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EFFECT OF SHOCK WAVE RISE TIME ON MATERIAL EJECTION FROM ALUMINUM SURFACES

J. R. Asay

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by

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ABSTRACT

The effect of shock wave risetime on material ejection in aluminum has been studied for loading stresses of 21 GPa. Uniform loading was accomplished with plate impact techniques by mounting specimens on a ramp wave generator. Projectile impact on one side of the wave generator produced a wave which dispersed with propagation distance. This wave was then made incident to an aluminum specimen, so that the specimen experienced non-shock loading. It was found that mass ejection from aluminum surfaces can be reduced by over two orders of magnitude relative to shock loading conditions by accelerating the surface with a wave risetime greater than about 35 ns. These results suggest an explanation for the apparent discrepancies which are sometimes observed in mass ejection measurements utilizing either plate impact or electron beam deposition to generate stress waves.

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I. INTRODUCTION

Several investigators have previously shown that material can be ejected from surfaces of various specimens that are shocked with high amplitude stress waves.¹⁻⁶ In these previous experiments, it was also possible to tentatively identify several sources which could cause shock-induced ejecta.³⁻⁵ These possibilities include (1) surface defects such as pits and scratches, (2) impurities or inclusions near the surface and (3) internal defects such as grain boundaries or dislocation slip bands. In each of these cases, it would be expected that a characteristic time would describe the ejection process. For example, if jetting of mass from small pits on the surface were the major effect, then the risetime of waves incident on these pits would likely influence the amount of material ejected. Similarly, wave interactions in impurities which cause spalling from the surface would also involve a characteristic time which is related to the transit time of a wave across the impurity. Finally, if thermal heterogeneities and subsequent melting or vaporization at crystal defects influence mass ejection, then the characteristic time would be related to thermal diffusivity. Thus most of the mechanisms influencing mass ejection would involve a characteristic time for the ejection process. Under this assumption, it is therefore expected that mass ejection will be sensitive to the risetime of loading waves incident on a surface.

There has been no prior systematic study regarding the effects of shock risetime on mass ejection. However, there has been some previous work which suggests that risetime effects are important. Perry and Mix⁷ have recently observed that essentially no material is ejected with velocities exceeding 20 percent of the free surface velocity from polished surfaces of 6061-T6

aluminum when shock waves in the material were induced by electron beam deposition. On the other hand, it has been found that when 6061-T6 specimens are loaded to nominally the same stresses with plate impact techniques, about $10 \mu\text{g}/\text{cm}^2$ is ejected from the surface with velocities up to 2 or 3 times the free surface velocity.³⁻⁵ For the impact case, it is known that the shock risetime is less than 5-10 ns (resolution limited) for shock pressures greater than about 20 GPa. However, for electron beam-driven shocks the risetime is thought to be greater than this, especially for target thicknesses of one to two electron ranges, due to the finite region over which electrons are deposited in a material and the duration of the beam pulse. Therefore, the existing discrepancy between these two sets of data strongly suggested that shock risetime is an important variable influencing mass ejection. For this reason, a series of experiments were systematically performed in the present work to provide a quantitative basis for this speculation.

The effect of shock risetime on mass ejection was studied in 6061-T6 aluminum specimens for driving stresses of about 21 GPa. Different risetimes in the aluminum specimens were obtained by using plate impact techniques to first generate high amplitude stress waves in a material which exhibits negative curvature in its stress-strain response. A glass ceramic (Corning ware 9608 Pyroceram) was used for this purpose. Because of the negative stress-strain curve, the shock wave initially created at impact decayed into a ramp wave with nearly constant acceleration. After propagating through a given thickness of the generator, the risetime of the wave at the back surface of the Pyroceram was approximately 0.5 μs . The aluminum specimens which were bonded to the back surface of the

generator thus experienced uniform ramp loading, rather than shock loading. Since the positive stress-strain curvature of aluminum serves to steepen ramp waves as they propagate, the risetime of the stress wave at the back free surface of the aluminum specimens could be easily controlled by varying the specimen thicknesses. It was found that mass ejection was completely suppressed (to within the $0.05 \mu\text{g}/\text{cm}^2$ resolution of the technique) by accelerating the aluminum free surfaces with stress waves whose risetimes were greater than 50 ns. This experimental observation of risetime - controlled mass ejection gives strong support to the hypothesis that the differences reported between the plate impact and electron beam data arises from differences in the stress wave risetimes obtained in the two techniques.

The present report is organized as follows: In the second section, plate impact techniques for producing non-shock loading of specimens are described. The application of this method to aluminum and the results on mass ejection obtained with non-shock loading are presented in the third section.

II. IMPACT METHOD FOR PRODUCING NON-SHOCK LOADING OF SPECIMENS

It is well known that the formation of steady shock waves in materials is a consequence of the competing effects of non-linear stress-strain response and dispersive effects, such as material viscosity.⁸ This effect is illustrated in Fig. 1, which shows the response expected for plane one-dimensional loading. The non-linear effects of wave propagation are manifested by the positive curvature of the stress-strain shock loading curve (Hugoniot) of the material. Because of this curvature, different stress increments in an arbitrary wave propagate with the local value of $a + u$, where a is sound speed and u is particle velocity. Sound speed, a , is defined in terms of stress and strain as

$$a^2 = \frac{(1 - e)^2}{\rho_0} \left(\frac{\partial \sigma}{\partial e} \right)_s, \quad (1)$$

where σ is longitudinal stress, e is engineering strain (defined in terms of initial and final densities as $e = 1 - \rho_0/\rho$), and s is entropy. For loading curves with positive curvature, both a and u increase with increasing stress. Therefore, this effect causes steepening of a stress wave. However, wave steepening is offset by dissipative effects, such as dislocation flow, thermal conduction, diffusion etc., which cause broadening of the wave front. A steady wave (i.e., a wave whose shape remains unchanged with propagation distance) is ultimately obtained when these two effects are in exact balance. In this case, the loading path followed by a material element occurs along the Rayleigh line illustrated in Fig. 1. If the rate-controlling process for shock formation is viscous, the total stress achieved during loading by the stress wave can be approximated as

Figure 1. Formation of steady plane shock waves. The engineering strain, e , is defined in terms of initial and final densities as $e = 1 - \rho_0/\rho$. For steady waves, all states achieved during loading lie on the Rayleigh line.

$$\sigma = \sigma_H(e) + \sigma_{vis} \quad , \quad (2)$$

where $\sigma_H(e)$ represents the Hugoniot and σ_{vis} is the viscous contribution to the total stress. If the viscous stress can be approximated as Newtonian, the shock thickness, Δx , is given approximately as⁸

$$\Delta x = \frac{\eta \sigma_1}{\rho_o U \Delta \sigma_{vis}} \quad , \quad (3)$$

The risetime, τ , of the wave is therefore

$$\tau = \frac{\eta \sigma_1}{\rho_o U^2 \Delta \sigma_{vis}} \quad , \quad (4)$$

where η is a viscous coefficient, U is the steady shock speed, and $\Delta \sigma_{vis}$ is the maximum viscous stress obtained along the loading path. This can be estimated from the maximum offset between the Rayleigh line and the Hugoniot.

In metals, viscosities are typically a few hundred poise,^{9,10} so that shock risetimes are often only a few nanoseconds when the peak stress σ_1 is a few tens of GPa. Therefore, in order to produce larger risetimes with plane waves, it is necessary to provide non-shock loading of a specimen. This procedure is demonstrated in Figs. 2 and 3 for an elastic-plastic material. In Fig. 2, we have assumed that uniform loading with constant acceleration is applied to one boundary of a plane specimen. The stress-strain curve for the specimen is illustrated in Fig. 3. The shock loading path¹¹ is assumed to be elastic up to the Hugoniot elastic limit (HEL) and plastic for higher stresses. It has also been assumed that the driving stress, σ_1 , is large enough to generate a single, stable steady wave for sufficiently large propagation distances. This would be the case if the

Figure 2. This figure illustrates the non-shock loading of a specimen. The stress history at the impact face consists of constant acceleration to the final value σ_1 .

Figure 3. This figure illustrates the wave profiles that would be expected if an elastic-plastic material is loaded with a uniform acceleration (as in Fig. 2) to a final stress that is sufficient to support a single steady shock wave. The stress above which a single wave is possible is referred to as the elastic overdrive stress. The stress-position histories expected for this case are illustrated qualitatively in the figure for different times. In the early evolution of the shock, an elastic wave traveling with velocity c_l is formed and this is followed by a plastic compression wave. Because of the nonlinearity in the loading curve (assumed to be a Hugoniot), the plastic wave will steepen into a shock which will eventually over-run the elastic wave and form a single steady shock traveling with velocity U .

final stress is greater than the elastic overdrive stress.

The elastic wave, which has an amplitude equal to the HEL, propagates in the material with a constant velocity, c_ℓ , which is nearly equal to the elastic longitudinal velocity at zero stress. However, because of the nonlinearity in the stress-strain response, the upper region of the plastic wave travels faster than the lower part (which travels at the local value of bulk sound speed, c_0). Since $c_\ell \simeq 1.2 c_0$ in most metals, the elastic wave will tend to separate from the plastic wave during early times. However, at later times (for example, t_4 in Fig. 3) a steady plastic shock is formed. Since the driving stress is greater than the overdrive stress, this wave will travel faster than the elastic wave. Ultimately a single plastic shock ($t \geq t_7$) will be formed which travels with velocity U and with a risetime which is governed by Eq. 4. Hence, this qualitative description suggests that the risetime of stress waves in a material, and therefore the acceleration of free surfaces, can be controlled by accelerating one surface of a sample and then varying the propagation distance.

The actual material used to provide a constant acceleration loading to aluminum specimens in the present work was a glass-ceramic, which is commonly referred to as Pyroceram. The stress-strain response for this material (for uniaxial strain) exhibits negative curvature for impact stresses up to about 17 GPa.¹³ Therefore, a stable shock wave is not possible⁸ over this range and a ramp wave output is achieved for a shock input. The total risetime of the ramp can be easily controlled by varying the Pyroceram thickness. A thickness of about 6.3 mm produced a risetime of about 0.5 μ s when the driving stress was 17 GPa. The stress-uniaxial strain response for this material is illustrated in Fig. 4.

Figure 4. The longitudinal stress-strain response for Pyrocera 9608. This material exhibits anomalous behavior during loading, in that the stress-strain curvature is negative.

III. EXPERIMENTAL TECHNIQUE AND RESULTS

Figure 5 shows schematically the experimental technique used to produce ramp loading in aluminum specimens. The figure also illustrates the method employed to measure the mass ejected from the back surface of an aluminum specimen. A powder gun was used to accelerate projectiles with copper facings to about 1.8 km/s. Impact of the copper with a Pyroceram ramp wave generator produced an impact pressure of about 17 GPa. The thickness of the Pyroceram was nominally 6.33 mm in the present work. Because of the negative curvature of the stress-strain curve for this material (see Fig. 4), a ramp loading was produced at the left boundary of aluminum specimens which were bonded to the Pyroceram. By varying the thickness, x , of the aluminum specimen, it was possible to control the maximum acceleration of the aluminum free surface, as illustrated in Fig. 3.

A witness foil of aluminum (4.31 μm in thickness) was used to collect mass ejected from the back surface of the aluminum specimen. The gap separating the witness foil from the aluminum specimen ranged from about 2.5 to 4.0 mm. The mass, m , collected by the foil was estimated from the following relation,³⁻⁵

$$\frac{dm}{dt} = \frac{M}{v - V} \frac{dV}{dt}, \quad (5)$$

where M is the foil mass, V is foil velocity and v is the propagation velocity of ejecta across the gap.

Two VISAR interferometers¹⁴ were used in these experiments. In most experiments one measured the particle velocity history of the back surface of the aluminum specimens (VISAR 1 in Fig. 5) and one monitored the velocity of

Figure 5. Experimental technique for producing accelerative loading of aluminum specimens and measuring the mass ejected from the back surface. The witness foils used to collect the ejected mass were 4.31 μm aluminum foils.

the collecting foil (VISAR 2). In both interferometers, the particle velocity, $V(t)$, which was monitored is related to the fringe count, $F(t)$, produced in the interferometer through the relation,¹⁴

$$V(t) = \frac{\lambda}{2\tau} \frac{1}{1 + \delta} F(t) \quad , \quad (6)$$

where λ is the wavelength of light used (514.5 nm), τ is the delay time of the interferometer (typically ranging from 0.2 to 2.0 ns) and δ is an optical calibration constant (0.034). In the majority of experiments, the light from a laser was focused to a spot about 0.2 - 0.3 mm in diameter on either the sample or the witness foil.

The particle velocity resolution of the technique was about 0.001 km/s; the time resolution was about 10 ns; and the mass resolution was about $0.05 \mu\text{g}/\text{cm}^2$. The dimensions of all components in the target assembly were chosen so as to maintain conditions of uniaxial strain for times of interest.

The aluminum specimens studied in these experiments were prepared from plate stock 6061-T6 alloy. This alloy is a precipitation hardened material with principal impurities of Fe (0.7%), Si (0.6%), Cu (0.3%), Mg (1.0%), Mn (0.2%), Zn (0.3%), and Cr (0.2%). The average grain size of the specimens was about $0.1 \mu\text{m}$. The back surfaces of the samples were prepared by first lapping the surface with $17 \mu\text{m}$ Al_2O_3 compound and then polishing with $1 \mu\text{m}$ paste. A representative photomicrograph of a polished surface is illustrated in Fig. 6. The polishing technique employed here produced some scratching of the surface and also caused a relatively high density of pits, which are due to the removal of inclusions near the surface. The surface density of pits and inclusions was about 10^4 cm^{-2} .

—|—
0.1 mm

Figure 6. Typical photomicrograph of a 6061-T6 aluminum surface studied in these experiments, (Exp. 12B) 100X. Numerous pits and scratches are apparent.

and 10^5 cm^{-2} , respectively. The average size of both inclusions and pits was about $5 \mu\text{m}$, although some were as large as $25 \mu\text{m}$.

All experiments were performed in an evacuated chamber at pressures of nominally 6.7 Pa ($50 \mu\text{m Hg}$). The projectile velocity in each experiment was measured with an accuracy of about 0.2 percent.

Table I summarizes the results obtained in these experiments. The peak acceleration, a , reported in the table refers to the average value attained in the plastic portions of the wave profiles. The corresponding shock risetime at the free surface is designated by τ . The average impact pressure attained in aluminum was about 21 GPa for all experiments.

In some of the experiments reported in Table I, we did not use a witness foil to collect ejecta mass and only the wave profiles on the aluminum back surfaces were recorded. Even though the ejected mass was not actually monitored in these experiments an estimate of the mass is still possible and is presented in the table. This estimate is based on the previously reported observation⁴ that a correlation exists between the amount of ejected mass and the intensity of light reflected from the surface. Since negligible changes in intensity were recorded in these experiments, it is estimated that the amount of ejected mass is less than $0.05 \mu\text{g}/\text{cm}^2$.

Fig. 7 illustrates the particle velocity histories measured on different aluminum specimens. The initial, nearly linear, ramp loading at the left boundary of the specimens ($x = 0$) represents the input loading history. The remaining profiles are presented in the same order listed in the table. Note the similarity to the evolutionary behavior described qualitatively in Fig. 3. One slight difference to the results expected from Fig. 3 is the early formation of a plastic shock near a particle velocity of 0.6 km/s , which grows slightly in amplitude as the wave propagates.

TABLE I

IMPACT PARAMETERS FOR SHOCK RISE TIME EXPERIMENTS ON ALUMINUM

Exp.	Impact ^a Vel. km/s	Pyroceram Thick mm	Aluminum Thick mm	Gap Separation mm	Maximum Acceleration ^b km/s ²	Shock Risetime ^b ns	Ejected Mass ^c μg/cm ²	Maximum Ejecta Vel. km/s
8B	1.803	6.325	0.737	---	4×10^6	560	$< 0.05^c$	---
7B	1.846	6.336	1.552	2.530	5×10^6	430	< 0.05	---
11B	1.808	6.337	2.416	---	8×10^6	280	$< 0.05^c$	---
9B	1.808	6.342	3.150	4.036	9×10^6	260	< 0.05	---
13B	1.797	6.337	3.818	---	1×10^7	220	$< 0.05^c$	---
13A	1.797	6.337	5.240	---	1.5×10^7	150	$< 0.05^c$	---
10B	1.802	6.335	6.332	---	4×10^7	55	$< 0.05^c$	---
10A	1.802	6.335	7.742	---	1×10^8	22	---	---
12B	1.829	6.350	12.446	2.843	$> 2 \times 10^8$	< 10	2.0	4.5

a. The average impact pressure attained in these experiments was 21 GPa.

b. Average values obtained in the plastic portions of the waves.

c. Estimated from the observation that no light intensity change was observed when the plastic wave arrived at the back surface.

Figure 7. Particle velocity profiles measured on the back surface of aluminum specimens that were loaded with a nearly uniform acceleration to a final stress of about 21 GPa. The thickness of the aluminum specimens is denoted by x . The 0.5 GPa elastic wave in aluminum is observable as the first small particle velocity amplitude (~ 0.1 km/s) in front of the main plastic wave.

The average plastic wave risetimes reported in the table were estimated by taking the time difference from the foot of the plastic response to the final particle velocity. There is some latitude in choosing this quantity, so that the wave risetimes and corresponding free surface accelerations reported in Table I are accurate to only about 20 percent.

A witness foil was used to monitor ejecta on Exp. 12B, and this provided a measurement of about $2 \mu\text{g}/\text{cm}^2$ for the total ejected mass. In this experiment, the maximum ejecta velocity was also estimated to be 4.5 km/s, which is approximately a factor of two larger than the free surface velocity. These two observations are compatible to those measured previously on shock-loaded 6061-T6 aluminum.³⁻⁵ In some of the other experiments where collecting foils were used, no ejecta mass was observed (to within the $0.05 \mu\text{g}/\text{cm}^2$ resolution of the technique). There is only one additional experiment where it is thought that mass was ejected during free surface acceleration. This occurred in Exp. 10A in which the wave risetime was about 20 ns and the reflected light intensity decreased abruptly by about 30 percent when the plastic wave arrived at the free surface. From analogy with the previous correlation between reflected light intensities and mass ejecta, this behavior indicates that mass was ejected. However, it is not possible to make a quantitative estimate of the total ejected mass.

From the data reported in Table I, it is possible to assign an upper limit of about 50 ns to the wave risetime necessary to cause mass ejection, with an average value of 35 ns as the time where transition from no ejection occurs. Although there is some uncertainty in the exact value, this estimate is certainly good to within about 50 percent.

Figure 8 presents the results of mass ejection experiments in graphical form. The ejecta mass measured experimentally is less than $0.05 \mu\text{g}/\text{cm}^2$ for risetimes greater than about 50 ns; whereas, a rapid increase is observed in the total amount of ejecta mass in the vicinity of 35 ns risetime. For risetimes less than about 10 ns, the total mass is increased by about two orders of magnitude. The region between 10 and 50 ns has been dashed because of uncertainty in the exact amount of ejecta in this region.

The measurement for Exp. 12B (plastic wave risetime less than 10 ns) is consistent with the earlier reported data on 6061^{4,5} to within a factor of five. In the earlier work, shock loading of the specimen was used to study mass ejection so that the elastic precursor shown in Fig. 7 was not present. In those experiments, the risetime was also estimated to be less than about 10 ns, which was the resolution of the electronic equipment. Therefore, a direct correlation between the differences observed for the cases of shock and non-shock loading is not realistic. However, it is possible to state that the risetime of the plastic wave obtained in Exp. 12B must be greater than the risetime of a similar amplitude single plastic wave which was achieved by direct shock loading. This conclusion results from the fact that the initial elastic wave will reflect from the free surface and then "bounce" back and forth between the oncoming plastic wave and the free surface.¹⁵ This has the effect of increasing the risetime of the plastic wave at the free surface. Thus, it would be expected that the risetime of the plastic wave in the present experiments is larger than that obtained for shock loading, even if it cannot be measured directly. Hence this effect may account for the decreased amount of mass observed in Exp. 12B, relative to that observed for direct shock loading.⁴

Figure 8. Total mass ejected from 6061-T6 aluminum surfaces that were loaded to 21 GPa with different accelerations. The average risetime of the wave incident at the back surface is plotted on the abscissa. For risetimes greater than about 50 ns, no ejected mass was observed (to within the experimental resolution of about 0.05 $\mu\text{g}/\text{cm}^2$). The time resolution obtained with this technique is about 10 ns.

The estimation of 35 ns as an upper limit for ejection of mass provides a plausible estimate of a characteristic time for mass ejection. It has been proposed^{3,4} that mass ejection at these stress levels in aluminum is controlled primarily by either microjetting from pits and scratches or microspalling of inclusions and impurities. Scratch dimensions observed on these surfaces are usually less than 1 μm . As indicated earlier, the pit depths are estimated to be about 5 μm , on the average, with some as deep as 25 μm . It would, therefore, be expected that a characteristic time for microjetting could be estimated to a first approximation as a small multiple of the double transit time for a wave across a pit. For a pit that is 5 μm deep, the resulting time would be about 1.5 ns and for a 25 μm pit it would be about 7 ns (similar estimates would apply to a double transit of waves in impurities or inclusions near the surface). Although these times are apparently not in agreement with the risetime necessary to induce ejection, the experimental results do not preclude a correlation. For example, a 20 GPa wave with a risetime of 35 ns is nearly equivalent to a series of about twenty 1.0 GPa step waves that are separated in time by 1.5 ns (at the other extreme, five 4.0 GPa steps that are separated in time by 7 ns). Thus, if the lower limit in stress which is required to induce mass ejection is on the order of 1-4 GPa, a correlation would exist between the experimentally measured risetime necessary to cause ejection and a characteristic transit time. The lower limit in stress required to eject mass from aluminum surfaces has not yet been measured so that this correlation is presently speculative. However, the question could be answered more definitively either by varying shock stress experimentally in specimens with well-defined grooves⁴ or by performing two-dimensional numerical calculations.¹⁶

IV. CONCLUSION

In summary, the present results demonstrate that mass ejection from shock-loaded surfaces is strongly dependent on wave risetime. In particular, it was found that mass ejection from 6061-T6 aluminum surfaces can be essentially eliminated by loading the surface with 21 GPa stress waves whose risetimes are greater than 50 ns. When the risetime is less than this, the mass ejected from the surface increases rapidly by about two orders of magnitude. Thus, a simple way to suppress mass ejection is to provide non-shock loading of surfaces. This concept has important implications in various engineering applications, such as inertial confinement techniques, and also in equation of state studies using interferometry to monitor surface motion. It has been found previously that mass ejection can degrade interferometer experiments because of scattering and absorption losses. Therefore, the ability to suppress mass ejection allows time-resolved measurements of wave profiles on free surfaces, as demonstrated in the present work.

The present work also serves to resolve a discrepancy that has been noted between the contradictory results obtained on mass ejection in aluminum, utilizing either electron beam deposition or impact loading. It has been previously observed that loading aluminum samples to nominally the same final stress of about 20 GPa with electron beams produces no ejecta, whereas about $10 \mu\text{g}/\text{cm}^2$ is obtained with impact loading. Impact loading normally produces shocks with risetimes that are viscosity-controlled and therefore less than about 10 ns in most metals (at these stress

levels). On the other hand wave risetimes obtained with electron beam deposition are usually larger because of the finite distance over which electrons are deposited in a material, as well as the time duration ($\sim 0.15 \mu\text{s}$) of the beam pulse. Therefore, it is likely that the difference in mass ejection obtained with these two techniques is due to a risetime effect.

The transition time of 35 ns for mass ejection estimated from the present work is not in direct correlation with the characteristic time of 2 - 7 ns for wave interactions at typical jetting sites. However, the lower limit in stress required for mass ejection in aluminum has not yet been measured. If this is on the order of 1 - 4 GPa, then the transition time of 35 ns would be compatible with the expected characteristic time.

These results illustrate that non-shock loading of a surface can be an effective means of reducing surface ejecta when the ejecta results primarily from microjetting and microspalling mechanisms. It would be interesting to determine whether surface ejecta is reduced by non-shock loading when ejection results from other mechanisms. For example, it has been reported that shock-induced melting enhances material ejection in lead.⁴ In this case, microjetting or microspalling may not be the primary mechanisms of ejection. However, since the dissipative energy deposited in a material is considerably reduced by non-shock loading, mass ejection may also be reduced in this case.¹⁷

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REFERENCES

1. B. Craig, Los Alamos Scientific Laboratory, private communication.
2. B. Olinger, Los Alamos Scientific Laboratory, private communication.
3. J. R. Asay, L. P. Mix and F. C. Perry, Appl. Phys. Lett., 29, 284 (1976).
4. J. R. Asay, "Material Ejection from Shock-Loaded Free Surfaces of Aluminum and Lead," Sandia Laboratories Report SAND 76-0542, Albuquerque, New Mexico, (1976).
5. J. R. Asay, submitted to J. Appl. Phys. (1977).
6. S. A. Borodulin, A. I. Bricklin, K. V. Volkov, Yu. V. Ol'khovskii, and A. P. Rybakov, Solv. Phys. Solid State, 18, 1644 (1976).
7. F. C. Perry and L. P. Mix, Sandia Laboratories, private communication.
8. G. E. Duvall, "Shock Waves and Equations of State," in Dynamic Response of Materials to Intense Impulsive Loading, ed. by P. C. Chou and A. K. Hopkins (Air Force Materials Laboratory, 1973).
9. In the MKS system, the unit of viscosity is the pascal-second (kg/m-s), which is equal to 10 poise.
10. F. E. Prieto and C. Renero, J. Appl. Phys., 40, 4321 (1969).
11. Strictly speaking, the loading path is neither isentropic nor a Hugoniot for non-shock loading of an elastic-plastic solid (see Ref. 8). However, for final stresses up to a few tens of GPa, the Hugoniot does not differ significantly from an isentrope, so that it can be approximated reasonably well as the loading path.
12. Corning Product, Pyroceram Type 9608.
13. W. B. Benedick and J. R. Asay, "High Pressure Ramp Generators," Bull. Am. Phys. Soc. 21, CE3 (1976).
14. L. M. Barker and R. E. Hollenbach, J. Appl. Phys., 43, 4660 (1972).
15. Actually, the elastic wave does not reflect off the oncoming plastic wave. Rather, the elastic wave reflection from the free surface places the material ahead of the plastic wave inside the yield surface. Thus, when the elastic-plastic wave interaction occurs, a new elastic wave is therefore formed, and the amplitude of the initial plastic wave is decreased. This process occurs for multiple reflections so that the plastic wave risetime is effectively increased.

16. L. D. Bertholf, Sandia Laboratories, private communication.
17. For example, if thermal heterogeneities play a role in mass ejection, reduction of the dissipative energy deposited in the material would reduce the total residual energy and presumably the extent of thermal heterogeneities.

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