Icarus 238 (2014) 13–22

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Jetting during vertical impacts of spherical projectiles

B.C. Johnson [a,*], T.J. Bowling [b], H.J. Melosh [b]

[a] Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, United States
[b] Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, 550 Stadium Mall Drive, West Lafayette, IN 47907, United States

ARTICLE INFO

Article history:
Received 5 February 2014
Revised 18 April 2014
Accepted 4 May 2014
Available online 15 May 2014

Keywords:
Impact processes
Cratering
Collisional physics

ABSTRACT

The extreme pressures reached during jetting, a process by which material is squirted out from the contact point of two colliding objects, causes melting and vaporization at low impact velocities. Jetting is a major source of melting in shocked porous material, a potential source of tektites, a possible origin of chondrules, and even a conceivable origin of the Moon. Here, in an attempt to quantify the importance of jetting, we present numerical simulation of jetting during the vertical impacts of spherical projectiles on both flat and curved targets. We find that impacts on curved targets result in more jetted material but that higher impact velocities result in less jetted material. For an aluminum impactor striking a flat Al target at 2 km/s we find that 3.4% of a projectile mass is jetted while 8.3% is jetted for an impact between two equal sized Al spheres. Our results indicate that the theory of jetting during the collision of thin plates can be used to predict the conditions when jetting will occur. However, we find current analytic models do not make accurate predictions of the amount of jetted mass. Our work indicates that the amount of jetted mass is independent of model resolution as long as some jetted material is resolved. This is the result of lower velocity material dominating the mass of the jet.

1. Introduction

Early in the contact stage of an impact, highly shocked material is ejected at low angles possibly forming an 'impact flash' (Eichhorn, 1975). The jet of material squirts from the contact point of the target and the projectile, reaching velocities greater than the impact velocity. Although jetting during the oblique convergence of two thin plates (often driven by shaped charges) (Walsh et al., 1953) is well studied, the process of jetting in bolide and planetesimal impacts has received comparatively little attention (Ang, 1990; Melosh and Sonett, 1986; Vickery, 1993). Here we present the first numerical models that resolve jetting during impacts of spherical projectiles.

Many impact studies focus on the relatively well-understood process of crater formation and collapse (Melosh, 1989). Jetting as an impact process is usually overlooked in numerical studies because it requires extremely high resolution. It is prohibitively computationally expensive to resolve jetting as well as crater formation and collapse, which involves a much larger spatial region. This is not a problem for the study of impact cratering, because jetting has essentially no effect on the bulk flow associated with crater formation. Although jetting only involves a small amount of material, a few percent of a projectile mass, it may be an important impact process. Jetted material reaches high shock pressures and can cause melting and vaporization even at low impact velocities (Kieffer, 1977). Potential solutions to several outstanding problems in planetary science rely on the intense pressure and temperature conditions which occur during jetting.

Kieffer et al. (1976) and Kieffer (1977) argue that grain-on-grain impacts in shocked sandstone causes melt to jet into collapsing pores. However, current models of impact melting in porous material neglect this effect (Kowitz et al., 2013). Kieffer (1975) suggests that jetting during relatively low velocity impacts between small particles in space can produce chondrules. More recently, Johnson et al. (2014) argue that jetting during large accretionary impacts may form chondrules. Melosh and Sonett (1986) proposed that the Moon might be composed of material jetted during a massive impact. De Gasparis et al. (1975) first introduced the idea that tektites may be composed of material jetted during bolide impacts. They argue that these jets may penetrate the atmosphere before they break up, allowing tektites to retain their large sizes (de Gasparis et al., 1975). Vickery (1993) contends that jetted material should be composed of a mixture of both projectile and target material, while tektites do not exhibit any sign of contamination by projectile material (Koeberl, 1986). Even so, the idea that tektites formed by jetting is pervasive. For instance, a recent review of ejecta from the Ries crater indicates that tektites formed

* Corresponding author.
E-mail address: brcjohns@mit.edu (B.C. Johnson).

http://dx.doi.org/10.1016/j.icarus.2014.05.003
0019-1035/

by jetting (Stöffler et al., 2013; their Fig. 40a). As we show in Section 3.1, our numerical results seem to contradict the conclusions of Vickery (1993). Nevertheless, a deeper understanding of the jetting process will clarify its role in the aforementioned processes.

In Section 2 we introduce the theory of jetting. Section 2.1 focuses on the theory of jetting during the collision of thin plates. Section 2.2 describes the geometry and theory of jetting during the impact of a spherical projectile, both with a flat target and another equal sized spherical projectile. In Section 2.2, we also introduce some previous works, which use thin plate theory to describe jetting during the impact of a spherical projectile. We point out the advantages our numerical study has over these preceding works. Namely, we argue that, for the impact of a spherical projectile, thin plate theory can only be applied to the onset of jetting and does not apply to the flow at later times. In Section 3 we present our numerical results for the vertical impact of a sphere into a flat target (Section 3.1) and the head on collision of two equal sized sphere (Section 3.2). Finally, in Section 4 we discuss the limitations of work and how oblique impacts and different materials may affect our result.

2. Jetting theory

First we will introduce the theory of jetting during the symmetric collision of two thin plates (Section 2.1) and then extend this idea to the impact of a spherical projectile with a flat target or another sphere (Section 2.2).

2.1. Thin plate theory

To begin, we consider the case when the collision of two thin plates will create a jet. As we will subsequently describe, jetting occurs when the angle between the free surfaces of the impacting plate, α, is greater than some critical value. The two most common reference frames used when describing thin plate collisions are the standard frame and the collisional frame (described in Fig. 1).

Although not strictly valid across shocks or for a compressible flow, Harlow and Pracht (1966) apply Bernoulli's law for an incompressible fluid along the stream lines shown in Fig. 1 (right) and show that $f \equiv V_1/U_0 \leqslant 1$. Moreover, they show numerically and experimentally that $f \approx 1$ (Walsh et al., 1953; Harlow and Pracht, 1966). Thus, the velocity of the jet in the standard frame is given by

$$V_j \approx V_1 + V_c = V_p\left(\frac{1}{\sin\left(\frac{\alpha}{2}\right)} + \frac{1}{\tan\left(\frac{\alpha}{2}\right)}\right) \quad (1)$$

This implies that the jet velocity becomes arbitrarily large as the angle α approaches zero. However, jetting only occurs when the shock becomes detached from the collision point. This allows rarefactions propagate from the free surface, accelerate material to high velocity, and form a jet. Below the critical angle the shock stays attached to the collision point and no jet can form (Fig. 2). For a given plate velocity V_p, there is a critical angle α_{cr} such that when $\alpha \geqslant \alpha_{cr}$, a single shock is incapable of turning the plate with velocity U_o through the angle α to end up with a velocity U (Walsh et al., 1953). When $\alpha \geqslant \alpha_{cr}$ the shock detaches from the collision point and a jet forms.

Using the equations for conservation of mass and momentum across a shock, Walsh et al. (1953) show that when $\alpha = \alpha_{cr}$

$$\frac{dP}{d\mu} = \frac{P(P - \rho_0 U_0^2)}{(\mu+1)[\mu\rho_0 U_0^2 - P(\mu+2)]} \quad (2)$$

where $\mu = (\rho/\rho_0) - 1$, ρ_0 is the uncompressed density, and P is the pressure of material shocked to a density ρ. Using an equation of state to find when Eq. (2) is satisfied we can then express the angle $\alpha = \alpha_{cr}$ as

$$\alpha = 2\tan^{-1}\left[\frac{P\left(\rho_0 U_0^2\left(\frac{\mu}{\mu+1}\right) - P\right)}{\left(\rho_0 U_0^2 - P\right)^2}\right]^{1/2} \quad (3)$$

Generally the critical angle monotonically increases with increasing impact velocity (Walsh et al., 1953).

For thin plates, a smaller critical angle generally corresponds to thicker jets independent of the plate angle α. At the critical angle the jet has zero thickness. Assuming the jet density is equal to the plate density, which must be true at some time during the collision, at $\alpha = 90°$ the jet must be as thick as one of the plates. The modeled linear dependence of jet thickness on angle alpha (Harlow and Pracht, 1966) then requires that for any angle α a material with a larger critical angle, α_{cr}, will produce a less massive jet. Using estimates of the critical angle, one can determine how important jetting is for a given material. For a stiffened gas equation of state, Harlow and Pracht (1966) show that less compressible materials have lower critical angles and jets that are more

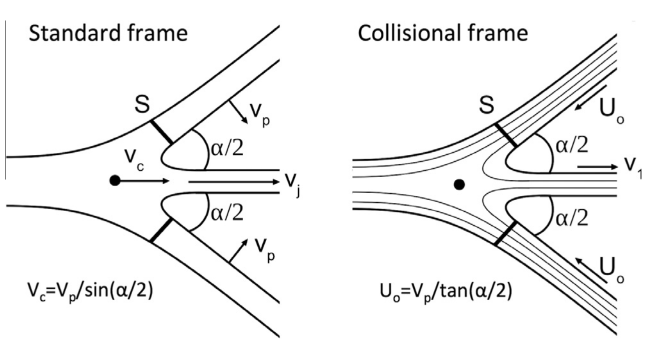

Fig. 1. Thin plate collision producing a jet. These schematics show a cross section of the plates, such that the plates extend into and out of the page. The standard frame (left) is the reference frame in which the velocity of the un-shocked plates, V_p, is perpendicular to the plates. In the standard frame the stagnation point (large black dot), which acts as a proxy for the collision point, moves with a velocity $V_c = V_p/\sin(\alpha/2)$. The thick black lines labeled as S represents the shock. Material to the left of the collision point is called the slug. While material to the right of the collision point is either un-shocked plate material or jetted material, which has a velocity V_j. The collisional reference frame (right) is defined such that the stagnation point, a proxy for the collision point is fixed. In the collisional frame the velocity of the un-shocked plates, $U_o = V_p/\tan(\alpha/2)$, is parallel to the plates. In the collisional frame the velocity of the jet is $V_1 = V_j - V_c$. The thin lines in the collisional frame roughly represent streamlines. The vectors in this plot are drawn roughly to scale with respect to one another.

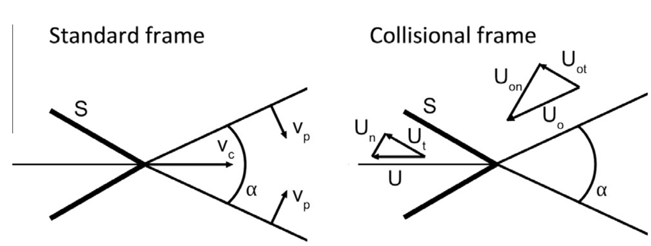

Fig. 2. Thin plate collision where no jet forms. These schematics show a cross section of the plates, such that the plates extend into and out of the page. These schematics focus on the collision point and do not show the backsides of the plates. The standard frame (left) is the reference frame in which the velocity of the un-shocked plates, V_p, is perpendicular to the plates. In the standard frame the collision point moves with a velocity $V_c = V_p/\sin(\alpha/2)$. The thick black lines labeled as S represents the shock. The collisional reference frame (right) is defined such that the collision point is fixed. In the collisional frame the velocity of the un-shocked plates, $U_o = V_p/\tan(\alpha/2)$, is parallel to the plates. U is the velocity of the slug in the collisional frame. The components of U and U_o normal to and parallel to the shock are also shown. The conservation of momentum requires that $U_{ot} = U_t$, so that the vectors in this plot are drawn roughly to scale with respect to one another.