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Recent studies for structural integrity evaluation and defect inspection of J-PARC spallation neutron source target vessel

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ABSTRACT

An examination of the structural integrity and defects of a fabricated mercury target vessel for Japan Proton Accelerator Research Complex (J-PARC) spallation neutron source is presented. Ultrasonic testing (UT) and radiographic testing (RT) were employed as nondestructive inspection methods. The mercury target vessel is composed of SUS316L stainless steel and was designed with multi-walled structures consisting of double-guard vessels with thin walls of 3-mm thickness and assembled by tungsten inert gas welding. The mercury target vessel has complex characteristic, and the weld defect for the thin walls is often very difficult to detect using conventional UT techniques. To overcome this barrier, we employed two new UT techniques, namely 1) immersion ultrasonic with a 50-MHz ultrasonic probe and 2) phased arrays ultrasonic with the full matrix capture (FMC) and the total focusing method (TFM). The examination revealed the formation of small defects and cracks wherein the wall thickness was less than 6 mm. Therefore, new UT techniques are useful for evaluating the structural integrity and defects of the new fabricated mercury vessels.

The design and the fabrication process of the mercury target vessel was also evaluated and improved in this study. The use of wire electric discharge machining (EDM) in the fabrication process is desirable to reduce the amount of welding and subsequent welding deformation. The roughness and chemical compositions of the processed surface layer by wire EDM were also examined. The oxide layer was perfectly removed by two-step chemical polishing, and the chemical composition of the layer was analyzed using energy dispersive X-ray spectrometry. In addition, the surface roughness was reduced after polishing to enhance fatigue life and minimize internal defects caused by welding.

1. Introduction

A mercury target vessel for the Japan Spallation Neutron Source (JSNS) has been installed at the Materials and Life Science Experimental Facility (MLF) in Japan Proton Accelerator Research Complex (J-PARC) to promote material and life science studies using the world's highest intensity pulsed neutron source[1]. The first proton beam of 4 kW was injected into the mercury target vessel in May 2008, and the beam power has gradually increased over time [2]. The user program began in December 2008 with a beam power of 20 kW and stable beam operations took place at 300 kW for extended periods of time, including at 500 kW for approximately one month. The goal of the facility is to achieve steady and stable operations with a power of 1 MW for 5000 h. The mercury target vessel, which is composed of 316 L stainless steel, is designed with a triple-walled structure consisting of the mercury vessel and a double-walled water shroud with internal and external vessels. The water shroud with cooling flow channels covers the mercury vessel to prevent the leakage of radioactive mercury and other radioactive products to the surroundings in the event of a failure of the mercury vessel. In addition, a space between the mercury vessel and

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the water shroud is filled with helium gas which is monitored to detect leaks of radioactive noble gases from the mercury vessel to surroundings. The mercury vessel and water shroud are assembled by tungsten inert gas (TIG) welding.

When pulsed proton beams with a size of approximately 80 × 180 mm and 1 μs 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 vessel and mercury. The mercury target vessel experiences a large degree of cyclic stress owing to proton beam-induced pressure waves, which cause cavitation damage on the interior surface of the mercury vessel [3]. A bubbler is used to mitigate the pressure waves by injecting micro-bubbles in the mercury vessel. A reduction of pitting damage was confirmed by inspecting a sample cut from the used mercury vessel [4]. The mercury target vessel experiences cyclic thermal stresses owing to beam trip after beam operation was discontinued. Furthermore, the mercury target vessel experiences radiation damage in the proton and neutron environment. In an initial design stage, the radiation damage was limited to a threshold below 5 dpa, corresponding to an operation time of 2500 h at 1 MW, based on the expected ductility under an irradiation environment.

During the beam operation at 500 kW, a small amount of water leakage from a small crack near the weld of the external vessel was detected in the fifth mercury target vessel. Furthermore, a small amount of water leakage, from the internal vessel to the space between the water shroud and mercury vessel, was detected in the seventh mercury target vessel. Although the leakage point of the inner vessel covered with the outer vessel could not be confirmed directly, leakage from portion near a particular weld was assumed based on results of a weld mockup model. The structure of the mercury target vessel should be improved for reducing the static and dynamic stresses generated by proton beam injections and to avoid fracture at the weld. Hence, the present evaluation of the structural integrity, based on detailed numerical analyses and improved fabrication techniques, is warranted.

Each step of the fabrication process involves several important considerations. It is generally known that impurities, such as sulfur and phosphorus, increase susceptibility to cracking [5,6]. Furthermore, the susceptibility to cracking greatly increases when the ratio of chromium (Cr_{eq}) to nickel equivalences (Ni_{eq}), Cr_{eq}/Ni_{eq}, is less than or equal to 1.48 [6]. During material procurement, materials with few impurities and high Cr_{eq}/Ni_{eq} ratio should be used to reduce the possibility of hot cracking at the welds of the mercury target vessel. Wire electric discharge machining (EDM) is useful for fabrication of vessel parts with numerous narrow channels and the assembly of these parts thereby reducing the number of weldments. The fatigue strength of heat-treated 0.45% carbon steel specimen processed by rough cutting using wire EDM was reported to decrease by approximately 44% compared with that of the electropolished specimen [7]. It is a necessary step to eliminate the effects of surface processing caused by wire EDM.

Potential failure caused by crack propagation due to weld defects must also be considered, because high cyclic stresses generated in the mercury vessel. After the welding, the welds should be inspected for defects. Radiographic testing (RT) and ultrasonic testing (UT) are considered as nondestructive inspection methods. UT has been used to evaluate the damages caused by radiation and ensure safe operation of nuclear reactors [8–11]. The Japan Industrial Standards (JIS) prescribed using ultrasonic methods for plates with thicknesses more than 6 mm [12]; however, these methods prove to be challenging when inspecting the mercury target vessel with 3-mm thin walls.

In this study, the fabrication of a mercury target vessel for a neutron spallation source was investigated using numerical simulations based on the evaluation of structural integrity. The use of surface treatment to remove the effects of wire EDM, and subsequent evaluation of the effectiveness using nondestructive inspection testing has gained particular interest. Since mechanical polishing many narrow channels of the mercury target vessel is difficult, chemical polishing was employed, and suitable treatment conditions were investigated. The multi-walled vessel was subjected to RT and UT to evaluate the structural integrity of the fabricated vessel. The investigations focused on inspecting weld defects using immersion UT and phased array UT with the FMC and the TFM [13,14].

2. Evaluation of structural integrity

2.1. Technical specifications

A schematic of the mercury target vessel is shown in Fig. 1. The length, flange diameter, and total weight are approximately 2.0 m, 1.2 m and 1600 kg, respectively. In the mercury vessel covered with a double-walled water shroud, the mercury flows across the proton beam along six flow vanes of 10-mm thickness to eliminate the heat generated by spallation. The water shroud is bolted to the mercury vessel. A schematic of the bolt that fixes the water shroud onto the mercury vessel is shown in Fig. 2, and the specifications of the mercury target vessel are given in Table 1. The thicknesses of the upper and lower sides of the mercury vessel, and the internal and external vessels of the water shroud are 8, 3 and 3 mm, respectively.

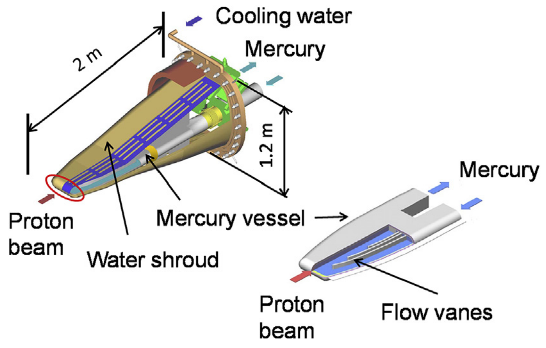

Fig. 1. Structure of the multi-walled mercury target vessel. The mercury vessel is covered a double walled water shroud.

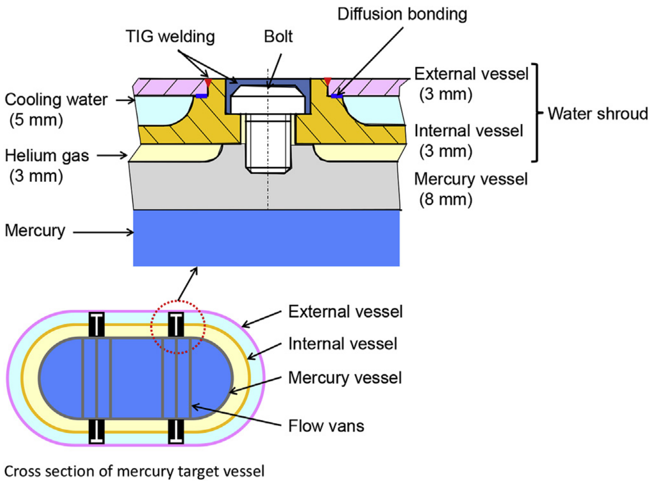

Fig. 2. Schematic of the cross section of the triple-walled vessel. The water shroud consisting of the external and internal vessels is bolted to the mercury vessel.

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