Hypervelocity Impact Response of Ti-6Al-4V Plates Mounted on Cylinders

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ABSTRACT

The study investigates the effects of hypervelocity impacts on spacecraft hydrazine fuel tanks, specifically focusing on the detonation mechanisms of hydrazine vapor in low-pressure reservoirs. The goal is to understand the fracturing conditions of propellant tanks and develop protective designs against space debris impacts.

A high-speed impact test was conducted using a two-stage light gas gun at ISAS-JAXA.

Polycarbonate spheres (Φ7.18 mm) were used to achieve impact velocities of 7 km/s. Specimens were circular plates of Ti-6Al-4V, with internal pressures varied from no pressure to 1 MPa.

The impact tests showed different penetration and fracturing behaviours depending on the internal pressure. At 0.62 mm plate thickness, unpressurized plates only showed penetration, while pressurized plates (0.6 MPa) exhibited bumps and cracks. At 1.09 MPa, fracturing occurred, and fragments were separated.

We found that internal pressure significantly affects the penetration and fracturing of Ti-6Al-4V plates under hypervelocity impacts.

1 Introduction

We will consider the case of a spacecraft hydrazine fuel tank and the consequences of a hyper-velocity impact from space debris. The final purpose of this study is to better understand the mechanisms of detonation of hydrazine vapor during a hypervelocity impact on a low-pressure reservoir.

In the ratio of hoop stress to fracture stress vs. crushing limit energy described in ISO16126, the explanation is that the operation starts at a stress ratio of 0.5 and does not fracture from about 0.25. Understand the fracturing conditions of propellant tanks for spacecrafts and protect against debris that could lead to total loss of spacecrafts.

Obtain basic data on the guidelines for protective design. In the process, a circular tank that simulates an actual tank is prototyped, and the experimental correlation equation presented in ISO for tank fracturing is evaluated and compared, and the presence or absence of crushing due to the difference between pressurized and non-pressurized is confirmed. As part of this effort, the response to a hyper velocity impact of 7 km/s under pressurized and unpressurized Ti-6Al-4V plates used in tank materials is shown and discussed.

2 Backgrounds & Motivation

In 2020 ISO-16126 added the requirement to "An analysis of the space debris and meteoroids (SD/M) impact-induced probability of failure of the spacecraft" to the requirements of ISO-16126 added. Pressurized tanks have the potential to cause a catastrophic break-up of spacecraft even with minor damage, and the risk of damage from micro-debris impacts in the mm class needs to be assessed.

To understand the Ballistic limit and the process of microcrack initiation and then crack propagation, to clarify the damage mode that a catastrophic break-up of spacecraft, and to present the SD/M impact conditions that cause failure of the spacecraft.

The applicability of the Ballistic limit equation [(1) (2)]to plates which is titanium alloy or CFRP of the same material as the pressurized tank used in JAXA spacecraft will be clarified using tests and numerical analysis.

Considering the number of pieces of debris that have been generated, the dispersion of the debris, and the Lebel of damage, such as whether the damage to the pressurized tank is simply penetration or propagation of cracks.

Perform testing and numerical analysis on tanks with internal pressure.

Considered several cases of spacecraft design parameters such as structural design of the pressurized

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tank, structural panels around the tank, and separation distance from the structure that serves as a protective shield.

Tests and analyses will be conducted under conditions similar to those of the actual structure to clarify the debris impact conditions that will cause to a catastrophic break-up of spacecraft.

The results obtained will be reflected in the Space Debris Protection Design Manual (JERG-2-144-HB001).

From flat to curved to pressurized, we analysed images using a high-speed camera, determine whether the process of microcrack initiation to crack propagation, collection of fracture fragments after the test, and simulation will allow us to evaluate whether tank fracturing can be evaluated as a simple unloaded target impact test, with or without penetration, and whether the fracture mechanics process is not overlooked.

Invite experts in the spacecraft tank field to WG3A to review to design criteria with no omissions and prioritization.

The pressurized tanks were tested and we will also consider simulating pressurization in tension, etc.

We obtain Ballistic limit for the titanium alloy that is the main material of the tank [(5)].

Since spacecraft propulsion tanks are cylindrical or spherical in shape, a curved surface impact simulation will be performed based on the actual tank shape to sort out the differences from a flat plate.

Confirm the effect of curved surfaces with the results of an experiment simulating a pressurized tank, which will be conducted separately after the third year.

3 Experimental Set-up

We confirmed the sabot function at the maximum energy that can be performed with the ISAS-JAXA two-stage light gas gun in Fig.1.

A high-speed impact test of 7 km/sec was conducted using the injection of a polycarbonate sphere Φ7.18 mm, which can achieve the maximum energy conditions.

A pressurized vessel was created, and the test was started. A specimen chamber was made in the shape of two circular plates sandwiched together in Fig.2 and Fig.3, and the internal pressure was varied from no pressure to 1 MPa to verify whether the appearance of penetration, fracturing, etc. during impact would differ depending on the internal pressure. The impact velocity was also varied from 5 to 7 km/sec to verify whether the appearance of impact would differ depending on the impact energy.

Figure 1. Two-stage light gas gun @ ISAS-JAXA

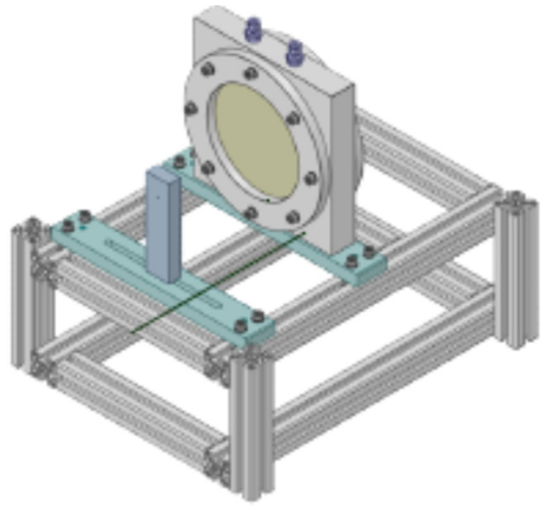


Figure 2. Image of a pressurized vessel

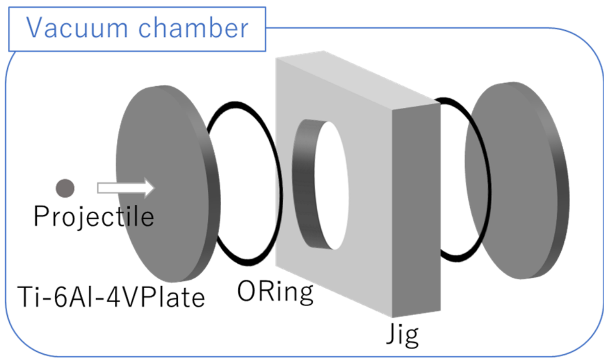


Figure 3. Image of Experimental set-up

4 Results

The thickness of the titanium plate on the impact surface was 0.62 mm, only penetration occurred without pressurization, and two bumps and cracks occurred in the direction of the impact surface at 0.6 Mpa. Furthermore, when the pressurization was 1.09 Mpa, fracturing occurred from the penetrating portion and half of the fragments were separated.

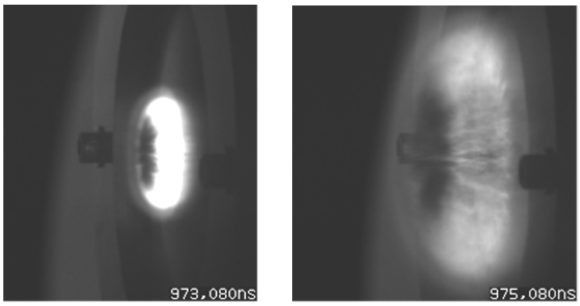
As a result, it was found that the difference in the internal pressure of the test specimen at least caused a difference in penetration and fracturing in table1. We will continue to examine the effects of pressure and the energy conditions that cause fracturing, and we plan to conduct verification using test specimens equivalent to the tanks actually used in orbit.

5 Discussion

After Impact, through-hole occurrence and then through-hole generation in Fig 4. Shock propagation in the target that occurs in the event of an impact (Front peeling?)）. The state of the ejector that occurs during penetration. Effect on the internal gas of the ejector (compression?), propagation of shocks generated during an impact. Because Pressure environment changes in the tank (gas jets and vibrations?), target vibration and internal pressure change time series. Effects of shock propagation and effects of changes in pressure environment. It is necessary to understand the size of both. Finally Crack propagation from the target hole.

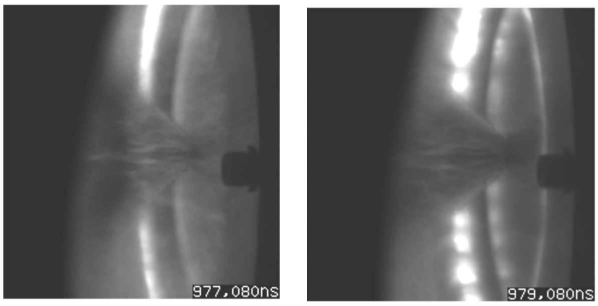
Table 1. Test results for pressurized tank

Velocity [km/s]	Pressure （GN2）：MPa	Target thickness：mm	Test results （Crushing status）	Hole diameter [mm]
7.009	No	1.20	Penetration	11.7
6.990	1.09	1.20	Penetration ＋**Spout Rise**	12.4
Figure 4 7.039	1.09	**0.62**	**Crushing occurs from the fracture part** **Half-split debris detachment**	**12.2** **Half-split reference value**
6.907	No	0.62	Penetration	9.5
7.024	0.60	0.62	Penetration+**Spout Rise** ＋**2 cracks**	10.7

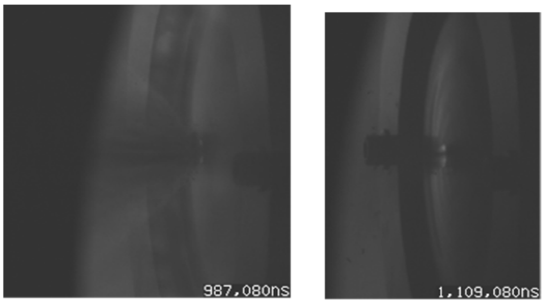


(a) Impact moment (b) Impact moment after 2μs

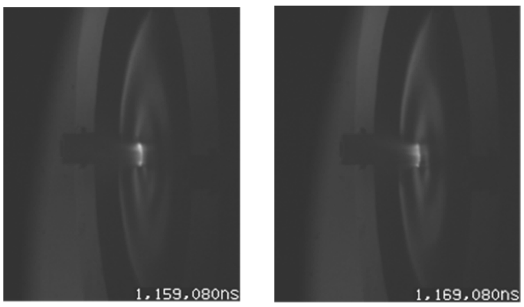
@ Projectile deformation and Anterior detachment rupture



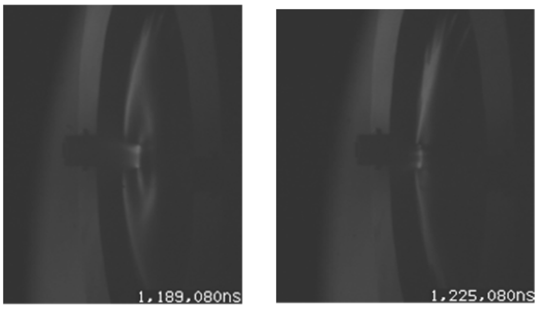
(c) Impact moment after 4μs (d) Impact moment after 6μs Both of Gas ejection and Anterior detachment rupture



(e) Impact moment after 8μs (f) Impact moment after 10μs

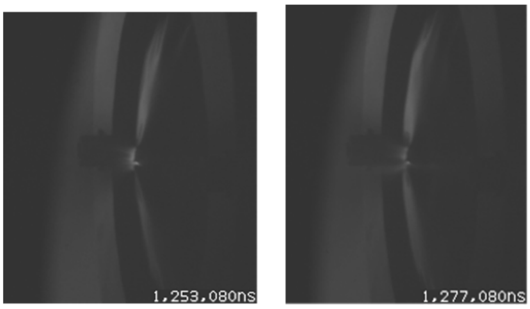


(g) Impact moment after 50μs (h) Impact moment after 60μs Circular vibration initiation

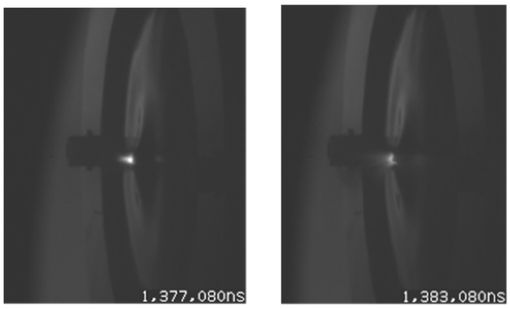


(i) Impact moment after 216μs Vibration maximum

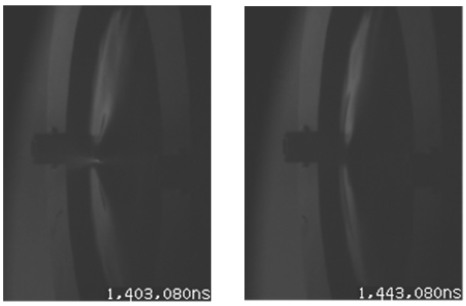
(j) Impact moment after 252μs Start of rising from the hole



(k)Impact moment after 280μs Start of rising from the hole (l) Impact moment after 304μs



(m) Impact moment after 404μs (n) Impact moment after 424μs Re-ejection of internal gases ?



(O) Impact moment after 430μs (n) Impact moment after 470μs

Figure 4. Photo of High speed video at velocity is 7.039 km/sec, Target thickness is 0.62 mm

6 Conclusion

Under non-pressurized conditions, there was no difference in the penetration limits of flat and curved plates [3].

There was no difference between the non-pressurized condition and the Ballistic limit under the condition of pressurization 1 Mpa on a 64 titanium alloy flat plate (central displacement 5.2 mm).

The maximum energy that can be implemented at the ISAS test facility (polycarbonate projectile Φ7 mm, impact velocity 7 km/sec) was performed under the condition of 1 Mpa pressurization (titanium alloy thickness 0.6 mm), and it was confirmed that crushing occurs instead of penetration, cracking occurs at 0.5 Mpa, and only penetration occurs at non-pressurized conditions.

From the results, it was found that there was and was not crushing under the pressurized condition and the non-pressurized condition. It was also confirmed that during pressurization, vibration occurred on the impact surface due to the influence of pressure air in the vessel, leading to cracking and crushing.

It was found that the difference in the size of the energy seems to be larger than the difference in the diameter of the projectile (the size of the impact area) and the material, but since it was not possible to conduct a test to make the energy the same with different materials, the conditions have not been scrutinized.

The behaviour of the impact surface during crushing and penetration was photographed with a high-speed camera for more than 2 ms after the impact, and the prototype pressurized tester was able to observe the process of crushing due to the injection of pressurized gas from the inside and the cylindrical vibration mode. However, since the volume and shape of the tank are very different from the original tank, it became clear that it is essential to test and analyse the tank sphere or cylindrical tank in order to scrutinize the crushing conditions in the future.

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