INFLUENCE OF PRESSURE AND TEMPERATURE ON THE FATIGUE STRENGTH OF TYPE-3 COMPRESSED-HYDROGEN TANKS

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ABSTRACT

The pressure of compressed hydrogen changes with temperature when mass and volume are constant. Therefore, when a compressed-hydrogen tank is filled with a certain amount of hydrogen it is necessary to adjust the filling pressure according to the gas temperature. In this study, we conducted hydraulic pressure-cycle tests to investigate the fatigue life of Type-3 compressed- hydrogen tanks when environmental temperature and filling pressure are changed. The results indicated that the fatigue life at low temperatures (-40°C, 28MPa) and room temperature (15°C, 35MPa) was almost equal. However, the fatigue life at high temperatures (85°C, 44MPa) was shorter than that under other conditions, suggesting that stress changes caused by thermal stress affect the fatigue life of the Type-3 tank.

1.0 INTRODUCTION

Compressed-hydrogen tanks for vehicles are fatigued by cycles of filling and consumption, so evaluation of their fatigue life is essential. As methods for assessing their fatigue life, the hydraulic-pressure-cycle test and the hydrogen-gas-cycle test are discussed in Global Technical Regulations (GTR) on hydrogen and fuel cell vehicles. The hydraulic- pressure-cycle test for 10,000 cycles can be completed within a few days because the cycle time is under one minute per cycle. In contrast, the hydrogen gas-cycle test requires one to two hours per cycle and requires a few months to complete. Therefore, it is desirable to evaluate fatigue life with the hydraulic-pressure-cycle test. While the tank temperature is constant under hydraulic-pressure cycles, the gas temperature changes simultaneously with the pressure in the tank during hydrogen-gas cycles, so the tank temperature will not remain constant [1-3]. Furthermore, when a compressed-hydrogen tank is filled with a certain mass of hydrogen, the filling pressure must be changed according to the gas temperature. Therefore, to judgment a tank filled up, it is necessary to use State of chargh (SOC) which is filling degree based on the hydrogen mass in the tank. If the case in which filling such a mass of hydrogen results in 35MPa at 15°C is assumed to be SOC 100% filling, the SOC 100% is achieved when the result is approximately 28MPa at -40°C or approximately 44MPa at 85°C. From current research, it is known that the fatigue life of compressed-hydrogen tanks is influenced by filling pressure and temperature [4,5].

To establish a fatigue-life evaluation method for tanks in Global Technical Regulations (GTR) on hydrogen and fuel cell vehicles, it is necessary to examine whether the hydrogen-gas-cycle test can be replaced with the hydraulic-pressure-cycle test based on the above-mentioned differences. Therefore, we implemented hydraulic-pressure-cycle tests on the assumption of filling at SOC 100% while changing the environmental temperature and pressure, and then investigated the influence of the tests on the fatigue life of a Type-3 tank. Furthermore, we investigated liner stress by measuring the strain on inner surface of the liner to determine the liner stress when the environmental temperature and pressure changed.

2.0 MATERIALS AND METHODS

2.1 Materials

A total of eight Type-3 tanks of the same model were used for the tests (each of two tanks under four different test conditions). Table 1 lists the specifications for the tank (Fig. 1). The whole aluminum liner of the Type-3 tank is fully wrapped with Carbon Fiber Reinforced Plastic (CFRP) using the filament winding method. In this case, thermal stress due to changes in temperature can be expected because the thermal expansion rate differs significantly between aluminum alloy and CFRP.

Table 1. Specifications for the test tank

Specification	Type-3 tank complied with JARI S 001
Filling pressure	35 MPa
Volume	28 L
Diameter x Length	280 x 730 mm
Liner material, Coefficient of thermal expantion	Aluminum alloy (A6061-T6), 24.3 $\times 10^{-6}$/°C
Reinforcing material, Molding method, Coefficient of thermal expantion	CFRP, Filament winding, 0~1 $\times 10^{-6}$/°C

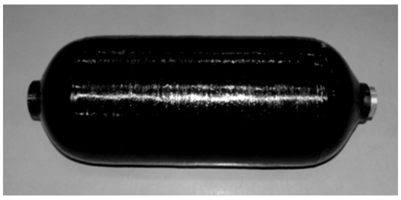

Figure 1. Test tank

2.2 Conditions of the pressure-cycle tests

Pressure-cycle tests were conducted on each of two tanks under totally 4 conditions(see Table 2). Three conditions assuming SOC 100%: at low temperature (LT: -40°C, 28MPa), at room temperature (RT: 15°C, 35MPa), and at high temperature (HT: 85°C, 44MPa). One condition specified in JARI S 001[6] Room-Temperature Pressure-Cycle Test (NT: Normal temperature (15°C to 35°C, with no temperature control), 44MPa, corresponding to SOC 125%). Each tank was soaked at each condition until fluid temperature in the tank become equal to environmental temperature.

Table 2. Conditions of pressure-cycle tests

	LT	RT	HT	NT
Environmental temperature	-40°C	15°C	85°C	15°C~35°C
Maximum pressure	28 MPa (FP×80%)	35 MPa (FP×100%)	44 MPa (FP×125%)	44 MPa (FP×125%)
Minimum pressure	0 MPa (FP×0%)			
Fluid (medium)	Perfluoro-polyether	Deionized water		
Frequency	15 sec/cycle			
Waveform	Sine curve			
Termination	Occurrence of leak before break			

*FP : normal Filling Pressure = 35 MPa

2.3 Liner strain measuring method

For a Type-3 tank, fatigue of the liner often determines the fatigue life of the tank. In this case, the fatigue life is determined by the stress range of the liner. However, strain measurements taken on the outer surface of the tank, as commonly implemented, can measure only the strain in the CFRP and therefore cannot determine the liner stress. To determine the exact liner stress, we developed a measurement method that attaches strain gages on the inner surface of the liner and extends a measurement cable to the outside of the tank. Using this arrangement, we measured the strain on the inner surface of the liner for this study (Fig. 2).

Stresses applied to the Type-3 tank included residual stress, stress due to internal pressure, and thermal stress. By measuring the liner strain directly, we measured these stresses discretely to determine the liner stress.

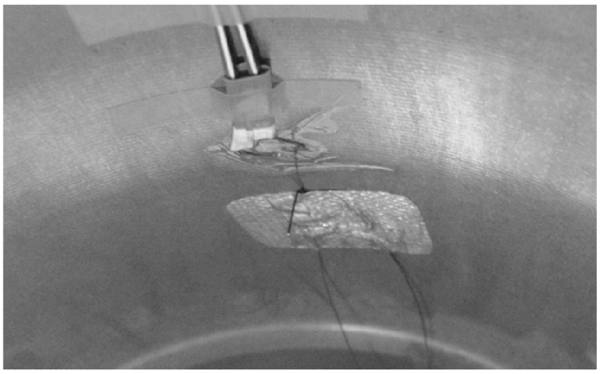

Figure 2. Measuring strain in the liner

2.4 Residual stress measuring method

Type-3 tanks are subjected to autofrettage in order to improve their fatigue strength. In autofrettage, internal pressure sufficient to cause the stress of the aluminum liner to exceed the proof stress is applied to the tank so as to deform the liner outward plastically. In this case, because the CFRP is deformed within its elastic range, the CFRP compresses the expanded liner when the internal pressure has been removed. Therefore, compressive stress resides in the liner and tensile stress resides in the CFRP layer, so the stress in the tensile direction that occurs in the liner during hydrogen filling is partially offset by the residual compressive stress.

After the pressure-cycle test, strain gages were attached to the outer surface of the CFRP and the inner surface of the liner. The residual strain was then measured by cutting the tank at room temperature to release the residual strain. The residual-strain measuring method is illustrated in Fig. 3.

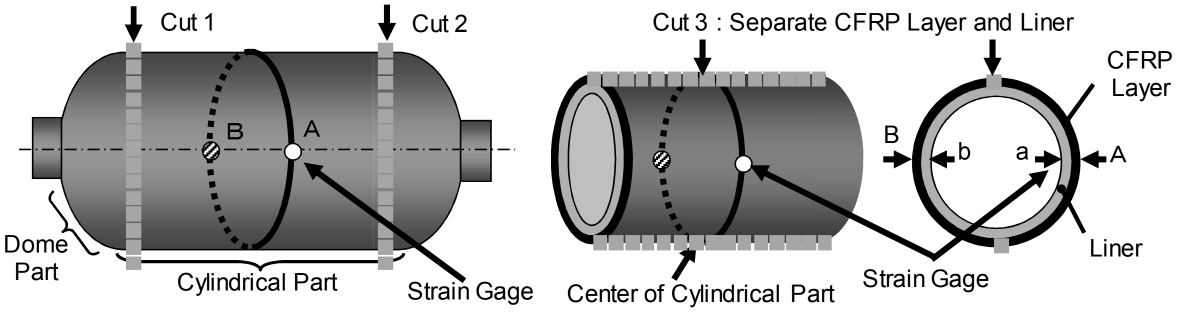

Figure 3. Measuring residual strain

2.5 Measuring method for stress due to internal pressure

Strain gages were attached to the outer surface of the CFRP and the inner surface of the liner near the center of the tank. The strain due to internal pressure was measured by applying pressure to the tank. The stress was calculated from the result of this measurement.

2.6 Thermal stress measuring method

To precisely measure the elasto-plastic strain of the aluminum liner due to thermal stress, an aluminum liner with CFRP removed (hereinafter called "an aluminum tube") was prepared. This aluminum tube was used to measure, with high accuracy, the apparent strain needed to cancel the thermal-expansion strain of the aluminum liner. The thermal stress measuring method for the tank is illustrated in Fig. 4. Strain gages and thermocouples were attached to the inner surfaces of the tank and the aluminum tube, and these were set in a thermostatic chamber. With the indication of strain set to "zero" at the reference temperature of 15°C, changes in the strain were measured as the temperature in the thermostatic chamber changed from -40°C to 85°C. In this case, the elasto-plastic strain due to thermal stress at temperature T can be expressed by Eq. (1).

$$\varepsilon_{ts(T)} = \varepsilon_{1(T)} - \varepsilon_{2(T)} \tag{1}$$

Where,

$\varepsilon_{ts(T)}$: Elasto-plastic strain due to thermal stress at temperature T

$\varepsilon_{1(T)}$: Indicated strain at temperature T (Tank)

$\varepsilon_{2(T)}$: Apparent strain at temperature T (Aluminum tube)

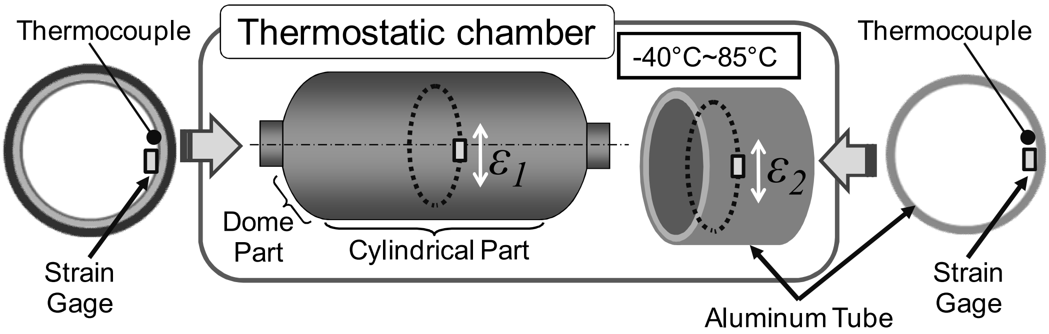

Figure 4. Method for measuring liner strain by thermal stress

3.0 RESULTS

3.1 Fatigue life determined by a hydraulic pressure-cycle test that assumes SOC 100% filling

Pressure-cycle tests with various condition were conducted on each of two tanks under 4 conditions. As a result, leaks occurred in all tanks. The fatigue life determined by a leak occurrence is indicated in Fig. 5. As a result, the lengths of life at low temperature (LT: -40°C, 28MPa) and at room temperature (RT:15°C, 35MPa) were almost equal, but the life at high temperature (HT:85°C, 44MPa) differed. Furthermore, the lives under the SOC 100% conditions were longer than under the conditions specified in JARI S 001 Room-Temperature Pressure-Cycle Test (NT: Normal temp. (15°C to 35°C, with no temperature control), 44MPa: Corresponding to SOC 125%).

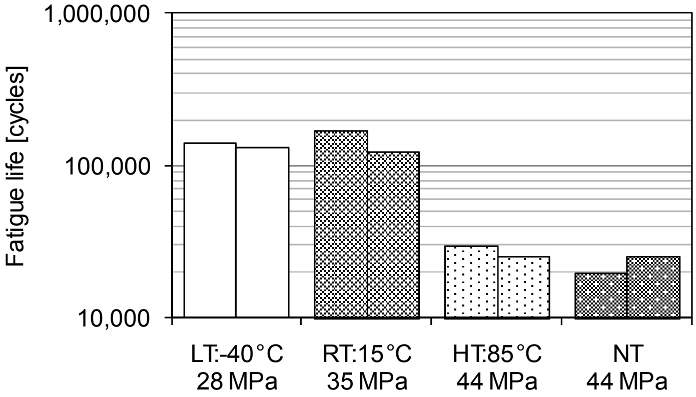

Figure 5. Fatigue life under each condition

3.2 Locations of leaks during the pressure-cycle test

After the pressure-cycle test, all tanks were cut and dye penetrant tests were conducted on the liners. The locations of identified leaks are indicated in Fig. 6. Leakage occurred in the dome part at low temperature and at room temperature, while leakage occurred in the cylindrical part only at high temperature.

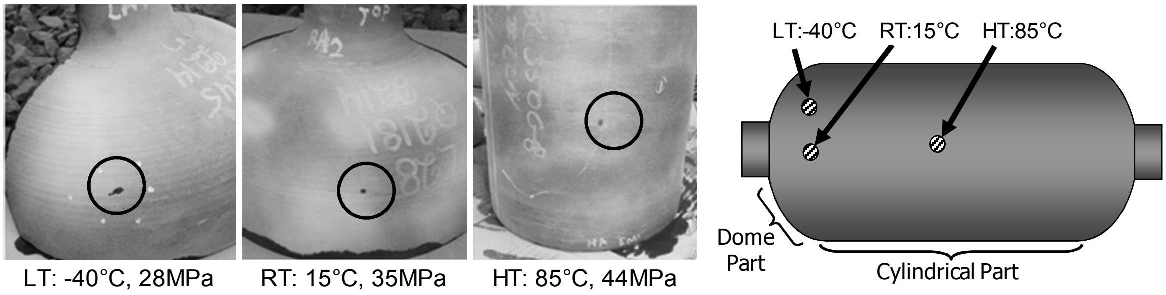

Figure 6. Locations of leaks

3.3 Residual stresses after the pressure-cycle test

Residual stresses in the tank after the pressure-cycle test, as obtained from the measured strain, is listed in Table 3. While the residual stresses in the tank after the pressure-cycle test were almost equal between different tanks at low temperature and at room temperature, the residual stresses after the pressure-cycle test was smaller only in the tank at high temperature.

Table 3. Residual stresses of the liner

	axial [MPa]	Circumferential [MPa]
LT(-40°C)	-182	-256
RT(15°C)	-171	-239
HT(85°C)	-104	-126

3.4 Relationship between pressure and strain

Figure 7 depicts measurements of the strain due to internal pressure acquired by attaching strain gages to the outer and inner surfaces of the tank. For the test tanks, the strain on the inner surface of the aluminum liner was about 20% greater than the strain on the outer surface of CFRP in both the axial and circumferential directions.

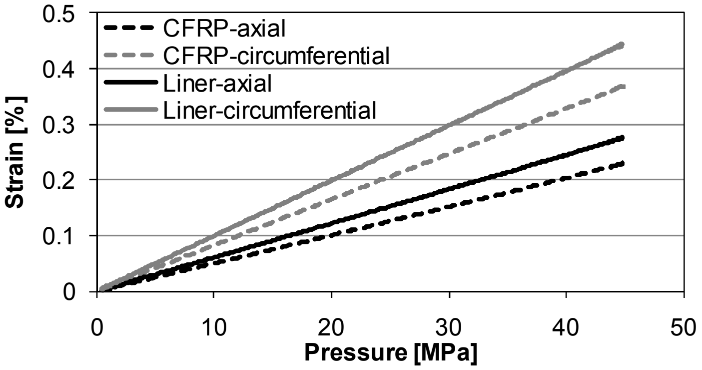

Figure 7. Relationship between strain and pressure

3.5 Relationship between temperature and strain

Figure 8 depicts the measured strain due to thermal stress for the first run, and Fig. 9 depicts that for the second run. In the first run, the strain traced a hysteresis curve on the high-temperature side. Therefore, after the first run, the indication of strain was reset to "zero" at 15°C before the second run. In the second run, the strain was linear in both the axial and circumferential directions.

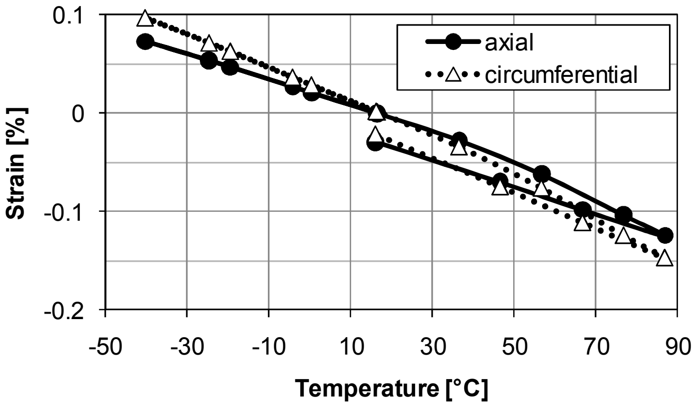

Figure 8. Liner strain produced by thermal stress (first run)

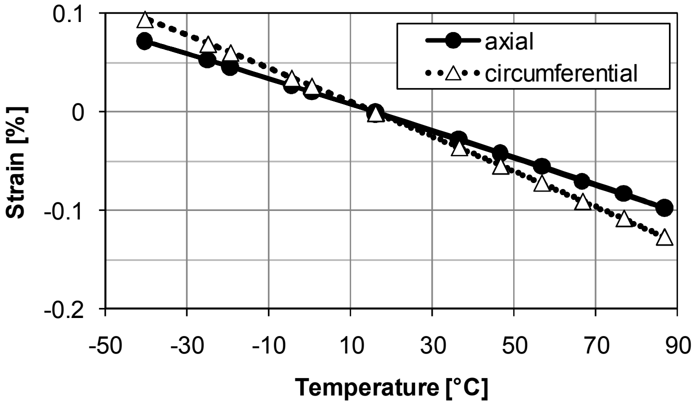

Figure 9. Liner strain produced by thermal stress (second run)

4.0 DISCUSSION

4.1 Influence of high temperature on the Type-3 tank

After completion of the test at high temperature, the residual compressive stress in the tank was smaller than the other tanks (Table 3). The cause of this is one of the following two possibilities. First, when the epoxy resin of the CFRP softened and the CFRP became loose, the residual compressive stress in the liner decreased. Second, the liner, already loaded with residual compressive stress, was further loaded with compressive stress due to thermal stress, so the liner was deformed plastically on the compression side. An investigation of the relationship between temperature and strain (first run) it was found that the compressive strain in the liner increased due to high-temperature load (Fig. 8). This indicates that plastic strain occurred in the liner due to high-temperature load. Therefore, revealed that the tank liner was deformed plastically on the compression side after a high-temperature test, with compressive stress due to thermal stress added to compressive stress due to residual stress, so the residual compressive stress decreased. This result suggests that the fatigue life decreases more at high temperature (HT:85°C, 44MPa) than under other SOC 100% conditions.

4.2 Relationship between liner stress and temperature in the Type-3 tank

Gas pressure changes with temperature, even if the same mass is filled, so the volume of hydrogen gas that results in 35MPa at a homogeneous temperature of 15°C is defined as State of Charge (SOC) 100% for a 35-MPa tank. The pressure of the hydrogen gas when the temperature changes in the SOC 100% filled state is plotted in Fig. 10 assuming the hydrogen gas to be an ideal gas. If the tank is filled with the same mass of hydrogen, the pressure of 35MPa at 15°C becomes 28MPa at -40°C and 44MPa at 85°C.

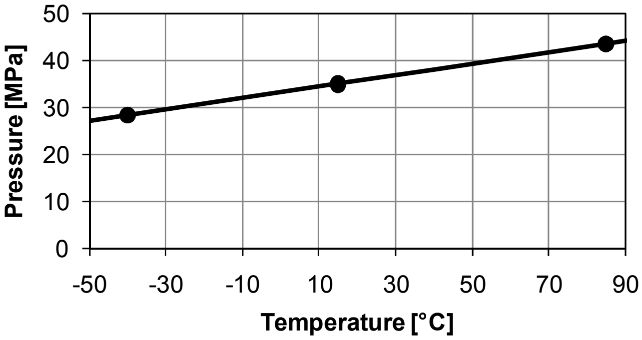

Figure 10. Relationship between temperature and pressure when filling to SOC 100%

The relationships between temperature and circumferential stress of the liner in a Type-3 tank at SOC 0% and SOC 100% were derived from the measurement results of residual stress, stress due to internal pressure, and thermal stress and the relationships between temperature and pressure at SOC 100% (Fig. 11). During a hydraulic-pressure-cycle test at high temperature, the liner is deformed plastically on the compression side with compressive stress due to the thermal stress added to the compressive stress due to residual stress, so the stress range shifts to the tensile side. The shifted stress is indicated by the dotted line on Fig. 11.

This figure indicates that the tensile stress at NT (corresponding to SOC 125%) exceeds that under any SOC 100% condition, even with a higher stress range. Indeed, as depicted in Fig. 5, the fatigue life at NT (corresponding to SOC 125%) is less than that under any SOC 100% condition, and thus the correlation between stress and fatigue life was obtained. In other words, the condition for a room-temperature pressure-cycle test as specified in JARI S001 (corresponding to SOC 125%) is more severe than any SOC 100% condition. Furthermore, hydrogen gas is fill only up to SOC 100%. Therefore, the safety of a Type-3 tank against fatigue can be secured by subjecting it to a room-temperature pressure-cycle test.

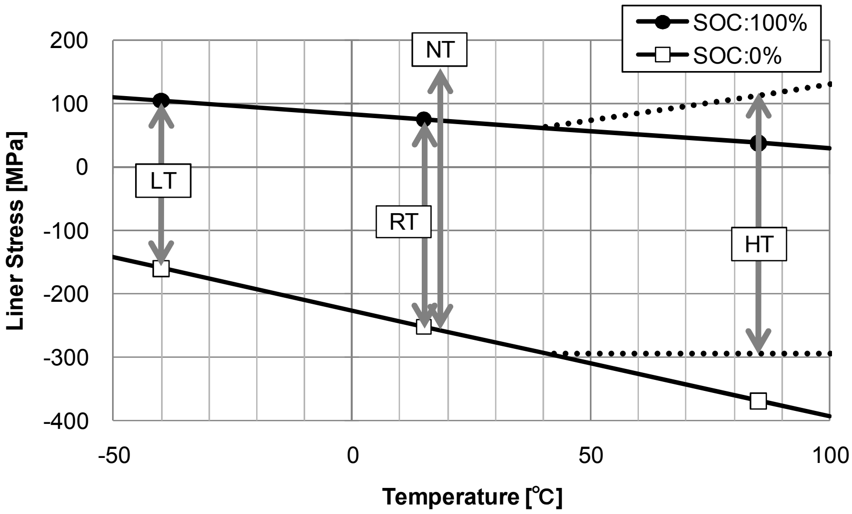

Figure 11. Relationship between temperature and circumferential stress of the liner

Solid lines indicate the liner stress without plastic deformation.

Dotted line indicates the shifted stress by the plastic deformation.

4.3 Comparison between hydraulic-pressure cycle and gas cycle

Figure 12 was prepared by adding dashed arrows representing the stress amplitude of the liner as assumed under gas cycles to Fig. 11. While the temperature of fluid and tank does not change very much during hydraulic-pressure cycles, during gas cycles the temperature of gas and tank rises when the pressure increases and falls when the pressure decreases. Therefore, the stress range during gas cycles is smaller than that during hydraulic pressure cycles by the amount of thermal stress. Furthermore, while the liner is deformed plastically and the stress range shifts to the tensile side at high temperatures and low pressures during a hydraulic-pressure cycle, the liner will not be deformed plastically and the stress range will not shift during gas cycles because of the alternating a high-temperature and high-pressure condition and a low-temperature and low-pressure condition. Therefore, comparison of the stress ranges of the liner indicates that a hydraulic-pressure cycle is a more severe test condition than a gas cycle. Incidentally, the hydraulic-pressure test has been adopted for evaluating fatigue life in Japanese domestic standards, and this report demonstrates the relevance of the hydraulic-pressure-cycle test.

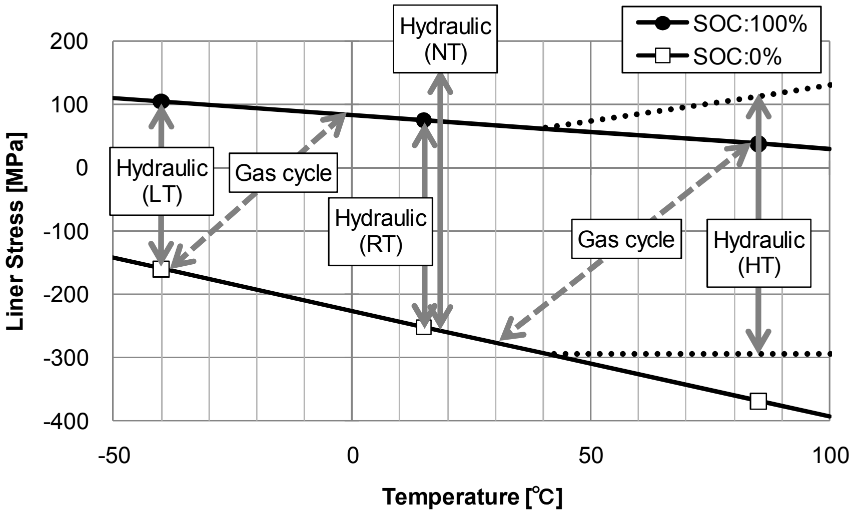

Figure 12. Relationship between temperature and circumferential stress of the liner

5.0 CONCLUSION

Pressure-cycle tests assuming SOC 100% and investigation of liner stress in 35-MPa Type-3 test tanks yielded the following findings.

- The fatigue life determined by pressure-cycle tests assuming the SOC 100% is longer than that determined by the room-temperature pressure cycle test (room temperature, corresponding to SOC 125%).

- When hydraulic-pressure test is conducted at high temperatures, the liner is plastically deformed on the compression side with compressive stress due to thermal stress added to compressive stress due to residual stress. So the stress range shifts to the tensile side.

- A room-temperature pressure-cycle test (room temperature, corresponding to SOC 125%) can ensure the safety of a Type-3 tank against fatigue.

- A comparison of the stress ranges of the liner revealed that the conditions of the hydraulic-cycle test are more severe than those of the gas-cycle test. Incidentally, the hydraulic-pressure test has been adopted for evaluating fatigue life in the Japanese domestic standards.

- It is estimated that a Similar result is obtained even if a Type-3 tank of other manufacturers is tested. Because, all Type-3 tanks have two common points. It is required an autofrettage treatment in order to improve their fatigue strength. It is subjected to a thermal stress due to the difference between the coefficients of thermal expansion of CFRP and aluminum alloy.

・Hydraulic-cycle test is more severe than gas-cycle test and can be completed for a short period. Therefore, hydraulic-cycle test will be adopted in Global Technical Regulations (GTR) on hydrogen and fuel cell vehicles becase it is recognized the advantage and necessity of the test. However, gas-cycle test is also adopted for some problem specific to hydrogen gas.

ACKNOWLEDGMENTS

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