INFLUENCE OF TEMPERATURE ON THE FATIGUE STRENGTH OF COMPRESSED HYDROGEN TANKS FOR VEHICLES

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ABSTRACT

The influence of environmental temperatures on the fatigue strength of compressed-hydrogen tanks for vehicles was investigated. The fatigue strength of Type-3 tanks was found to decrease in a low-temperature environment and increase in a high-temperature environment. The Type-3 tank has been subjected to autofrettage to improve fatigue strength. The investigation clarified that the effect of autofrettage changes according to the environmental temperature due to the difference between the coefficients of thermal expansion of carbon fiber reinforced plastic (CFRP) and aluminum alloy. This causes life strength to change with changes in temperature. These results indicate that the service life of the Type-3 tank is influenced by the environmental temperature. The Type-4 tank has a very long fatigue life and did not break after 45,000 cycles in a room-temperature or low-temperature environment. In a high-temperature environment, however, the tank broke in fewer than 45,000 cycles. The fatigue of CFRP was promoted in the high-temperature environment, resulting in breakage of the tank.

1.0 INTRODUCTION

Compressed-hydrogen tanks for vehicles become fatigued while being subjected to cycles of filling and consumption of fuel. Although fast filling is unavoidable for the popularization of hydrogen vehicles, the interior temperature of the tank increases as a result, largely due to heat generation caused by the compression of hydrogen gas. In contrast, the temperature decreases during consumption of hydrogen gas due to the decrease in pressure. Therefore, ambient-temperature pressure-cycle test and environmental test (including pressure-cycle tests in -40 deg.C and 85 deg.C environments) are specified in the "Technical standard for containers of compressed hydrogen vehicle fuel devices JARI S 001" to ensure that the fatigue strength of the tanks is adequate. However, neither the environmental temperature nor the pressure-medium temperature is specified for ambient-temperature pressure-cycle tests. Furthermore, while the fatigue strength of the tanks is believed to be influenced by environmental temperature, the degree or mechanism of this influence has not yet been clarified. Therefore, the influence of the environmental temperature on the fatigue strength of tanks must be investigated. It is also necessary to examine whether or not the environmental and pressure-medium temperatures need to be specified in the technical standard.

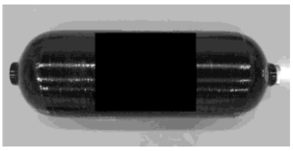
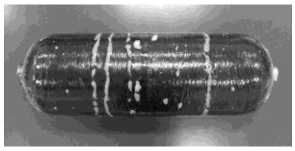
This study investigated the influence of environmental temperature on the fatigue strength of compressed-hydrogen tanks for vehicles. Pressure-cycle tests were therefore conducted until failure or 45,000 cycles in high or low environmental temperature. Furthermore, burst tests were conducted on tanks that were not broken after 45,000 cycles to investigate the residual burst strength.

2.0 MATERIALS AND METHOD

2.1 Materials

There are two types of compressed-hydrogen tanks for vehicles, i.e., the Type-3 tank, with a metallic liner fully wrapped with CFRP, and the Type-4 tank, with a plastic liner fully wrapped with CFRP. In this test, tanks of each type with a normal filling pressure (FP) of 35MPa were used. The specifications for the test tanks are listed in Table 1.

Table 1. Specifications for Test Tanks

Specification	Type-3 tank	Type-4 tank
Filling Pressure [MPa]	35	35
Volume [L]	34	40
Diameter x Length [mm]	280 x 830	287 x 884
Type of FRP	CFRP	CFRP
Liner Material	Al (A6061-T6)	Polyamide
Appearance		

2.2 Test Apparatus

Tests were conducted using water-pressure test equipment and environmental-cycle test equipment. The water-pressure test equipment includes a 120MPa intensifier, a 300MPa intensifier and a test pit, enabling pressure-cycle tests with a maximum pressure of 120MPa, and burst tests with a maximum pressure of 300MPa in a room-temperature environment. The environmental-cycle test equipment includes a 120MPa intensifier and a large constant-temperature, constant-humidity chamber (temperature control range -40 deg.C to 150 deg.C), hereinafter called the "thermostatic chamber," enabling pressure-cycle tests with a maximum pressure of 120MPa in a controlled environmental temperature. Figure 1 shows the water-pressure test equipment, and Figure 2 shows the environmental-cycle test equipment.

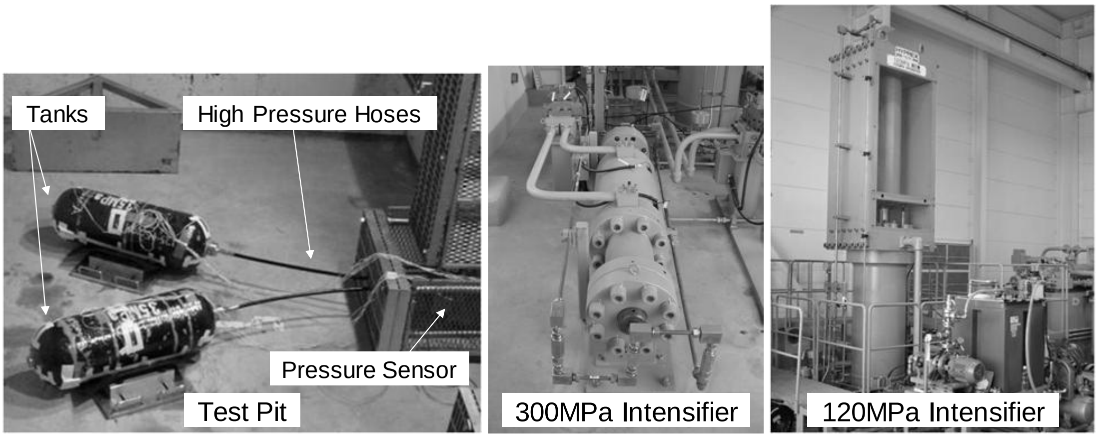


Figure 1. Water-pressure Test Equipment

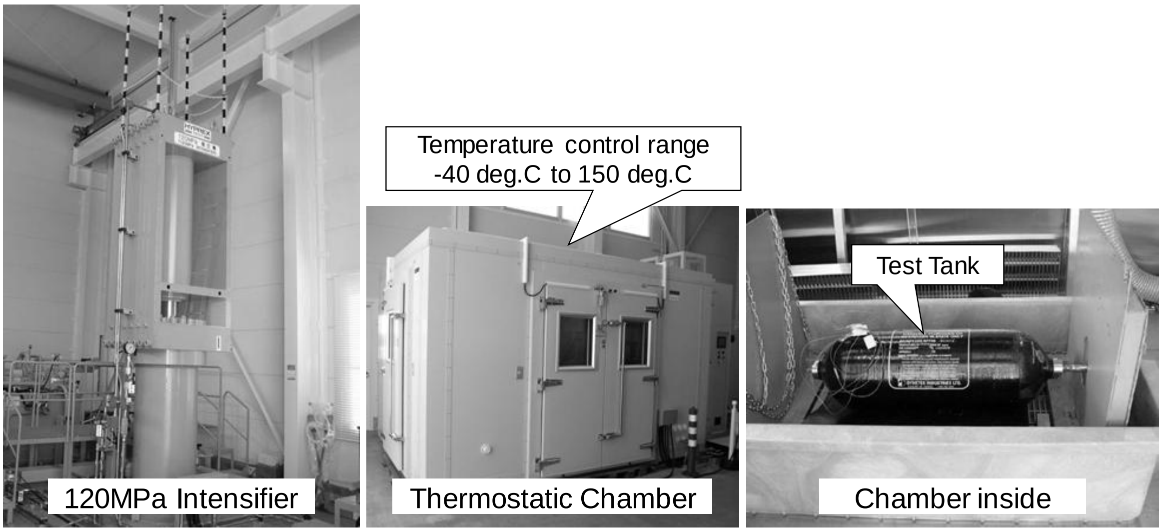


Figure 2 Environmental-cycle Test Equipment

2.3 Pressure-Cycle Test Procedure

Three environmental conditions were used, a room-temperature condition (without temperature control), a high-temperature condition (+85 deg.C, 95% relative humidity (RH)), and a low-temperature condition (-40 deg.C). Table 2 presents details of the test conditions.

Pressure-cycle tests were performed in accordance with the following procedure.

(a) Fill the tank to be tested with a non-corrosive fluid.

(b) Stabilize the tank at zero pressure and at the test temperature.

(c) Cycle the pressure in the tank between less than 1MPa and more than 125% of the normal filling pressure at four cycles per minute until failure or 45,000 cycles.

The test temperature was controlled by a thermostatic chamber during procedures (b) and (c).

Table 2. Pressure cycle test conditions

	Low-Temp. Test	Room-Temp. Test	High-Temp. Test
Test Place	Thermostatic Chamber	Test Pit	Thermostatic Chamber
Temperature	-40 deg.C	Room temp (15~25 deg.C)	+85 deg.C
Humidity	-	-	95 %RH
Fluid (Medium)	Perfluoropolyether	Deionized water	
Maximum Pressure	44 MPa (125% of the Normal Filling pressure)		
Minimum Pressure	1 MPa		
Frequency	4 cycles/minute		
Waveform	Sine curve		
Termination	Occurrence of leak or break, or 45,000 cycles		

2.4 Pressure-Cycle Measurement Conditions

The number of pressure cycles, the circumferential strain on the surface of the tank, the surface temperature of the tank, and the internal temperature of the tank were measured during the test. Measurements were performed by attaching a strain gauge and a thermocouple to the center portion in the longitudinal direction of the tank as depicted in Figure 3. The pressure-medium temperature inside the tank was measured at the center of the tank using a thermocouple inserted into the tank from the end plug.

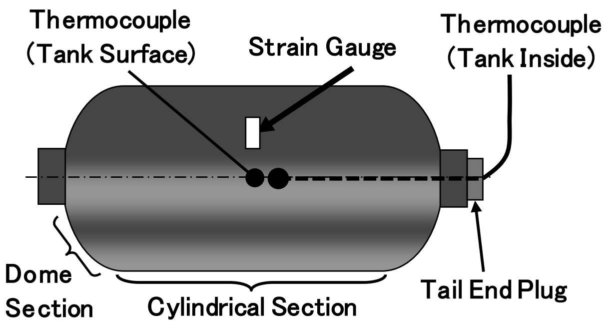


Figure 3. Measurements of Temperature and Strain

2.5 Investigation of the liner

The liner of tested tank was investigated if a leak were detected in the pressure-cycle test. Die penetration tests were conducted on the liners to locate the area of the leak.

2.6 Burst-test procedure

Burst tests were conducted on tanks that were not broken after 45,000 pressure cycles in order to investigate the residual burst strength. The burst strength of a new tank was also investigated for comparison.

3.0 RESULTS AND DISCUSSION

3.1 Number of cycles before breakage

Pressure-cycle tests with varying environmental temperatures were conducted until the tank break or for 45,000 cycles. Figure 4 indicates the number of cycles before the Type-3 test tank leaks at each environmental temperature. In all tanks, leaks occurred in the cylindrical section. Comparing these results revealed that the fatigue life of the Type-3 test tank decreases in a low-temperature environment and increases in a high-temperature environment. This suggests that the fatigue strength of the Type-3 tank was influenced by environmental temperature.

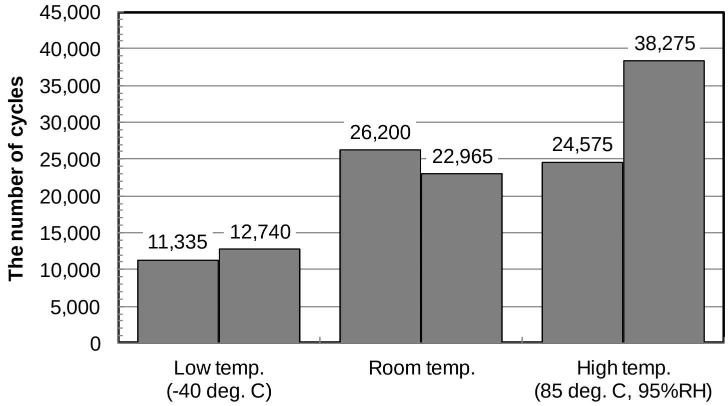


Figure 4. Relationship between the Environmental Temperature and the Number of Cycles before Leaking for the Type-3 Test Tank

Figure 5 indicates the number of cycles before the Type-4 test tank breaks at each environmental temperature. No tank breaks within 45,000 cycles in the room-temperature or low-temperature environment. In the high-temperature environment, however, the CFRP layer of the tank broke during pressure cycling. This suggests that the service life of the CFRP layer of a Type-4 tank decreases in a high-temperature environment.

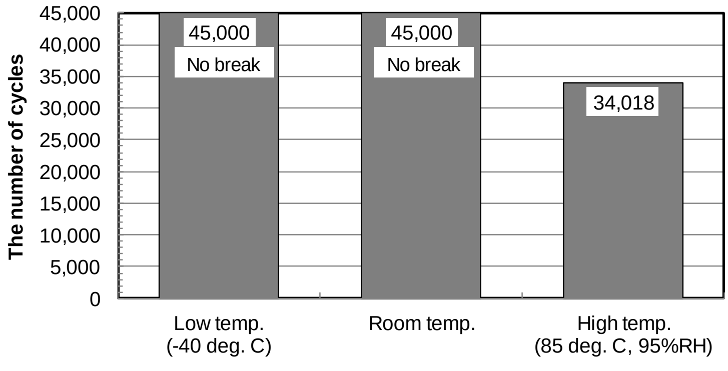


Figure 5. Relationship between the Environmental Temperature and the Number of Cycles before breakage for the Type-4 Test Tank

3.2 Relationship between pressure and the strain on the tank surface

Figure 6 presents an example of the relationship between the circumferential strain at the center of the cylindrical section of the tank and the test pressure in the initial stage of the pressure-cycle test. It can be seen that an almost proportional relationship is established in both the Type-3 and Type-4 test tanks within a pressure range of 125% of FP, regardless of the test temperature. The circumferential strain in the Type-3 test tanks was approximately 70με/MPa, and that in the Type-4 test tank was approximately 135με/MPa. The two tanks are almost the same size, but the strain in the Type-4 test tank is twice as large as that in the Type-3 test tank, confirming that the Type-4 test tank imposes a larger load on the CFRP than does the Type-3 test tank.

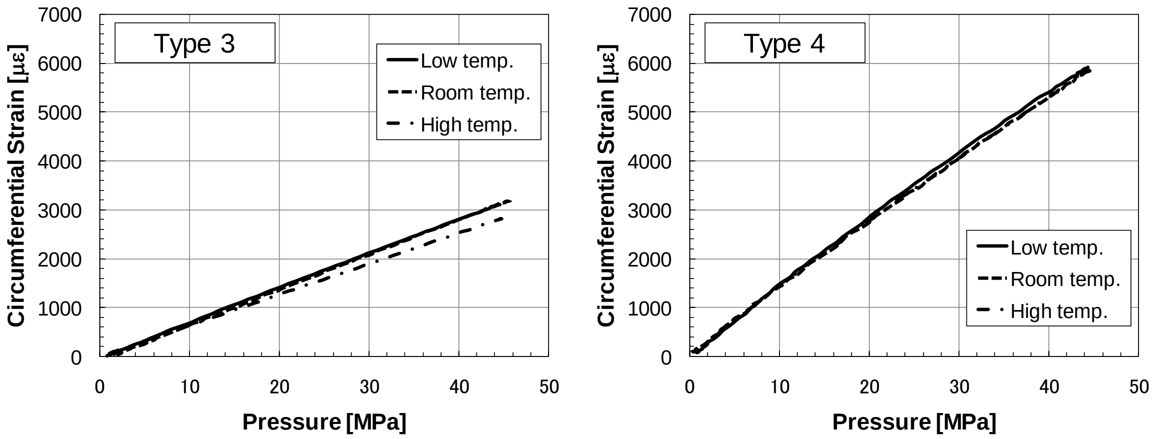


Figure 6 Typical Relationship between Circumferential Strain and Pressure
("με" means strain [$\times 10^{-6}$])

3.3 Investigation of the liner for the Type-3 tank

The Type-3 test tank leaked in the cylindrical section, so we investigated the liner for that tank. Figure 7 presents the results of dye-penetration tests conducted on the aluminum liner. Through cracks were observed near the center of the cylindrical section of the tank after both high-temperature tests (24,575 LBB cycles) and low-temperature tests (11,335 LBB cycles). This confirmed that circumferential strain near the center of the cylindrical section is the main strain affecting the fatigue strength of this tank and that the service life can be evaluated using circumferential strain.

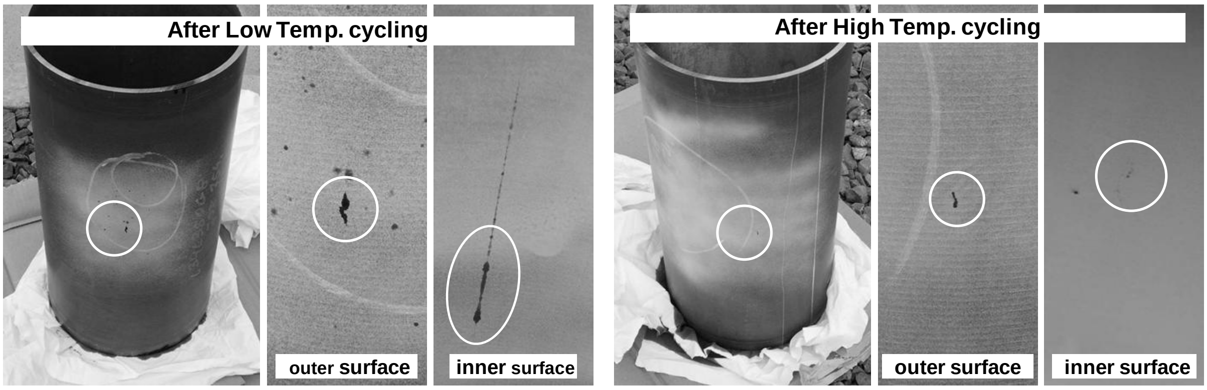


Figure 7. Results of Dye-Penetration Tests

3.4 Influence of environmental temperature on the effect of autofrettage for the Type-3 tank

The Type-3 tank is subjected to autofrettage to induce plastic deformation of the liner by applying a pressure exceeding the operating pressure in the manufacturing process in order to improve the fatigue strength. This processing produces residual compressive stress in the liner and residual tensile stress in the CFRP layer in the non-filled state, so the tensile stress generated in the liner during filling will be offset by the residual compressive stress. This test revealed that the fatigue strength of the Type-3 tank decreases at low temperatures and increases at high temperatures. Supposably, the effect of autofrettage varies according to the environmental temperature due to the difference between the thermal-expansion rates of CFRP and aluminum alloy.

Therefore, the residual compressive stress in the Type-3 test tank was measured in a room-temperature environment. The dome sections of the Type-3 test tank were removed and a strain gauge was attached to the inner surface of the aluminum liner. The strain in the aluminum liner released by cutting the CFRP layer was measured. Figure 8 depicts the measurement method.

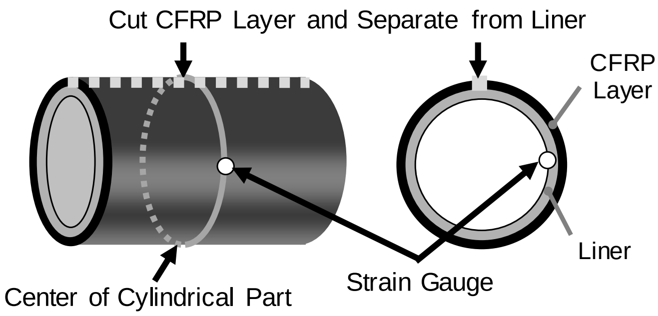


Figure 8. Measurement of Residual Strain

Residual strain measurements revealed a strain of 2,579με in the circumferential direction and a strain of 1,082με in the axial direction. Using Hooke's law, the residual compressive stress in the circumferential direction can be estimated as 226MPa.

Hooke's law:

$$\sigma_x = \frac{E}{1-\gamma^2}(\varepsilon_x + \gamma\varepsilon_y), \qquad \sigma_y = \frac{E}{1-\gamma^2}(\varepsilon_y + \gamma\varepsilon_x), \qquad \tau_{xy} = G r_{xy}$$

(It was assumed that Young's modulus E = 70GPa and Poisson's ratio γ = 0.3.)

Next, the strain in the aluminum liner was measured while changing the environmental temperature in order to investigate the influence of the environmental temperature on the effects of autofrettage. Figure 9 illustrates the measurement method. The tank was placed in a thermostatic chamber with both dome sections removed and with a strain gauge and a thermocouple attached to the inner surface of the tank. The strain was assumed to be zero at 25 deg.C as the reference temperature. Changes in the strain in the circumferential direction were measured while changing the temperature of the thermostatic chamber from -40 deg.C to 85 deg.C.

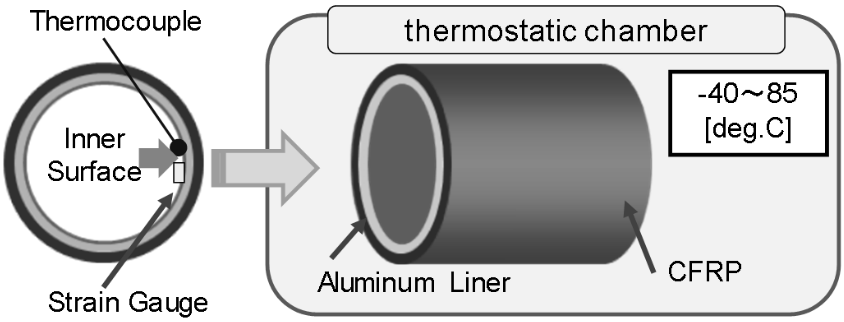


Figure 9 Measurement of Thermal Strain

Figure 10 plots the strain in the circumferential direction in the aluminum liner as a function of the environmental temperature, with the strain at 25 deg.C assumed to be zero. As seen in the figure, a tensile strain of 1,050με occurred at -40 deg.C, and a compressive strain of -1,200με occurred at 85 deg.C. It is assumed that almost equal volumes of strain are also occurring in the axial direction due to the difference between the thermal expansion rates of aluminum alloy and CFRP. Assuming that the strains in the circumferential direction and axial direction are almost equal to each other, the stress in the circumferential direction is obtained using Hooke's law. A tensile stress of 105MPa can be expected at -40 deg.C, and a compressive stress of 120MPa can be expected at 85 deg.C.

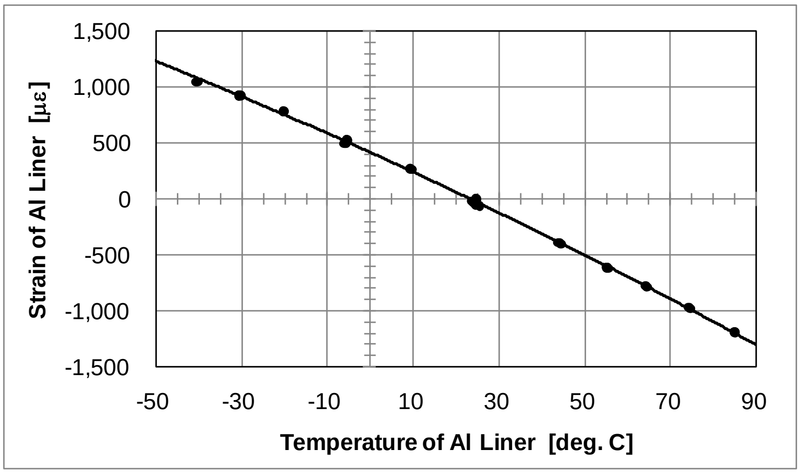


Figure 10. Relationship between Temperature and Strain for the Aluminum Liner

Changes in residual stress in the aluminum liner due to changes in environmental temperature were calculated by adding the changes in stress in the aluminum liner due to the environmental temperature to the residual compressive stress in the circumferential direction of the Type-3 test tank at room temperature (225Mpa). Figure 11 presents the relationship between the residual stress and the environmental temperature for the Type-3 test tank. The figure indicates that a compressive stress of -226 MPa in the room-temperature environment decreases to a compressive stress of -121 MPa in the low-temperature environment. In other words, the effect of autofrettage decreases in the low-temperature environment. In contrast, the compressive stress increases to -345MPa in the high-temperature environment, resulting in a larger effect of autofrettage.

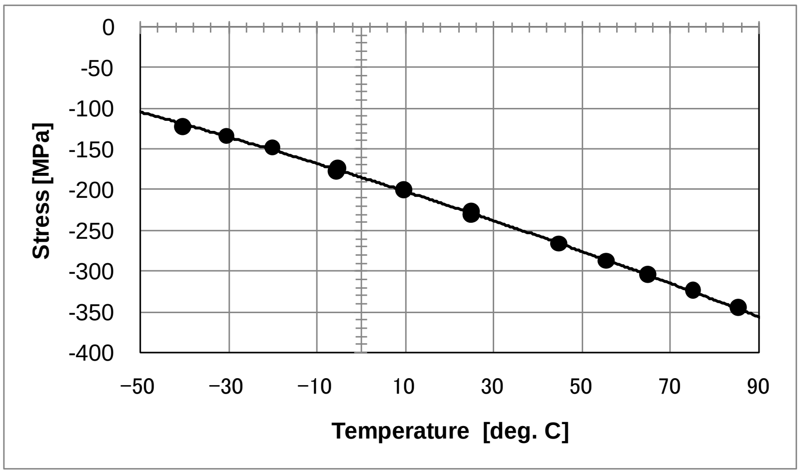


Figure 11. Relationship between the Temperature of the Aluminum Liner
and Residual Autofrettage Stress for the Type-3 Tank

The above results clarified that the environmental temperature influences the fatigue strength of the Type-3 tank because the effect of autofrettage changes with changes in environmental temperature. Therefore, it is necessary to define an environmental temperature and a pressure-medium temperature for ambient-temperature pressure-cycling tests. In a high-temperature environment, the effect of autofrettage is most likely enhanced, leading to an increase in fatigue strength. Therefore, we consider that either the environmental temperature or the maximum temperature of the pressure medium must be defined.

3.5 Influence of the number of pressure cycles and the environmental temperature on the residual burst pressure of the Type-4 tank

The Type-4 test tank burst after 34,000 pressure cycles in the high-temperature environment but did not break within the specified 45,000 cycles in the room-temperature and low-temperature environments. Therefore, we investigated the influence of the number of pressure cycles and the environmental temperature on the residual burst pressure by conducting a burst test after the pressure-cycling test. Figure 12 presents the relationship between the burst pressure at each temperature and the number of pressure cycles.

In the low-temperature and room-temperature environments, the residual burst strength did not decrease, even after 45,000 cycles. In the high-temperature environment, in contrast, the tank burst at approximately 34,000 cycles during cycling, but the residual burst strength did not decreased after 22,500 cycles. In other words, the residual burst strength does not decrease gradually as the number of pressure cycles increases, but instead decreases rapidly. The above results clarified that a high-temperature environment influences the fatigue strength of the Type-4 tank.

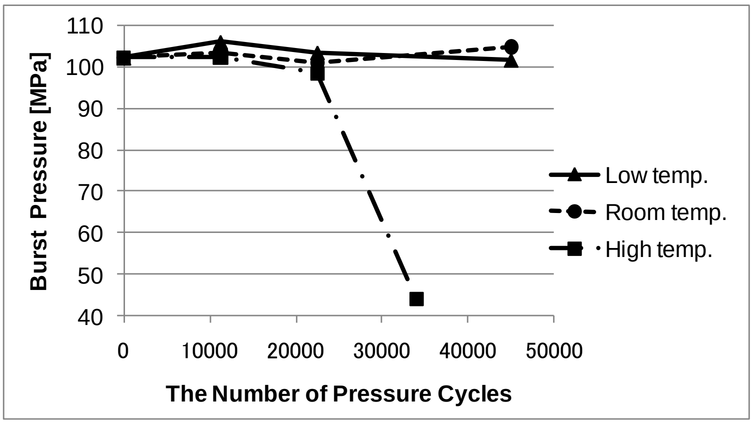


Figure 12 Influence of the Number of Pressure Cycles and Test Temperature on Residual Burst Pressure

4.0 CONCLUSION

Investigation of the influence of the environmental temperature on the fatigue strength of compressed-hydrogen tanks for vehicles (Type-3 and Type-4) revealed the following.

・The fatigue strength of the Type-3 tank decreases in a low-temperature environment and increases in a high-temperature environment.

・The major cause of the changes in the fatigue strength of the Type-3 tank is the increase and decrease in the effect of autofrettage caused by the difference between the thermal expansion rates of the CFRP and the aluminum alloy liner.

・The Type-4 tank burst during pressure cycling in a high-temperature environment. In other words, the fatigue strength decreased in a high-temperature environment.

The above results demonstrate that the environmental temperature influences the fatigue strength of the Type-3 tank because the effect of autofrettage changes with changes in the environmental temperature. It was found that a high-temperature environment influences the fatigue strength of the Type-4 tank. Therefore, it is necessary to define the environmental temperature and the pressure-medium temperature for ambient-temperature pressure-cycling test. It is also necessary to develop verification tests that can assure sufficient safety in both high-temperature and low-temperature environments.

Therefore, the pressure cycle test at room temperature implied the necessity of examining the specifications for environmental temperature and the temperature of the pressure medium.

ACKNOWLEDGMENTS

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REFERENCES

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