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A study on failure characteristic of spherical pressure vessel

Ho-Sung Lee [a,*], Jong-Hoon Yoon [a], Jae-Sung Park [a], Yeong-Moo Yi [b]

[a] Department of Structures & Materials, Korea Aerospace Research Institute, 45 Eoeun-Dong, Yuseong-Gu, Daejeon, 305-333, Republic of Korea

[b] KSLV Technology Division, Korea Aerospace Research Institute, 45 Eoeun-Dong, Yuseong-Gu, Daejeon, 305-333, Republic of Korea

Abstract

Currently many aerospace vehicle systems require lightweight, high performance pressurized tank for storage of propellant, nitrogen, oxygen, or other medium. Aircrafts have several needs for high-pressure stored gas, like aircraft escape slide inflation systems, emergency oxygen supply, landing gear actuator, engine pressurized air start system and on-board inert gas generating system nitrogen enriched air receivers. For spacecraft application, the high-pressure gas is utilized for attitude control of the vehicle and propulsion purpose. Therefore, the leakage of the pressure vessel results in serious malfunction of the vehicle system causing a mission failure or mishap. It is prudent to recognize the fact that pressure vessels can fail in spite of high standard of qualification program.

This paper reports an experimental investigation of the failure behavior of pressure vessels during high pressure of hydraulic loading. The pressure vessels were manufactured by two different procedures. One method is spin forming and tungsten inert gas (TIG) welding process and the other is blow forming and solid-state diffusion bonding process. The failure behavior has been studied and the effect of forming method has been analyzed. The result shows that the pressurization rate and the acoustic emission signal increasing rate provide a similar tendency for a vessel of integrity, while the signal increasing rate is much higher than the pressurization rate for a vessel with defects. It is clear that the acoustic emission response of the vessel to the pressure loading can be successfully applied to predict the structural integrity and failure behavior of the vessels manufactured with both methods.

Keywords: Pressure vessel; Spinning forming; Diffusion bonding; Acoustic emission

1. Introduction

The pressure vessel has been used in a various field of aerospace application, like emergency oxygen supply or propulsion tank systems [1]. Therefore, the prevention of pressure vessel failure to enhance safety and reliability has received considerable attention. Major characteristics for aerospace structural components include high strength and lightweight properties for structural stability in order to improve the performance of aerospace flight vehicles and maximize the on-flight carrying load. To satisfy these requirements, the aerospace structural components have been designed and manufactured with materials with high specific strength, like titanium alloys and composite materials [2]. The typical application of the titanium alloy is pressurized vessels for attitude control, which store relatively high-pressure gas or fuel. The titanium tank can be fabricated by spin forming, blow forming or machining, and the first two methods are well utilized to reduce manufacturing cost.

In this study, the titanium tanks are fabricated by two different methods. During the pressurizing test, the strain and acoustic emission (AE) signals are observed to investigate the effect of manufacturing method on the failure mode and performance of the tank.

2. Experimental

2.1. Design and manufacturing

The typical shape of aerospace pressure tank is spherical to effectively maintain the internal hydrostatic gas pressure. In this study, two different types of tanks are manufactured: one is for attitude control and the other is for valve driving in aerospace systems. Since each aerospace component must

* Corresponding author.
E-mail address: hslee@kari.re.kr (H.-S. Lee).

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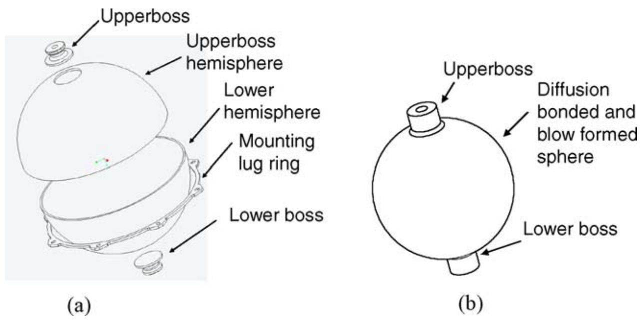

Fig. 1. Designed shape of spherical titanium tanks. (a) Attitude control tank and (b) valve driving tank.

satisfy different specifications, these tanks are manufactured by different methods.

Fig. 1 shows the design configuration of the tanks depending on the application, and schematic design specification of two different tanks is in Table 1.

The nitrogen tank for the attitude control is to store high-pressure nitrogen gas in spherical shape, which is fabricated from two hemispheres. Ti–15V–3Al–3Cr–3Sn is selected as a material of hemispheres for its good spin formability and good heat treatable properties. Hemispheres are made by hot spin forming as show in Fig. 2 and are welded together by tungsten inert gas (TIG) welding for its flexibility of the manufacturing tolerance control [3]. Material properties of the parent material and those of spun part after heat treatment are compared. Fig. 3 is the process flow of TIG welding procedure.

The helium pressurization tank for valve driving is for storage of high-pressure helium gas to operate the pneumatic valve. Since the internal diameter of the tank is relatively smaller than the thickness of the tank the spin forming is not determined to be effective, and therefore, the tank is fabricated with blow forming method with Ti–6Al–4V. The initial blank and boss were diffusion bonded and the final sizing was obtained by blow forming [4].

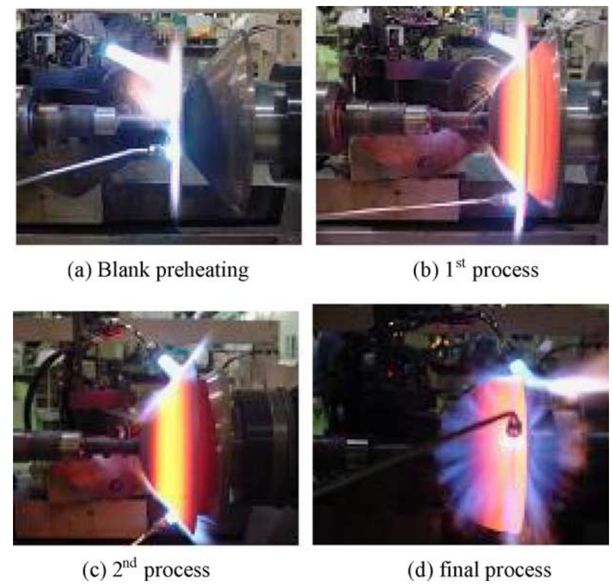

Fig. 2. Hot spinning process of hemisphere for attitude control tank.

2.2. Inspection

After fabricating the titanium tanks, the X-ray radiographic test and thickness measurement were performed to

Table 1
Design specification of titanium tanks

Type	MEOP[a] (MPa)	Proof factor	Material	Wall thickness (mm)
Attitude control tank	20.6	1.5	Ti–15V–3Al–3Cr–3Sn	4.0
Valve driving tank	31	1.5	Ti–6Al–4V	3.0

[a] MEOP = maximum expected operating pressure.

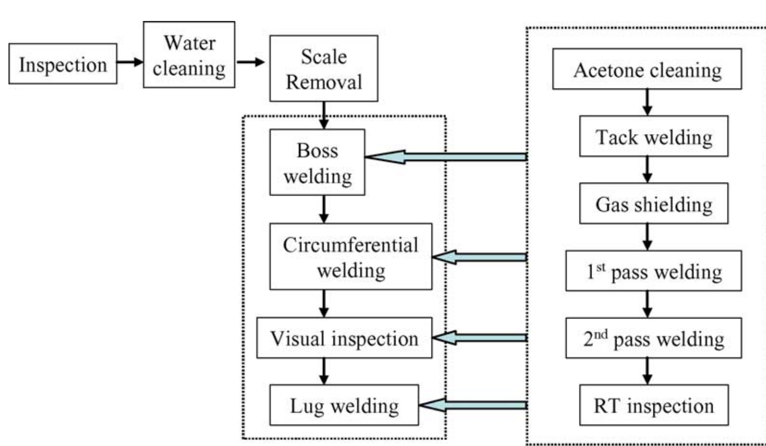

Fig. 3. Flow chart of TIG welding.

Table 2
Radiographic inspection results of attitude control tanks

No.	Hemisphere welding line	Inspection result	Boss welding line		Inspection result
ACT-01	(0–1)	Undercut		0–1	Porosity (1 mm)
	(1–2)	Undercut	Upper boss	1–2	Porosity lack of fusion (5 mm)
	(2–3)	No defect		2–0	No defect
	(3–4)	No defect		0–1	Lack of fusion (3 mm)
	(4–0)	No defect	Lower boss	1–2	Porosity (2 mm)
				2–0	No defect
ACT-02	(0–1)	Undercut		0–1	No defect
	(1–2)	No defect	Upper boss	1–2	No defect
	(2–3)	Undercut		2–0	No defect
	(3–4)	No defect		0–1	No defect
	(4–0)	No defect	Lower boss	1–2	No defect
				2–0	Porosity (2 mm)

evaluate the manufacturing process. The X-ray test was performed on the welding zone of pressurization tanks for attitude control and diffusion bonding area of the nitrogen tank for valve driving control. For the helium tank, X-ray test shows the integrity of the bonded zone and for the nitrogen tank, the partial defects on the welded area. This is due to the fact that the diffusion bonding is solid-state joining process and the TIG welding produces temporarily liquid-state.

Inspection results (Table 2) from radiographic inspection show the main defect in hemispherical welding zone is undercuts and the boss area has defects of porosities and deficient flow of filler. The undercut is a dented region formed at the boundary of parent material with fillers and may result in stress concentration.

The hemispherical welding area of attitude control tanks is divided by five in circumferential direction and the boss welding area is divided by three for inspection.

The thickness profile of the attitude control tank and the valve driving tank measured by ultrasonic method are studied. The measuring points are near the bonded area of hemisphere and boss, lying on 90° each along an equatorial plane. The result (see Table 3) shows the attitude control tank is satisfactory with the thickness design requirement profile of uniform distribution of 4 mm. However, the equatorial area of the valve driving tank is thicker than the design requirement (see Table 4), while as the thickness near boss region is about 50–65% of the requirement. This is because reduction of thickness is localized on boss area due to the use of uniform thickness in initial blank. As a result of the nondestructive evaluation using X-ray and ultrasonic device, the spin formed tank performs better in terms of thickness variation, while as diffusion bonded and blow formed tank includes little defects.

Table 4
Thickness measurement of valve driving tank

Position	0°	90°	180°	270°
Upper hemisphere				
Upper boss region	1.43	1.44	1.17	1.25
Upper hemisphere	4.31	4.60	4.72	4.46
Lower hemisphere				
Lower boss region	1.95	1.98	1.73	1.89
Lower hemisphere	3.36	3.82	3.95	3.13

2.3. Pressure test

The performance of each tank was tested by the pressurizing test in which the hydraulic pressure was increased to the proof pressure and then decreased [5]. In order to measure the deformation and the acoustic emission signal during hydraulic loading, the strain sensors were located as Fig. 4. For the attitude control tank, low frequency AE sensors were located between the strain gage nos. 5 and 9, high frequency AE sensors between the strain gage nos. 8 and 10, and wide band AE sensors between the strain gage nos. 5 and 10. For the valve driving tank, wide band AE sensors were located near the strain gage nos. 9 and 11.

Table 3
Thickness measurement of attitude control tank

Diffusion bonded area	0°		90°		180°		270°	
	Tank #01	Tank #02	Tank #01	Tank #02	Tank #01	Tank #02	Tank #01	Tank #02
Upper hemisphere								
Upper boss	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Upper hemisphere	4.92	4.98	4.92	4.71	4.89	4.74	5.03	4.81
Lower hemisphere								
Lower boss	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Lower hemisphere	4.92	4.70	4.93	4.88	4.96	4.95	4.90	4.95

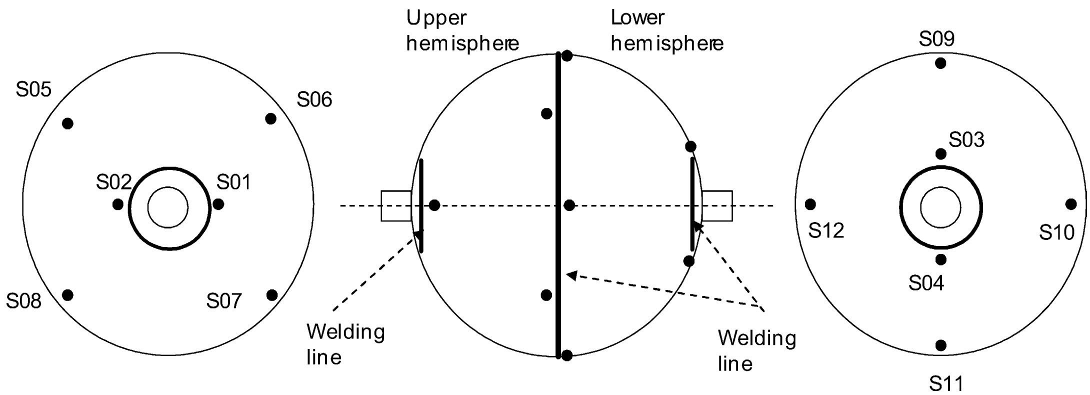

Fig. 4. Map for strain and acoustic emission sensors.

3. Results and discussion

Figs. 5 and 6 illustrated the results from the pressurizing test of attitude control tank. It is shown that the tank ACT-01 has relatively large amount of defects comparing to ACT-02, there was no damage or leakage with increasing the hydraulic pressure up to the proof pressure of 31 MPa and no residual deformation was observed after decreasing the hydraulic pressure. The maximum strain was observed at upper welded region with boss, which was 4600×10^{-6} and the strain of the weld region of the hemisphere was 2700×10^{-6}. In case of the tank ACT-02, the damage occurred at a lower pressure, which is 30.2 MPa at the site of boss welding area (Table 5).

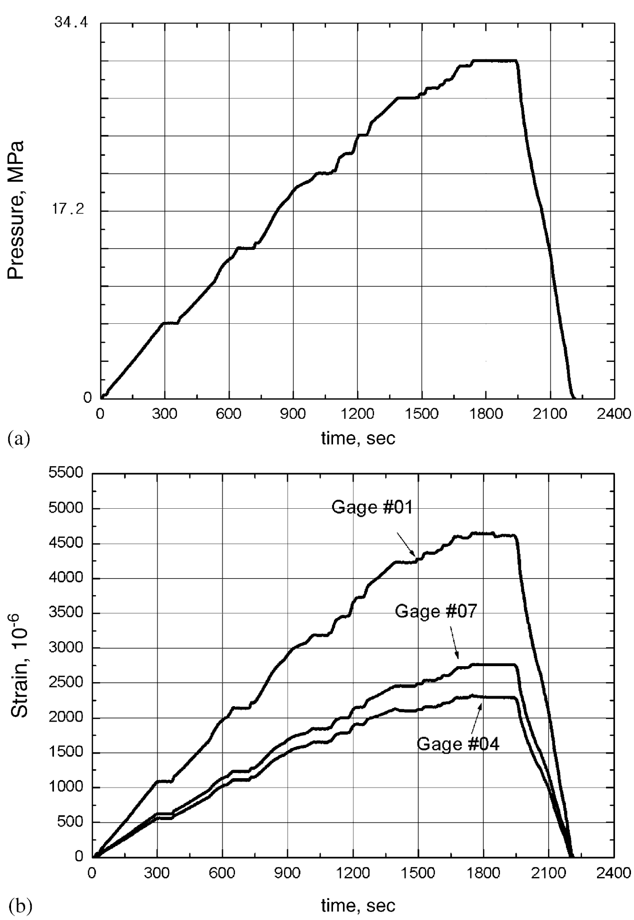

Fig. 5. Pressure test results of attitude control tank ACT-01. (a) Time vs. pressure and (b) time vs. strain.

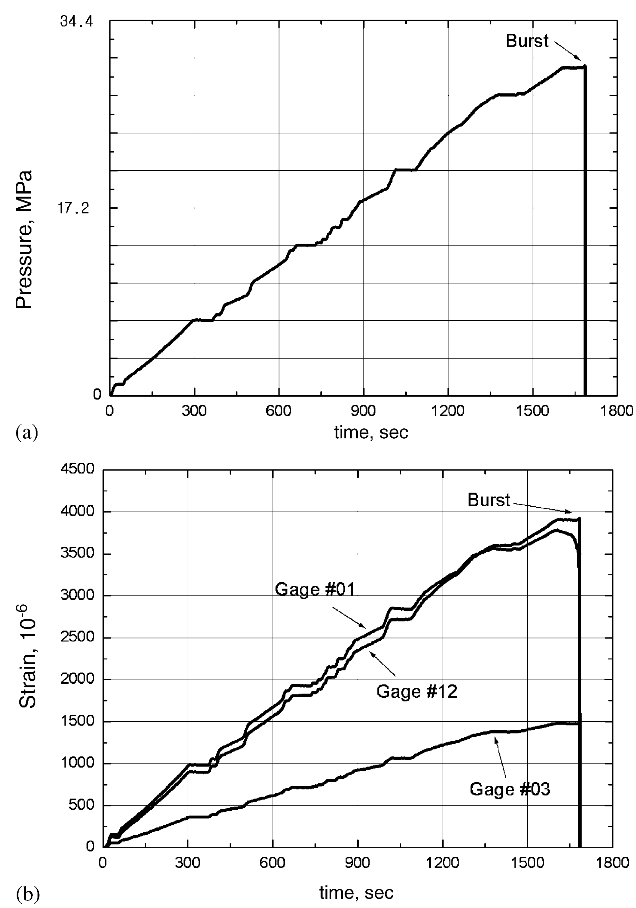

Fig. 6. Pressure test results of attitude control tank ACT-02. (a) Time vs. pressure and (b) time vs. strain.

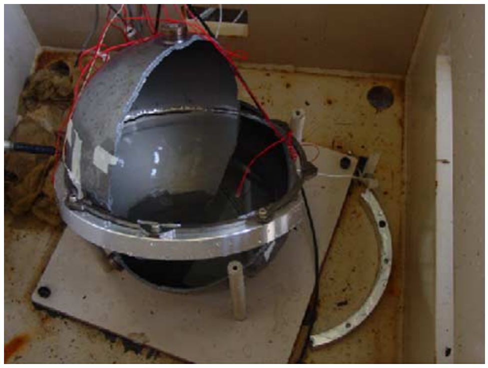

Fig. 7. Failure of attitude control tank ACT-02.

Fig. 9. Failure mode of valve driving tank.

Fig. 7 shows the failure of the attitude control tank ACT-02 and the fracture starts at the weld region of the hemisphere propagating to the upper boss region. As the results of the pressurizing test and nondestructive test, the undercuts produce more stress concentration than porosities or a lack of filler, and it is important to remove all undercut defects if possible to increase the reliability of the tank.

The result of the pressurizing test of helium tank for valve driving is depicted in Fig. 9. As shown in Fig. 8(a) the failure occurred near the boss with the hydraulic pressure of 29.8 MPa, which is lower than maximum expected operating pressure (MEOP). This is because the thickness at this region is about 50% of the design thickness. Fig. 8(b and c)

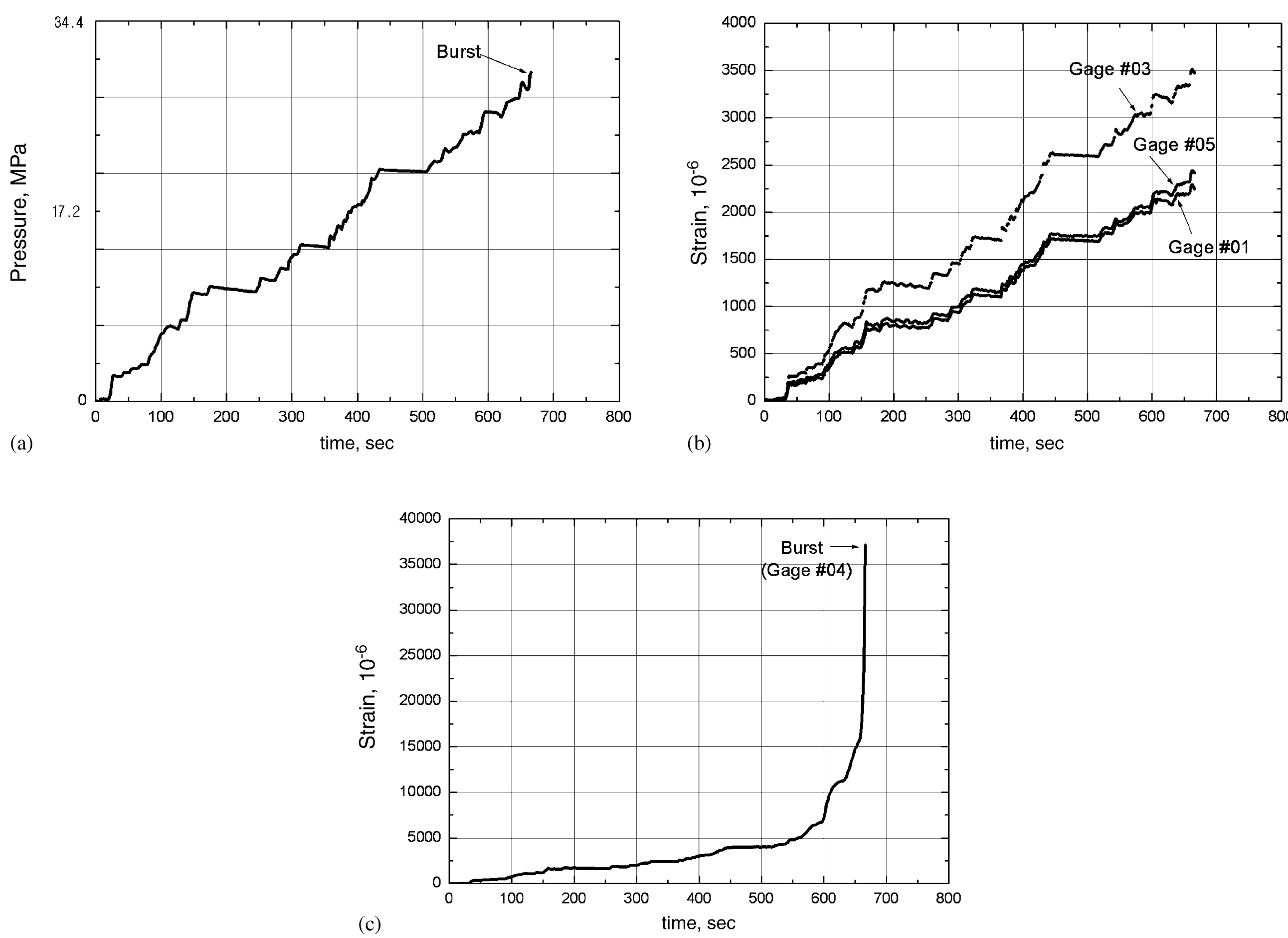

Fig. 8. Pressure test results of valve driving tank. (a) Time vs. pressure (b) time vs. strain and (c) time vs. maximum strain.

Table 5
Measured maximum strain of attitude control tank during pressure test

Serial number	Strain of welding region, $\times 10^{-6}$ strain						Pressure (MPa)
	Upper boss region		Lower boss region		Center of shell		
	Strain	Gage no.	Strain	Gage no.	Strain	Gage no.	
ACT-01	4650	1	2310	4	2760	7	31
ACT-02	3780	1	1480	3	3920	12	Burst at 30.27

presents the results of strain measurement from the boss area and the symmetric plane of upper and lower hemisphere with hydraulic loading time. It was shown that the boss area experienced higher deformation and the maximum strain was obtained at the location where fracture occurred. By increasing the hydraulic pressure linearly with time, the strain increases drastically after 26.2 MPa up to failure as shown in Fig. 8(c). The result of failed valve driving tank is shown in Fig. 9.

The result of acoustic emission signal measurement of attitude control tank ACT-01 is illustrated in Fig. 10. It is shown that the AE signals are not obtained for the previously loaded duration and the amount of the AE signals depends on rather the pressurized rate than the absolute pressure over pressurizing region (Periods ② and ③). The AE signals can be also obtained in the constant pressure region, but the amount is not significant.

Fig. 11 is the result of acoustic emission signal measurement of attitude control tank ACT-02 and the AE signals are not obtained for the previously loaded duration like the tank ACT-01. The acoustic behavior in the constant pressure or holding pressure region (Periods ① and ③) shows a slightly different signals are produced depending on the constant pressure. The AE signals during the pressurizing region (Periods ② and ④) show similar tendency and since the pressurizing rate is lower at high pressure, the amount of AE signals increase for high pressure comparing with pressurizing rate. It is clear that the difference in amount of signals during the constant pressure region depends largely on the pressure itself rather than the pressurization rate. Since the tank ACT-02 failed below the qualification pressure, it can be concluded that the amount of AE signals depend on the pressure value itself during the constant pressure region and the pressurizing region for tanks with defects so that the early failure can be anticipated.

Fig. 12 indicated the result of acoustic emission signal measurement of the valve driving tank. The increasing amount of AE signals was obtained during the constant pressure region (Period ①) and drastic increase of signal was observed just before the failure (Period ④). In addition, the amount of signals was high in pressurizing region in case of high hydraulic pressure. Since the tank was previously loaded to 10.3 MPa, no significant signals were obtained under this pressure.

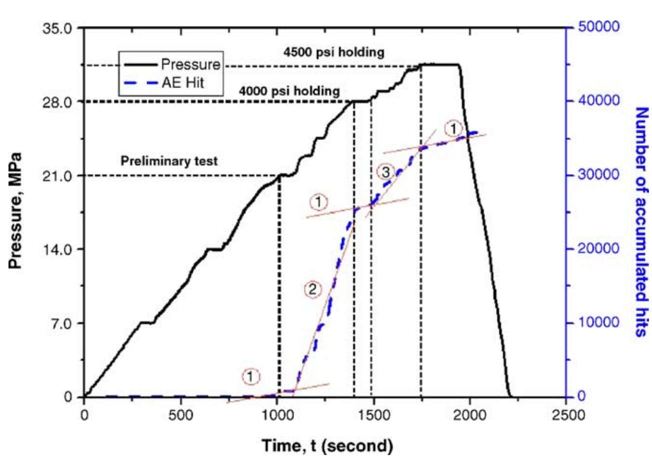

Fig. 10. Measurement of AE signal of attitude control tank ACT-01.

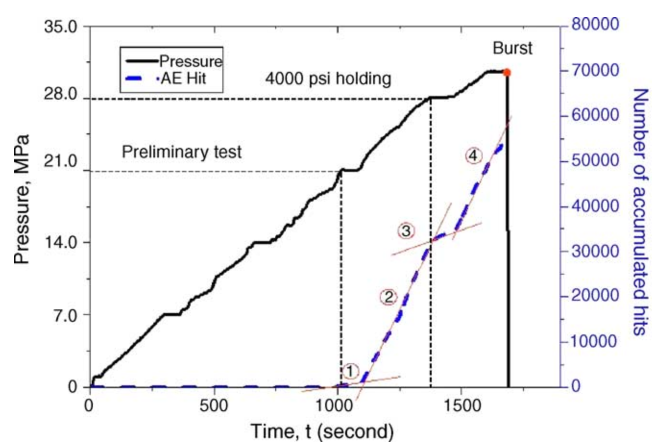

Fig. 11. Measurement of AE signal of attitude control tank ACT-02.

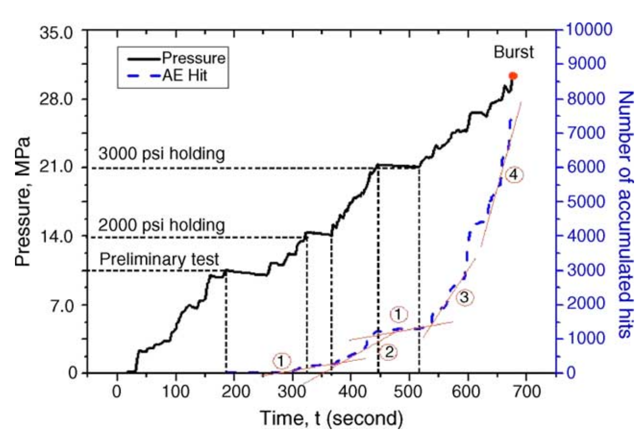

Fig. 12. Measurement of AE signal of valve driving tank.

From the above results, the increasing rate of AE signals before fracture is much higher than the pressurization rate. However, since it is not clear to distinguish the AE signals of a bonded region from those of a parent material using current test data, the further study must be performed to differentiate these data.

4. Conclusion

In this study, the titanium tanks were manufactured by two different methods. The attitude control tanks were spin formed and TIG welded, while the valve driving tank was diffusion bonded and blow formed. These tanks were hydraulically loaded and deformation behavior and AE signals were analyzed.

(1) In the attitude control tank, the difference in strain increase rate was not observed in welded region even near to failure and the final failure mode was brittle. This is assumed to be due to the microstructural change in heat affected zone (HAZ).
(2) The fracture of the valve driving tank occurred at the parent material near the boss and the increasing rate of strain change was drastic before the fracture.
(3) The AE signals characteristic shows that the pressurization rate and the signal increasing rate show a similar tendency for non-failed tank, while the signal increasing rate is much higher than the pressurization rate for failed tank.
(4) The curve of the AE signals increases with similar pattern as deformation increases.
(5) Regardless of manufacturing methods, the AE signals increased approaching the failure, but the difference in terms of signal characteristic from failures of two pressure vessels was difficult to obtain.

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