Micrometeoroid Impact Damage on Thin Ceramic Component for Interplanetary Probe

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A new ceramic thruster for an interplanetary probe is currently under development. Monolithic silicon nitride (Si$_3$N$_4$), which has good heat resistance and high fracture toughness among conventional structural ceramics, is a promising material for a high performance thruster. However ceramics are brittle compared to metallic materials. In order to evaluate reliability of the ceramic thruster as a space-use component, fracture behavior against micrometeoroid impacts was investigated. First the risk probability of the meteoroid impacts which may occur during a mission was estimated based on impact energy which may cause failure of the material. Second, damage of the silicon nitride ceramics by a possible micrometeoroid impact was investigated experimentally. Hypervelocity impact tests were carried out on the silicon nitride ceramic samples with a two-stage light-gas gun. Impacts at various velocities ranging from 1.0 km/s up to 4.5 km/s brought about three types of failure. However no shattering occurred by the hypervelocity impact with a possible energy. The experimental results together with the risk evaluation considering the flight mission conditions show that the Si$_3$N$_4$ ceramic thruster for the interplanetary probe would have no serious problems caused by a meteoroid impact during the flight mission even with local damage.

Key Words: Micrometeoroid Impact Risk Evaluation, Silicon Nitride, Impact Damage, Hypervelocity Impact Test

1. Introduction

Deep space exploration attracts large interests in recent years and a number of space science missions have been implemented, such as MUSES-C1), Venus Express 2), Deep Impact 3), etc. In order to accomplish the further deep space missions, a high performance thruster is required to be onboard an interplanetary probe. A thruster is a small engine of a space probe or a satellite to control its orbit or attitude. So the material is exposed to high temperature and the temperature limit of the material restricts the performance of the thruster.

Conventionally niobium alloy is used for a bipropellant thruster. However it needs disilicide coating due to its low oxidation resistance. The coating material limits the maximum allowable temperature of the thruster up to approximately 1350 °C. For further possibility of a deep space exploration, higher thrust performance is desirable.

Some materials have been examined as a candidate for a next generation thruster, as listed in Table 1. Ceramics have higher oxidation resistance and higher temperature limit than the niobium alloy. In addition to such excellent thermal properties, ceramics have low density which is also suitable as a space-use structural material. Monolithic silicon nitride ceramic (Si$_3$N$_4$) has relatively high fracture toughness among engineering ceramics and has stable quality compared to SiC/SiC ceramic composites. Among several grades of silicon nitrides, SN282 (Kyocera Co., Japan) has been considered most suitable as a thruster material because of its balanced mechanical properties between high temperature strength and toughness. SN282 is sintered with rare-earth oxides i.e. Lu$_2$O$_3$ as a sintering additive both to toughen the grain boundaries and to increase the high-temperature mechanical properties. Finally a thruster made of SN282 has started to be developed as a 500-N class bipropellant (N$_2$/H$_2$/MON-3) orbit maneuvering engine and is planned to be onboard a next interplanetary probe of Venus exploration mission PLANET-C (Fig. 1.), which is currently promoted in Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA) 4).

However the brittleness of the ceramics could be a problem as a structural material. An engineering model of the ceramic thruster was already manufactured as shown Table 1. Some candidate materials for a high performance thruster.

<table>
<thead>
<tr>
<th>Material</th>
<th>Max. temperature</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precious metal</td>
<td>&lt; 2000 °C</td>
<td>High cost / High density</td>
</tr>
<tr>
<td>(i.e. Ir, Pt)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C/C composite</td>
<td>&gt; 2000 °C</td>
<td>Oxidation / Unstable quality</td>
</tr>
<tr>
<td>Ceramic composite</td>
<td>&lt; 1600 °C</td>
<td>Oxidation / Unstable quality / Exfoliation</td>
</tr>
<tr>
<td>(SiC CMC)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monolithic ceramics</td>
<td>&lt; 1500 °C</td>
<td>Low cost / Low density / Stable quality</td>
</tr>
<tr>
<td>(Si$_3$N$_4$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Niobium alloy</td>
<td>&lt; 1350 °C</td>
<td>Conventional / Low temperature / Oxidation</td>
</tr>
<tr>
<td>(with disilicide coating)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
in Fig. 2. The basic shape of the thruster was fabricated by the drain casting process followed by diamond milling after milling. Since the combustion chamber will be subjected to thermal stresses under service, its surface were finished with emery paper (400 grit) by hand in the direction parallel to the thruster axis which will be a stress axis and this procedure eliminated the first machine grinding traces which might be a fracture origin. After fabrication non-destructive tests were carried out to find out potential defects in addition. Then a series of mechanical and firing tests was conducted on it. The test results showed feasibility of the monolithic silicon nitride ceramic thruster under the launching (mechanical) and firing (thermal) conditions. But a space component always faces a risk of impacts of a flying particle at a hypervelocity in space such as a micrometeoroid. For securely reliability of the ceramic thruster as a space component, its toughness against such hypervelocity impacts has to be examined as well as quasi-static strength in mechanical and/or thermal environment.

In this study, the risk probability of the micrometeoroid impacts encountering during the PLANET-C mission was first evaluated based on an interplanetary flux model. Since damage in the material is brought about by impact energy, an energy-based risk evaluation was suggested. Next, hypervelocity impact tests were carried out on the SN282 samples and the fracture behavior against the hypervelocity impacts was examined considering the impact risk probability. Crack development in the subsurface was investigated as well as failure morphology on the surface. The reliability of the silicon nitride thruster during the mission against the micrometeoroid impact was, then, discussed.

2. Energy-based risk evaluation

The silicon nitride thruster is to be applied to the Venus probe. In this section the risk probability of the micrometeoroid impacts during the mission is evaluated. Since impact damage of a material will be caused by impact energy, an energy-based risk evaluation taking in to account the micrometeoroid flux and the velocity distribution is introduced here.

2.1. Micrometeoroid flux model

Several dust flux models in the Solar system have been proposed. The risk probability of debris impacts is estimated negligible, because the PLANET-C Venus probe will experience the debris environment near the Earth in a very short period. Here we adopt the interplanetary flux model derived by Grün et al. The cumulative flux of masses larger than \( m \) [g] at the heliocentric distance of \( r = 1 \) AU, \( F_0(m) \) [m\(^2\)s\(^{-1}\)], is written as follows:

\[
F_0(m) = (c_2 m^{c_2} + c_3)^{c_4} + c_5 (m + c_6 m^{c_7})^{c_8} + c_9 (m + c_10 m^{c_11})^{c_12},
\]

where \( c_2 = 2.2 \times 10^8 \), \( c_3 = 1.5 \), \( c_4 = 1.3 \times 10^{-9} \), \( c_5 = 10^{11} \), \( c_6 = 10^{27} \), \( c_7 = 1.3 \times 10^{-16} \) and \( c_8 = 10^{46} \). Their units are not written here. This flux model is easy-to-use and widely applied to engineering or scientific works (e.g. (7)). The flux model above can be modified for \( 0.3 \) AU < \( r < 1.0 \) AU according to the relationship that the spatial density of the meteoroids is proportional to \( r^{-1.3} \), and written as in the following form:

\[
F(m) = F_0(m) \left( \frac{r}{n} \right)^{-1.3}.
\]

The cumulative number of impacts of a specific mass \( m \) or larger on an area \( A \) [m\(^2\)] during a certain period of time \( T \) [s], \( N(m) \), is calculated as

\[
N(m) = A \cdot T \cdot F(m).
\]

2.2. Micrometeoroid velocity distribution around Venus

The impacting particles in the heliocentric orbits have a velocity distribution. The impact velocity distribution around Venus (0.7 AU) can be assumed to have approximately a Weibull distribution\(^9\); the cumulative distribution function \( G_r(v) \) and the probability density function \( g_r(v) \) [s/km] of the velocity distribution are written by

\[
G_r(v) = 1 - e^{-(v/b)^a},
\]

\[
g_r(v) = \frac{dG_r(v)}{dv} = \left( \frac{a}{b} \right) v^{a-1} e^{-(v/b)^a},
\]

where the two parameters are given by \( a = 2.30 \) and \( b = 20.3 \) [km/s] for 0.7 AU through extrapolating the data set from 1 AU to 4 AU\(^9\).
2.3. Energy-based impact probability around Venus

The flux and the velocity of micrometeoroids around Venus have widely distributed ranges, as mentioned above. The energy of a flying particle is calculated with multiplication of \( m \) and \( v^2 \). Thus the risk probability based on the impact energy can be derived from multiplication of the two distributions. The probability density of impact frequency \( h(E) \) of an impact with energy \( E \) is given by considering both the mass and the squared velocity distributions (Eq. (3) and Eq. (5)), as follows:

\[
h(E) = \int \frac{dN(m)}{dm} \frac{dG_{\nu}(v^2)}{dv^2} \delta(k(m, v^2, E)) \, dm \, dv^2,
\]

where \( \delta \) is the Dirac-delta function and the function \( k(m, v^2, E) \) is given by

\[
k(m, v^2, E) = E - \frac{1}{2} mv^2.
\]

Using the following transformation

\[
\int \frac{dG_{\nu}(v^2)}{dv^2} \delta(k(m, v^2, E)) \, dv^2 = \frac{dG_{\nu}(v^2)}{dv^2} \bigg|_{v^2=k(m, E)} \frac{1}{d(k/m)/dv^2} \,
\]

Eq. (6) is converted into an integral form only of a variable \( m \),

\[
h(E) = \int \frac{2 \, dN(m)}{dm} \frac{dG_{\nu}(v^2)}{dv^2} \bigg|_{v^2=2E/m} \, dm.
\]

The cumulative probability of impact frequency at the energy \( E \), \( H(E) \), is calculated by integrating \( h(E) \) over \( E \) to \( E_{\infty} \).

\[
H(E) = \int_{E}^{E_{\infty}} h(E) \, dE.
\]

Now we estimate the impact probability of the thruster in the PLANET-C mission. The nominal operation term of PLANET-C till the spacecraft enters the orbit around Venus is scheduled to be \( T = 0.5 \) year. All impacts are treated as normal impacts in the risk evaluation here because they are more severe than oblique impacts for ceramic components. The maximum projected area of the thruster is taken into account and is set \( A = 0.06 \) m\(^2\), most of which is occupied by a nozzle skirt. The cumulative probability of the impact frequency \( H(E) \) at \( r = 0.7 \) AU is estimated according to the energy-based evaluation derived above, as shown in Fig. 3. The cumulative probability is 1 at the point where the impact energy is \( E_1 = 5.0 \times 10^{-3} \) J. Similarly the cumulative probabilities become 0.1 and 0.01 at the impact energy of \( E_2 = 0.13 \) J and \( E_3 = 1.6 \) J, respectively. For the PLANET-C mission, it is summarized that an impact with energy larger than \( 5.0 \times 10^{-3} \) J will occur with 100 % probability during the mission and that with energy larger than 0.13 J and 1.6 J will occur with 10 % and 1 % probability, respectively.

3. Hypervelocity impact test procedures

Hypervelocity impact tests were carried out on SN282 silicon nitride targets in order to measure toughness against the micrometeoroid impact with the energy estimated to encounter during the mission in the previous section. The accelerator was a two-stage light-gas gun. Projectiles were stainless steel balls with diameter of 300 and 500 µm, and glass balls with 300 µm in diameter. The densities of the steel and glass projectiles were 7.9 g/cm\(^3\) and 2.5 g/cm\(^3\), respectively. The gun can accelerate a polycarbonate sabot filled with small projectiles up to 4.5 km/s with helium gas. Various combinations of the glass or steel projectiles and the impact velocities could simulate several impact energies up to 5 J.

The material used in this study was a commercial silicon nitride SN282 manufactured by Kyocera Co. Japan. Its mechanical properties are listed in Table 2. Test specimens were 30 mm × 50 mm rectangular plates with five different thicknesses (1.0, 1.5, 2.0, 2.5 and 3.0 mm). These thicknesses were selected by considering the thickness of the nozzle skirt of the ceramic thruster (2.0 mm), which part will be mostly exposed to the risk of the micrometeoroid impacting in space. The ceramic specimens were set normal to the flying direction of the projectile in a gun chamber under room temperature in vacuum.

Observations by an optical microscope and a laser microscope were made after the impact tests. Subsurface damage was also observed on some cross-sections of an impact site polished with diamond paste.

<table>
<thead>
<tr>
<th>Young's Modulus ( E ) [GPa]</th>
<th>Bending strength ( \sigma_B ) [MPa]</th>
<th>Poisson ratio ( \nu )</th>
<th>Thermal conductivity ( \lambda ) [W/mK]</th>
<th>Fracture toughness ( K_{IC} ) [MPam(^{1/2})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>324</td>
<td>738</td>
<td>0.29</td>
<td>64.0</td>
<td>5.5</td>
</tr>
</tbody>
</table>

4. Experimental results and discussions

4.1. Failure morphology by hypervelocity impact

Fig. 4. shows examples of typical failure patterns
obtained in the hypervelocity tests. The failure morphology was able to sort into three types. The first type was formation of a crater on the front surface, which is denoted as Type 1. This behavior was observed on thick samples with low impact energies. The second type had spallation on the rear face in addition to the crater on the front face (Type 2). The last one called Type 3 had a perforation in the middle of the crater and the rear-face spallation. There was observed the tendency that high impact energy produced the Type 3 failure. In all the test cases, shattering or complete breakdown of the sample did not occur.

The tendency of the three failure morphology patterns were plotted in a diagram against the target thickness and the impact energy in Fig. 5. Although the experiments were conducted with various velocities, projectile sizes and materials, the three failure patterns were well categorized according to the impact energy and the target thickness. From this diagram, it can be said that the failure pattern will change depending on a plate thickness even with the same impact energy; e.g. perforation (Type 3) was formed on a 1.0-mm thick plate with impact energy of about 1 J, while Type 2 failure occurred on a 1.5-mm thick plate with equivalent impact energy. Fig. 6. shows an example of Type 2 failure on a 1.5-mm specimen with the impact energy of 1.04 J measured by a laser microscope.
The spall plane on the back face showed macroscopically rather flat plane, whereas the crater had deep valley-like shape. The depth of the spall plane was 466 μm and the deepest point of the crater was 517 μm deep from the surface. As the sum of the depths of the both faces’ failure in the 1.5-mm thick plate was ca. 1 mm, it can be said that the perforation was formed by linking of the front-face crater and the back-face spallation.

4.2. Subsurface damage observation

Fig. 7 shows the subsurface observation of a 1.5-mm thick sample after the impact test with impact energy of 1.04 J. Type 2 failure occurred in this sample. The dashed lines drawn in the top view image show the locations of each cross section. Near the edge of the crater on Cross-section A, a few spall cracks were observed, which were nearly parallel to the impact face as indicated with arrows in Fig. 7(a). The thickness of the plate decreased and the density of cracks increased in the subsurface as approaching the center of the crater (Fig. 7(b)). On Cross-section C at the center of the crater in Fig. 7(c), many radial cracks were developed and very complex crack network was formed together with the spall cracks. The back-face spallation was caused with the radial cracks and the spall cracks. So it had a truncated cone shape as shown in Fig. 6(b). Since a silicon nitride ceramics has relatively high fracture toughness among structural ceramics, the specimen did not shatter even with so many cracks in the subsurface as shown in Fig. 7.

4.3. Reliability of the SN282 ceramic thruster against micrometeoroid impact

The experimental results show toughness of the SN282 against the small particle impacting with impact energy up to 5 J. All the test results indicate that the ceramic thruster will still keep the geometric configuration even with some local damage caused by a micrometeoroid impact. The three failure behaviors of the SN282 obtained in the series of the impact tests can be categorized well according to the plate thickness and the impact energy as shown in Fig. 5. As for the case of the impacting probability of 1%, the impact energy threshold was estimated 1.6 J in Section 2.3, which yields Type 2 failure with crater and spallation formation on the designed thickness of 2 mm. And at the impact energy threshold of 0.13J with the impact probability of 10 %, only a crater will be formed on the impact face.

The subsurface observation revealed that complex crack network forms under the impact site. The existence of such cracks will degrade the materials strength, but hardly thermal and/or mechanical stress will be induced even during the operation on the nozzle skirt which is subjected to the impact risk evaluated above. Thus those cracks will not cause an unstable fracture of the thruster during the operation even if an micrometeoroid impact on the nozzle skirt occur at the threshold impact energy before entering into the Venus orbit.

Above discussion is based on the impact energy. But the impact velocity around Venus is much higher than the velocity achieved with our test facility. The effect of the impact velocity is to be investigated for higher reliability of the ceramic thruster.

5. Summary

A new ceramic thruster made of silicon nitride is under development for the interplanetary probe of the PLANET-C Venus exploration mission promoted in ISAS/JAXA. In order to investigate the reliability of the silicon nitride thruster as a space-use component, the probability of a micrometeoroid impact around Venus was estimated based on impact energy. The impacting probability for the energy larger than 0.13 J was estimated to be 10 %, and that for the energy larger than 1.6 J was to be 1 %.

The failure behavior against a hypervelocity impact of the silicon nitride was investigated experimentally with the two-stage light-gas gun. The three failure patterns were obtained and well categorized according to the plate thickness and the impact energy. All the failure patterns were localized and did not result in fatal fracture although complex crack network was formed in the material.

As far as considering the impact probability and the experimental results obtained based on the impact energy, the ceramic thruster would feasible as a component of the Venus probe. The experimental results were, however, obtained at the velocities lower than those of the micrometeoroids around Venus. To guarantee higher reliability of a ceramic component used in space, the
effect of higher impact velocity on the failure behavior should be investigated.

References


