EXPERIMENTAL INVESTIGATION OF HYPERVELOCITY IMPACT ON GAS-FILLED STAINLESS STEEL PRESSURE VESSELS

HUANG Jie, NIU Wenxia, XU Xiang, MA zhaoxia, JIAN Hexiang, LIU Sen

(Hypervelocity Aerodynamics Institute, China Aerodynamics R&D Center, Mianyang 621000, China)
Email: cardc@my-public.sc.cninfo.net

ABSTRACT

Hypervelocity impact tests were conducted on gas-filled cylindrical stainless steel thin wall pressure vessels. Without shield the vessels can be penetrated by even Φ1mm 2A12 aluminum projectiles. With shield the damage of vessels was slightly affected by interior pressure of 0~6 MPa, strongly affected by interior pressure 8~10 MPa, even burst at 10 MPa. Ballistic limit curve under experimental condition was obtained.

The relation between failure and pressure of vessels was analyzed through conservative fracture mechanics approach. Then a critical *P-a* curve of pressure vessels was constructed which described relation between inner pressure and crack size. It was considered that crack of the pressure vessels was intensely growing during the process of burst, and crack of pressure vessels suffering to hypervelocity impact was governed by the combination of inner pressure P and additional shock pressure $\Delta P'$, which was calculated as 0.47MPa. Based on above result a predictive critical *P-a* curve was got to forecast if pressure vessels would burst or not.

a——crack length [mm]
d——projectile diameter [mm]
E——kinetic energy [J]
L——length of pressure vessels [mm]
P——vessel inner pressure [MPa]
P_b——reduced static burst pressure [MPa]
P_c——critical inner pressure [MPa]
ΔP——additional shock pressure [MPa]
$\Delta P'$——additional shock pressure(under crack) [MPa]
R——diameter of pressure vessels [mm]
r——radius of pressure vessels [mm]
S_c——critical strain energy density factor
t——thickness of pressure vessels [mm]
v——impact velocity of projectile [km/s]
θ——angle measured from direction of crack to direction of crack grow [deg]
β——angle measured from direction of crack grow to tangent of loop stress [deg]
σ_b——intensity limit [MPa]

1. INTRODUCTION

Particle impacts on gas-filled pressure vessels can lead to gas leakage or catastrophic failure, if pressure and projectile energy exceed certain limit values catastrophic rupture of the vessel can send high-velocity fragments in all directions and secondary damage becomes a serious threat to the spacecraft [1]. Even if catastrophic rupture does not occur, penetration of a vessel can jeopardize vehicle control due to venting of the pressurized contents [2].

The damage of the impact on a pressure vessel has been studied since the late 20th century. A variety of materials including aluminum soft drink cans, aluminum alloy, titanium alloy were investigated in the experiments of F.Schäfer, E.Schneider, M.Lambert, and I.Telitchev with the striking velocities in the range of 5-7km/s, focusing on the damages induced by fragment cloud impact on the back wall and on axial cloud velocities as a function of gas pressure, experimental determination of projectile energies and corresponding vessel pressure that lead to catastrophic failure of a thin-walled pressure vessel[1~4].

An extensive test program is also conducted at the NASA Johnson Space Center (JSC) to investigate the responses of pressure vessels to HVI and determine the effects of important pressure vessel parameters and impact conditions on the response of both shielded and unshielded pressure vessels which were filled with water or gaseous nitrogen[5~7]. Zhang Wei had tested 6063 aluminum pressure vessels [8].

The purpose of this paper is to investigate the responses of stainless steel pressure vessels to HVI, to determine the effects of pressure and impact conditions on the response of both shielded and unshielded pressure vessels, to get a better understanding of the phenomena of impact on pressure vessels to design more effective shielding and impact resistant pressure vessels.

2. EXPRIMENTAL SETUP

The tests were performed at the Hypervelocity Impact Range A of HAI, CARDC (Fig.1), which has two stage light-gas guns of *Φ*7.6mm caliber, a test chamber of *Φ*1m diameter. This range is equipped with transient

Figure 1 Hypervelocity Impact Range A

Proc. '5th European Conference on Space Debris', Darmstadt, Germany 30 March – 2 April 2009, (ESA SP-672, July 2009)

phenomena measurement apparatus, such as laser velocimeter which can obtain projectile velocity at the range of 0~10km/s, a sequenced laser shadowgrapher used to record the attitudes of flying projectiles[9].

The pressure vessels were cylindrical with 1.0 mm in thickness, 175 mm in length and 75 mm in diameter, made by stainless steel (0Cr18Ni9Ti) tubes. A flat bottom plate was welded to the bottom of the tube, and closed by a top plate which contained a tubule for a pressure gauge and a valve for pressurization. The tests included two groups. One group was conducted without shield. In another group 2A12 shielded plate was placed with thickness 1mm and spaced distance 50mm in front of pressure vessels. The experimental set-up was installed in the vacuum target chamber，schematically displayed in Fig.2.

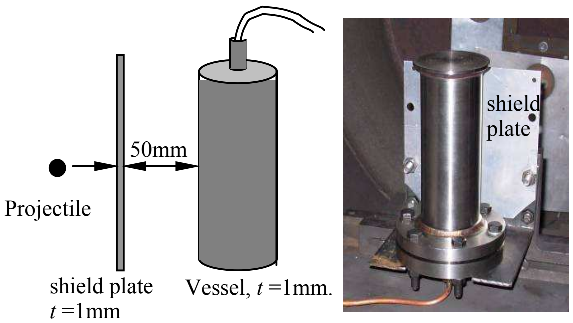


Figure 2. Experiment Setup

All projectiles were aluminum alloy (2A12) spheres, at a impact velocity around 5 km/s. Vessels were filled with nitrogen of pressures *P* ranging from 0 to 10 MPa. To determine the projectile diameters and vessel pressures which would cause pressure vessel failure, the kinetic energy was increased in subsequent tests for a given vessel pressure until failure occurred. Variation of kinetic energy was realized by variating projectile diameters *d* ranging from 3.5 to 5.0mm.

In this paper, failure was defined that gas leakage occurred after the vessel was hit.

3. TEST RESULTS

3.1. Results of Unshielded Test

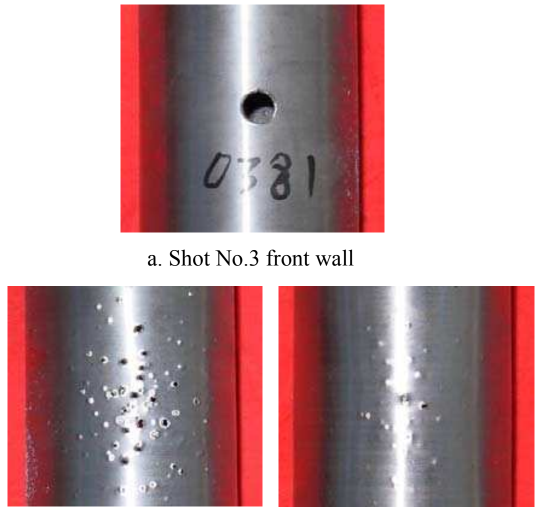
The unshielded tests includes four shots, as listed in Tab.1.

Table 1. Shot Parameters and Results of Unshielded Vessels

Shot No.	*d*/mm	*P*/MPa	*v*/km/s	*E*/J	Damage of	
					front	rear
1	1.00	-	5.22	23.2	p	b
2	2.46	-	5.35	240.4	p	b
3	5.00	-	4.94	2218.3	P	b, p
4	4.98	3	4.75	2060.0	p	b, p

p=perforation, b=bulge.

An unpressurized thin-wall cylindrical vessel can basically be modeled as a double bumper system of thin plates, i.e. a Whipple Shield, except for the curvature of the vessel wall. Like the damage of Whipple Shield, in all unshielded experiments perforation holes were found on the front wall of the vessel (Fig.3). The rear wall damage covered somewhat large area, producing numbers of tiny bulges and pinhole perforations even spallation.



a. Shot No.3 front wall

b. Shot No.3 rear wall, *P*=0MPa, *d*=5.00mm

c. Shot No.4 rear wall, *P*=3MPa, *d*=4.98mm

Figure 3. Vessel Damage without Shield

At the interior pressure of 3MPa, the same damage characteristic was shown on the vessels′ front wall and rear wall (Fig.3c), except slightly decrease of rear wall damage due to the fragments are decelerated and ablated in the gas. In all above experiments, no rupture occurred.

3.2. Results of Shielded Test

There were ten shots with 2A12 shield plates, as listed in Tab.2.

Table 2. Shot Parameters and Results of Shielded Vessels

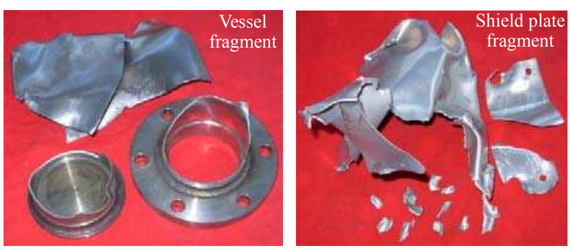
Shot No.	*d*/mm	*P*/MPa	*v*/km/s	*E*/J	damage
0374	3.50	0	4.79	744.5	c, s
0372	3.80	0	5.34	1146.3	p, s
0375	3.49	1	4.85	761.0	c, s
0376	3.80	1	5.12	1051.2	p, s
0377	3.50	3	5.01	808.2	c, s
0378	3.82	3	5.15	1072.8	p, s
0403	3.82	6	5.07	1034.6	p
0402	4.46	8	5.14	1750.3	p
0400	4.00	10	5.05	1220.3	c
0401	4.48	10	4.90	1601.5	burst

c= crater, s=spallation, p=perforation.

Debris cloud generated from shield plate impacted the front wall of the vessel covering a very large area, producing thousands of tiny pinhole perforations and small craters (Fig.4a). The majority of the debris, however, was concentrated within a circular region in a familiar pattern.

When interior pressure varied from 0 to 6MPa, damages were front wall perforation and leakage occurred. The same phenomena occurred at 8MPa pressures and 4.50mm projectile diameter. Catastrophic rupture initiated in the vessel front wall when pressures reached 10MPa and projectile diameter was 4.48mm. As shown in Fig.4b, the shield plate burst into several debris by strong shock wave. The vessel was ripped into a large piece with vessel top and bottom plates unzipped. Particularly, the vessel front side was perforated and cracked in axial direction, reaching at least to the end plates, partial unzipping. There was no rear side crater. It was believed that much higher inner pressure was necessary to induce catastrophic failure.

a. d=4.00mm, v=5.05km/s



b. d=4.48mm, v=4.90km/s

Figure 4. Damage of Shielded Vessels with 10MPa Inners Pressure

Based on above results, pressure vessels damage depends strongly on the projectile kinetic energy and inner pressure. In Fig.5, all results were compiled in a diagram. The experimental results are divided into failure and non-failure. The borderline that separates the parameter regimes has been fit. The field below this line is safe, whereas front wall perforation and different types of non-catastrophic damage, even to catastrophic rupture occurs for experimental parameters taken from above the curve.

For further considerations, the ballistic limit diameter for perforation is defined here as the critical projectile diameter leading to failure and non-failure of pressure vessel front wall with given thickness although other definitions exist. Ballistic limit diameter curve of vessels was shown in Fig.6. Ballistic limit diameter was 3.65mm when interior pressure ranging of 0~6 MPa, increased when pressure above 6MPa, up to 4.24mm at 10MPa pressure.

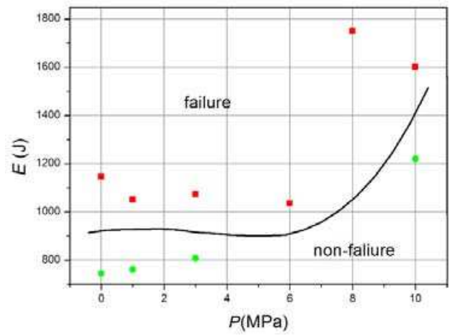


Figure 5. Kinetic Energy VS Inner Pressure

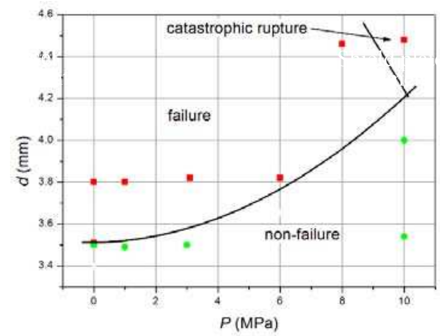


Figure 6. Ballistic Limit Diameter Curve (v=5km/s)

A conclusion could be brought out for pressure vessels: higher pressure, more impact resistant, however, more probability of catastrophic burst.

4. THEORETIC ANALYSES FOR RELATIONSHIP BETWEEN PRESSURE AND FAILURE

During hypervelocity impact the projectile penetrates and perforates the shield plate, generating a fragment cloud[10]. The expanding propagates to the vessels front side. If the energy of leading fragment in debris cloud is high enough to penetrate and perforate the vessels front side, new fragment cloud initiates and propagates in the vessel, a strong gas shock wave is generated that travels along with the fragment cloud. The shock wave reaches the rear side, reflects, travels to front side and produces a pressure pulse ΔP.

When inner pressure P and additional shock wave pressure ΔP exceeds a certain critical limit, i.e. reduced static burst pressure P_b, failure will occur. This meets the inequation by F. Schäfer[11]:

$$P + \Delta P > P_b \tag{1}$$

By a general way, the reduced static burst pressure P_b of stainless steel pressure vessel could be calculated by following formula [12]:

$$P_b = \frac{\sigma_b \cdot t}{r} \tag{2}$$

0Cr18Ni9Ti steel has σ_b for 520MPa[13], then P_b was calculated as 13.9MPa. Given P=10MPa，we can get $\Delta P \geqslant 3.9$MPa from Eq.(1). Hypervelocity impact leads to specific impact size, i.e. hole diameter and damage zone, thus the reduced static burst pressure ΔP would decrease to $\Delta P'$, which means

$$0 < \Delta P' < 3.9\text{MPa}$$

The rupture of vessels initiate in the rim of the impact hole, grow in axial direction, reach at least to the end plates, which reflect that rupture of vessel is caused by crack growth of vessel (Fig.7). In the following paragraph, a liner-elastic fracture mechanics was used to investigate the critical pressures and front side failure of the pressure vessels, even calculate $\Delta P'$ value.

Figure 7. Crack Growth of Rupturing Vessel

Various approaches have been developed to use in fracture failure, most through Fracture Failure Criterion to predict probability of fracture failure. Strain Energy Density Factor (S) describes intensity of crack-tip strain energy density field, used to analyze blended crack type[14]. Critical crack size and the crack growth direction can be worked out by S Criterion. In this paper crack caused by hypervelocity impact was represented through blended crack，which could overcome the disadvantage that singleness scalar quantity, i.e. K, cannot entirely represent growth of blended crack[14].

Two hypothetical explanations for S Criterion predicting growth of crack are given: (1) crack grows along direction of minimum strain energy density; (2) crack grows when S reach the critical value S_c , then rupture occur. S_c can be calculated as:

$$S_c = \left(\frac{P_c r}{2t}\right)^2 \pi a F(\beta, \theta_0) \tag{3}$$

Schematic Representation of β、θ were shown in Fig.8. When Poisson's Ratio v of stainless steel was 0.25, β and θ have certain function relationship, i.e. β=90^0, θ=0 [12], which means crack growth in axial direction.

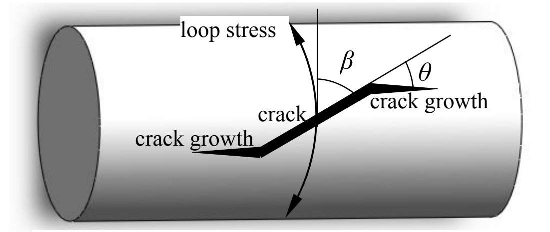


Figure 8. Schematic Representation of β、θ

transformed (3) into

$$\frac{P_c r}{2t}(\pi a)^{\frac{1}{2}} = \left[\frac{S_c}{F(\beta, \theta_0)}\right]^{\frac{1}{2}} \tag{4}$$

To apply Eq.(4), two reduces for rupture of pressure vessels are given. One of reduces is value β to 90^0, which is in accordance with experiment result (fig.6). In theory of S Criterion, the value of $\frac{P_c r}{2t}\sqrt{\pi a}$ are decided by v and β. When v=0.25, the value of $\frac{P_c r}{2t}\sqrt{\pi a}$ is list in Tab.3 with variety of β.

Table 3. Value of Eq.(4) When v=0.25[14]

β	$P_c r(\pi a)^{1/2}/2t$	β	$P_c r(\pi a)^{1/2}/2t$
0°	44.0	50°	28.4
10°	41.0	60°	24.3
20°	37.5	70°	23
30°	32.9	80°	22.2
40°	29.2	90°	22.0

from Tab.3 we can get

$$\frac{P_c r}{2t}(\pi a)^{\frac{1}{2}} = 22 \tag{5}$$

Thus S_c needn't to be calculated in the equation, the P_c of pressure vessels is shown as a function of the crack size a, that is critical P-a curve Ⅰ, as shown in Fig.9. It is a borderline that divides safety and riskiness. The crack doesn't grow below curve Ⅰ. Above curve Ⅰ the crack grows, vessel ruptures. It can be found that increasing of both pressure and crack size can both lead to failure of vessels.

A second reduce for the case of front wall fracture suggests that perforation diameter of pressure vessels equal to crack size a. This reduce is reasonable and corresponds to the observations in experiments. And then a curve that relates pressure and perforation diameter of experiment result is given in Fig.9, as curve Ⅱ, which lies below curve Ⅰ. But burst occurred on the point C.

As above, crack of pressure vessels impacted by hypervelocity particles is governed by the combination of inflation pressure P and additional shock pressure $\Delta P'$. In this case, the dynamic have to be taken into account. Comparing coordinate of point A, B and C, it shows that critical pressure or critical crack size leading to rupture of pressure vessels decreases because of hypervelocity impact. It is deduced that the actual gross inner pressure at least 10.47MPa in the test, and

$$\Delta P' \geqslant P_B - P_C = 0.47\text{MPa}$$

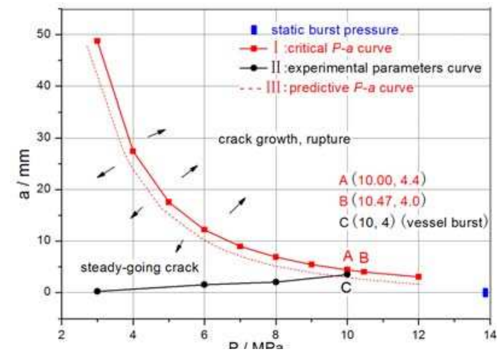


Figure 9. The Relation of Pressure,Crack Size and Damage

Comparing $\Delta P'$ with ΔP, hole or crack accelerates the failure of vessels, giving a curve Ⅲ in Fig.9. Below curve Ⅲ, vessels are simply perforated and leakage occurs, whereas above curve Ⅲ vessels rupture or catastrophic failure occurs. Curve Ⅲ offers a theoretic way to evaluate pressure vessels burst or not.

5. CONCLUSIONS

Hypervelocity impact tests were performed on stainless steel pressure vessels filled with nitrogen. Without shield the vessels can be penetrated by even 1mm projectiles. With shield the damage of vessels was slightly affected by interior pressure in the range of 0~6 MPa, strongly affected by interior pressure in the range of 8~10 MPa, even burst at 10 MPa, and ballistic limit diameter curve under experimental condition was obtained accordingly with range of 3.65~4.24mm. A diagram was compiled with the inner pressure P and kinetic energy E which divided experimental results into failure and non-failure.

The relationship between failure and pressure of vessels was analyzed. It was considered that crack of the pressure vessels was intensely expanding during the process of burst. Crack of pressure vessels impacted by hypervelocity particles with variety diameters were governed by the combination of inner pressure P and additional shock pressure $\Delta P'$, that is, vessels burst with P of 10MPa and $\Delta P'$ of 0.47MPa in the experiment. Comparing the critical P-a curve of pressure vessels with experiment parameters, it was indicated that critical crack size and critical inner pressure leading to burst decreased because of hypervelocity impact. A predictive critical P-a curve was obtained to offer a theoretic way to evaluate pressure vessels burst or not.

The analysis of the paper was limited to the experimental condition.

ACKNOWLEDGEMENT

The authors appreciate the assistance of Li Yi, Chen Hong CARDC Hypervelocity Aerodynamics Institute who provided the engineering advice in this study. In addition, the authors appreciate the excellent support provided by Hypervelocity Impact Test Facility (HIT-F) personnel including Zhou Junfeng, Chen Ping, Luo Qing, He Guishen, Liu Xiaolong.

REFERENCES

1. Michel Lambert,Eberhard Schneider．Hypervelocity impacts on Gas Filled Pressure Vessels[J]．*Int. J. Impact Engng*, 1997 (20): 491-498
2. Frank K.Schafer，Eberhard E.Schneider，Michel Lambert．Hypervelocity Impact on cylindrical Pressure Vessels experimental results and damage classification．Proceedings of the 1997 ASME Pressure Vessels and Piping Conference. Orlando,florida,USA,1997.
3. F. Schäfer, E. Schneider, M. Lambert. Propagation of Hypervelocity Impact Fragment Clouds in Pressure Gas[J]. *Int. J. Impact Engng*, 1997 (20): 697-710.
4. Igor Ye. Telitehev,Dmitri Eskin. Engineering Model for Simulation of Debris Cloud Propagation Inside Gas-Filled Pressure Vesssls[J]. *Int. J. Impact Engng*, 2003 (29): 703-712.
5 PROTECTION MANUAL．Prepared by the IADC WG3 members．Inter-Agency Space Debris Coordination Committee, 2004.
6. Gregory D.Olsen，Angela M.Nolen．Hypervelocity Impact Testing of Pressure Vessels to Simulate spacecraft Failure．*Int. J. Impact Engng*，2001 (26)555-566.
7. E. L. Christiansen, J. H. Kerr, J.P. Whitney. Debris Cloud Ablation in Gas-filled Pressure Vessels. *Int. J. Impact Engng,* 1997(20)173-184.
8. ZHANG Wei, GUAN Gong-shun. Experimental Investigation of High Velocity Projectile Impacts damage on Pressure Vessels[J]. *Journal of experimental Mechanics*, 2004,19(2): 229-235.
9. LIU Sen, HUANG Jie, LI Yi. Research in Hypervelocity Impact at CARDC. 3rd National Symposium on Space Debris. Beijing. July 2005.
10. LIU Sen, HUANG Jie, LI Yi. Hypervelocity Impact Tests for Spacecraft against Orbital Debris at HAI, CARDC. 58th International Astronautical Congress. England, Sep 2007.
11. I.Telitchev, F. Schäfer, E. Schneider, etc. Analysis of the Fracture of Gas-Filled Pressure Vessels under Hypervelocity Impact[J]. *International Journal of Impact Engineering*, 1999,23(1): 905-919.
12. XING Zhi-xiang. Qualitative Analysis about burst of Pressure Vessels[J]. Science and technology of fire, 1997(4): 32-34.
13. ZHANG Si-yu. New Manual of Metal Material Symbol, Performance, Use and Comparison China to Foreign [M]. Chinese Science and Technology Culture Press, 2005.3
14. LI Hao, CHEN Shu-jian, GUO bi-jian. Fracture Mechanics and Composite Materials Mechanics[M]. 174-196.