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BUMPER DEBRIS CLOUD STRUCTURE ESTIMATED BY SHOCK CALCULATIONS

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Abstract

A relatively simple shock analysis is developed for hypervelocity impact onto spacecraft bumpers. The example treated is a copper disc striking aluminum. The shape of the debris cloud scales with the impact velocity and is determined only by the shock impedances of the projectile and bumper materials. The bumper and projectile debris clouds separate. The peak bumper debris velocity exceeds the impact velocity; the peak projectile debris velocity is equal to the impact velocity. The differential motion of the front and rear of the projectile cloud causes spall in the projectile.

Introduction

Use of sacrificial bumpers to protect space vehicles from impact of natural and man-made particles has been investigated for several years^{/1-3/}. Early work mainly focused on particles whose density was similar to the bumper, such as glass or aluminum striking aluminum. These studies have led to several analytical models that described debris clouds as expanding hollow spherical shells^{/4-6/}.

Piekutowski^{/7-8/} has shown that when the density of the particle is quite different from the bumper, the debris cloud has considerably more structure than predicted by spherical models. These findings have recently been confirmed by other investigators^{/9-10/}.

Fig. 1, for example, illustrates a cloud from a copper disc striking an aluminum bumper at 6.53 km/s. There is a high speed conical-shaped aluminum outer cloud, followed by a slower and denser copper cloud that is roughly diamond shaped.

Analysis of debris clouds such as Fig. 1 was presented in^{/8/}. There it was shown that for copper discs striking aluminum bumpers: (a) the particles in the debris cloud do not interact with one another once the cloud is formed. (b) The shape of the cloud does not depend on the size scale of the experiments, for projectile masses from 1 to 10 g. (c) The shape of the cloud is only weakly dependent on impact velocity, for velocities from 3.45 to 6.53 km/s. (d) The velocity of the cloud scales with impact velocity. (e) The cloud is only affected by the material that is "punched out" by the projectile, not by bumper material adjacent to the impact.

Fig 1. Radiograph from Shot 863 at 6.53 km/s, showing structure of the debris cloud. Arrow points to leading edge.

Simple model

Compared to earlier work with spherical projectiles, the disc-shaped projectiles used in^{7-8/} also result in an impact process that is easier to analyze in terms of fundamental shock interactions. Fig. 2 is a simplified sketch of the debris cloud shown in Fig. 1. Fig. 3 is a sketch of shock interactions in the bumper and projectile, assuming no impact yaw or obliquity, and an impact velocity of 6.3 km/s. Fig. 3 is drawn from a "Lagrangian" perspective, in which the coordinate system is attached to the particles; thus, there is no movement of material shown in Fig. 3. Fig. 4 is an "x,t" diagram for the idealized shock interactions along the center line of the impact, ignoring off axis effects. Interaction regions shown in the figures are discussed below.

Before impact the bumper and the target are in states A_2 and A_1 , respectively. The peak shock states of the bumper and projectile after impact are obtained from "impedance match" solutions^{11-12/}. This process is illustrated in Fig. 5, which is a stress-particle velocity diagram (not to scale) for the shock interactions shown in Fig. 4. The lines labelled P and B in Fig. 5 are projectile Hugoniot and bumper Hugoniot, respectively. (Ref. data for Hugoniot of engineering materials can be found in ^{11,13/}). The slopes of the Hugoniot curves in Fig. 5 are equal to the shock impedances of the projectile and bumper, which in the example are assumed constant. In drawing Fig. 5, we also ignored the relatively small difference between shock paths (e.g. Hugoniot) and unloading paths (isentropes).

Before impact, the bumper particle velocity is $u = 0$, and the projectile particle velocity is $u = V_0$. The initial shock brings both the bumper and projectile to velocity u_s , where $0 < u_s < V_0$. Both the stress and particle velocity of the projectile and the bumper are the same here. The B Hugoniot is footed at the origin, because the bumper is initially at rest; the projectile Hugoniot is footed at the impact velocity, V_0 , because this is the particle velocity when the projectile is at zero stress. The intersection gives the point where $u = u_s$. This is state B. The change in particle velocity associated with the peak shock stress in the bumper is,

$$\Delta u_p = u_s \quad (1)$$

while the change in particle velocity associated with the peak shock in the projectile is,

Fig 2. Sketch of debris cloud.

Fig. 3. Wave fronts in impact of copper onto aluminum at 6.35 km/s. 0.45 μ s after impact.

$$\Delta u_p = V_0 - u_s. \quad (2)$$

Velocity u_1 occurs when the shock wave in the bumper reflects from the rear surface of the bumper, bringing that region to zero stress. This is state C_1 . It can be seen by inspection of Fig. 5 that in state C_1 ,

$$u_1 = 2u_s. \quad (3)$$

Velocity u_3 occurs when the shock wave in the projectile reflects from the rear surface of the projectile, again resulting in a stress-free region (state C_2). Again, it can be seen from Fig. 5 that,

$$u_3 = u_s - \Delta u_p = 2u_s - V_0. \quad (4)$$

For the geometry that we are considering, as shown in Fig. 4, the release wave in the bumper arrives at the projectile/bumper interface before the release wave in the projectile. Since the projectile has a higher shock impedance than the bumper, the bumper separates from the projectile at this point. The particle velocity of the entire bumper is now u_1 . However, the particle velocity of the projectile (state D) which is denoted u_2 , results from a release wave from the peak shock state B. Hence,

$$u_2 = V_0. \quad (5)$$

bumper, and Δu_p in the projectile. These expansions account for the radial velocities of the debris cloud. Release in the bumper is complicated by the contiguous material next to the impact site. In the projectile, radial expansion occurs with velocity u_4 given by,

$$u_4 = \Delta u_p = V_0 - u_s. \quad (6)$$

The conical shape of the debris cloud results from the transition from material that is shocked and relieved on axis, resulting in the velocities given by Eq. 3-5, to material that is first relieved from the sides, receiving a vector velocity that has an axial component u_s and a radial component given by Eq. 6.

According to this analysis, the shape of the inner and outer debris cloud is determined only by the peak shock particle velocity u_s . The value of u_s is a function only of the impact velocity and Hugoniot of the bumper and projectile. For most combinations of materials u_s is effectively linearly proportional to V_0 .

Comparisons with experimental data

Predictions of calculations with this model are compared with experimentally observed cloud dimensions reported in^{8/}. The results are given in Table 1. Data precision is generally about ± 3 percent. It can be seen that the agreement is generally excellent.

Table 1. Comparison of data and model for Cu striking aluminum.

IMPACT			MEASURED (REFERENCE 8)				MODEL				REF. 11
Shot	V_0	Yaw	u_1	u_2	u_3	u_4	u_1	u_2	u_3	u_4	u_1
Number	km/s	(°)	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0
936	6.39	4.6	1.44	1.02	0.36	0.35	1.35	1.00	0.35	0.33	1.41
969	6.36	7.8	1.44	1.01	0.36	0.36	1.34	1.00	0.34	0.33	1.41
1007	6.38	10.7	1.42	0.99	0.35	0.38	1.34	1.00	0.34	0.34	1.41
863	6.56	2.5	1.46	0.97	0.35	0.34	1.35	1.00	0.35	0.33	1.42
971	3.45	2.5	1.37	0.96	0.43	0.30	1.36	1.00	0.36	0.32	1.39
972	4.85	4.7	1.43	0.99	0.39	0.36	1.36	1.00	0.36	0.32	1.40

The prediction for leading edge velocity, u_1/V_0 , is about 7 percent too low. The prediction for the primary projectile debris, u_2/V_0 , is about 1 percent too high. The prediction for the trailing projectile debris, u_3/V_0 , is about 6 percent too low on average. Predicted lateral velocity of the projectile, u_4/V_0 , is about 5 percent too low. The trends predicted by the analysis are consistently followed by the data, namely scaling by impact velocity, and $u_1 \cong 1.3u_2$, $u_3 \cong u_4$, and the leading projectile debris travels at the impact velocity.

The agreement with measured debris velocities can be improved if we take into account the isentropic release which differs slightly from the Hugoniot. Using the free surface data calculated for copper in^{11/} reduces the discrepancies in u_1/V_0 to the values shown in the column labelled "Ref. 11".

Discussion

This model gives a quantitative account of the debris clouds formed when hypervelocity high impedance flat projectiles strike low impedance bumpers. It also provides insight into many other scenarios.

When the projectile and bumper are the same material, then the bumper will not rebound off the projectile face. Moreover, $u_s = V_0/2$, which will result in a single spherical debris cloud.

When the projectile is spherical, the same processes will occur, but because of the geometry, the maximum values of velocities presented in the previous section may not occur. As shown in^{8-9/}, however, the separation of the debris cloud into bumper and projectile components still occurs.

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