Irradiation Tests of the Sleeve for the Telescopic Arm of the ITER Blanket Remote Handling System

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The ITER blanket remote handling system (BRHS) must operate with high precision within the confines of the ITER vacuum vessel, which will become a gamma-ray environment filled with radioactive dust. The main structural component of the BRHS, a telescopic arm, will be covered with a sleeve that must prevent not only the radioactive dust from infiltrating into the system but also lubricant from leaking out into the vacuum vessel. Verifying the radiation resistance of this sleeve is crucial and will ultimately affect the operation scenarios and timing of preventive maintenance for the BRHS. Thermoplastic polyurethane was selected as a candidate material for the sleeve. This paper presents the results of gamma-ray irradiation tests up to either 1 MGy or 2 MGy for polyurethane sheets and the results of subsequent bending, tensile, and hardness tests. Based on the results of these tests, mock-ups of the sleeve were manufactured and were also irradiated up to either 1 MGy or 2 MGy, after which the mock-ups underwent expansion and contraction tests to simulate actual operations in ITER. We have concluded from conservative estimates that, although these polyurethane sleeve mock-ups have over 1 MGy of radiation resistance, the sleeves of the BRHS should be replaced at 1 MGy.

Keywords: ITER, blanket remote handling system, remote maintenance, radiation resistance

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1. Introduction

The ITER blanket remote handling system (BRHS), shown in Fig. 1, will exchange the blanket modules (composed of first wall panels and shield blocks) in the vacuum vessel after plasma shutdown [1]. These blanket modules can weigh up to 4.5 tonne and must be handled stably and with a high degree of positioning accuracy in a high radiation environment. The in-vessel components of ITER will be activated by neutrons, resulting in gamma-ray radiation, which in turn may cause the remote handling components of the BRHS to degrade. In this study, we focused on the radiation resistance of the BRHS components. The most important operation for the BRHS is a two-year maintenance campaign in which all 440 first wall panels must be replaced. This campaign is scheduled at the beginning of D-T operation, during which the dose rate in the vacuum vessel is estimated to be 250 - 500 Gy/h [2]. The radiation resistance of the BRHS components should be confirmed to assess the timing of preventive maintenance of the BRHS in the two-years campaign. The telescopic arm of the BRHS (Fig. 2) has a sleeve covering to prevent radioactive dust from entering the system and prevent lubricant from leaking out of the telescopic arm and into the vacuum vessel. This paper reports the results of irradiation tests on polyurethane sheets and sleeve mock-ups.

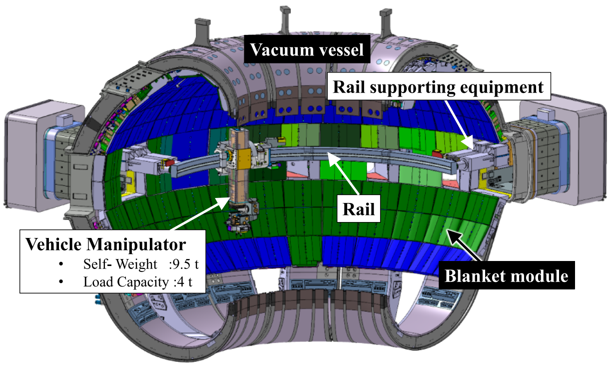

Fig. 1 ITER blanket remote handling system.

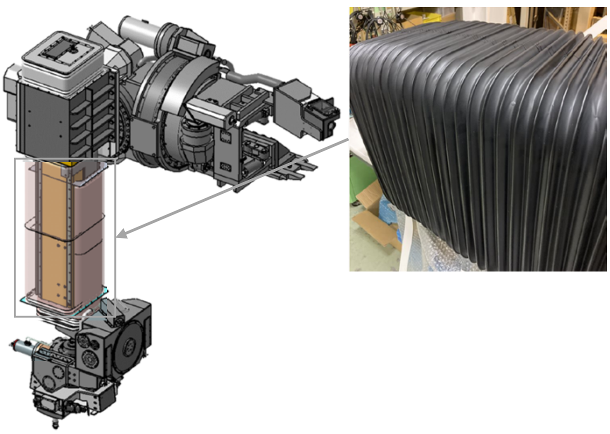

Fig. 2 Telescopic arm and sleeve.

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2. Experiments

The blanket modules will be regularly replaced by the BRHS. A polyurethane sleeve having a bellows-like structure covers the telescopic arm of the BRHS to avoid being contaminated by radioactive materials and also to avoid contaminating the vacuum vessel with lubricant from the BRHS. We examined the gamma-ray radiation resistance of the polyurethane sleeve material. Subsequently, mock-ups of the sleeve were made. The mock-ups were subjected to irradiation tests using gamma-rays from a cobalt-60 (Co^{60}) source. After irradiation, the mock-ups underwent expansion tests to verify durability. Infrared spectra were also used to investigate the degradation mechanism.

2.1 Irradiation tests of polyurethane as a candidate material for the sleeve

Polyurethane sheets (210 mm × 297 mm, 0.3 mm in thickness, shown in Fig. 3) were irradiated at 3700 Gy/h to either 1 MGy or 2 MGy. Two types of sheets (with adhesion and without adhesion) were prepared to confirm whether adhesion affects strength. These sheets were irradiated at ambient air without humidity control at the Co^{60} gamma-ray irradiation facility of the Takasaki Institute for Advanced Quantum Science [3]. Irradiation dose rates for the sheets were estimated according to their distance from the radiation source.

After the sheets were irradiated, test pieces were cut from the sheets according to the standard Japanese Industrial Standards (JIS) K 7161 (Fig. 4). Bending tests, tensile tests, and hardness tests were performed on these test pieces. For the bending tests, each test piece ($N = 3$) was secured to a testing machine (NABELL Corporation proprietary model, 40-mm strokes, test speed of 7 mm/min) and was bent for 10000 strokes. The test machine's stroke value of 40 mm is approximate to the distance between the rings of the actual sleeve (45 mm). Changes in physical appearance of the test pieces were verified by visual inspection (Fig. 5). According to the manufacturer (NABELL Corporation), wrinkles in the material could potentially lead to failure so visual inspections were conducted to check for the presence of wrinkles on the test pieces. The tensile tests were performed according to JIS K 7161, Sec. 3.6.4. Each test piece ($N = 3$) was grasped from both ends by a testing machine and then pulled until they fractured. The maximum load and elongation percentage (displacement) were measured by dividing the displacement of the head unit of the testing machine throughout elongation by the initial distance between the grips. The acceptance criteria was to be within ±20% of the initial value after irradiation. The hardness tests were performed according to JIS K 7311. An indenter struck each test piece ($N = 3$) at a pressurized load of 1 kgf and hardness values of the individual test pieces (0.3 mm thickness) were obtained based on the depth of the indenter. The acceptance criteria was to be ±2 of the pre-irradiation value (Shore A hardness scale). All tests were performed 3 times with 3 different test pieces to examine reproducibility.

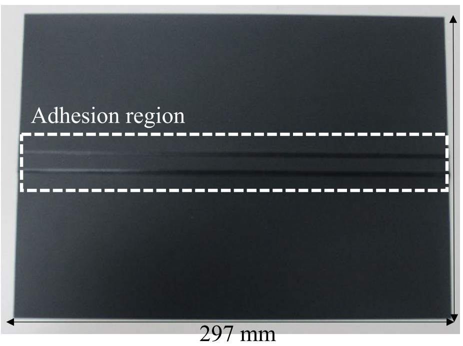

Fig. 3 Sheet sample with adhesion.

2.2 Manufacturing and irradiation tests of sleeve mock-ups

Sleeve mock-ups were manufactured based on the promising results of the tests using the polyurethane material. Table 1 shows the specifications of the sleeve mock-ups. These sleeve mock-ups have a square, bellows-type structure that fits over the telescopic arm. Square shaped sleeves, however, are prone to stress-induced creases because the folds of the bellows fold inwards and concentrate stresses at the corners. The edges of the sleeve end plates also tend to crack if they come into contact with the edges of the sheets of the sleeve. These sleeve mock-ups were designed with radiation- resistant materials, such as type 304 stainless steel (SUS304) for the rib rings and polyether

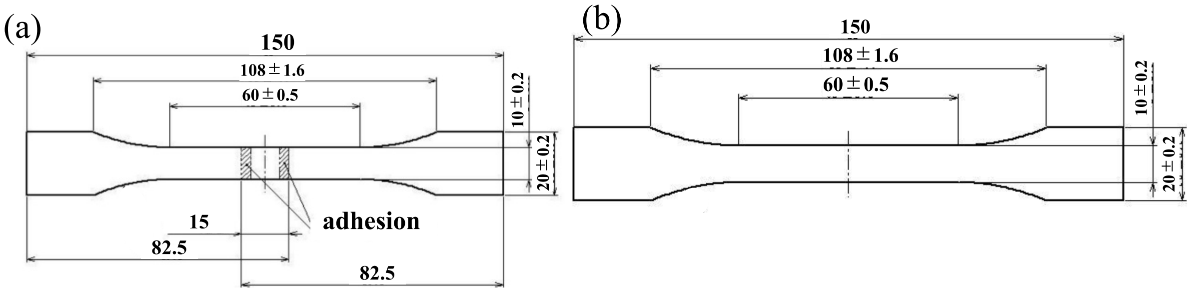

Fig. 4 Dumbbell-shaped test pieces (a) with adhesion and (b) without adhesion.

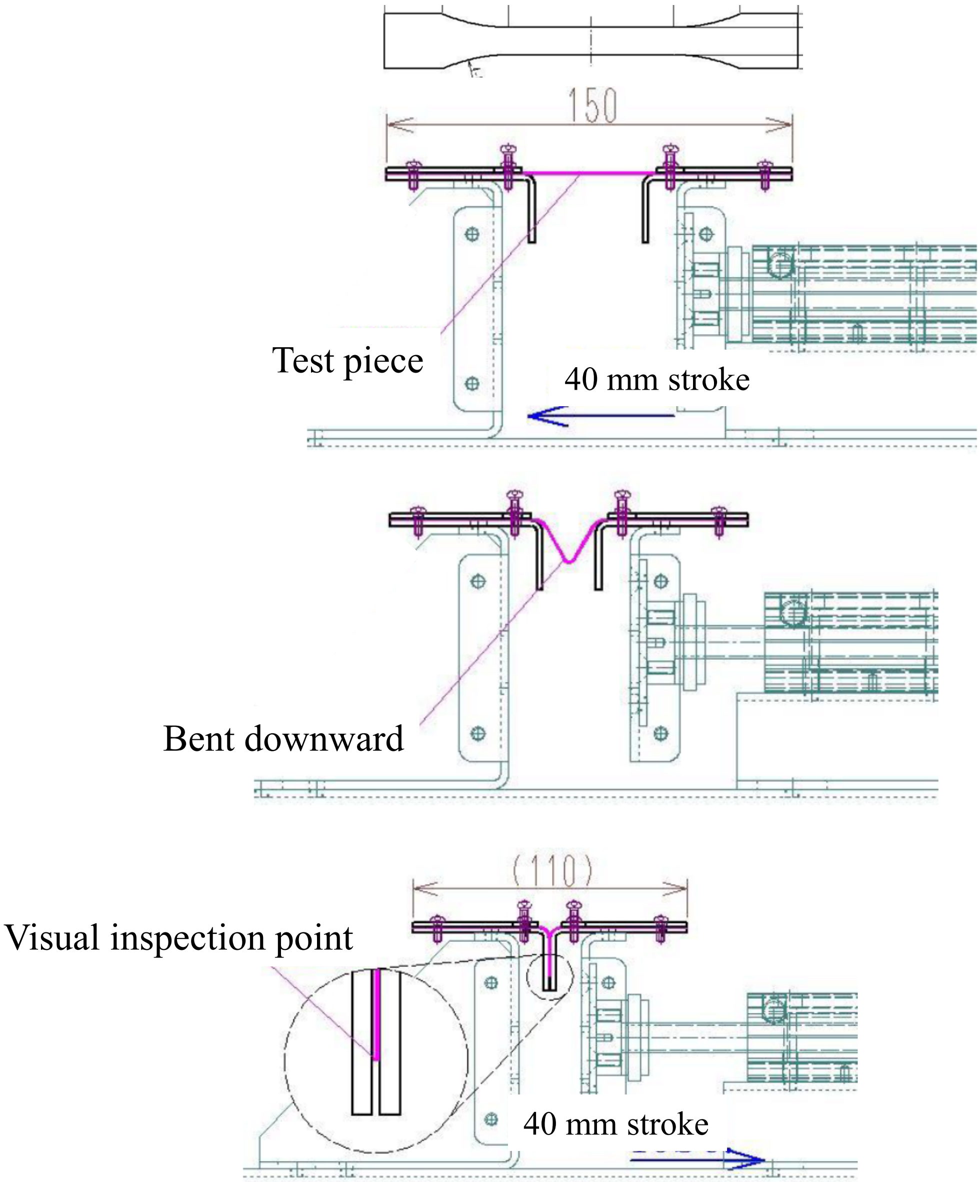

Fig. 5 Bending test machine operation and test piece visual inspection point.

Table 1 Sleeve mock-up specifications.

Materials	Sleeve: thermoplastic polyurethane (polyester), thickness of 0.3 mm End plates, frame plates, rib rings: SUS304 Intermediate supports: PEEK, thickness of 2 mm
Size	410 mm × 550 mm Contracted length: 110 mm Expanded length: 805 mm
Travel length	695 mm (Half of actual BRHS design)
Weight	13 kg
Number of mock-ups	2 (N = 1 for 1 MGy and 2 MGy)

Table 2 Design customizations for the BRHS sleeve mock-ups.

Part	
Corner rounding chamfer	R = 90 mm Corner rounding chamfer was maximized, thus reducing wrinkling of the sleeve material at the corners.
Distance between rings	31.5 mm
Rib ring diameter	3 mm
Frame plate corners	Rounding chamfer R = 1.5 mm The edges of the frame plates are chamfered to mitigate contact with the sleeve material.
Two-row adhesion positions	Two-rows of adhesion Each row is 2.5 mm wide.

ether ketone (PEEK) for the intermediate supports [4]. Table 2 lists the customizations made to commercial-off-the-shelf sleeves that were used for the BRHS sleeve mock-ups, such as corners and rings to maintain the shape and functionality of the sleeve even after they have been irradiated.

The sleeve mock-ups were irradiated at 150 - 2670 Gy/h, as determined by the distance from the Co^{60} source. The sleeve mock-ups themselves were quite large, thus the dose rate differed considerably between the side nearest to the source and the side furthest from the source. Accordingly, the dose rates were measured at six different points around each sleeve mock-up (Fig. 6) and the sleeve mock-ups were physically moved so that all six measurement points were irradiated uniformly up to either 1 MGy or 2 MGy. Sleeve mock-ups were fully contracted for the irradiation tests, which were conducted at ambient air without humidity control, as the irradiation tests of the sheets. After irradiation the sleeve mock-ups were attached to a testing machine, a schematic drawing of which is shown in Fig. 7.

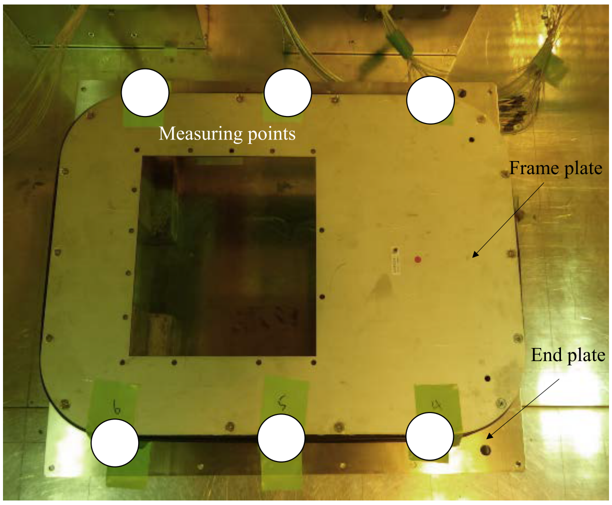

Fig. 6 Six measuring points for the sleeve mock-ups (radiation source is located at the upper side).

2.3 Expansion/contraction tests and surface analysis by FT-IR

After irradiation, the sleeve mock-ups were attached to the testing machine and expansion tests were performed using the testing machine in Fig. 7 and the conditions shown in Table 3. Overviews of the testing machine system and driving mechanism are shown in Figs. 9 and 10,

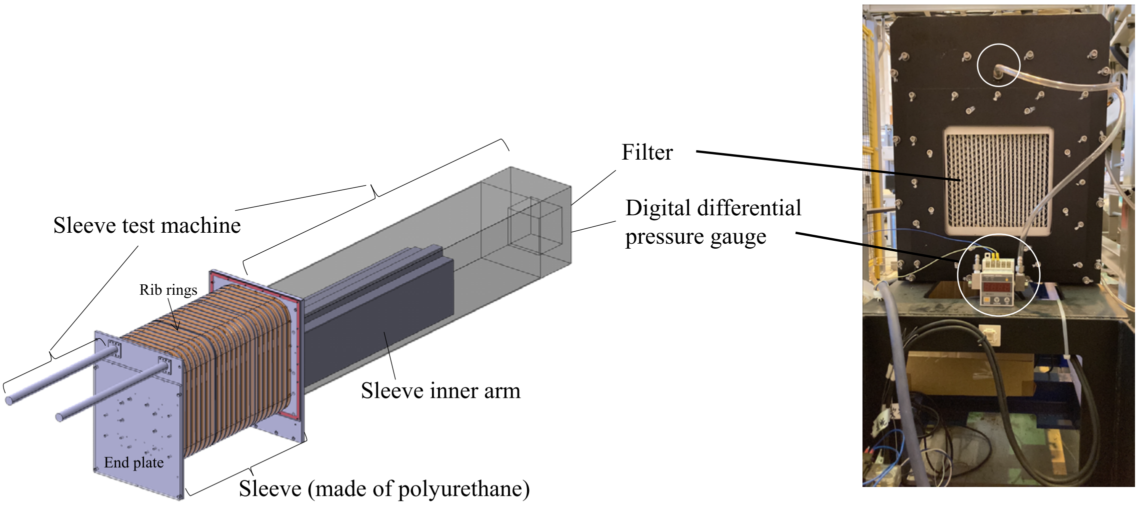

Fig. 7 Schematic drawing of the sleeve mock-up testing machine.

Table 3 Testing machine specifications and test conditions.

Test speed	277.8 mm/min
Number of strokes	450
Driver	AC servo driver GDR-2
Control software	LabVIEW 2015 (National Instruments Co., Ltd)
AC servomotor	BNRII075BC (Waco Giken Co., Ltd)
Gear reducer	ANFX-P130N-8ELD-45 (Sumitomo Heavy Industries, Ltd.)
Filter	Standard HEPA (ATM-1.5-Q) (from Nippon Muki Co., Ltd) 200 mm L × 200 mm W × 150 mm D
Digital differential pressure gauge	1 GC62-241-30N280 (Nagano Keiki Co., Ltd)
Data logger	NR500 (Keyence Co., Ltd)

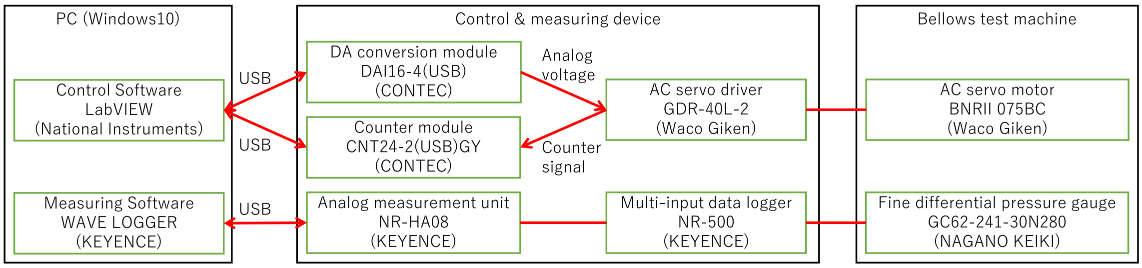

Fig. 9 Testing machine system overview.

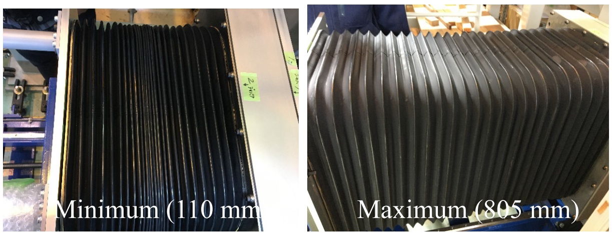

Fig. 8 Contracted length and expanded length of the sleeve mock-up.

respectively. The sleeves were expanded and contracted by a servomotor, which drives a rolled ball screw via a planetary gear reducer. The rated speed of the motor was 278 mm/min. Thus, one full stroke (expanding and contracting the sleeve mock-ups, Fig. 8) takes approximately 5 minutes. The expansion and contraction of the sleeve mock-ups were controlled by a program called LabVIEW (version 2015 made by National Instruments Co., Ltd), which regulates and monitors servomotor speed by using analog voltage commands via a digital/analog conversion module and servomotor position by using counter signals via a counter module. The LabVIEW program provides only simple speed control and position monitoring, not precise position control. The servo driver was configured to operate at a constant speed because it performs proportional-integral control based on speed commands. After a default number of strokes, the servo driver decelerates and returns to its original position. The sleeve mock-ups were also monitored for holes or tears by using a differential pressure gauge installed at the rear of the testing machine and an analog measurement unit. A HEPA filter was also installed at the rear of the testing machine because the ITER BRHS sleeve will require ventilation to prevent the sleeve from rupturing and the support rings from dislodging as the internal pressure increases. This ventilation passage must be covered with a filter to prevent dust from entering [5].

The number of cracks on the sleeve mock-up irradiated up to 2 MGy was confirmed by submersion tests, the test apparatus for which is shown in Fig. 11. One side of the sleeve mock-up was sealed and secured vertically in a water basin (the sleeve mock-up endplates are airtight at

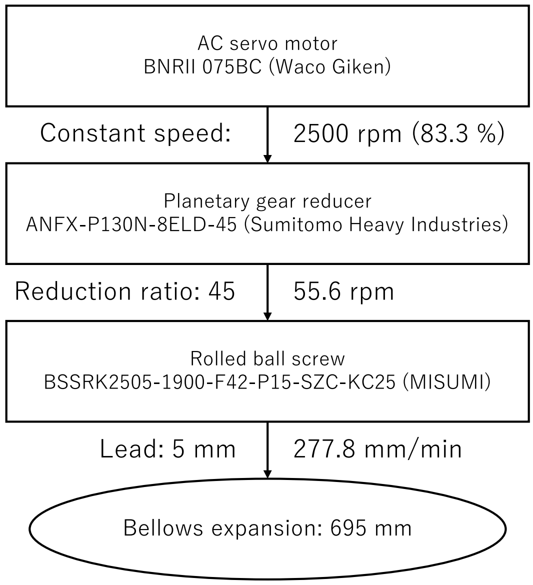

Fig. 10 Testing machine drive mechanism.

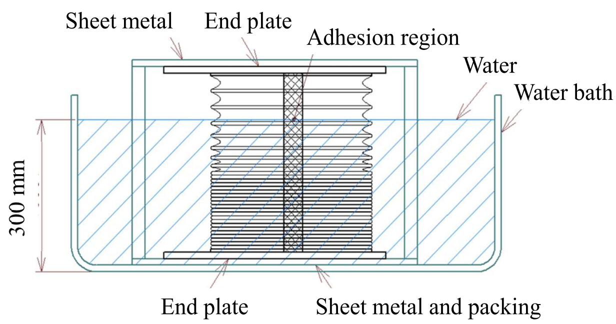

Fig. 11 Submersion test apparatus.

both sides). Water was filled to the halfway point of the sleeve mock-up and it remained submerged for 30 minutes to check for cracks. After 30 minutes, the mock-up was flipped over on its opposite side and the procedure was repeated.

Since the sleeves are made of ester-based polyurethane and the humidity was not controlled during the irradiation, hydrolysis was expected as a cause of degradation [6]. We performed Fourier transform infrared spectroscopy (attenuated total reflectance, ATR-

Table 4 FT-IR measurement conditions.

Measurement method	Attenuated total reflection (ATR)
Resolution	4 cm^{-1}
Detector	Mercury cadmium telluride (MCT)
Number of times of integration	64
FTIR spectral data	Sadlter spectra database
Notes	-The peaks around 2350 cm^{-1} from CO_2 in the measurement environment were deleted from Fig. 18. -In the ATR method, the peak intensity varies depending on the contact area between the prism and sample. Therefore, peak intensities cannot be compared between figures (Fig. 18 (a)-(c)).

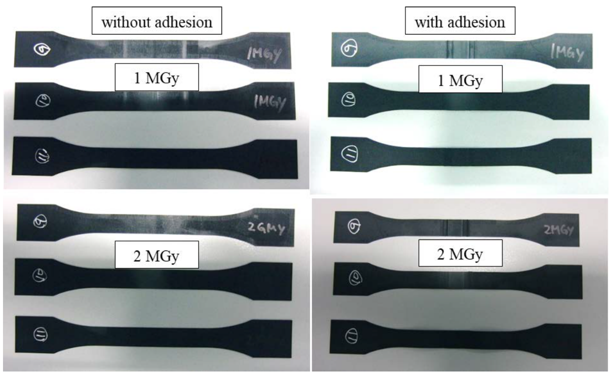

Fig. 12 Test pieces after bending tests (three test pieces were cut out from each sheet and labelled a, b, and c).

FTIR) to analyze the cause of the polyurethane sheet degradation [7, 8]. Nicolet iN10 MX and Nicolet 6700 measurement devices (Thermo Fisher Scientific Inc.) were used, the measurement conditions of which are shown in Table 4.

3. Results and Discussion

3.1 Radiation resistance of polyurethane as the sleeve material

No cracks or fractures were observed in the dumbbell-shaped test pieces irradiated up to 1 MGy or up to 2 MGy even after 10000 bending strokes, as shown in Fig. 12. Figures 13 (a) and (b) show the changes in test piece elongation from before irradiation (0 MGy) to after irradiation (1 MGy and 2 MGy) for test pieces without or with adhesion, respectively. A decrease in elongation was observed in both cases. In particular, the elongation percentages were lower in the test pieces having adhesion. All test pieces having adhesion broke at their adhesion zones, which suggests that adhesion decreases tensile strength. However, owing to the structure of the sleeves, tensile forces were quite low. Figure 14 shows the hardness of the test pieces before irradiation (0 MGy) and after irradiation (1 MGy and 2 MGy). There was virtually no change in hardness after irradiation. These results satisfy the acceptance criteria, and polyurethane can be used as the material for the BRHS sleeves. Sheet hardness did not affect adhesion, so the sheets were not differentiated based

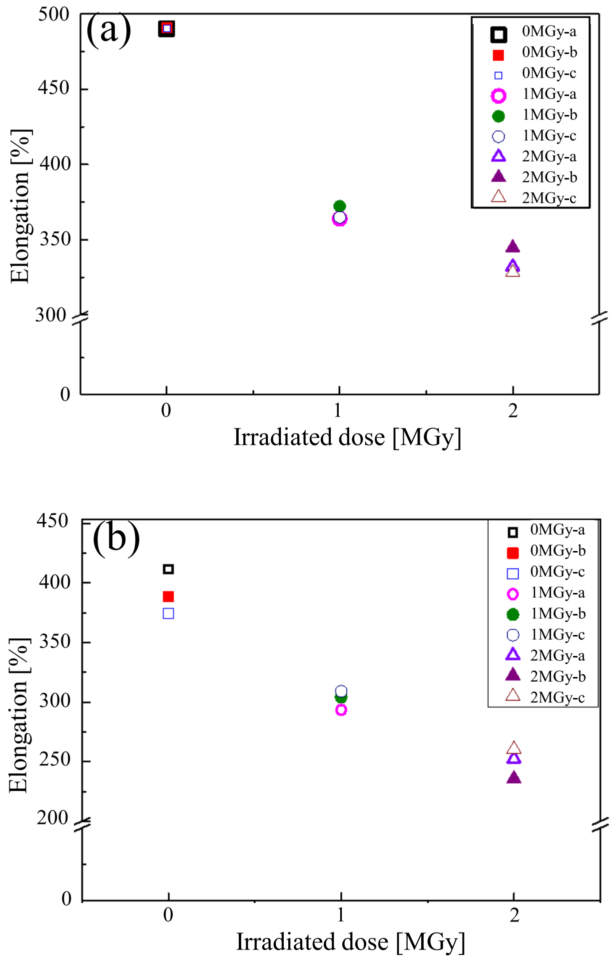

Fig. 13 Elongation percentage (measured by the method described in 2.1) of test pieces after irradiation (a) without adhesion and (b) with adhesion.

Fig. 15 Sleeve irradiated up to 1 MGy and after moving 450 strokes.

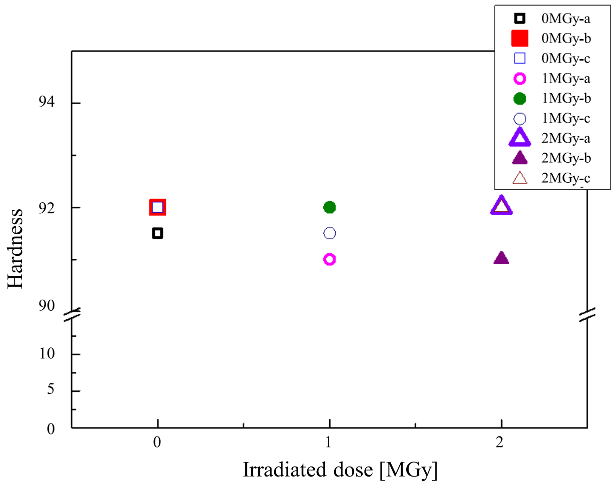

Fig. 14 Shore A Hardness (measured by the method described in 2.1) of test pieces after irradiation.

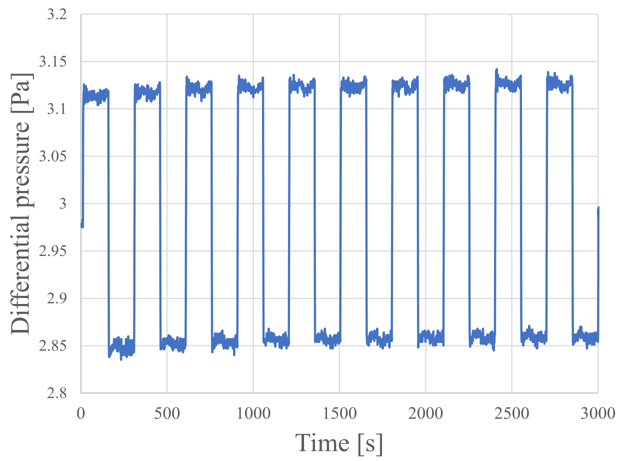

Fig. 16 Differential pressure gauge data (pressure outside the sleeve relative to pressure inside the sleeve) from the 1 MGy sleeve.

on hardness. The sheet material itself is not being pulled, rather, the material is folded in on itself, and then is extended and contracted. Although the elongation percentage of the sheets decreased, the polyurethane material can be used in the sleeves up to 2 MGy because it is resistant to bending.

3.2 Expansion/contraction tests and degradation mechanism of the sleeve

The sleeve mock-up irradiated up to 1 MGy and after moving 450 strokes is shown in Fig. 15. The corners and adhesion zones of the sleeve were illuminated and observed every 10 strokes, but no cracks were observed. The differential pressure outside the sleeve relative to inside the sleeve was also measured, as shown in Fig. 16. Based on the data given in this figure (no change in pattern), we determined there were no cracks. Since a HEPA filter was attached at the rear of the test machine, as shown in Fig. 6, air flows through the filter as the sleeve expands and contracts. However, because the sleeve expands/contracts at a constant speed, the change rates of volume and differential pressure were constant, i.e., the differential pressure gauge data has a rectangular block pulse waveform. Submersion testing to check for cracks was not performed after irradiation up to 1 MGy. However, for the sleeve mock-up irradiated up to 2 MGy, after moving 420 strokes, cracks were observed on the corners, as shown in Fig. 17, even though the differential pressure gauge data did not fluctuate abnormally. As a result of the submersion tests, nine cracks were observed at the corners of the sleeve mock-up irradiated up to 2 MGy.

Figure 18 shows the FT-IR spectra before and after irradiation, with the horizontal axis showing the wavenumber (cm^{-1}) and the vertical axis showing the absorbance. Ester polyurethanes, as the name implies, have ester bonds (-COO-) and urethane bonds (-NHCOO-). The peak at 3335 cm^{-1} indicates urethane N-H bonds (measured value is 3333 cm^{-1} in Fig. 18) and the peak at 1732 cm^{-1} indicates polyester polyol esters. Hydrolysis of ester polyurethanes results in the formation of carboxylic acid and alcohol. This hydrolysis also cleaves the urethane bonds, which forms an amine. Therefore, as polyester moieties hydrolyze, the peak at 1732 cm^{-1} is expected to decrease, and the peak at 3335 cm^{-1} is expected to increase

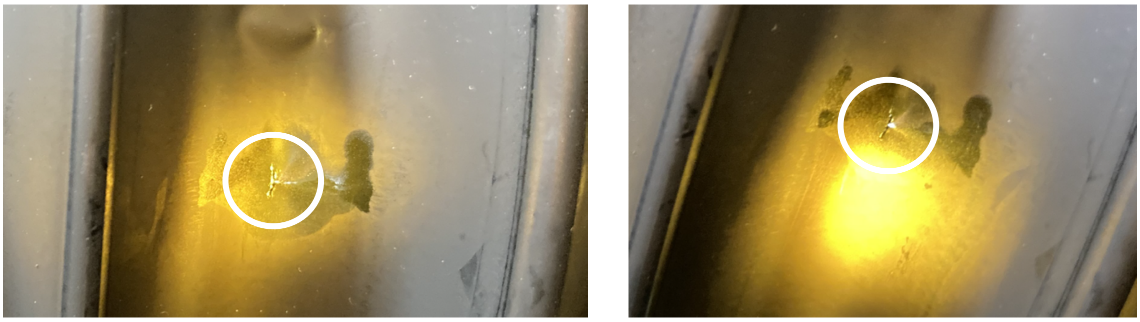

Fig. 17 Sleeve irradiated up to 2 MGy and after moving 420 strokes.

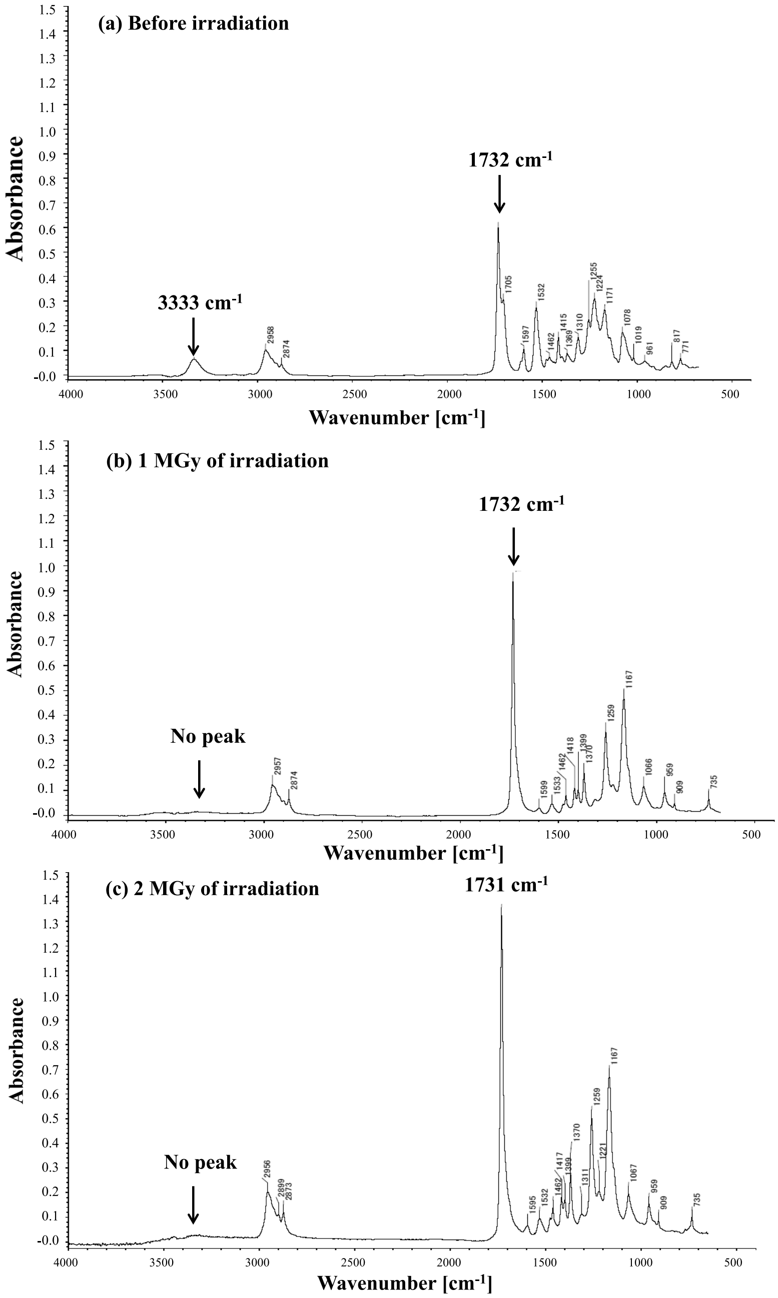

Fig. 18 FT-IR spectra (a) before irradiation, (b) after 1 MGy of irradiation, and (c) after 2 MGy of irradiation.

with additional peaks of NH_2, -COOH, and -OH. Comparing the spectra after 1 MGy and 2 MGy of irradiation (b and c, respectively) with the spectrum before irradiation (a), almost no change was observed in the polyester moieties owing to hydrolysis. On the contrary, the peak from the urethane bonds decreased, indicating reduction in molecular weight. After irradiation up to 2 MGy, degradation occurred only in the mock-up test and not in the sheet test.

3.3 Applicability of the polyurethane sleeve

This anomaly as described in 3.2 (sheets irradiated up to 2 MGy were maintained their structural integrity but the mock-ups irradiated up to 2 MGy fractured) can be attributed to the low dose rates in the sleeve mock-up tests. The mock-ups were irradiated at a dose rate of 4% at the low end and 70% at the high end compared with the sheet test. Therefore, the cracks observed after 2 MGy in the mock-up irradiation tests are considered to be due to the lower irradiation rate. Urethane oxidizes about 0.2 mm from the surface when irradiated at low dose rates via molecular chain scission [9]. In the sheet tests, no oxidative degradation occurred owing to the higher dose rate. In the mock-up tests, however, oxidative degradation (molecular chain scission) occurred because of the lower dose rate. Since the dose rate during the mock-up test is similar to the actual conditions of ITER, the results of the mock-up test are considered to show the radiation effects on the sleeve in the ITER vacuum vessel. Furthermore, considering that the sleeve in ITER will perform 450 strokes while being irradiated (not after being irradiated) up to 2 - 3 MGy, these sleeve mock-ups tests are conservative compared with the actual conditions of ITER because the 420 strokes were performed after being irradiated up to 2 MGy.

4. Conclusion

Thermoplastic polyurethane sheets and sleeve mock-ups were irradiated up to 2 MGy. We confirmed that the polyurethane sheets kept their typical characteristics (structural integrity) even after 2 MGy of irradiation. However, the mock-ups developed several cracks after 2 MGy of irradiation and after moving 420 strokes. We consider that this disparity is due to the difference in the dose rate; the sheets were irradiated at a high dose rate (3700 Gy/h) and the mock-ups were irradiated at a low dose rate (150 - 2670 Gy/h). Moreover, the cause of urethane degradation was not hydrolysis. Rather, it was oxidation (molecular chain scission) according to the results of FT-IR spectroscopy. Since the dose rate used to irradiate the mock-ups is similar to the actual dose rate of ITER, we expect that the sleeve will degrade at around 2 MGy of irradiation in the ITER vacuum vessel. Therefore, the sleeve should be replaced with a new sleeve at 1 MGy of irradiation as a preventive maintenance measure for the ITER BRHS.

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Disclaimer

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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