STRAIN BEHAVIOUR OF CFRP HIGH PRESSURE VESSEL DURING MANUFACTURING PROCESS

T. Kosaka[1*], K. Osaka[2], J. Suzuki[3], Y. Sawada[2]
[1] Dept. Systems Engineering, Kochi University of Technology, Kami-City, Kochi, Japan,
[2] Graduate School of Engineering, Osaka City University, Osaka, Japan
[3] SAMTECH Co., Ltd, Kashiwara-City, Osaka, Japan

* Corresponding author(kosaka.tatsuro@kochi-tech.ac.jp)

Keywords: *Pressure vessel, Autofrettage process, Strain monitoring, CFRP, manufacturing process monitoring*

1 Introduction

A hydrogen automobile is promised to be a next-generation eco-car for reduction of greenhouse gas. In order to extend range of hydrogen cars, a very-high pressure vessel has been developed recent years. A CFRP high pressure vessel, which is made by combination of an aluminum liner and CFRP layers, is a most promising technology for hydrogen cars[1]. Manufacturing process of the pressure vessel has filament winding (FW) process of carbon fibers, cure process, cooling process and autofrettage process. During these manufacturing processes or transportation, delamination between a liner and CFRP layers or matrix cracks may occur by thermal stress or autofrettage pressure. The pressure vessels which contain these initial damages generated during manufacturing process may have different residual stress distribution from non-damaged vessels after manufacturing. Therefore, it is important to investigate effect of initial damages by manufacturing on mechanical behavior of pressure vessels.

In the present study, strains at several points of a liner and CFRP layers during cure, cooling process and autofrettage processes were monitored. After manufacturing, pressure tests were conducted. These experimental results were compared to analytical results calculated by an FEM analysis.

2 Specimen and experimental procedures

2.1 CFRP pressure vessel

Figure 1 shows shape and dimensions of a CFRP pressure vessel used in this study. A liner is an aluminum alloy tank whose volume is 7.5 liters. Carbon fibers impregnated with thermosetting epoxy resin were wound on a liner. Winding conditions were 13 layers of 90° (hoop winding) and 10 layers of 16° and 20° (helical winding, $16_4/20_2/16_4$). Volume fraction of CFRP layers was controlled to be 65%. After winding, the pressure vessel is cured by heating in a furnace. After cooling process, autofrettage process was conducted by applying pressure up to 72MPa.

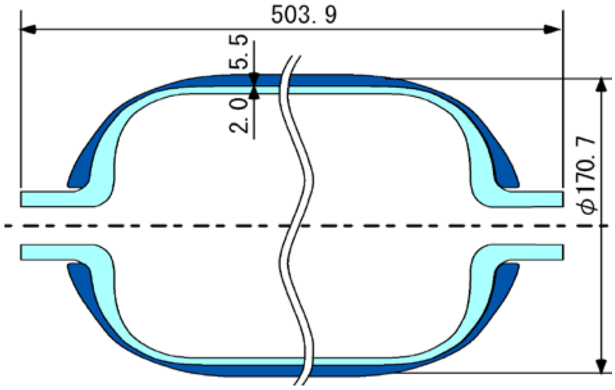


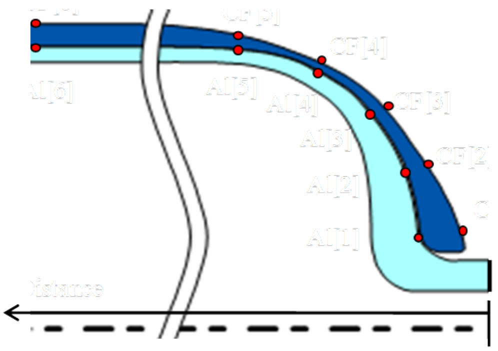
Fig.1. Shape and dimensions of a CFRP pressure vessel used in this study.

2.2 Material properties of CFRP layers

Material properties of CFRP layers were experimentally obtained. In the present study, Filament wound CFRP pipes which are made of the same filaments, matrix resin and has the same volume fraction as the CFRP pressure vessels. From the results of tensile tests of 30°, 45°, 60°, 90° FW pipes, mechanical constants of unidirectional CFRP were obtained. Thermal strains were also measured by thermal loading tests from room temperature to 140°C. These materials constants were shown in Table 1.

Table.1 Properties of unidirectional CFRP

E_L (GPa)	191.9
E_T (GPa)	8.7
G_{LT} (GPa)	5.34
ν_L	0.29
α_L ($\mu\varepsilon$/°C)	2.68
α_T ($\mu\varepsilon$ /°C)	32.67



Distance from inlet/outlet port edge (unit: mm)

No.	Al[ ]	CF[ ]
1	34	25
2	38	33.5
3	45	43.3
4	58	57
5	74	74
6	252	252

Fig.2. Positions of strain gauges.

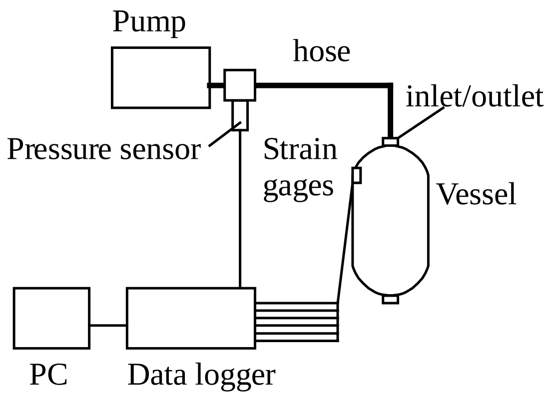


Fig.3 Experimental set-up for measuring strain and pressure during autofrettage process and pressure test.

2.3 Sensors and experimental set-up

In the present study, 2-axial strain gauges were adhered on the surface of the aluminum liner (Al[1]-[6]) and CFRP layers (CF[1]-[6]) in order to measure meridian and circumferential strains as shown in Fig. 2. Strain gages were also adhered at the opposite side (180° from the other side around center axis of the tank). Sensor positions were defined as a distance from the edge of inlet/outlet port. Sensors No.1~5 were at the dome part and sensors No.6 were at center of the cylinder part.

Only strains of the liner were measured at cooling process. After cooling, strain gages were adhered on the surface of CFRP. Then, both strains of the liner and CFRP were monitored during autofrettage process and pressure tests.

Figure 3 shows an experimental set-up for measuring strain and pressure during autofrettage process and pressure tests. Applied pressure was measured by a presser sensor and collected by a data logger with strain data of the pressure vessel. In the autofrettage process, pressure was increased from 0MPa to 72 MPa with a rate of 5.4 MPa/min., kept for 2 minutes, and then decreased to 0 MPa. In the pressure test, pressure was increased from 0MPa to 52 MPa with a rate of 7.8 MPa/min.

3 Experimental results and discussions

3.1 Thermal strain of liner during cooling process

Thermal strain of the aluminum liner was measured during cooling process. Strains at Al[2] are plotted against temperature in Fig.4. From the figure, it can be clearly seen that a relationship between strain of the liner and temperature show bilinearity at 70°C. Strains at Al[1]-[5] except Al[6] showed such bilinear behavior by cooling after heating cure process. The figure 5 shows CTEs (Coefficients of thermal expansion) of meridian strain at all positions. From the figure, it was found that CTEs of Al[1]-[5] under 70°C were almost the same as CTE of aluminum ally (23.6 $\mu\varepsilon$/°C). These experimental results showed delamination between the liner and CFRP layers occurred at dome part of the pressure vessel. However, it can be considered that the delamination occurred partially since constrained strain of the linear by CFRP layer was not released as shown in Fig.4. On the other hand, CTE of Al[6] was almost constant from 134°C to 29°C but sudden small decrease by -200 $\mu\varepsilon$ could be seen at 29°C. Therefore, it can be thought that the delamination area distributed in the cylinder part is small.

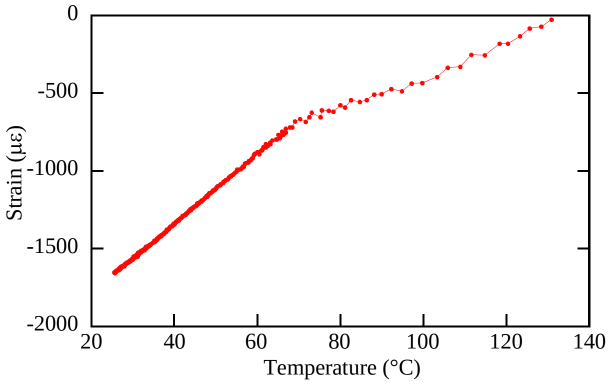


Fig.4 Temperature – strain (Al[2]) curve during cooling process.

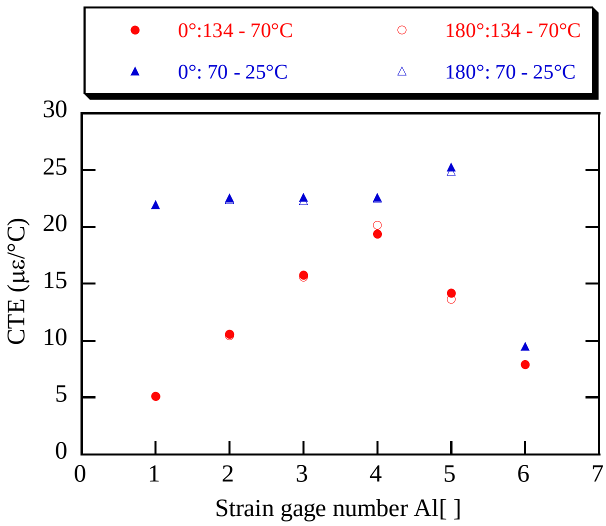


Fig.5 Thermal coefficient of meridian strain of the liner during cooling process.

3.2 Strain measurement during autofrettage process

Strains of the liner and CFRP layers were monitored during autofrettage process. Figures 6 and 7 show pressure-strain curves for meridian strains CF[3]-[5] of the CFRP layers and Al[3]-[5] of the liner, respectively. From the experimental results of Fig.6, it was found that the strain behavior of CFRP layers showed strong nonlinearity when pressure increasing during autofrettage process. The variation of meridian strains was very small when the applied pressure was lower than about 10MPa. On the other hand, the figure 7 showed monotonic increase of strain by increasing pressure. Therefore, it was

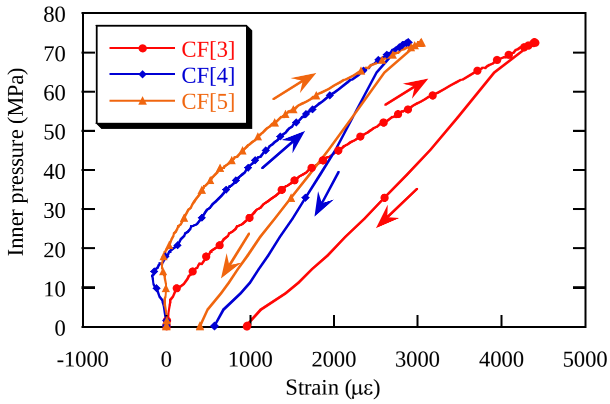


Fig.6 Relationships between applied pressure and meridian strain of CFRP layers during autofrettage process (CF[3],[4],[5]).

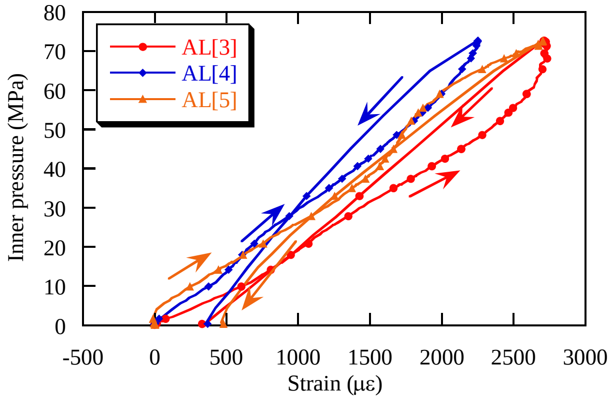


Fig.7 Relationships between applied pressure and meridian strain of aluminum liner during autofrettage process (Al[3],[4],[5]).

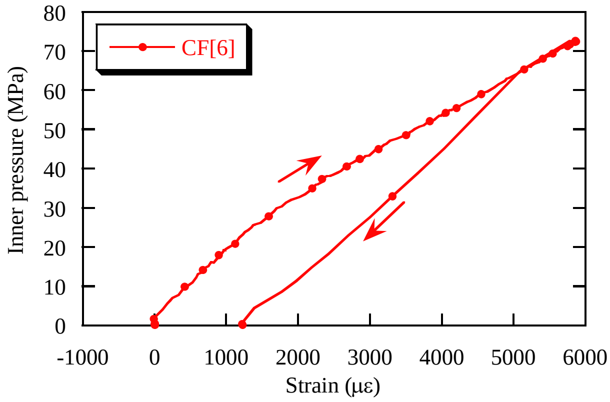


Fig.8 Pressure- axial strain curve during autofrettage process (CF[6]).

considered that this low strain sensitivity of the CFRP dome to pressure under 10MPa was caused by delamination gaps between the liner and CFRP layer generated during cooling process. When pressure exceeded 40MPa, the slopes of pressure-strain curves of both the liner and CFRP varied due to yield of the liner. The initial nonlinearity of the curves disappeared during reduction process of pressure because the gaps were closed by residual stress of CFRP layers.

On the other hand, a pressure-strain curve of meridian strains CF[6], which was in the cylinder part, is shown in Fig.8. This curve shows that the strain of cylinder part started to increase at 2MPa. This knee point stress is much less than 10MPa shown in Fig.6 due to small delamination area.

Circumferential strains of CF[3]-[5] were plotted against applied pressure in Fig.9. From the figure, it was found that Circumferential strains of CF[4] and [5] of CFRP dome showed very large strain variation under about 10MPa. This reason is considered that expansion of the cylinder part by applying pressure caused circumferential deformation of the dome part of CFRP layers.

3.3 Strain measurement during pressure test

After autofrettage process, a pressure test up to 52MPa was conducted. Figure 10 shows pressure-meridian strain curves for CF[3]-[6] during the pressure test. Here, strains at 0MPa were residual strains generated by the autofrettage process. These results showed that CFRP layer deformed elastically in whole part of pressure vessel. Therefore, it can be concluded that delamination gaps generated during molding process were closed perfectly by autofrettage process and frictional sliding between the liner and CFRP layers did not affect linearity of pressure-strain behavior of CRRP pressure vessels after manufacturing.

4 FEM analysis

FEM analyses during autofrettage process were conducted in order to take account of the effect of delamination on strain behavior of CFRP layers. An FEM model of pressure vessel is illustrated in Fig.11. The model was represented by 8 nodes axial element and material properties of CFRP were shown in Table.1. Elasto-plastic properties of aluminum liner were also experimentally obtained. In the calculation, a line friction element between the liner and CFRP layers were used to represent the delamination and the friction ratio was 0.2 (Delamination model). We also used a bonded model in which the liner was bonded perfectly with CFRP layers.

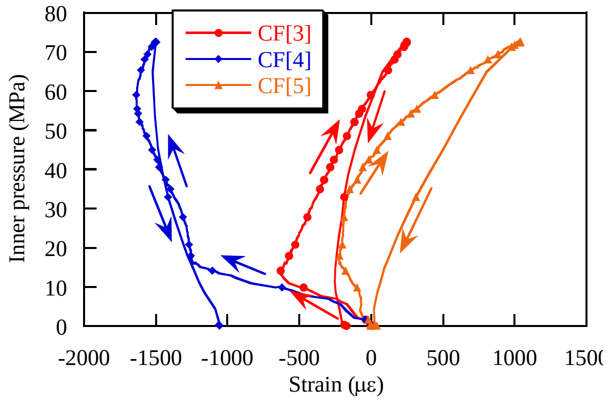


Fig.9 Pressure – circumferential strain curve during autofrettage process (CF[3],[4],[5]).

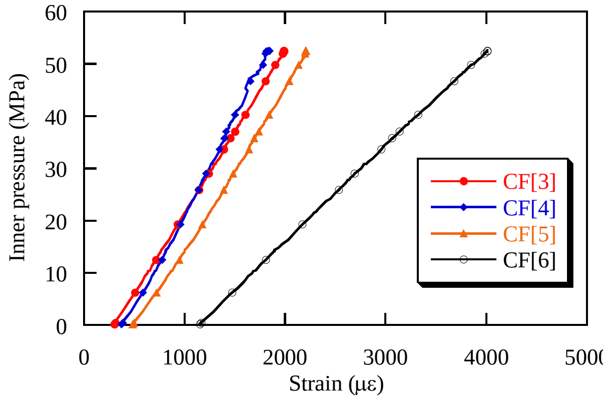


Fig.10 Relationships between applied pressure and meridian strain of CFRP layers during pressure test (CF[3],[4],[5],[6]).

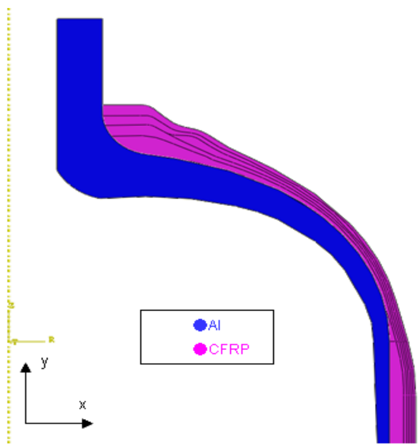


Fig.11 FEM model of pressure vessel.

Experimental and analytical data of circumferential strain CF[4] during autofrettage process were plotted against pressure in Fig. 12. From the figure, it was found that the pressure-strain curve of the slide model had a negative slope similarly to experimental results. However, the initial nonlinearity seen in the experimental curve could not be represented because there was no initial gap between the liner and CFRP in the present model. From these results, it appeared that delamination between a liner and CFRP layers affected pressure-strain behavior of dome parts of pressure vessel strongly in autofrettage process.

Figures 13 and 14 show relationships between applied pressure and elastic strain obtained by experiments and FEM analysis of the delamination model during a pressure test. Abscissa axes in Fig.13 and Fig.14 are meridian strain and circumferential strain, respectively. From the figures, it was found that the analytical slopes of pressure-strain curves are tend to be larger than experimental results, while tendency of experimental and analytical curves are similar to each other. Especially, behavior of CF[5], which is adhered at edge of the 90° hoop layer ,cannot be represented well by the present FEM model. It can be considered that plastic behavior of the liner during autofrettage process affected elastic behavior of the vessel after manufacturing. More detail analysis including cooling process and partial delamination is necessary to discuss difference between experimental and analytical results.

5 Conclusions

In this study, mechanical behaviors of CFRP high pressure vessel were investigated during manufacturing process and a pressure test. From the experimental results, it was found that delamination between the liner and CFRP layers occurred during cooling process. The experimental results of autofrettage process up to 72MPa, it appeared that strong nonlinearity could be observed in pressure-strain behaviors at a dome part of the vessel due to closure of the delamination gap. The experimental results of pressure test after manufacturing showed elastic strain responses. The results of FEM analysis showed that the delamination affects elastic mechanical behaviors of the vessel in both of autofrettage process and a pressure test.

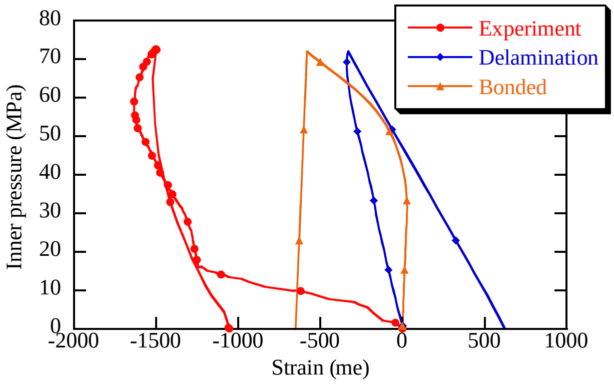


Fig.12 Comparing of experiment and analysis during autofrettage process (CF[4] circumference strain).

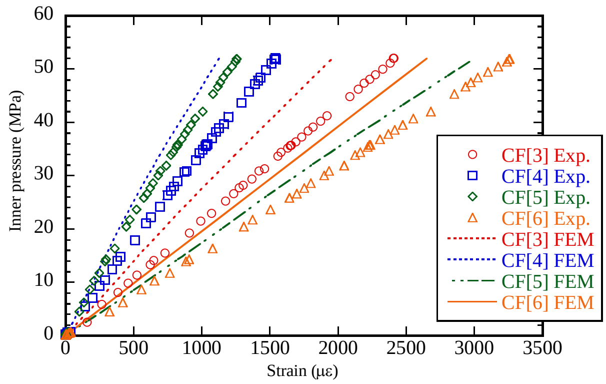


Fig.13 pressure-elastic strain curves obtained by experiments and FEM analysis during pressure test (meridian strain).

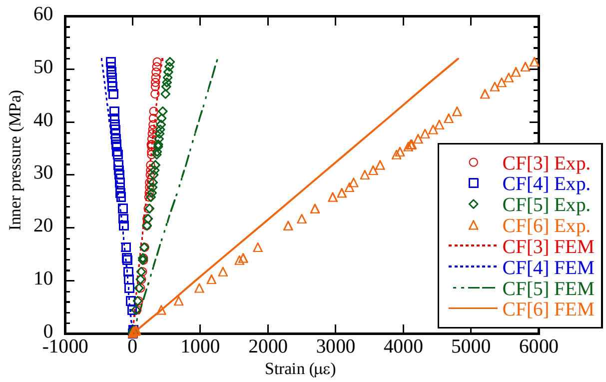


Fig.14 pressure-elastic strain curves obtained by experiments and FEM analysis during pressure test (circumferential strain).

References

[1] W. Iwasaki "An Evaluation of 35 MPa hydrogen storage tank system for FCV". *J. High Pressure Institute Japan*, Vol.43, No.4, pp.200-207, 2005.