STUDY OF DAMAGE OF GAS-FILLED SPHERICAL PRESSURE VESSEL SUBJECTED TO HYPERVELOCITY IMPACT BY SPACE DEBRIS WITH DIFFERENT VELOCITY

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ABSTRACT

As an important component of spacecraft, if a gas-filled pressure vessel is impacted by space debris, it might occur even overall bursting. Spherical aluminum projectiles are used to simulate space debris impacting gas-filled spherical pressure vessel with hypervelocity. Projectiles impact places with the same thickness in different tests. By analyzing the maximum gas pressure of the spherical vessel, the inflation pressure is determined: 1.075MPa. By numerical simulation, the critical impact velocity to perforate the front wall is determined: 2.02mm ~ 2.31mm. As the projectile velocity increases, the damage patterns of the back wall are of different bulged outwards patterns.

1 INTRODUCTION

With the unceasing development of space activity, the total number of space debris is ever increasing, which greatly threaten orbiting space vehicles. Spacecraft often employ pressure vessels to contain gases and liquids. A pressure vessel subjected to hypervelocity impact by meteoroids and space debris can represent a significant hazard to a space vehicle because of the energy stored within the vessel. Vessel can occur venting through the impact hole[1].

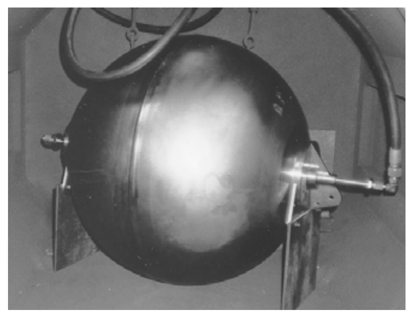

Figure 1. Typical Spherical Pressure Vessel[2]

A typical gas-filled spherical pressure vessel is shown in Fig. 1[2]. Pressure vessels are usually set outside spacecraft or close to the main structure, and are exposed to the meteoroid / space debris environment, and the risk of collisions is relatively high[3]. If a gas-filled pressure vessel is impacted, it may lead to craters in the vessel, surface spalling, perforation, crack instability under the pressure of the inner gas, and the vessel may burst[4]. The perforation will lead to a leakage. The gas thrust may change the spacecraft attitude. It may also lead to the loose of the pressure vessel, deformation or fracture of weak connection point on the spacecraft. In addition, the bursting produces secondary debris with hypervelocity. It will also cause further damage to the spacecraft and its surrounding equipments, resulting in premature failure of the spacecraft.

Hypervelocity impact tests are taken to simulate

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space debris impacting gas-filled spherical pressure vessel with hypervelocity. The production process of spherical pressure vessel lead to the unevenness of the wall thickness. Taking this situation into consideration, projectiles impact the places with the same thickness in different tests, researching the damage patterns of gas-filled spherical pressure vessels under different velocity of projectiles.

2 MAXIMUM WORKING PRESSURE

2.1 Thickness Measurement

The spherical gas-filled pressure vessel used in the tests is shown in Fig. 2. The outer diameter is 250mm. The manufacturing process of the pressure vessel is tension and compression molding of sheet. And then take a pair of hemispherical shells welded together. As a matter of the actual manufacturing process, the pressure vessel wall thickness is uneven. Therefore, measuring the wall thickness is necessary.

Figure 2. Spherical Gas-filled Pressure Vessel Used in the Tests

An ultrasonic thickness gauge with the model No. HT140 is used to measure the vessel wall thickness. The measurement scheme is shown in Fig. 3. Each vessel has almost the same thickness of the same position for bulk processing, and the thickness differences of the same position is negligible. The material of the spherical pressure vessel is Al-6061, and the wall thickness data are shown in Tab. 1.

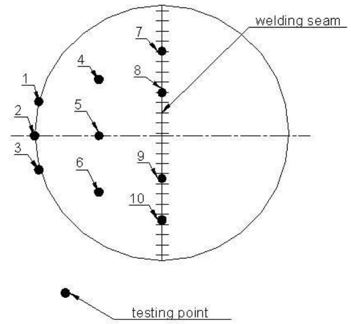

Figure 3. Spherical Pressure Vessel Thickness Measure Point Distribution Plan

Table 1. Spherical pressure vessel thickness

Measure Point	1	2	3	4	5
Thickness	2.23	2.29	2.24	2.15	2.14
Measure Point	6	7	8	9	10
Thickness	2.14	2.19	2.14	2.16	2.15

In addition to the 10 points measured in Tab. 1, random measurements are taken to every vessel used in the tests. Based on the actual measurement results，the thinnest place of the spherical pressure vessel wall is 2.02mm, while the thickest is 2.31mm. The thickness gap is 0.29mm. As the distance from the weld seam increases, the thickness of the pressure vessel wall increases.

2.2 Maximum Working Pressure

The maximum working pressure to the pressure vessel is analyzed according to JB-T4734-2002 (aluminum welding container).

2.2.1 Additional Amount of Thickness

The additional amount of thickness C（mm）is：

$$C = C_1 + C_2 \tag{1}$$

C_1 is aluminum thickness of negative deviation. When $C_1 \leqslant 0.25$mm，and less than 6% of the nominal thickness, it can be ignored; C_2 is the allowance for corrosion. The inner gas is nitrogen in this test, and C_2 can be ignored. So $C=0$.

2.2.2 Allowable Stress

The allowable stress of the spherical pressure vessel $[\sigma]$ is the minimum value from Eq. 2 to Eq. 5.

$$[\sigma] = \sigma_b / 4.0 \tag{2}$$

$$[\sigma] = \sigma_b^t / 4.0 \tag{3}$$

$$[\sigma] = \sigma_{p0.2} / 1.5 \tag{4}$$

$$[\sigma] = \sigma_{p0.2}^t / 1.5 \tag{5}$$

σ_b (MPa) is the minimum value of Al tensile strength at room temperature; σ_b^t (MPa) is the minimum value of Al tensile strength at standard temperature; σ_p (MPa) is minimum value of standard proof stress of nonproportional elongation at room temperature; σ_p^t (MPa) is minimum value of standard proof stress of nonproportional elongation at standard temperature.

As the material of the vessel is Al-6061, and the working temperature is room temperature, Eq. 2 is chosen to be the calculating selection. $[\sigma]$ is 41.25MPa.

2.2.3 Welding Joint Coefficient

Single-sided welding is used in the spherical pressure vessel, and the welding joint form is butt. A local non-destructive testing is used to test the welding joints. The welding joints coefficient is:

$$\phi = 0.8 \tag{6}$$

2.2.4 Maximum Working Pressure

The maximum working pressure (MPa) at the standard temperature is:

$$[p_w] = \frac{4\delta_e[\sigma_b]\phi}{D_i + \delta_e} \tag{7}$$

D_i (mm) is the inner diameter of the spherical vessel, and 245.38mm⩽ D_i ⩽245.96mm; δ_e (mm) is the effective thickness of the spherical vessel.

$$\delta_e = \delta_n - C \tag{8}$$

δ_n (mm) is norminal thickness of the spherical vessel. According to the conclusion mentioned above, C=0, then:

$$\delta_e = \delta_n \tag{9}$$

Based on the actual measurement of spherical pressure vessel wall thickness , 2.02mm⩽ δ_e ⩽ 2.31mm. Then, 1.075MPa⩽ $[p_w]$ ⩽1.231 MPa.

Taking the safety of the experiment into account, $[p_w]$ is 1.075MPa.

3 CRITICAL PERFORATION VELOCITY

3.1 Geometric Model

SPH solver of AUTODYN v6.0 is used to simulate the projectile impacting the pressure vessel process. Compared with the traditional Lagrange and Euler method, smooth particle hydrodynamics (SPH) method can simulate the debris cloud's generation and its development from hypervelocity impacting better. It is suitable for the simulation of the problems with high strain rates and large deformation such as hypervelocity impact[5, 6].

The curvature of the projectile is quite larger than that of the pressure vessel, and therefore the spherical pressure vessel wall could be treated as flat. A two-dimensional axisymmetric model is established for the sake of the axial symmetry of the problem. The diameter of the particles is 0.1mm, as is shown in Fig. 4.

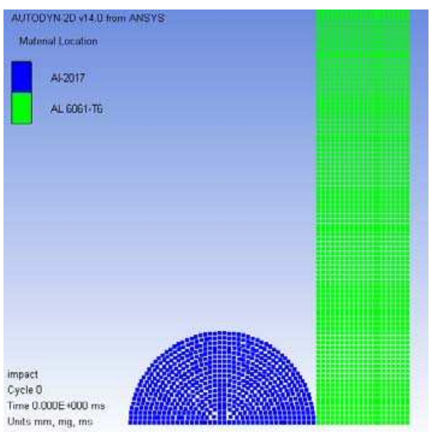

Figure 4. Two-dimensional geometry model in axial symmetry

3.2 Material model

The state equation is $Mie-Grüneisun$, and the equations and related material parameters are as followes[7, 8]:

$$\begin{cases} p = p_H + \Gamma\rho(e-e_H) \\ \Gamma\rho = \Gamma_0\rho_0 = const, U = c_0 + su_p \\ p_H = \dfrac{\rho_0 c_0{}^2\mu(1+\mu)}{[1-(s-1)\mu]^2}, \\ e_H = \dfrac{p_H}{2\rho_0}\left(\dfrac{\mu}{1+\mu}\right), \mu = \dfrac{\rho}{\rho_0} - 1 \end{cases} \quad (10)$$

Table 2. Material parameters of $Mie-Grüneisun$ equation of state

	ρ_0 (kg/m3)	C_0 (m/s)	S	Γ_0
2017	2.8×10^3	5328	1.338	2
6061	2.7×10^3	5328	1.338	2

p and e are hydrostatic pressure and specific internal energy separately; p_H and e_H are the reference values of hydrostatic pressure and specific internal energy separately on the impacting Hugoniot curve; Γ and ρ are $Grüneisun$ parameter and density separately; and Γ_0 and ρ_0 are $Grüneisun$ parameter and initial density separately; U and u_p are the velocity of shocking wave and wave-particle velocity; c_0 is the volume speed of sound; s is the slope of the linear relationship between U and up; μ is the compression ratio.

The strength model is Johnson-Cook model[7]:

$$\sigma_y = \left(A + B\varepsilon_p^n\right)\left[1 + C\ln\left(\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0}\right)\right]\left(1 - T^{*m}\right) \quad (11)$$

σ_y is the yield stress; ε_p is the equivalent plastic strain; $\dot{\varepsilon}_p$ is the equivalent plastic strain rate; T is the temperature; Reference strain rate $\dot{\varepsilon}_0 = 1s^{-1}$. A, B, n, C and m are material constants. A is the yield strength of the material in the quasi-static; *B* and n are the strain hardening; *C* is the strain rate sensitivity index; *m* is the temperature softening coefficient.

If the room temperature is T_{Room}, and the melting point is T_{Melt}, then the definition of the temperature of the system is :

$$T^* = (T - T_{Room}) / (T_{Melt} - T_{Room}) \quad (12)$$

Johnson-Cook model parameters for the material are shown in Tab. 3[8].

Table 3. Material parameters of Johnson-Cook strength model

	A (MPa)	B (MPa)	C	m	n	T_{room} (K)	T_{melt} (K)
2017	270	426	0.015	1.0	0.34	300	775
6061	276	290	0.015	1.0	0.34	300	1220

According to the measurement results of the pressure vessel wall thickness, the pressure vessel wall thickness is between 2.02mm ~ 2.31mm. Simulation results show that when the pressure vessel wall thickness is 2.02mm, the critical perforation velocity is 0.715km/s; when the pressure vessel wall thickness is 2.31mm, the critical perforation velocity is 0.817km/s.

Therefore, in order to ensure the front wall of the pressure vessel can be perforated, the impact velocity of the projectile is no less than 0.817km/s.

4 HYPERVELOCITY IMPACT TESTS

4.1 Test Apparatus

A two-stage light gas gun (Fig. 5), which is owned by space debris hypervelocity impact research center of Harbin Institute of Technology, is used to simulate the impacting process.

Figure 5 Two-stage light gas gun

4.2 Test Methods

Hypervelocity impact experiments were carried out 6 times under different impact conditions. The diameter of spherical projectile is 3.97 mm. The material of spherical projectile is Al-2017.

The target is spherical pressure vessels, which is made of material Al-6061. It's outer diameter is 250mm, and the inner gas is nitrogen. According to the results of the maximum allowable pressure of the pressure vessel, the inner gas pressure is 0.6MPa.

The impact velocities of projectiles are about 2.0km/s ~ 4.5km/s. And the impact angle is 0 °.

The welding seam is the weak point of the pressure vcessel. In the case of no external impact, the failure portion of the pressure vessel is usually starting from the welding seam. Therefore, in order to exclude the welding factors, the impacting point should avoid the welding seam.

4.3 Test Results and Analysis

In this test, the impact velocity is the main parameter, while the projectile diameter, the structure and the material of the pressure vessel, and the type and pressure of the inner gas are constants. Therefore, the impact velocity affects the failure behavior of the pressure vessel under the impact of the projectile. Tab. 4 shows the velocity of projectiles in each test.

Table 4. Velocity of Projectiles （km/s）

Vessel No.	1	2	4	5	7	8
Impact velocity	2.23	2.60	3.29	4.17	4.51	3.55

Fig. 6 to Fig. 11 are the impact patterns of pressure vessels under different velocity mentioned in Tab. 4.

(a) Front Wall (b) Back Wall

Figure 6. The Pressure Vessel Impact Pattern under the Impact Velocity of 2.23 km/s

(a) Front Wall (b) Back Wall

Figure 7. The Pressure Vessel Impact Pattern under the Impact Velocity of 2.60 km/s

(a) Front Wall (b) Back Wall

Figure 8. The Pressure Vessel Impact Pattern under the Impact Velocity of 3.29 km/s

(a) Front Wall (b) Back Wall

Figure 9. The Pressure Vessel Impact Pattern under the Impact Velocity of 4.17 km/s

(a) Front Wall (b) Back Wall

Figure 10. The Pressure Vessel Impact Pattern under the Impact Velocity of 4.51 km/s

(a) Front Wall (b) Back Wall

Figure 11. The Pressure Vessel Impact Pattern under the Impact Velocity of 3.55 km/s

As can be seen from Fig. 6~ Fig. 11, the front walls of the pressure are perforated under the hypervelocity impact from 2.23km/s to 4.51km/s, while the back wall appears different bulged outwards patterns.

Tab. 5 and Tab. 6 are the relevant parameters of the injury patterns of the front wall and the back wall respectively. An ultrasonic thickness gauge is used to measure the thickness around the perforation.

Table 5. Relevant Parameters of Injury Patterns of the Front Wall

Vessel No.	*V* *（km/s）*	D_{hole} *（mm）*	*C* *（mm）*
1	2.23	9.20	2.27
2	2.60	9.52	2.28
4	3.29	11.82	2.28
8	3.55	11.64	2.19
5	4.17	12.16	2.23
7	4.51	11.90	2.25

V——projectile velocity;

D_{hole}——perforation diameter of the front wall;

C——average wall thickness arround perforation

Table 6. Relevant Parameters of Injury Patterns of the Back Wall

Vessel No.	*V* (*km/s*)	D_{bulge} (*mm*)	H_{bulge}	*N*
1	2.23	7.60	1.50	1
2	2.60	9.10	2.30	1
4	3.29	10.10	0.39	5
8	3.55	6.72	0.27	6
5	4.17	6.30	<0.20	11
7	4.51	4.00	<0.10	10

V——projectile velocity;

D_{bulge}——diameter of bulge place on the back wall;

H_{bulge}——height of bulge place on the back wall;

N——number of bulge place on the back wall

Average wall thickness arround perforation is from 2.19mm~2.28mm of the 6 times hypervelocity tests. The thickness gap is 0.09mm, about 3.9% of the wall thickness. Therefore, it is credible that 6 times hypervelocity tests has basically the same impact place, and the tests results are comparable.

According to Fig. 6~ Fig. 11, the injury pattern of the pressure vessel under the conditions of the tests are: the front walls are perforated, and bluged places appear on the back wall. As the impact velocity increases, D_{hole} increases.

As the impact velocity increases, both of D_{bulge} and H_{bulge} firstly increases and then decreases, while *N* increases.

When the projectile velocity is less than or equal to 2.60km/s, the projectile is not broken. Therefore, there is a a single bulge place on the back wall; When the projectile velocity is 3.29km/s ~ 3.55km/s, the projectile starts to crush, but not completely broken, and a main debris whit some small pieces appears; When the projectile velocity is 4.17km/s ~ 4.51km/s, it is completely broken up into fragments of substantially the same size, while the rear wall of the pressure vessel showing substantially the same size of bulge places.

As the projectile velocity improves, the projectile fragmentation degree increases, and the damag effects to the back wall firstly enhanced and then weakened.

5 CONCLUSION

(1) The production process of spherical pressure vessel leads to the unevenness of the wall thickness. An ultrasonic thickness gauge is used to measure the wall thickness of the pressure vessel. Taking this situation into consideration, projectiles impact the places with the same thickness in different tests. The actual wall thickness is between 2.02mm and 2.31mm, and the thickness gap is 0.29mm.

(2) The maximum working pressure of the pressure vessel is 1.075MP, according to JB-T4734-2002 (aluminum welding container). Taking the safety factor into account, the pressure is determined as 0.6MPa.

(3) SPH solver of AUTODYN v6.0 is used to simulate the projectile impacting the pressure vessel. Simulation results show that when the pressure vessel wall thickness is 2.02mm, the critical perforation velocity is 0.715km/s; when the pressure vessel wall thickness is 2.31mm, the critical perforation velocity is 0.817km/s. Therefore, the impact velocity of the projectile is no less than 0.817km/s.

(4) The front walls of the pressure are perforated under the hypervelocity impact from 2.23km/s to 4.51km/s, while the back wall are of different bulged outwards patterns.

(5) With the increase of the projectile impact velocity, the diameter of the perforation hole in the front wall increases; while the degree of fragmentation of projectiles also increases.

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