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スラスタ用窒化ケイ素セラミックスの超高速衝突損傷評価

Damage evaluation of silicon nitride ceramics subjected to hypervelocity impact

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ISAS/JAXA では人工衛星・惑星探査機用スラスタの高性能化を目的に、高耐熱温度・高強度・高靭性の構造用セラミックスである窒化ケイ素セラミックスを用いたスラスタを開発している。
宇宙用構造部材として脆性材料を用いる際には、熱的・機械的な準静的強度特性に加えて、スペースデブリやメテオロイドなどの宇宙浮遊物との超高速衝突に対する動的破壊特性の評価も必要となる。
そこで、窒化珪素セラミックスの超高速衝突に対する損傷評価を目的に、超高速衝突実験を行った。衝突により生じるクレータ深さを、衝突体の直径・密度・速度の指数関数として表現することにより、超高速衝突に対する貫入方程式を構築した。超高速衝突損傷形態は、クレータ損傷、クレータ＋スポール損傷、貫通損傷に分類された。各損傷形態が生じる衝突条件は、損傷形態に依存した係数を貫入方程式に掛け合わせることにより記述され、窒化珪素セラミックスの超高速衝突に対する損傷形態の予測が可能となった。

A new advanced ceramic thruster made of monolithic silicon nitride has been developed in ISAS/JAXA. In order for secure operation of a spacecraft, the reliability of the ceramic component against space debri and micrometeoroid impact has been investigated through hypervelocity impact tests. Silicon nitride plates were impacted by spheres of stainless-steel and other materials with 0.2-0.8-mm diameters in the velocity range up to 8.0 km/s using a two-stage light-gas gun. Using crater depth data under various impact conditions, the penetration equation of silicon nitride was determined. The impacted samples showed fracture patterns of three types: cratering, cratering with spallation, and perforation. These fracture patterns were well categorized by the multiple forms of the penetration equation.

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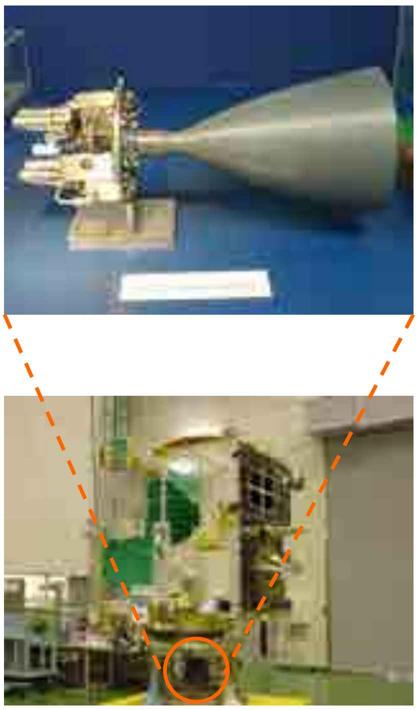
Ceramic thruster

Ceramic:
Although its fracture pattern is brittle, it has good mechanical property.
✓ high strength, high heat resistance, low density, high corrosion resistance



Si_3N_4 ceramic thruster

Thruster: Small rocket engine for a spacecraft

- Higher thrust performance than a conventional Nb-alloy thruster because of its high combustion temperature
  - ✓ Temperature limit: 1350℃→1500℃

Installed on a Venus climate orbiter "AKATSUKI"

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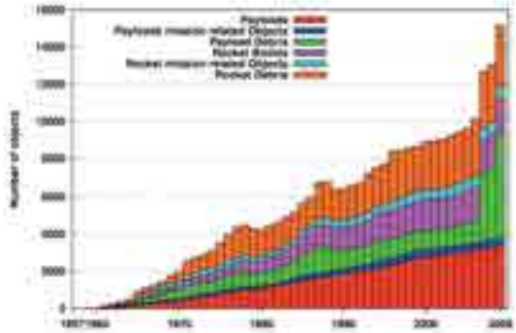
Space debris

All non-functional, man-made objects in Earth orbit
(e.g., derelict spacecraft, debris released during mission operations)

- The space objects bigger than 10 cm in Earth orbit

Ref. ESA web site



H. Klinkrad, Proc. HVIS2010

The number of debris is increasing accompanied with the space development.
(the number of 1~10 cm: 500,000 , < 1 cm: 100 million)

Damage caused by impact of debris is a growing concern

Damage evaluation of ceramic thruster

To use of brittle materials for structural application in space:

- Evaluation of static strength under operating environment (e.g., thermal stress state at thruster-firing condition)

Brittle material: sensitive to hypervelocity impact (HVI)

Importance of the evaluation of damage induced by debris and meteoroids impact

1. Evaluation of damage geometry induced by HVI
   - Generate the equation of to predict the failure pattern
     (This talk or N.Kawai et al., Int. J. Impact Eng. **38**, 542 (2011).)
2. Internal damage structure induced by HVI
   - Observation of internal damage and numerical simulation
     (N. Kawai et al., Proc. HVIS 2010, pp. 722-733.)

Hypervelocity-impact experiment

Two-stage light-gas gan

✓ It can accelerate a single particle with diameter of 0.1~3.5 mm up to 7.0 km/s using a sabot.

N. Kawai et al., Rev. Sci. Instrum. 81, 115105 (2010).

Projectile condition

Size: 0.2~1.0-mm sphere

Material: Steel, Al, Al_2O_3, Glass, Ir, Pt, WC

Impact velocity: 1.5~7.0 km/s

Si_2N_3 target

Material: SN282 by Kyocera Corp.

Size: 50 × 50 × 1.5~3 mm

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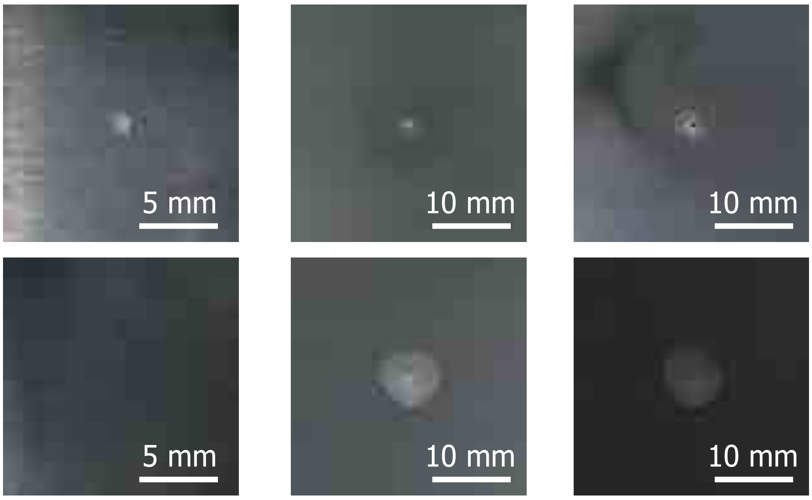
Impact-induced fracture pattern

Impact surface

Rear surface



Projectile	Steel 300 μm	Steel 500 μm	Steel 500 μm
Impact velocity	4.43 km/s	3.52 km/s	3.85 km/s
Kinetic energy	1.10 J	3.22 J	3.85 J
Fracture pattern	Crater	Crater + Spall	Perforation

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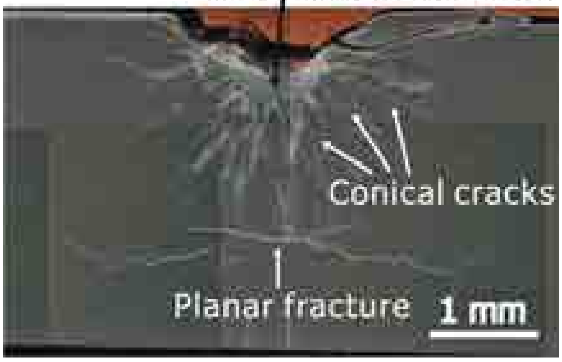
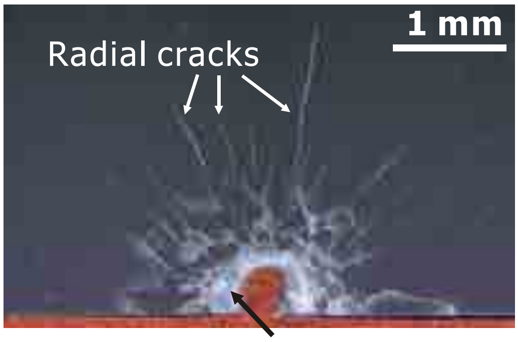
Impact-induced damage

Along impact axis



Perpendicular to impact axis (at a depth of 0.5mm)



- Highly damaged Si_3N_4 was observed immediately beneath and around the crater.
- Conical and radial cracks propagated inside the sample from the highly damaged region.

Impact-induced damage pattern

Cratering

- Highly deformed area beneath the crater
- Conical crack propagation

Planar spallation

- Thin planar fracture induced by rarefaction

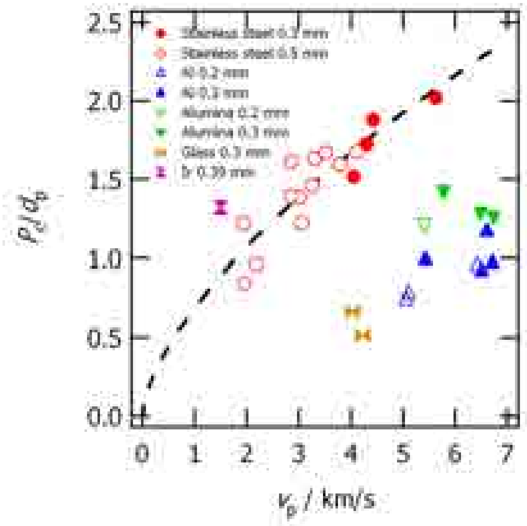
Conical spallation

- Fracture by conical cracks

Perforation

- By linking the crater and the conical spall

Crater depth



Crater depth is taken as a damage cracteristic.

Crater depth measurement: by a laser microscope

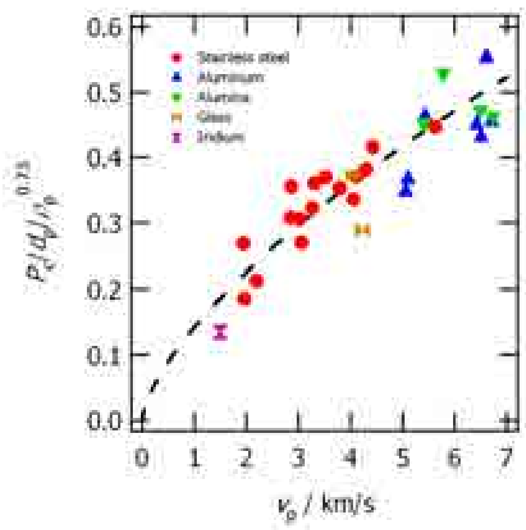
■ Crater depth formed by the impact of a steel sphere

$$P_{ss} = 0.69 d_p v_p^{0.64}$$

P_c:crater depth, d_p:projectile diameter, v_p:projectile velocity

□ The differences of crater depths between steel and other materials are caused by differences of the material density.

Penetration equation



Effect of projectile density

✓ Assuming a power-low relation α:exponent for density

$$\left(\frac{P_c}{P_{ss}}\right) = \left(\frac{\rho_p}{\rho_{ss}}\right)^{\alpha}$$

ρ_p:projectile density, ρ_{ss}:steel density=7.8 Mg/m^3

Penetration equation

$$P_c = 0.142 d_p \rho_p^{0.73} v_p^{0.67}$$

In the case of other brittle materials

For Glass

$$P_c = 0.53 d_p^{1.06} \rho_p^{0.5} v_p^{2/3}$$

B. G. Cour-Palais, IJIE **23**, 137 (1999).

For C/C composite coated by SiC

$$P_c = 0.61 d_p \left(\rho_p / \rho_t\right)^{0.5} \left(v \cos\theta\right)^{2/3}$$

Christiansen and Friesen, IJIE **20**, 153 (1997).

Impact-induced damage pattern

Cratering

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- Conical crack propagation

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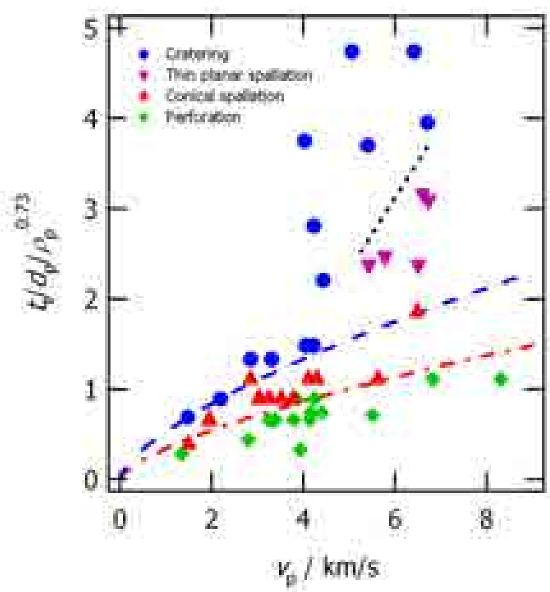
Failure morphology map



t_t: Target thickness

- Critical target thickness for each fracture pattern is described by a multiple form of the penetration equation.

Critical thickness equation

$$t_f = 0.142 k d_p \rho_p^{0.73} v_p^{0.67}$$

k: Fracture factor

t_f: Critical thickness to prevent fracture

for Conical spallation

$k = 3.7$ Metal: 2.2 Glass: 7.0

for Perforation

$k = 2.4$ Metal: 2.2

Impact test of nozzle throat model

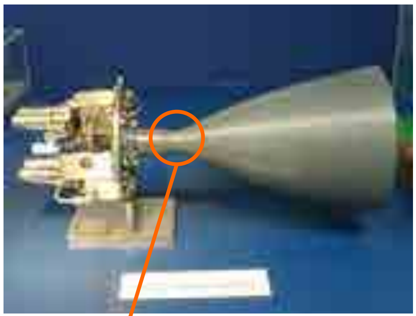
Impact test of nozzle throat model

Size：φ29 mm×φ23 mm×L60 mm
t=3.0 mm

Projectile：Al sphere φ0.3 mm

Impact velocity：5.07 km/s

Impact energy：0.49 J
(99.9% of cumulative probability of impacts during "AKATSUKI" mission.)



Nozzle throat model after impact

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Thermal stress test after impact

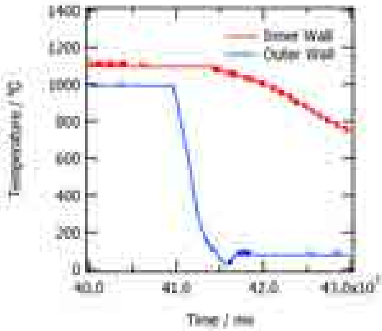
Impact test of nozzle throat model

Size：φ29 mm×φ23 mm×L60 mm
t=3.0 mm

Projectile：Al sphere φ0.3 mm

Impact velocity：5.07 km/s

Impact energy：0.49 J
(99.9% of cumulative probability of impacts during "AKATSUKI" mission.)



Thermal stress test

Impact crater after impact

after thermal stress test

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Summary

- HVI tests were performed on a silicon nitride plate in the velocity range up to 8 km/s to investigate its HVI-induced fracture behavior.
- The penetration equation of silicon nitride was determined.
- Impact-induced fracture patterns of three types were observed: cratering, cratering with spallation, and perforation.
- The boundaries of each fracture pattern were well described by the multiple form of the penetration equation.