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Cavitation damage in double-walled mercury target vessel

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ABSTRACT

A liquid mercury target is operated as part of a spallation neutron source at the Japan Proton Accelerator Research Complex (J-PARC). The mercury target vessel is made of 316L stainless steel, (3 mm thick) and its beam window is damaged by cavitation due to pressure waves in mercury. To mitigate the pressure waves and the cavitation damage, a double-walled structure with a narrow channel of 2 mm was added to the beam window along with gas microbubbles injection technology. After operation of up to 670 MWh for 1670 h, the beam window of the used target vessel was cut out using an annular cutter to investigate the effect of the double-walled structure on mitigating cavitation damage. Band-like damage distribution due to cavitation was observed on the outer wall that faced the narrow channel, where the maximum pit depth was estimated to be 25 μm. Furthermore, to clarify the mechanisms possibly contributing to the band-like damage distribution, numerical simulations were conducted in terms of flow velocity, gap width, and pressure waves in the narrow channel. The results show that the distribution of accumulated saturation time of negative pressure period obtained from FEM simulation correlated well with the experimentally observed band-like damage distribution.

1. Introduction

Liquid mercury target systems have been operated in the spallation neutron source at the Japan Proton Accelerator Research Complex (J-PARC) and the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL) to provide intense pulsed proton beams for developing innovative materials and life science research [1,2]. The beam power goal for the J-PARC neutron source is 1 MW at 25 Hz with 1 μs pulse duration. At the moment of proton beam injection into the mercury, pressure waves are generated owing to abrupt heat deposition in mercury, and these waves induce cavitation at the interface between the mercury and the enclosure vessel made of type 316L stainless steel, the so-called target vessel [3]. This cavitation causes severe erosion damage at the beam entrance region of the target vessel wall, also called beam window. The cavitation-induced erosion rate is likely to increase with proton beam power. The thickness of the beam window of the target vessel was 3 mm to reduce thermal stress. The structural integrity of the target vessel decreases drastically owing to the cavitation erosion [4]. In recent years, post irradiation examinations of used target vessels were performed at the SNS and J-PARC, and cavitation damage was observed at the beam window: the damage penetrated through the inner wall (3 mm thick) of the double-walled SNS target operated up to 3055 MWh (379 MW average power) [5], and the maximum depth of 250 μm was observed in case of the J-PARC neutron target vessel operated up to 475 MWh (128 kW average power) [6].

The injection of gas microbubbles into flowing mercury is one of the prospective techniques to mitigate the pressure waves that cause cavitation [7]. At J-PARC, a gas microbubble generator for injecting helium gas microbubbles measuring less than 50 μm in radius was developed to mitigate pressure waves and their propagation [8]. It was installed in the mercury target system along with the closed gas circulation system in October 2012, and pressure wave mitigation was confirmed by means of vibration measurement of the target vessel [9,10]. The previously mentioned target, in which a damage depth of 250 μm was observed, was operated without gas microbubbles injection.

To mitigate the growth of cavitation bubbles by increasing flow velocity, a double-walled structure at the beam window of the target vessel contributing to a narrow mercury flow channel was adopted in addition to gas microbubble injection. It was reported

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that the mercury flow deforms the growth and collapse of cavitation bubbles and reduces cavitation damage [11], and the damage tends to decrease with increasing flow velocity [12]. The double-walled target vessel, target No. 5 in terms of fabrication number, was operated from October 2013 to May 2014; the resulting accumulated beam energy was approximately 680 MWh for 1671 h of operation. Operation of the double-walled target was terminated owing to failure of the water shroud. Before replacing the target vessel, samples were cut from the beam window to examine the cavitation damage inside the target vessel. In this study, the cavitation damage on samples from the beam window was observed, and the damage depth was measured quantitatively with a surface replication method. Furthermore, the relationship between the damage distribution and the saturation time related to negative pressure [6,13], which was estimated from numerical simulation, was investigated.

2. Damage inspection of target vessel

2.1. Beam window cutting

A schematic drawing of the double-walled mercury target vessel is shown in Fig. 1. The beam window of the target vessel is composed of a double-walled (inner/outer wall) mercury vessel and a double-walled water shroud. The thickness of the mercury vessel inner wall is 5 mm and that of the other walls is 3 mm. The gap of the narrow channel is set to 2 mm to achieve a mercury flow velocity of approximately 4.0 m/s. The gap width used in the target was based on the results of off-beam cavitation damage experiments in stagnant mercury, which demonstrated that a narrower gap is likely to reduce cavitation damage because the direction of ejection of the micro-jet changes due to the interference of the wall boundary [14].

The target beam window was sampled using an annular cutter without any lubricant by using the same procedure as that described in Refs. [6,15]. For target No. 5, it was necessary to cut through four layers of 316L SS to inspect the innermost wall of the mercury vessel. A photograph of target vessel cutting is shown in Fig. 2 (a). Fig. 2 (b) and (c) show photographs of the annular cutter before and after cutting. The cutter teeth broke due to the stress imposed during cutting operation, and heat was generated owing to the cutter body rubbing on the target after the teeth were damaged. Because the replacement cutters continued to break, we stopped sampling of the mercury vessel inner wall.

2.2. Visual inspection

The specimens cut out from the outer/inner water shrouds walls and the outer wall of mercury vessel were washed in an ultrasonic water bath for 60 min to remove mercury and spallation products. No visible damage was observed on the surface of the outer/inner water shrouds facing the water. Fig. 3 shows photographs of the specimen cut from the mercury vessel outer wall. The orientation of target vessel (top/bottom) on the specimen is unknown. The band-like damage occurred parallel to the flow direction. Machining scratches suggesting non-severe damage compared to the damage to the center part are present on the top/bottom side. The inner wall surface observed through the cutting hole is shown in Fig. 4. No visible damage could be observed, except for machining scratches on the surface, although surface discoloration was

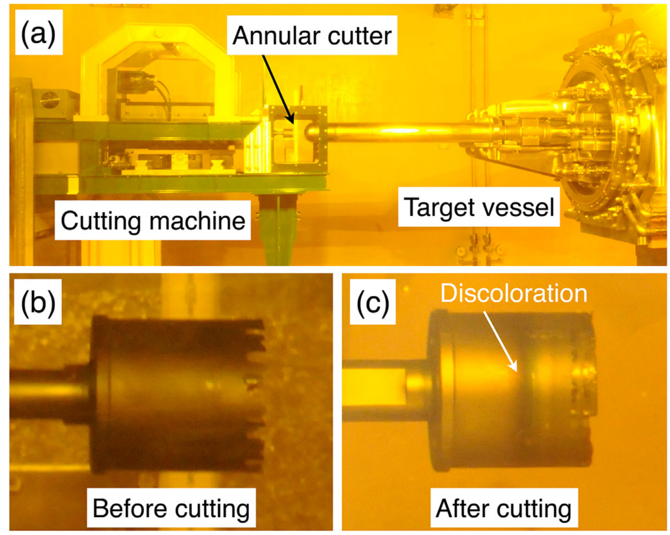

Fig. 2. Photographs of (a) target vessel cutting machine, annular cutters (b) before and (c) after cutting.

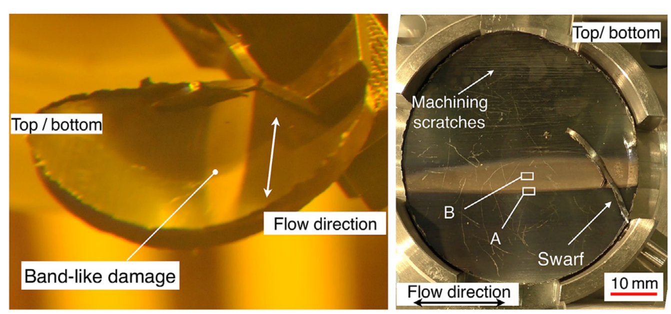

Fig. 3. Photographs of specimen from mercury vessel outer wall.

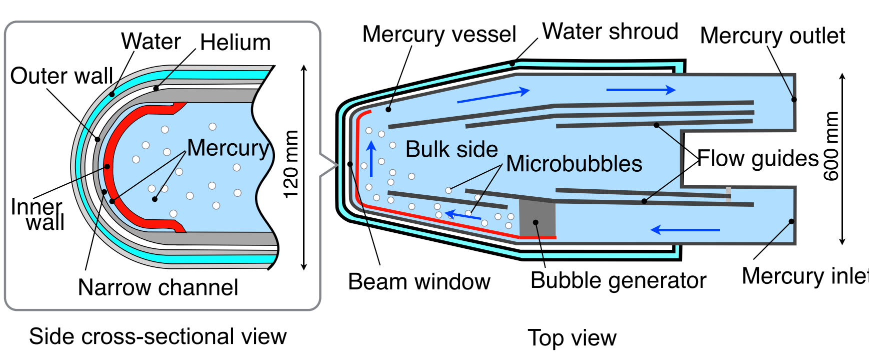

Fig. 1. Schematic of double-walled mercury target vessel at J-PARC with gas microbubble generator. (Target No. 5).

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