself and they are bolted. Although an essential internal structure fore and rear part is same, some parts are mounted in the mercury vessel of the only rear part. The thicknesses of the mercury vessel and the water shroud are 8 and 3 mm, respectively. The space between the mercury vessel and water shroud is 3 mm and filled with a helium gas. Internal design pressures of the mercury, helium gas and cooling water are 0.5, 0.1 and 0.2 MPaG, respectively. The mercury and cooling water inlet temperature are 50 and 25 °C, respectively. Figure 2 shows the heat density distribution of center of each vessel along the beam axis at 1 MW beam operation [4]. The heat density decreases as the distance from the front wall increases. The maximum temperature of the mercury vessel and water shroud is 200 and 150 °C, respectively. A designed number of beam trips in an operation of 5000 hr is $10^4$ times assuming that the beam trip rate is twice an hour.

Fig. 1. Schematic drawing of the mercury target vessel. Fig. 2. Heat density distribution along beam axis.
3. **Structural integrity estimation**

In a structural integrity estimation of the mercury target vessel, a criteria of the pressure vessel code prescribed in the Japan Industrial Standard (JIS) B8265 [7] was applied. Numerical simulations of the mercury target vessel were conducted using conventional finite element method code; ANSYS R14.0. A Half model was used in consideration of a vertical symmetry. The total number of 10-node tetrahedron elements was approximately 244,000. Internal pressure and thermal loading shown in Section 2 were used as the analysis condition. An example of the resulting Tresca stress distribution in the inner surface of the mercury vessel and the water shroud (internal and external vessel) caused by internal pressure and thermal loading is shown in Fig. 3. The maximum stress was 437 MPa at the fore part of the water shroud around the connection part with the mercury vessel. This high stress was generated due to the difference in the thermal expansion between the mercury vessel which was heated by spallation reaction and the water shroud which was cooled by cooling water. Because half of this value is lower than the allowable stress based on the elastic design criteria (324 MPa), it was confirmed that the operation with a beam power of 500 kW could be conducted.

![Mercury vessel](image1)  ![Internal vessel](image2)  ![External vessel](image3)

**Fig. 3.** Tresca stress distribution in the inner surface of the mercury vessel and the water shroud (internal and external vessel) due to the internal pressure and thermal loading.

4. **Improved fabrication using wire EDM**

Figure 4 shows a vertical cross section of the previous and improved design. The water shroud of the previous mercury target vessel was assembled using the diffusion bonding and the partial penetration welding. In the fore part, which length was approximately 0.3 m, of the improved mercury target vessel, the monolithic structure of the mercury vessel and water shroud were cut out from a block of stainless steel [6]. Wire electric discharge machining (EDM) was adopted as a machining method, because each vessel had small and long flow channels. In the rear part, the mercury vessel and the water shroud were fabricated individually by EDM, because the mercury vessel was composed of many parts. Disks for keeping airtightness were attached to the water shroud by the full penetration welding. Upper surfaces of the previous and improved designs are shown in Fig. 5 and Table 1. Note that the red lines in the figure denote the welding lines. The number of parts and total length of welding lines were reduced drastically. The total length of the welding lines in the fore part which was exposed to
high thermal load decreased to approximately 53 %.

(a) Vertical cross section             (b) Previous design      (c) Improved design
Fig. 4. Vertical cross section of the previous and improved design.

(a) Previous design              (b) Improved design   (c) Some parts of improved design
Fig. 5. Welding lines in the water shroud of the previous and improved design.
5. Nondestructive inspections on welding line

UT was adopted as a non-destructive inspection on welding lines of the water shroud with a thickness of 3 mm. A frequency of a sensor probe which described in JIS [5] is 2 or 5 MHz. A detection limit is almost same as a wavelength of used sensor probe. The wavelength of 5 MHz-sensor probe is more than 1 mm. This value is larger than an allowable defect size of 0.4 mm. Therefore the 50 MHz-sensor probe was used to detect small defects. Immersion UT, which performing UT under the condition the vessel was immersed water, was conducted using ultrasonic system with a scanner (SONIX) to reduce a possibility that defect detection will be overlooked. A scan pitch is 0.1 mm. A typical result of radiographic testing (RT) and immersion UT on a mock-up model with welding defects was shown in Fig. 6. The accuracy of defect detection using C-scan imaging which indicates ultrasonic data two-dimensionally as a top surface image of the test object was equivalent to that of RT imaging and a minimum size of defect which could be detected by this UT system was 0.2 mm.

![Schematic drawing of RT image](image1)

![UT image](image2)

**Table I.** Effect of improvement on number of parts and total length of welding lines.

|                          | Previous design | Improved design | Effect (Reduction rate) |
|--------------------------|-----------------|-----------------|-------------------------|
| **Number of parts**      |                 |                 |                         |
| Mercury vessel (Whole)   | 15 parts        | 10 parts        | 70 %                    |
| Water shroud (Whole)     | 15 parts        | 11 parts        |                         |
| **Total length of welding lines (Whole)** | 10.6 m          | 6.2 m           |                         |
| Mercury vessel (Fore part) | 27.4 m          | 20.6 m          |                         |
| Water shroud (Fore part) | 10 parts        | 3 parts         |                         |
| **Number of parts**      |                 |                 |                         |
| Mercury vessel (Fore part) | 4 parts         | 3 parts         | 43 %                    |
| Water shroud (Fore part) | 10 parts        | 3 parts         |                         |
| **Total length of welding lines (Fore part)** | 2.7 m           | 1.8 m           |                         |
| Mercury vessel           | 8.5 m           | 4.1 m           | 53 %                    |
| Water shroud             |                 |                 |                         |

6. Completion of beam operation for mercury target vessel #8

The fabrication of mercury target vessel #8 was finished in September 2017. It took seventeen months since the redesigning the structure was started. In the about eight months of service operation, the beam power was ramped up to 500 kW [8]. After finishing the beam operation for the user program, this vessel achieved the operation under the maximum beam power of 1 MW for about 1 hour. Figure 7 shows the relationship between a beam power and a rise in temperature of the fore part of the mercury vessel during the service operation and the high power beam operation test. Measurement results were included in a range of 20 % of the analytical result. Beam trip
rates during the service operation with the beam power of 300, 400 and 500 kW were approximately 1.7, 1.6 and 1.4 times/hour, and lower than assumed value of twice an hour. Total number of the beam trip was approximately 7000 times in the service operation of approximately 4400 hour and lower than the design number of $10^4$ times.

Fig. 7. Relationship between beam power rise in temperature of fore part of mercury vessel during service operation and high power beam operation test.

7. Conclusion

Design, fabrication, and inspection processes for the mercury target vessel were improved based on the lessons from the water leakage incident of the water shroud. The number of parts and welding lines of the mercury target vessel #8 were drastically reduced by adopting the monolithic structure fabricated by the wire electrical discharge machining. The immersion ultrasonic testing which could detect defects with a size smaller than allowable size of 0.4 mm was adopted. The target vessel #8 achieved the stable beam operation for the user program up to 500 kW and 1 M- beam operation test.

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