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SCC Tests of the canister for spent nuclear fuel storage using full scale lid model

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Abstract

To verify the effectiveness of surface treatment techniques to the commercialized canister, the mock-up lid part of the canister made of SUS304L with a full-scale diameter was manufactured. Parts of the weld line were treated by the Low Plasticity Burnishing (LPB) technique to mitigate the residual tensile stress. An accelerated corrosion test was executed with the mock-up canister, in which the salt concentration on the surface of the weld lines was set to $4g/m^2$ as chloride. The test conditions were set at a constant temperature of 80°C with relative humidity RH=35% over 5000 hours. After the test, visual inspections and fluorescent penetration tests (PT) were executed along all of the weld lines and the suspicious areas for the occurrence of SCC were detected. The suspicious areas were selected by PT indications and cut into small plates. Using these plates, surface cracks and cross-section of the cracks were observed with optical microscope. This paper presents the results of the investigation and the effectiveness of the LPB technique.

Introduction

After the Fukushima Daiichi nuclear power plant accident in 2011, all nuclear power plants were shut down in Japan. In 2014, the Japanese cabinet approved the New Basic Energy Plan. The Plan states that nuclear power will be positioned as an important baseload power source and that the fuel cycle will continue to be promoted. Japanese electric power companies are determined to continue to contribute to the national energy policy by generating nuclear power while strictly ensuring safety. In 2015, Japan restarted its first nuclear reactor under new safety rules following the 2011 Fukushima accident. When a large number of nuclear power plants are restarted, the necessities of introducing interim storage facilities of spent nuclear fuel at or away from reactor sites will increase. Although the use of metal casks for spent fuel storage has been practically employed to date, the utilization of an alternative storage method, i.e. concrete casks are also needed from the perspective of cask procurement risk management and economic benefit. Around the world, especially in the U.S.A, the concrete cask system is used widely.

Since Japan is an island nation, chloride induced stress corrosion cracking (SCC) of welded stainless steel canisters in the concrete cask storage system should be evaluated and tackled. The canister shall not lose its containment function due to SCC during long-term storage. SCC occurs when stainless steel with welding residual stress is exposed to a salty air environment. Measures for one or two of the three factors must be taken, i.e. welding residual stress, and environment, to cope with SCC that may result in the containment function of the canister being lost. SCC of canisters is a common issue around the world. A lot of studies on this have been performed by several organizations [1-8]. We evaluated methods to maintain its confinement function of canisters made of normal stainless steel SUS304L materials during the storage period by comparing the amount of salt on the canister surface during storage with the minimum amount required to initiate SCC, and by comparing the humid time of the canister surface under a field environment with the lifetime of the SCC fracture of the canister material [9, 10]. Moreover, an alternative measure against SCC was investigated by reducing the welding residual stress of the conventional stainless steel canister and demonstrated by SCC tests using mock-up canisters made of SUS304L simulating wall thickness of the commercialized canister and welding methods [11, 12].

Experimental Equipment

To verify whether SCC occurs or not, an SCC demonstration test was performed using a mock-up of a canister lid.

Mock-up of canister lid

A typical canister for storage of spent nuclear fuel is about 1.8m in diameter and about 4.8m in length. To investigate canister SCC, it is important to reproduce the real stress and surface condition of the canister. The mock-up for the experiment is full-scale in diameter but short in length because of the limitation in size of the experiment chamber (Fig.1). Its outer diameter is about 1.832m and height is about 1m (Fig.2). The thickness of the shell is about 16mm. The mock-up is the lid part of the canister. SCC evaluation of the lid part is more complicated because the lid weld is a partial penetration weld. The mock-up is made of stainless steel type 304L. There are several lid designs for a canister. This mock-up used a lid with a ring plate. The ring plate is placed on the edge of the lid. After the lid was welded to the shell, the ring plate was welded to the shell and the lid. When the lid was welded to the shell, the top part of shell inclined to the inside. The shell weld in the axial direction was MIG weld. Firstly, two flat plates were welded. The welded plate was formed into a cylinder. Then, another weld in the axial direction was performed. Excess metal of the shell weld was removed by grinding. For the welding of the shell, Radiographic Testing (RT) and Penetrant Testing (PT) were executed. For the lid and ring plate welding, PT was executed. No flaw indications were observed.

Figure 1 Photographs of Mock-up

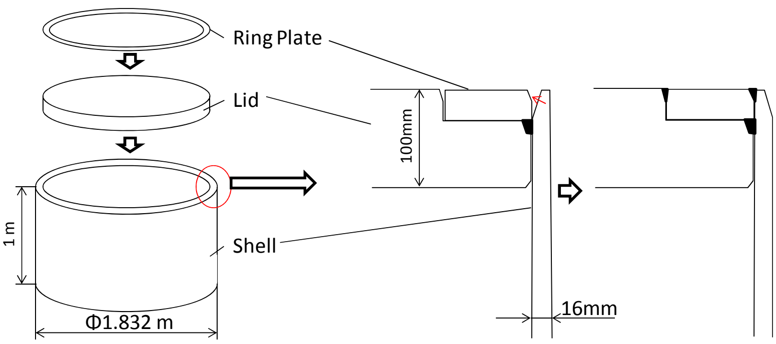


Figure 2 Dimensions of Mock-up

To confirm the effectiveness of the residual stress mitigation method, low plasticity burnishing (LPB) technology was applied to the shell surface part. The mock-up was set on the machining table and a special tool for LPB was pressed against the mock-up surface (Fig.3, 4). The LPB could not be applied to the ring welding part because the excess metal of lid welding cannot be removed when spent fuel is inside. It is difficult to apply LPB to uneven surfaces. Surface stresses were measured by X-ray diffraction method at several points of the mock-up. The measured stresses in LPB area were compressive.

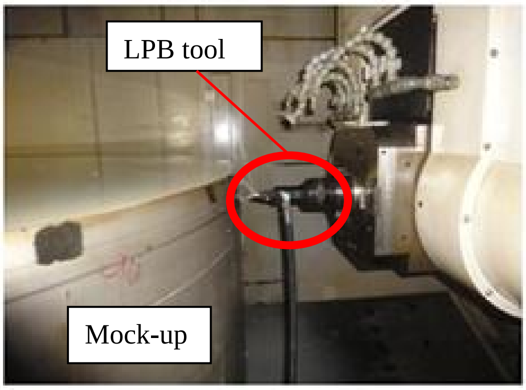


Figure 3 LPB process

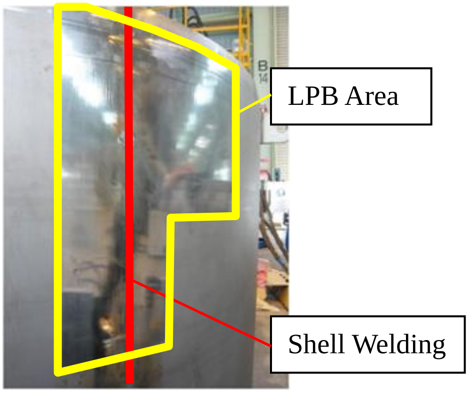


Figure 4 LPB area of Mock-up

Temperature and Humidity Chamber

To keep the environment conditions constant during experiments, the temperature and humidity chamber was used (Fig.5). The size of the chamber inner cavity is 2.2m in width, 2.65m in depth and 1.8m in height. The ceiling of chamber is removable. When the mock-up is set in the chamber using a crane, the ceiling is removed. The lid of mock-up is face-up in the chamber (Fig.6).

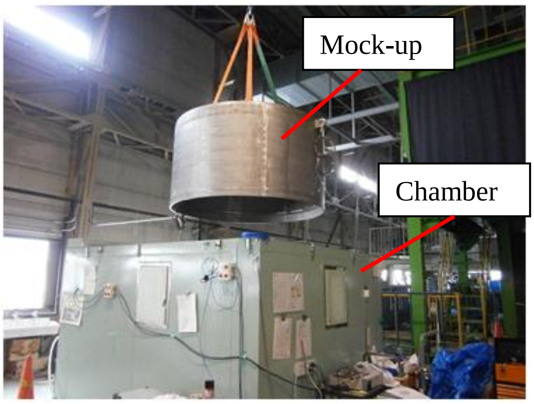


Figure 5 Handling Process of Mock-up

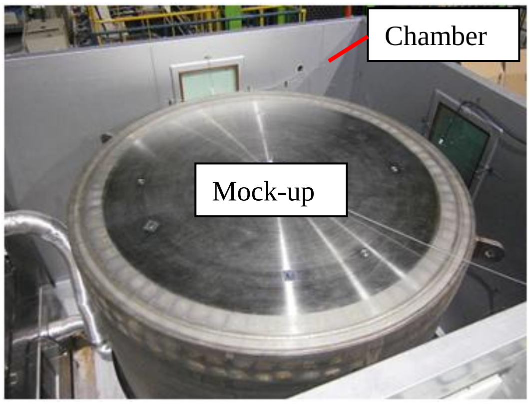


Figure 6 Mock-up in the Chamber

Experimental Method and Conditions

Salt Deposition of the mock-up

It is necessary to put salt on the mock-up surface for the SCC test. Artificial sea water was sprayed on the shell welding, shell near the top, ring plate welding and area applied with LPB on the mock-up surface (Fig.7, 8). To prevent sea water from dripping during the spraying process, the part of mock-up near the sprayed area was heated by electrical heater. The area in one spraying process was 75×75mm. After finishing spraying on one area, the spraying area was shifted to the neighbouring area. The amount of salt deposition was controlled by the time duration of spraying. In advance, the relation between the time duration of spraying and the amount of salt deposition was obtained. The deposition amount of chlorine ion was set to 4 g/m^2. This value is same as the previous test using the mock-up of the bottom part [11]. Threshold value of occurrence of SCC for SUS304L obtained by 4 bend specimens is 0.2 g/m^2 [12].

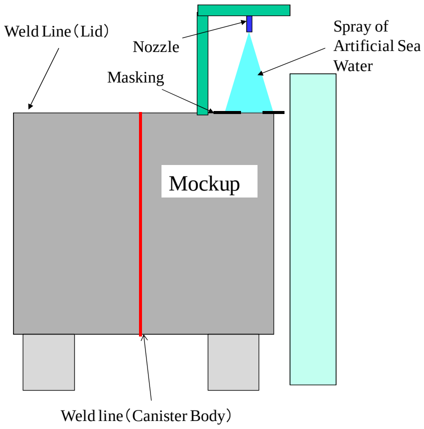


Figure 7 Outline of Spraying Process

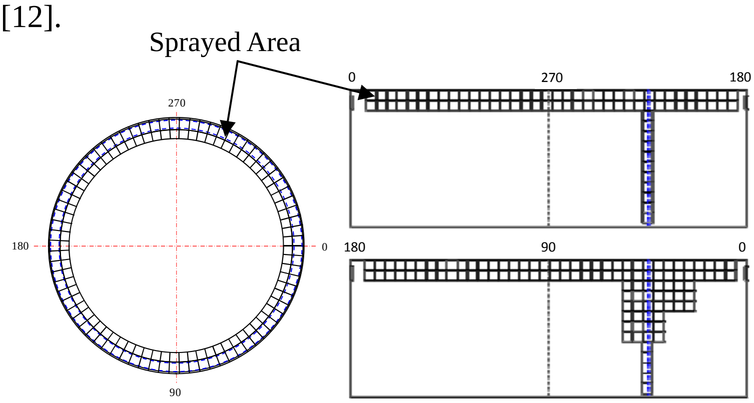


Figure 8 Sprayed Area

<u>Experimental Conditions</u>

The mock-up sprayed sea water was put into the temperature and humidity chamber. After closing the ceiling of the chamber, the operation of chamber was started. The conditions of the chamber were 80 degrees Celsius and 35% relative humidity. The experimental period was about 5000 hours. After stopping the operation of the chamber, the mock-up was taken out from the chamber.

Experimental Results

<u>Visual Testing (VT) and Fluorescent PT</u>

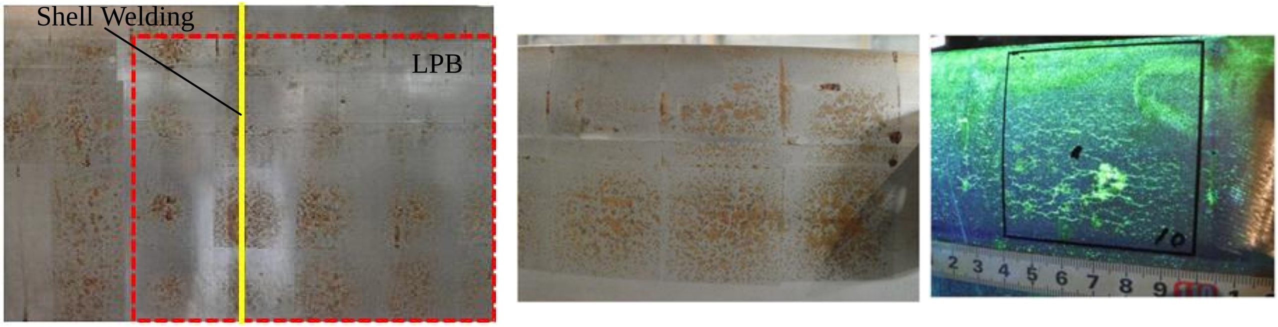
VT and Fluorescent PT were executed to the mock-up taken out from the chamber to check the state of corrosion and SCC. In the case of VT, general corrosion was observed in the whole area where the sea water was sprayed, including the area applied with LPB (Fig.9, 10). Suspicious areas of SCC were observed near the ring plate welding. The cracks were in a spider web shape (Fig.9 (b)(c)). In other areas, indications of the existence of SCC were not visible due to rust.

To check SCC clearly, Fluorescent PT was executed. Before Fluorescent PT, sea salt, dust and rust on the surface of mock-up were removed using a cloth dampened with cleaning solution. As a result of Fluorescent PT, the indications of SCC were additionally observed near the top of shell (Fig.10 (c)). The cracks were parallel to the top of shell. In this area, the shell was inclined to the inside because of lid and ring plate welding. It is presumed that surface stress in the axial direction is tensile.

Furthermore, indications of SCC were observed near the area of the lifting lug (Fig.11). The lifting lugs are welded only to this mock-up and not the actual canisters. Taking practical handling of the test into account, the lifting lugs were welded. If the temporary lifting lugs are welded during the fabrication process, it is necessary to pay attention to the residual stress after removing the lugs.

(a) After Test, Before Cleaning (b) After Test, After Cleaning (c) Fluorescent PT

Figure 9 Results of VT and Fluorescent PT in the area near the ring plate welding



(a) After Test, Before Cleaning (Shell welding and LPB Area) (a) After Test, Before Cleaning (Area near the Top of Shell) (c) Fluorescent PT (Area near the Top of Shell)

Figure 10 Results of VT and Fluorescent PT in the area near the shell welding and top of the shell

(a) Before Test (b) After Test, Before Cleaning (c) Fluorescent PT

Figure 11 Results of VT and Fluorescent PT in area near the Lifting Lug

<u>Crack Depth Measurements</u>

To determine SCC and measure the crack depth of SCC, the suspicious areas were selected by PT indications and cut into small plates of about 75×75mm in size. Fig.12 shows the positions where the plates were cut. Using these plates, surface cracks and cross-section of the cracks were observed using a microscope. Table 1 shows the measurement results of crack depth. Fig. 13 shows the cross section of the specimens.

On the LPB treated surface and shell welding area, SCC initiation was not observed. The measured crack depths were less than 4mm except for the area near the lifting lug welding. The results of crack depth were similar with four-point bend test results and SCC test of the bottom part mock-up [11]. The measured crack depth near the lug was about 7 mm.

As a result of this test, the effectiveness of LPB on SCC was confirmed.

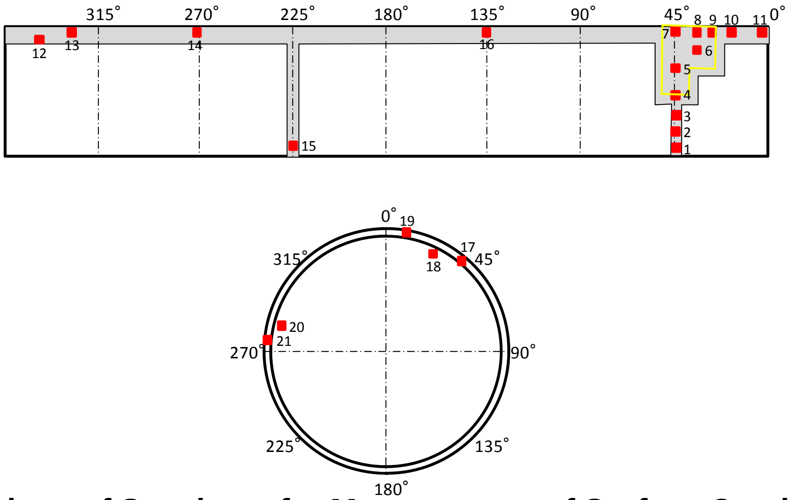
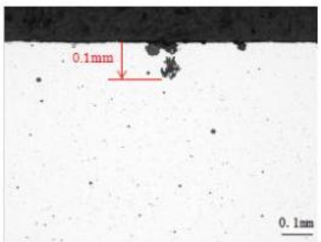


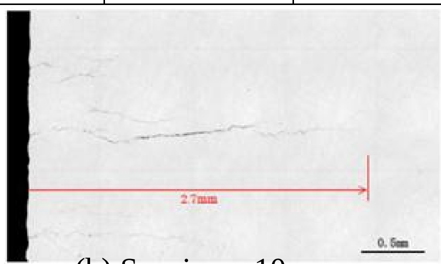
Figure 12 Positions of Specimen for Measurement of Surface Cracks and Crack Depth

Table 1 Measurement Results of Crack Depth

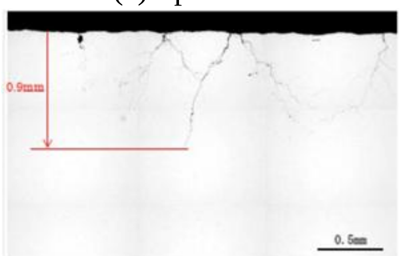
Specimen No	Crack Depth(mm)	Specimen No	Crack Depth(mm)	Specimen No	Crack Depth(mm)
1	No crack	8	1.1	15	No crack
2	0.1（Pitting）	9	1.1	16	3.8
3	No crack	10	2.7	17	1.0
4	No crack	11	7.2	18	1.4
5	No crack	12	No crack	19	0.9
6	No crack	13	2.2	20	0.7
7	1.8	14	0.3	21	0.6



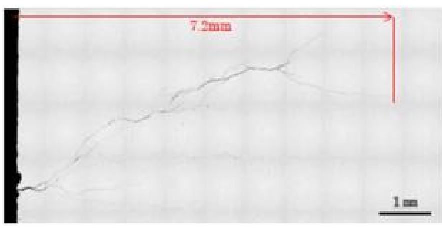
(a) Specimen 2



(b) Specimen 10



(c) Specimen 19



(d) Specimen 11

Figure 13 Photographs of Measurement of Crack Depth

Conclusions

To develop the evaluation method of SCC of canisters and verify whether SCC occurs or not, the SCC demonstration test was performed using the mock-up of canister lids with ring plates. The mock-up for the experiment is full-scale in diameter but short in length. To confirm the effectiveness of the residual stress mitigation method, LPB technology was applied to the shell surface part. For the SCC test, artificial sea water was sprayed to the shell welding, shell near the top, ring plate welding and area applied with LPB of the mock-up surface. The mock-up was put into a temperature and humidity chamber. The experimental period was about 5000 hours. After stopping the operation of the chamber, the mock-up was taken out from the chamber and several investigations were performed. The following results were obtained.

- With VT and Fluorescent PT, indications of SCC were observed near the ring plate welding and the top of the shell. In other areas, the indication of the existence of SCC was not visible due to rust.
- Using the plates cut from the mock-up, surface cracks and cross-section of the cracks were observed. On the LPB treated surface and shell welding area, SCC initiation was not observed. For SCC near the ring plate welding and the top of the shell, measured crack depths were less than 4mm. The results of crack depth were similar with four-point bend test results and SCC test of the mock-up of the bottom part.
- Effectiveness of LPB to SCC was confirmed.

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