Impact Jetting of Geological Materials

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Received May 23, 1994; revised March 17, 1995

INTRODUCTION

When two objects collide over a range of angles and impact velocities, high-velocity material is released from the contact zone between the two objects. This phenomenon is called jetting. Jetting has been extensively studied in the case of symmetric and asymmetric collisions of thin metal plates both theoretically and experimentally (Blinkhorn et al., 1984, Walsh et al., 1993, Wang 1989, Pack and Curtis 1990). Keffer (1977) applied the symmetric collision theory to the impact of geologic materials and predicted that molten silicate jets would be produced upon impact at velocities as low as 1–2 km sec⁻¹. Melosh and Sonett (1984), applying the theory of symmetric collisions to the collision of two unequal spheres, suggested that a mega-impact event on the proto-Earth may have created, via jetting, enough mass in a solid, liquid, and vapor plume from which the Moon formed. More recently, Vickery (1993), by using Melosh and Sonett’s model, calculated the jetting velocity, ejecta mass, and composition in the case of an asteroid impact on Earth. She concluded that for such events, the initially molten, now gassy objects that are recognized as tektites, which in several cases have streakfields of 10⁴–10⁵ km did not originate from the impact process. As most of the tektites’ strewn fields can be related to specific craters or places on Earth (Cohen 1963, Bhattacharya et al., 1992, Taylor and Epstein 1962), it appears that tektites are associated with the high-speed ejecta, which is lifted at large angles; >45° to the local horizontal. Although there have been several studies and applications of the jetting theory to geologic materials, virtually no experimental constraints are available for jetting phenomena of geological materials. This work summarizes previous preliminary results (Yang et al., 1992a, Yang and Ahrens 1992, 1994) as well as new results and provide a complete presentation of a previous theoretical model. We address three issues: (1) How much material is ejected by a jet? (2) How is the jetting angle related to the geometry of the impact? (3) What is the jetting velocity? We address the first two issues experimentally. Our results differ from predictions of an existing theory under most experimental conditions.

EXPERIMENTS

The experiments were conducted with a 40-mm propel-

lant gas, which accelerated 5-mm-thick gabro discs at 1.5–2 km sec⁻¹. Upon impact of these plates with inclined (30°–60°) rectangular target slabs (5–12-mm-thick gabro, novaculite, and porous sandstone), ejecta was collected in a catch box filled with styrofoam (2 kg m⁻³, 1 m thick). Figure 1 shows the experimental configuration. An X-ray image of the target and impactor during the impact process is shown in Fig. 2. The experimental conditions are shown in Table I. After an impact, unipectal shaped crater, ~5 cm long and ~2 cm wide, was formed. By careful measurement of the relative positions of the target and the crater created by the ejecta, the jetting angle was determined. Then the styrofoam which contained the ejecta was dissolved in chloroform and the ejecta was recovered. Table I summarizes the experimental results. The design of the present planar experiment has several advantages over that of a sphere impacting a half-space
are largely glass materials which have bulk major element compositions similar only to target materials. They contain very little water and in some cases only minute traces of the projectile materials. Scanning electron microscope (SEM) images were obtained. The sizes of the ejecta particles are less than a few micrometers (Fig. 4), despite the fact that grain sizes of the impactor and target can be as large as 3 mm.

**THEORETICAL MODEL**

Analytical asymmetric collision models are described by Wang (1989) and Pack and Curtis (1996). In our treatment we take the collision point as the origin of a moving frame (reference to the laboratory frame) the flow pattern of the impactor and target plates is shown in Fig. 5. From geometry, we obtain

\[ u_i = u_i \tan \theta \]
\[ u_o = u_o \sin \theta. \]

We assume that the flow depicted in Fig. 5 is incompressible and the surface between the impactor and the target remains planar. Then Bernoulli's theorem yields equal flow velocities of the jet \( u_i \), slug \( u_s \), and incoming flow \( u_0 \). If we further assume that the jet and slug move along a straight line, we write the conservation relations as conservations of masses:

\[ m_i = m_{i,0} + m_{s,0} \]
\[ m_i = m_{i,0} + m_{s,0} \]

conservation of momentum

\[ m_{i,0} \cos \theta_i = (m_{i,0} - m_{s,0}) u_i \]
\[ m_{s,0} \cos \theta_s = (m_{i,0} - m_{s,0}) u_s \]
\[ m_{i,0} \sin \theta_i = m_{s,0} \sin \theta_s \]

plus the geometric relation

\[ \alpha = \theta_i + \theta_s \]

yield

\[ \tan \theta_i = m_{s,0} \sin \theta_i / (m_{i,0} + m_{s,0} \cos \theta_i) \]
\[ \tan \theta_s = m_{i,0} \sin \theta_i / (m_{i,0} + m_{s,0} \cos \theta_i) \]

and the jet mass

\[ m_j = m_{i,0} + m_{s,0} = [m_{s,0} \cos \theta_i + m_{i,0} (1 - \cos \theta_i)] / 2. \]
From conservation of momentum, the average velocity of the jet in the moving frame is

$$u_i = (m_i u_{i1} + m_2 u_{i2})/m_i.$$  \hfill (12)

The jet velocity and jetting angle in the laboratory frame are

$$u_j = u_i^2 + a_i^2 + 2 u_i a_i \cos \theta_j$$  \hfill (13)

$$\delta_j = \arcsin(\sin(\delta_{i2} / a_j)).$$  \hfill (14)

The calculated $\theta_j$, $a_j$, and $q_j$ are shown in Table III.

In order to estimate the pressure and temperature the materials have experienced, Bernoulli’s equation is used again and the flow is assumed to be incompressible.

$$e + p + u_i^2/2 = e_h + p_h + a_i^2/2.$$  \hfill (15)

Let $e_h = p_h = 0$, substituting $e$ and $p$ with the Hugoniot relations

$$e = p(x_h - u_i^2)/2$$  \hfill (16)

$$p = c_i^2 \rho_i - 6v_i^2(1 - \rho h_i) + \rho s^2,$$  \hfill (17)

where $c_i$ and $s$ are constants of the equation of state $u_i = c_i + s x_i$ between the shock velocity $u_i$ and particle velocity $x_i$.

At the stagnation point, $u = 0$, $x_i = x_i$ or $x_i$. we can solve (15)-(17) for $p$ and $v$. With other thermodynamic parameters, the shock temperature and post-shock temperature the materials have experienced can be calculated (Yang et al. 1992b). The parameters used are listed in Table III.

**TABLE III**

<table>
<thead>
<tr>
<th>Shot no.</th>
<th>Ejecta mass (mg cm(^{-2}))</th>
<th>Jetting angle ((^\circ))</th>
<th>Ejecta velocity (km sec(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>846</td>
<td>53 (54(^a))</td>
<td>6.7</td>
<td>5.78</td>
</tr>
<tr>
<td>852</td>
<td>52 (53)</td>
<td>6.8</td>
<td>5.82</td>
</tr>
<tr>
<td>855</td>
<td>52</td>
<td>6.8 (6.5 \pm 0.5)</td>
<td>5.86</td>
</tr>
<tr>
<td>905</td>
<td>64 (39)</td>
<td>5.1 (4.7 \pm 0.5)</td>
<td>7.43</td>
</tr>
<tr>
<td>906</td>
<td>123 (62)</td>
<td>6.1 (5.5 \pm 0.1)</td>
<td>4.92</td>
</tr>
<tr>
<td>907</td>
<td>64 (30)</td>
<td>5.1 (8.1 \pm 0.1)</td>
<td>5.79</td>
</tr>
<tr>
<td>925</td>
<td>133 (42)</td>
<td>6.6 (9.0 \pm 0.1)</td>
<td>3.80</td>
</tr>
<tr>
<td>928</td>
<td>140 (54)</td>
<td>5.8 (10.2 \pm 1.3)</td>
<td>4.84</td>
</tr>
<tr>
<td>940</td>
<td>299 (45)</td>
<td>3.8 (3.2 \pm 0.6)</td>
<td>2.78</td>
</tr>
<tr>
<td>941</td>
<td>312 (52)</td>
<td>4.3 (10 \pm 5)</td>
<td>2.70</td>
</tr>
</tbody>
</table>

\(^a\) Experimental values are in parentheses.

**DISCUSSION AND CONCLUSIONS**

From Table III we can see that the calculated mass of the ejecta is significantly greater than that of the experiments except shots 846 and 852 (Table I). By plotting the ejecta masses versus inclination angle in Fig. 6, we immediately see that while the theory predicts an increase of ejecta mass as the inclination angle and plate thickness increase, the experiments show approximately a constant amount of ejecta mass (~50 mg cm\(^{-2}\)), despite the fact that the impact velocity, material, and plate thickness were varied considerably. Since increasing the thickness of the target does not appear to increase the mass of ejecta, we conclude that only part of the total thickness of the impactor and target contribute to the formation of jet. And this
thickness is about 5 mm (shots 846 and 852) under our experimental conditions.

In Melosh and Sonett's (1984) model, and also in Vickery's (1993) calculations, the thickness which is assumed to contribute to jetting is chosen as the radius of the impacting sphere. In light of the present experiments, the above assumption appears to be unsupported. Obviously different jet ejecta masses can be inferred by assuming different thicknesses. We have not discovered how to determine the thickness theoretically for the geometry considered by Melosh and Sonett. It seems that the jetting theory developed for thin metal plates does not apply well for thick geological materials.

Although our experiments were done at relatively low velocities, the impactor and target materials both experienced pressures far over their strengths; they should be...
have like fluid. In addition, the theoretical model predicts little ejecta mass change when impact velocity changes. Thus we believe that, the discrepancy between experiments and theory will not disappear at high impact velocities (e.g., 10 km/sec). From the X-ray diffraction patterns (Fig. 3), we find that the ejecta contains significant amount of impactor and target materials, which agrees with Vickery's calculations results. Since most tektites do not contain significant amounts of extraterrestrial component (Koeberl and Shirey 1993), by analogy we do not believe they are produced by the jetting process upon asteroid impact. However, the tektites may be produced by other processes after the jetting regime during impact events.

The jetting angles (Table II) are all less than 10°. This suggests that oblique (or asymmetric) impact is very dif-

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**FIG. 4.** SEM image of ejecta from shot 961 (gibbene against Salton Sea sandstone). The particles are associated inropy. The elongated features are mixtures of much smaller particles and styrofoam residues.

**FIG. 5.** (a) Flow pattern of the impactor and target in a moving reference frame. Origin, 0, is the collision point of the two plumes. (b) Velocity vectors in the laboratory frame. u_j and u_i are the jet velocity and jetting angle, respectively.

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**TABLE III**

| Parameter Used in Pressure and Temperature Calculations | Gibbene | Novaculite | s/s
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>y</td>
<td>5.7√</td>
<td>0.7√</td>
</tr>
<tr>
<td>A (K)</td>
<td>0.022√</td>
<td>999√</td>
</tr>
<tr>
<td>c_v (c/m/s)</td>
<td>5.8</td>
<td>3.0</td>
</tr>
<tr>
<td>e</td>
<td>0.85</td>
<td>1.35</td>
</tr>
<tr>
<td>P_{max} (GPa)</td>
<td>18</td>
<td>21</td>
</tr>
<tr>
<td>T_{max} (K)</td>
<td>815</td>
<td>1199</td>
</tr>
<tr>
<td>T_{max} (K)</td>
<td>364</td>
<td>411</td>
</tr>
</tbody>
</table>

*Note: y, Gruneisen constant; e, Debye temperature.

* This value is calculated from the formula y = αC_p/β, where α is the thermal expansion constant, C_p is thermal capacity (Toonishi et al. 1989).

* This value is obtained by fitting C_p to Debye's formula. u_i and u_j are shock and post-shock temperatures, respectively.

* Salton Sea sandstone.

* Sweeney 1990.
ferent from symmetric impact. This applying symmetric impact theory, as was used by Kieffer (1977), Melosh and Soffert (1984), and Vickery (1993), does not appear to be appropriate for asymmetric impacts. The calculated shock temperature and post-shock temperatures are still below the melting points of the materials used. This agrees well with the X-ray diffraction and SEM results in which no melting was detected. We also conclude in contrast to Kieffer (1977) that impact velocities greater than 2 km sec⁻¹ are needed to produce molten jets for the silicon materials used in our experiments.

ACKNOWLEDGMENT
Research is supported by NASA under NAGW 1841, Division of Geological and Planetary Sciences, Contribution 1799.

REFERENCES

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FIG. 6. Ejecta mass per unit area is impact angle.