Measurement of plasma for elucidation of crater formation mechanism on aluminum foam under high speed impact

Takanari SAKAI*, Koki UMEDA* and Keiko WATANABE**

*Department of Advanced Mechanical Engineering and Robotics, Ritsumeikan University,
1-1-1 Noji-higashi, Kusatsu, Shiga 525-8577, Japan
E-mail: rm0032hr@ed.ritsumei.ac.jp

** Department of Mechanical Engineering, Ritsumeikan University,
1-1-1 Noji-higashi, Kusatsu, Shiga 525-8577, Japan

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Abstract
It has been reported that when a high-speed projectile collides with aluminum foam, a unique crater with a narrow entrance and large cavity is formed, shaped like a turnip. In the case of a material with higher porosity, it is considered that a debris cloud is produced by the impact, and the crater is created by scattering the debris cloud inside of the target material. In addition, melting traces have been observed, and it is predicted that these are caused by the heat created by the impact. It is conceivable that the temperature of a plasma induced by high-speed impact is associated to indicate the temperature at impact, although this relationship has not yet been proven. Measuring temperature at impact point is difficult since the measuring device will have to avoid collision with the projectile. Therefore, it is essential to measure plasma apart from impact point and observe diffusion of plasma. In this paper, high-speed impact experiments in which plasma was measured with a triple probe and a high-speed camera was performed to confirm the above. The high-speed impact experiment was performed with a vertical gas gun at Ritsumeikan University’s Impact Engineering Laboratory. The impact speed was 400 m/s, and the target material was A5052. The high-speed camera had a maximum frame rate of 1.4 Mpfs and a minimum exposure time of 1.0 μs. Plasma signals were measured by the triple probe method, and at the moment of impact, the flash was recorded by the high-speed camera.

Key words : High-speed impact, Plasma, Triple probe method, Temperature, Aluminum foam, Crater

1. Introduction

Much space debris exists in orbit around the Earth. The amount of the space debris increases annually with the disposal of space crafts and collision between pieces of space debris (NASA, 2015). The speed of the space debris at a geosynchronous orbit is approximately 3 km/s, and approximately 7-8 km/s at a low Earth orbit distance. The speed with which space debris impacts the Earth is approximately 10 km/s.

Space debris greater than 10 cm across can be observed from the ground, and space crafts are able to avoid collisions with debris of this size. However, space debris under 10 cm across is not able to be observed or avoided. Even these small pieces of space debris colliding with space crafts induce functional loss or destruction because their impact energy is proportional to the square of the debris speed. One example of such a space debris collision occurred to an artificial satellite in 2009 (NASA, 2009). Therefore, countermeasures addressing space debris collisions are an important focus for the future of space development.

In 2009, a high-speed impact experiment was performed on aluminum foam to develop a debris shield that could defend spacecraft against space debris (Ryan et al., 2009). In this experiment, a uniquely shaped crater was formed around the impact point. The crater had a narrow entrance and then a large internal cavity, like a turnip. Figure 1 shows the cross section of such a turnip-shaped crater, where the red line outlines the shape of the crater. Traces of compaction and melting were confirmed on the surface of this crater: the compaction was caused by the spreading of the debris cloud, and the melting was caused by the high-speed impact. However, it is very difficult to measure the temperature at the
impact point with standard methods for two main reasons. One reason is that a thermometer placed on the target is instantaneously destroyed upon impact. The other reason is that there is not enough time resolution to measure transient temperatures at the impact point.

Plasma and flash emissions have been confirmed at high-speed impact (Tang et al., 2012; Tandy et al., 2014). It is conceivable that the temperature of a plasma induced by high-speed impact could indicate the temperature at impact, although this relationship has not yet been proven. Measuring plasma at the impact point is difficult because the projectile collide with the measuring device. Therefore, it is necessary to measure plasma at a distance from the impact point and observe the diffusion of the plasma. In this paper, high-speed impact experiments were performed in which the plasma was measured with a triple probe and a high-speed camera, for the purpose of confirming that the plasma temperature could indicate the temperature at impact.

2. Triple probe method

A single probe method was invented by Langmuir and Mott-Smith in 1962, in which a measuring probe was inserted in a plasma to measure the plasma parameters, such as electron temperature, electron density, and floating potential. The technique has been further improved by optimizing the plate and sphere shapes and double probe method using two probes (Amemiya et al., 2005). Plasma induced by high-speed impact is an instantaneous and unstable phenomenon. It is difficult for a single probe method or even a double probe method to measure this phenomenon (Chen, 1964). In this paper, a triple probe method (Chen and Sekiguchi, 1965) was used to measure the electron temperature of plasma induced by high-speed impact. Figure 2 shows the diagnostic device used in the triple probe method, referred to as the triple probe device.
The triple probe device consisted of three parallel copper wires, two power sources, and two resistors, as shown in Fig. 2. \( I_1, I_2, \) and \( I_3 \) represent the current flowing into each probe. \( V_2 \) and \( V_3 \) represent the voltages of the power sources. \( V_{d2} \) and \( V_{d3} \) are potential difference between each probe. Each current is calculated using Eqs. (1), (2), and (3), respectively, in which \( S \) represents the probe surface, \( J_e \) and \( J_i \) represent the electron saturation current and ion current density, respectively, and \( k \) and \( e \) represent Boltzmann’s constant and electric charge, respectively.

\[
-I_1 = -SJ_e \exp(-\phi V_1) + SJ_i
\]

\[
I_2 = -SJ_e \exp(-\phi V_2) + SJ_i
\]

\[
I_3 = -SJ_e \exp(-\phi V_3) + SJ_i
\]

Equation (4) is derived from Eqs. (1), (2), and (3).

\[
\frac{I_1 + I_2}{I_1 + I_3} = \frac{1 - \exp(-\phi V_{d2})}{1 - \exp(-\phi V_{d3})}
\]

In Eq. (4),

\[
\phi = \frac{e}{kT_e}
\]

The electron temperature is calculated from Eqs. (4) and (5).

3. Experimental procedure

High-speed impact experiments were performed at Ritsumeikan University’s Impact Engineering Laboratory (Shiga, Japan) using a vertical gas gun with a diameter of 15 mm and a length of 2 m; the gas gun is shown in Fig. 3. The maximum projectile speed was approximately 500 m/s (Gardiner et al., 2016).
The projectile consisted of a brass impactor and polyethylene sabot as shown in Fig. 4. The projectile speed was measured using a speed measurement device (magnet-coil system) based on the law of electromagnetic induction. A high-speed camera (Phantom v711; Vision Research, Inc.) with a maximum frame rate of 1.4 Mfps and a minimum exposure time of 1 μs was used to photograph the high-speed phenomenon. Figure 5 shows the experimental setup and Table 1 provides specifications of the experimental components.

Two triple probe devices were used to measure plasma parameters as shown in Fig. 6 (one device has been omitted from Fig. 5 because of the larger scale of that figure). In this study, the triple probe device had a diameter; \( D \) of 1 mm and a length; \( L \) of 10 mm. The distance between the wires; \( d \) was 1 mm. The parameters of the triple probe devices are presented in Table 2.

The copper wires were insulated except at the measurement section (refer to dotted line section in Fig. 6). The three wires were fixed by SUS tube. The outputs of \( V_{out}^2 \) and \( V_{out}^3 \) were measured by DL850 ScopeCorder (Yokogawa Meters & Instruments, Corp.), with a sampling rate of 10 MS/s and a vertical resolution of 12 bit. The layout of the triple probe device is illustrated in Fig. 7. The coordinates of the tips of the triple probe devices 1 and 2 were (15, 0, 5) and (-30, 0, 10), respectively (the origin was the center of the impact point).

<table>
<thead>
<tr>
<th>Projectile</th>
<th>Size [mm]</th>
<th>Mass [g]</th>
<th>Impact speed [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impactor</td>
<td>( \phi 14.8 \times 6 )</td>
<td>( \phi 14.9 \times 20 )</td>
<td>16</td>
</tr>
<tr>
<td>Sabot</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Target</td>
<td>Material</td>
<td>Size [mm]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A5052</td>
<td>55\times65\times20</td>
<td></td>
</tr>
<tr>
<td>High-speed camera</td>
<td>Spatial resolution [pixel]</td>
<td>Exposure time [μs]</td>
<td>Frame rate [fps]</td>
</tr>
<tr>
<td></td>
<td>112\times136</td>
<td>4.6</td>
<td>200,000</td>
</tr>
</tbody>
</table>

**Table 1 Specifications of experimental components.**
The projectile speed was 432 m/s. Figure 8 shows selected frames from the high-speed camera. The numerals under each image indicate the time elapsed after the impact. An impact flash (dotted line in Fig. 8) was confirmed at the right side of the images for approximately 150 \( \mu s \). It was estimated that projectile (solid line in Fig. 8) inclined to the left.

The original output signal of triple probe device 1 is shown in Fig. 9. Triple probe device 2 was not able to measure the plasma. The output of \( V_{2\text{out}} \) almost disappeared after 30 \( \mu s \), indicating that the plasma had diffused and the helium used to accelerate the projectile reached triple probe device 1 after 30 \( \mu s \). The plasma signal was measured for approximately 150 \( \mu s \). Figure 10 shows the magnified waveform from 5 \( \mu s \) and 10 \( \mu s \), which indicates that the plasma reached triple probe device 1 at 7.5 \( \mu s \). After the experiment, the distance from the impact point to the tip of triple probe device 1 was 10.3 mm. The plasma diffusion speed was calculated to be approximately 1.37 km/s. Figure 11 shows the current for each probe. \( I_2 \) and \( I_3 \) were calculated from \( V_{2\text{out}}/R_2 \) and \( V_{3\text{out}}/R_3 \), respectively. \( I_1 \) was the sum of \( I_2 \) and \( I_3 \). Figure 12 shows the time history of the electron temperature calculated from Eq. (4) and Eq. (5): the maximum electron temperature was found to be 4.92 eV, and the average electron temperature was found to be 3.52 eV.

The duration of the flash observed by the high-speed camera agreed with the time of the output signal from the plasma. Only triple probe device 1 at the side observed the flash emission, as obtained from the plasma signal. These results show that the plasma was included in the flash emission.
Fig. 8  High-speed framing images of impact flash.

Fig. 9  Output signal of triple probe device 1.
Fig. 10  Magnified waveforms from between 5 μs and 10 μs.

Fig. 11  Each current in triple probe device 1.
5. Conclusion

A high-speed impact experiment was performed with two triple probe devices and a high-speed camera. The results can be summarized as follows:

(1) The triple probe device detected plasma at 7.5 $\mu$s after impact. The plasma diffusion speed was calculated to be approximately 1.37 km/s. The maximum electron temperature was 4.92 eV, and the average electron temperature was 3.52 eV.

(2) Flash emission was confirmed at the right side of the images for approximately 150 $\mu$s.

(3) The duration of the flash observed by the high-speed camera agreed with the time of the output signal from the plasma. Only triple probe device 1 at the side observed the flash emission, as obtained from the plasma signal. These results show that the plasma was included in the flash emission.

References


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