ULTRAFAST IMAGING OBSERVATIONS OF THE IMPACT JETTING DURING OBLIQUE IMPACTS.

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Introduction: High-speed material ejection during oblique impacts between two flat plates has been observed in both hypervelocity impact experiments [e.g., 1, 2] and hydrocode calculations [e.g., 2, 3]. This phenomenon has been widely known as jetting [e.g., 1]. There are two important features in impact jetting [e.g., 4], which are (1) extremely high velocity greater than the impact velocity and (2) the high degree of shock heating. Jetting has been considered as a mechanism for the origin of chondrules [4], tektites and impact glasses [5], Pluto [6], and the Moon [7] based on above two features.

Jetting during a symmetric collision between two thin plates has been well studied [1-3]. However, the understanding of jetting for spherical impactors is essential for planetary applications [4-7] and it has not been obtained [8]. One of the reasons for this is the lack of the experimental data of hypervelocity jetting for obliquely-impacted spherical projectiles. Although the temperature of jetted vapor has been investigated under a wide range of experimental conditions [8, 9], only 3 data points have been reported as the jet velocity [10, 11], which is one of the important anchors for developing a jetting model [5].

In this study, we conducted a series of oblique impact experiments using spherical projectiles and 3 different targets and investigated the jet velocity as a function of impact velocity and target materials. Then, we constructed a physical model to explain the observed jet velocities.

Experiments: We used a two-stage light gas gun at Planetary Exploration Research Center of Chiba Institute of Technology. A polycarbonate sphere 4.8 mm in diameter was used as a projectile. Since polycarbonate is easily vaporized due to shock heating relative to silicates, we can investigate the effects of vaporization on the jet velocity in a laboratory. A plate (5 cm x 5 cm x 2 cmt) with different materials, including Cu, Al, polycarbonate, was used as a target. Impact velocity was ranged from 3.3 to 7.2 km/s. Impact angle was fixed at 45 degree, which is the most likelihood value for impact angle in natural impact events. The residual pressure in an experimental chamber prior to each shot was ~100 Pa. A high-speed video camera (Shimadzu, HPV-X) and a stroboscopic lamp were used for high-speed imaging. We used a self-adjustable pre-event pulse generator [12] to adjust the timing between the jetting initiation and the data acquisition of the camera accurately. The characteristic time for projectile penetration is 0.7 - 1.5 μs under our experimental conditions. The frame rate was 0.1 μs/frame to resolve the jetting initiation during projectile penetration.

Results: Figure 1a shows examples of high-speed images during projectile penetration. The material ejection from the contact surface occurred 0.1 μs after the impact. This clearly shows that we could capture the initiation of jetting during oblique impacts because this time is much shorter than the time for projectile penetration. A self-luminous jet moved along the target surface to the downrange of the impact direction and expanded to the upward of the target surface simultaneously. This expansion suggests that impact-induced vaporization occurs. The observed count of the jet is much higher than that of the shocked projectile, suggesting that the observed jet has the highest energy density during the impact. Figure 1b shows a time-stacked image for the same shot shown in Fig. 1 with image binarization. We measured the distance of the leading edge of self-luminous jet from the impact point as a function of time. The jet velocities were obtained with a linear function fitting for first 5 data points after the impacts. We observed no acceleration due to the vaporization during the downrange movement even at the highest impact velocity for copper target. Figure 2 shows the velocity ratio of the jet velocity to the impact velocity as a function of impact velocity along with theoretical predictions discussed in the following section. The ratio increases as the shock impedance of target increases at a given impact velocity and decreases with as impact velocity increases except for the data for polycarbonate at the lowest impact velocity.

Theoretical model for impact jetting: We obtained the first systematic data set for the jet velocity of spherical projectiles during oblique impacts. Using the data set, we test theoretical models in this section.

Standard jetting theory: Ang developed a simple model to explain a jetting initiation criterion and the jet velocity for spherical projectiles in vertical impacts [13]. Hypervelocity jet is initiated when the collision point velocity v_{col} along the projectile surface is equal to the shock velocity V_s in the projectile during penetration. The jet velocity v_{jet} at the jet initiation is obtained as $v_{jet} \sim v_{col} + V_s$. To apply oblique impacts with the angle θ_{imp}, we separate the impact velocity into vertical and horizontal component, $v_{imp}\sin(\theta_{imp})$

and $v_{imp}\cos(\theta_{imp})$, respectively. The V_s can be obtained using the vertical component $v_{imp}\sin(\theta_{imp})$ and the 1-D impedance matching method [e.g., 14]. The shock Hugoniot parameters are taken from [15]. The horizontal component $v_{imp}\cos(\theta_{imp})$ is added as the translational velocity to the v_{jet} to compare the observed jet velocities. The calculated results for projectile jet are shown in Figure 2 as three dotted lines. This simple model reproduces well the general trend of the experimental results. Note that we used v_{imp} as the V_s in the calculation when the calculated V_s is slower than the v_{imp}. The kinks on the blue lines for polycarbonate target are resulted from this treatment.

A physics-based model: Although the standard model works well even when oblique impacts of spherical projectiles as shown above, it is still phenomenological. Both the collision point velocity and the shock velocity are phase velocities, not material velocities in the shocked projectile. Thus, we constructed a simple jetting model using group velocities in a penetrating projectile. Jetting should be resulted from material deformation from the initial contact point to the outward. The typical speed of the deformation is the sound speed C_s of shocked materials. We employed the stagnation-point approximation [4] to estimate material and energy convergence at the jet initiation point due to such deformation because it provides the upper limit of the particle velocity u_p at the position [4, 8]. Tillotson EOS [16] for polycarbonate [17] was used to calculate the C_s and the particle velocity after isentropic release $u_{release}$ at the reference density. The $u_{release}$ was used as the ejection velocity. Consequently, the jet velocity was obtained as $v_{jet} = C_s + u_{release} + v_{imp}\cos(\theta_{imp})$. The results by our model are shown in Fig. 2 as three solid lines. Our predictions are slightly higher than almost of the experimental results. These overestimations may be caused by the stagnation-point approximation as mentioned above [4, 8]. Nevertheless, our physical model constrains well the upper limit of the jet velocity.

Geologic implications: Both the standard and our physical model predict the jet velocity during oblique impacts reaches ~2.5 times than the impact velocity. Although the mass of jetted materials must be small [e.g., 5] for energy conservation, the aerodynamic interaction between such hypervelocity jet and an ambient atmosphere may be significant because the heating rate of aerodynamic ablation is proportional to the cube of the velocity [e.g., 18]. In the case for an oblique impact on Titan, the jet velocity may reach ~30 km/s for typical cometary impacts and may generate strong EUV radiation from produced high-temperature plasma in the N_2-CH_4 atmosphere via aerodynamic interaction near the surface of Titan. Active chemical reactions of C-bearing species may be driven by the produced EUV [e.g., 19]. The available energy source near the current Titan surface is only cosmic rays [20]. Thus, hypervelocity jetting may be a new energy source for atmospheric chemistry on Titan.

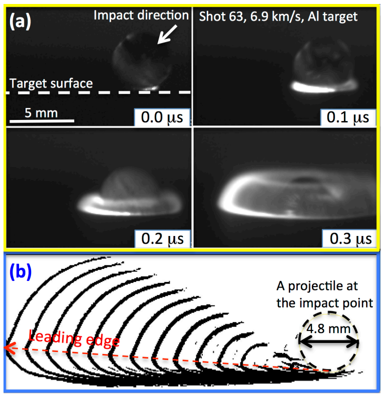

Fig. 1. (a) Examples of high-speed images. The time after the impact is shown in the figure. (b) A time-stacked image with image binarization. The time interval from image to image is 0.1 µs.

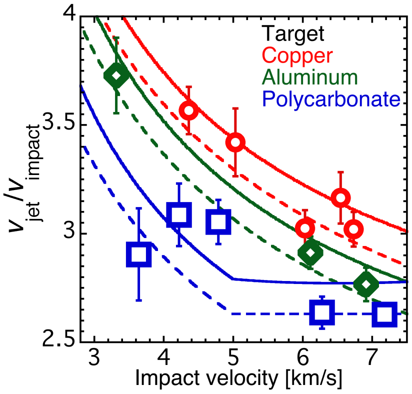

Fig. 2. The velocity ratio of the jet velocity to the impact velocity as a function of impact velocity. The solid and dotted lines are obtained by two models.

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