Effects of target temperature on size distribution of ejecta in hypervelocity impact: Toward revision of ISO11227

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Abstract
As a preliminary study, the effects of target temperature on ejecta size were examined at an impact velocity of 3.5 km/s with the goal of improving the ISO11227. At first, the size of each ejecta collected from test chamber, was examined by the image analysis software using a photograph of each ejecta (direct method). The cumulative number distributions of ejecta size were discussed. The effects of target temperature on ejecta size were small within a predictable range. After that, we compared the ejecta size distribution of the direct method with the results of the international standard method using witness plate (indirect method). The number of ejecta impact craters evaluated by the international standard method was very small at the high temperature. The results of international standard method using witness plate were easily influenced by temperature of target at the high temperature. It is highly possible that the international standard method underestimate the ejecta from target at high temperature.

Key words: Space debris, High velocity, International standard for experimental procedure, Spacecraft material ejecta, Image analysis, Witness plate

1. Introduction

Space debris is orbiting around the Earth and the number of the space debris increases year by year. When space debris in low Earth orbit strikes spacecraft at hypervelocities of over 1 km/s, the space debris is fragmented and many ejecta (fragments) are widely scattered from struck spacecraft materials. Therefore, spacecraft materials have to be selected from the viewpoint of ejecta evaluation as well as material strength and durability, e.g. JAXA structure design standard, JERG-2-320. A lot of studies have been conducted on spacecraft material ejecta until now. However, since they have been carried out under different experimental conditions, their results cannot be made a simple comparison each other.

For the purpose of the international standardization of test procedures to evaluate spacecraft material ejecta upon hypervelocity impact, Mandeville et al. (Bariteau et al. 2001, Siguier and Mandeville, 2007) and Sugahara et al. (2009) have been studying fragments and ejecta. After much discussion, the international standard, ISO 11227 (2012), with respect to the test procedure to evaluate spacecraft material ejecta upon hypervelocity impact was published. However, since its early publication was highly preferred, only basic experimental methods and conditions were decided. Every 5 years, all ISO standards are reviewed and updated as needed. Oblique impact conditions, temperature conditions and their evaluation methods have been studied for the purpose of the revision of ISO 11227 in 2017 (Masuyama et al., 2013, Fujimura et al., 2015, Serbouti et al., 2015).

This international standard prescribed experimental conditions in detail with respect to projectile, target, copper
plates called witness plate and experimental environment to be used. The number of crater size due to the impact of ejecta on the witness plates was counted within four ranges. Even though ISO 11227 did not prescribe a broad range of options about experimental temperature, the temperature of spacecraft and satellites in low Earth orbit vary widely, depending on whether it is the sunny side or not. The effects of temperature on hypervelocity impact behavior have been examined for a long time. Allison et al. (1960) examined the effects of target temperature on hypervelocity cratering. Myers et al. (2003) and Corbett (2006) examined the effects of temperature on the penetration hole diameter of thin plate bumpers in hypervelocity impact. Wells (2006) examined hypervelocity impact performance of coated thermoplastic films at low, room and high temperature. Ohtani et al. (2006) studied HVI crater holes of aluminum alloys and a composite material of targets at low temperatures using a shadowgraph technique. Numata et al. (2008) carried out several HVI tests on CFRP laminates at low temperature. Nishida et al. (2012) has been examining the effects of target temperature on crater and ejecta size and showed that target temperature affected the crater size and projectile fragmentation.

Based on the results of the authors’ previous study, the authors’ group examined the effects of temperature placing the primary focus on ejecta size distribution with the goal of improving the international standard. In this study, the effects of target temperature on ejecta size were examined at an impact velocity of 3.5 km/s as a preliminary experiment. We examined the number distribution of the ejecta impact craters using image analysis of the witness plates based on ISO 11227. We compared ejecta size distribution using the direct method, with size distribution of ejecta impact craters on the witness plate based on the international standard method, which we call indirect method.

2. Experimental Methods

Thick targets (30-mm thickness) with a 95 mm diameter made of aluminum alloy 6061-T6, with two cut-off surfaces, as shown in Figure 1 were used. The creation of cut-off surfaces resulted in an increase in contact area between the targets and the heater or cooler, which facilitated more efficient heating or cooling of the targets. Specimens’ temperature was raised to approximately 200°C using cartridge heaters. In order to decrease temperature, liquid nitrogen was introduced from the outside of test chamber using flexible tubes. The impact experiments were carried out at approximately -150°C. Results at the temperatures of 200°C, 20°C and -150°C were compared each other. Table 1 lists the values of the tensile strength, yield stress and elongation at break of aluminum alloy 6061-T6, obtained by performing static tests at high, room and low temperatures (Structural Alloys Handbook, 1996), as well as the measured Vickers hardness values.

Aluminum alloy 2017-T4 projectiles with a diameter of 4.5 mm (0.13 g) were employed. The two-stage light-gas gun of Nagoya Institute of Technology as shown in Fig. 2 was used to accelerate the projectiles with multi-piece sabots. The two-stage light-gas roughly consists of powder chamber, pump tube, pressure coupling, launch tube, blast tank and test chamber. The total length of the two-stage light-gas gun of Nagoya Institute of Technology is approximately 12 m and its capability with respect to the impact velocity ranged from 1 to 3.5 km/s. A photograph of multi-piece sabots is shown in Fig. 3. In this study, the impact velocities were fixed at approximately 3.5 km/s. Based on ISO11227, a witness plate made of copper, C1100P-1/4H, with 200 × 200 mm having a hole with a diameter of 25 mm, which the projectiles could pass through, was placed in front of each target to observe the impact craters caused by ejected particles (fragments) called ejecta.

Figure 4 shows photographs of larger ejecta collected from the test chamber after impact experiments when a projectile struck a target at an impact velocity of 3.20 km/s at a temperature of 22°C. After a photograph of each ejecta was taken, the maximum length of each ejecta, a, as defined in Fig. 5, was calculated using the image analysis software, ImageJ. Cumulative number of ejecta length, a, was mainly examined (Nozaki, et al., 2014). We refer to this method as the direct method because the size of actual ejecta (fragments) is measured. We measured only the ejecta having length over 0.5 mm. We also indirectly evaluated ejecta size distribution based on ISO11227. In conformity with ISO 11227, the number of impact ejecta craters on witness plate was counted and the number of crater diameter was evaluated in four categories. We refer to this method as the indirect method because the diameter of ejecta impact craters on witness plates are examined instead of measuring actual ejecta. In general, the indirect method has the advantages of reduced analysis time and evaluation of smaller ejecta. The scan system and scan method of Kyusyu Institute of Technology (Sugahara et al. 2009) as shown in Fig. 6 was used. We obtained images of witness plates before and after impact experiment and background differencing technique was applied to these images. Figure 7(a)
shows a photograph of witness plates after impact experiment and Fig. 7(b) shows the distribution of deciphered craters. The number of craters was counted using image analysis software, ImageJ. Based on ISO 11227, the crater diameter on the witness plate was classified into four categories ranging 0.025-0.05 mm, 0.05-0.1 mm, 0.1-1 mm, over 1 mm. However, with respect to evaluation method of ejecta using witness plate, since the early publication of the international standard was highly preferred, detailed evaluation methods and evaluation conditions were not decided. Therefore, a preliminary experiment was carried out and adequateness and debatable points of the evaluation method were also discussed. In this study, only the ejecta length, $a$, and the diameter of ejecta impact craters were examined. The average fragment (ejecta) size, $L_c=(a+b+c)/3$, is referred to as characteristic length. In the NASA breakup model for collision (Johnson et al. 2001), the cumulative number of characteristic length is used for the evaluation of fragments.

Table 1 Material properties of aluminum alloy 6061-T6 by static tests (Structural Alloys Handbook, 1996)

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>+204</th>
<th>+24</th>
<th>-196</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength [MPa]</td>
<td>131</td>
<td>310</td>
<td>414</td>
</tr>
<tr>
<td>Yield stress [MPa]</td>
<td>103</td>
<td>276</td>
<td>324</td>
</tr>
<tr>
<td>Elongation [%]</td>
<td>28</td>
<td>17</td>
<td>22</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>+200</th>
<th>+25</th>
<th>-150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vickers hardness</td>
<td>100</td>
<td>110</td>
<td>128</td>
</tr>
</tbody>
</table>

![Fig. 1 Target size in experiments.](image1)

![Fig. 2 Two stage light gas gun of Nagoya Institute of Technology.](image2)

![Fig. 3 Multi-piece sabots used in impact experiments.](image3)
Fig. 4  Photograph of ejecta collected from test chamber; impact velocity 3.20 km/s at +22°C.

Fig. 5  Definition of ejecta size; \(a\) length, \(b\) width, \(c\) thickness; \(a > b > c\).

Fig. 6  Photograph of scan system of Kyusyu Institute of Technology (Sugahara et al. 2009).

(a) Photograph of witness plate after impact experiment       (b) Ejecta crater distribution

Fig. 7  Analysis example of witness plate by indirect method; impact velocity 3.20 km/s, temperature +22°C.
3. Experimental Results

Figure 8 show photographs of larger ejecta collected from the test chamber. The temperature seemed to have little effect on the color, outward appearance and shape of ejecta. At first, the size distribution of ejecta was examined by the direct method. Figure 9 shows the cumulative number distribution of ejecta length, which means the number of ejecta with a length greater than that of ejecta on the horizontal axis. The measurement error of ejecta length in the image analysis was approximately 3.0%. Even though there is not a little variability between results under the same temperature condition, the temperature slightly affected the ejecta length. In particular, in Table 2 the number of ejecta length over 0.5 mm at the high temperature was about 5-10% less than those at the room and low temperatures. The temperature had a slight influence on the ejecta size and the number of ejecta. These results are similar to those of Myers et al. (2003), Corbett (2006) and Nishida et al. (2012).

Figure 10 shows the distribution of ejecta impact craters on witness plate using the indirect method. Craters were color-coded according to crater diameter as shown in Fig. 10. A ring consisting of ejecta craters was clearly observed. As the target temperature decreased, the ring became clear and thick. At low temperature, many ejecta craters with a diameter of 0.5 to 0.75 mm were observed and at high temperature the diameter and the number of ejecta craters were small.

Table 3 shows the number of crater diameter on the witness plates for each category based on ISO 11227. In every category, the number of craters at the high temperature was less that those at the room and low temperature. This tendency is similar to the results from the direct method. The total number of craters over 0.025 mm in diameter at the high temperature was less than half of that at the room and low temperatures. This is a larger difference compared with the results of the direct method. The main reasons for abrupt decrease at the high temperature are unclear. The total number of craters from 0.1 to 1 mm gradually increased with decreasing temperature. At any temperature, the number of craters of 0.025-0.05 mm accounted approximately 70% of the total number of craters over 0.025 mm. It is possible that temperature affects only smaller ejecta while temperature does not affect larger ejecta. Further experiments at different temperatures are needed to clarify the ejecta mechanism.

Figure 11 shows the cumulative number distribution of ejecta impact craters on the witness plate as a function of crater diameter, $D$. The number of ejecta impact craters increased quickly in the range of ejecta impact 0.5 to 0.6 mm in diameter and after that increased gradually other than the results at 22°C of black circles. This tendency is much different from the result of direct method as shown in Fig. 9. The size distribution of crater on the witness plate in Table 3 and Fig. 11 is not always the same as that of ejecta in Table 2 and Fig. 9 (direct method) because the impact of ejecta with a diameter of 0.5 mm on the witness plate does not always create the ejecta impact crater with a diameter of 0.5 mm on the witness plate. From the prior knowledge of cratering mechanism (e.g. Hayashi and Robinson, 1991), it is inferred that the diameter of ejecta impact craters on the witness plate are affected by ejecta size, ejecta hardness, impact angle, impact velocity and so on. Unlike to the results of direct method, the results of the indirect method in Table 3 shows that the number of craters at the high temperature was small. The international standard method using witness plate was easily influenced by temperature of target at the high temperature. It is highly possible that the international standard method underestimate the ejecta from target. It is highly possible that the difference in ejecta hardness at each temperature made a large discrepancy of the results between two methods. Further studies are needed in order to clarify the main reasons for the discrepancy. A calibration coefficient or a calibration formula is needed to estimate the ejecta size distribution from the crater size distribution on the witness plate.

Fig. 8 Photograph of ejecta and projectile fragments collected from test chamber.

(a) -156°C, 3.34 km/s    (b) +16°C, 3.30 km/s    (c) +205°C, 3.42 km/s
Fig. 9 Cumulative number distribution of ejecta length (fragment length) by direct method.

Table 2 Number of ejecta over 0.5 mm of ejecta length (fragment length) by direct method.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Impact velocity, km/s</th>
<th>The number of ejecta</th>
</tr>
</thead>
<tbody>
<tr>
<td>+205°C</td>
<td>3.42</td>
<td>390</td>
</tr>
<tr>
<td>+22°C</td>
<td>3.20</td>
<td>461</td>
</tr>
<tr>
<td>+16°C</td>
<td>3.30</td>
<td>422</td>
</tr>
<tr>
<td>-160°C</td>
<td>3.48</td>
<td>426</td>
</tr>
<tr>
<td>-156°C</td>
<td>3.34</td>
<td>411</td>
</tr>
</tbody>
</table>

Fig. 10 Ejecta crater distribution on witness plate.

Table 3 Number of crater diameter using indirect method.

<table>
<thead>
<tr>
<th></th>
<th>0.025–0.05 mm</th>
<th>0.05–0.1 mm</th>
<th>0.1–1 mm</th>
<th>1 mm &lt;</th>
<th>Total number</th>
</tr>
</thead>
<tbody>
<tr>
<td>+205°C (3.42 km/s)</td>
<td>3411</td>
<td>254</td>
<td>23</td>
<td>0</td>
<td>3688</td>
</tr>
<tr>
<td>+22°C (3.20 km/s)</td>
<td>7991</td>
<td>557</td>
<td>76</td>
<td>0</td>
<td>8624</td>
</tr>
<tr>
<td>+16°C (3.30 km/s)</td>
<td>7399</td>
<td>427</td>
<td>36</td>
<td>0</td>
<td>7862</td>
</tr>
<tr>
<td>-160°C (3.48 km/s)</td>
<td>6627</td>
<td>521</td>
<td>114</td>
<td>0</td>
<td>7262</td>
</tr>
<tr>
<td>-156°C (3.34 km/s)</td>
<td>8612</td>
<td>596</td>
<td>101</td>
<td>0</td>
<td>9309</td>
</tr>
</tbody>
</table>
4. Conclusions

As a preliminary study, the ejecta in hypervelocity impact were examined by the direct method and the indirect method. The results of the direct method showed that the increase in the target temperature brought a 10% decrease in the number of ejecta. The amount of change was in line with a forecast based on the experimental results of perforation holes at the high temperature (Corbett 2008). The preliminary conclusions of the indirect method showed that the number of ejecta at the high temperature was less than half of those at the low and room temperature for each category. It is highly possible that the hardness of ejecta affected the diameter of ejecta impact crater on the witness plates. The results of indirect method at the high temperature are in danger of underestimating the ejecta from target. The details of the indirect method using the witness plate are not fully established. The formation mechanism of ejecta impact craters on the witness plate is revealed and the accuracy of evaluation by the indirect method have to be improved. Moreover, a calibration coefficient or a calibration formula is needed to make a correlation between the indirect method and the direct method.

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International standard: ISO 11227, Space systems – Test procedure to evaluate spacecraft material ejecta upon


