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MATERIAL EJECTION FROM SHOCK-LOADED FREE SURFACES OF ALUMINUM AND LEAD

J. R. ASAY

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115
and Livermore, California 94550 for the United States Energy Research
and Development Administration under Contract AT (29-1)-789

October 1976

Sandia Laboratories

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Available from National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
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MATERIAL EJECTION FROM SHOCK-LOADED FREE SURFACES OF ALUMINUM AND LEAD*

by

J. R. Asay
Thermomechanical & Physical Research Division 5167
Sandia Laboratories, Albuquerque, New Mexico 87115

ABSTRACT

A discussion is presented regarding interferometer experiments conducted on free surfaces which are impulsively loaded with high amplitude shock waves. It is shown that material ejection from shocked surfaces can significantly degrade interferometer experiments. In particular, loss of both light intensity and contrast of interferometer signals can result from various scattering and absorption processes occurring in a cloud of ejected material. An experimental technique is presented which allows determination of the mass and velocity of material ejected from free surfaces during shock loading. The technique has been applied to a study of mass ejection occurring naturally from shocked surfaces of two aluminum alloys and from lead. These results show that the total ejected mass ranges from a few $\mu\text{g}/\text{cm}^2$ in the aluminum alloys studied to a few mg/cm^2 in lead, for shock pressures ranging from about 10 to 50 GPa (100 - 500 kbar). Surface defects, such as pits and scratches, are thought to strongly influence mass ejection in aluminum; whereas in lead, localized shock-induced melting and vaporization are thought to be the dominant mechanisms at the higher shock pressures. Experimental results are also presented for aluminum surfaces which contain artificial defects in the form of wedge-shaped cavities. These results show that the maximum ejecta velocities of approximately two to four times the free surface velocity which are observed in these experiments can be correlated with predictions of steady jetting theory.

*Work supported by the United States Energy Research and Development Administration (ERDA) under Contract AT-(29-1)-789.

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MATERIAL EJECTION FROM SHOCK-LOADED FREE SURFACES OF ALUMINUM AND LEAD

I. INTRODUCTION

One of the least well understood effects in shock wave phenomena concerns the behavior of surfaces shocked to high pressures with either impulsive or continuous loading techniques. As one example of shock-induced surface effects, it is known that reflection of strong shocks from free surfaces can cause ejection of particles from the surface.^{1,2} This effect is often detrimental to interferometer experiments performed on the surface.³ Such effects also hamper visual observation of shocked surfaces using conventional optical streak or framing camera methods.² Furthermore, local jetting from surfaces may be responsible for the production of undesirable electrical signals which are often observed in high pressure capacitance measurements of free surface velocities.⁴

A second class of surface problems concerns shock-induced perturbations on surfaces. It is known that accelerative or impulsive loading of the interface between two materials can cause development of unstable irregularities at the surface, which grow exponentially with time.⁵⁻⁸ Such perturbations are usually referred to as Rayleigh-Taylor instabilities. These effects can cause development of local irregularities during oblique impact of metal plates.⁹ They have also been observed in stress loading of aluminum surfaces using electron beam techniques.¹⁰ Furthermore, it has been speculated¹⁰ that under certain conditions of wavelength and growth rates, surface perturbations can be responsible for the loss of

contrast observed occasionally in interferometer experiments.^{3,11} Thus, these surface effects can also adversely affect measurement of material properties under dynamic conditions. In addition to possible limitations in instrumental techniques, surface perturbations from shocked surfaces may also be important in various applications. Inertial confinement techniques for producing thermonuclear fusion are particular examples of where these problems apply.¹²⁻¹⁷

Very little is currently known about material conditions and properties which influence these two effects. Because of this lack of information, a series of experiments was conducted in order to define shock-wave conditions under which material ejection from surfaces occurs. This work has presently been confined to two aluminum alloys and to pure lead.

In the first section of this report, problems occurring in interferometer experiments at high shock pressures which are related to material ejection are discussed. In the second section, techniques are discussed for studying ejection of mass from shocked surfaces using interferometry. By invoking several assumptions it is possible to estimate the mass-velocity distribution of material ejected due to shock wave reflection from a surface. These techniques have been applied to aluminum and lead, and the results obtained on these materials are discussed.

The data suggest that microjetting from pits and scratches on the surface of the aluminum specimens studied causes the largest amount of mass ejection. The present results obtained on aluminum surfaces with well-defined defects support this contention. On the other hand, effects

associated with shock-induced melting are thought to cause the large amount of ejected material observed in lead.

II. INTERFEROMETER MEASUREMENTS ON SHOCKED SURFACES

Interferometry on Free Surfaces

Most of the results presented in this report were originally motivated by the need to understand interferometer measurements conducted on surfaces subjected to high pressure impulsive loading. It is necessary to understand problems associated with these measurements in order to effectively use interferometry to investigate material properties at high pressure.

The basic technique for measuring the particle velocity of shocked surfaces with interferometry is shown in Fig. 1 for the special case of plane shock loading. Basically in such techniques, a laser is focused to a small spot on a specimen. Light reflected from the illuminated area is recollimated with a lens and used as incident light to an interferometer. The interferometer system which is most widely used in current shock wave studies is the VISAR¹⁸ (Velocity Interferometer System for Any Reflector), which is shown schematically in Fig. 2. This system operates on the principle that light reflected from the target is used as incident light to the two legs of a modified Michelson interferometer. One of these is an air leg and the other contains a series of fused silica etalons. Because of the difference in propagation time through the two legs, a net delay time, τ , occurs for the signal passing through the etalon delay leg. The superposed light signals therefore

Fig. 1. Interferometer technique for measuring particle velocity of a surface impulsively loaded with a plane shock wave. Plane shock waves were produced by using a powder gun to provide flat projectile impact with the specimen.

Fig. 2. Schematic of the Velocity Interferometer System for Any Reflector (VISAR) used to measure particle velocities of shocked surfaces.

exhibit Doppler-shifted frequencies which differ during periods of surface acceleration, and this frequency difference is recorded with two photo-multipliers. The recorded interference signals are nominally 90° out of phase due to double transit of the signal through an eighth-wave plate.

Mechanisms Causing Reflectivity and Contrast Loss of the Interferometer Signal

Normally, the fringe count produced in the interferometer is directly proportional to the particle velocity of the target area illuminated by the laser.¹⁸ However, in some cases phase information in the interferometer signal is ambiguous because of local differences in particle velocity occurring on the sample. This effect is illustrated in Fig. 3 and can occur in both window and free surface experiments. In either case, loss of contrast in the interferometer signal can result if local differences in particle velocity are present over the illuminated area. Because of diffraction limitations, spherical aberrations and beam divergence, the illuminated area is not a geometrical point, but covers a finite area on the specimen. Beam divergence is usually the largest contribution to spot size. If the angular divergence is α , and a lens of focal length f is used to focus the light, the resulting spot size is αf . For the range of focal lengths usually employed in interferometer experiments, this criterion gives spot diameters ranging from about 0.1 to 0.3 mm. If a shocked specimen contains inhomogeneities considerably smaller than this, local variations in particle velocity can occur over the illuminated section. Light reflected from the shocked surface will then contain rays with different Doppler shifts in frequency, depending upon where reflection from the surface occurred. Such effects subsequently cause a

Fig. 3. This figure shows how local particle velocity variations and ejection of material from free surfaces can affect interferometer experiments.

loss of contrast in the interference signal analyzed by the interferometer. These effects have been observed in window experiments on several different materials, including porous materials³ and explosives.¹⁹

A similar effect can also arise in free surface experiments. Local variations in Doppler-shifted frequencies can occur due to either local particle velocity variations on the surface or to reflection of incident light from particles ejected from the surface. In addition, free surface experiments can be further complicated by loss of light intensity returned to the interferometer. In particular, various scattering and absorption processes can cause significant light attenuation.²⁰ Thus, both contrast loss and intensity loss can combine to cause severely degraded optical measurements on free surfaces.

The resulting loss of contrast in the interferometer signal has recently been analyzed under the assumption of distributions in particle velocity which are either symmetric or asymmetric.^{3,21} The starting point for this analysis is to consider the two interference signals recorded by the photomultipliers in Fig. 2:³

$$y_1 = A [1 + C_0 \sin (ku + \delta)]$$

$$y_2 = A [1 + C_0 \sin (ku + \delta + \theta)]$$

where A is the signal intensity, C_0 is the initial contrast of the interferometer signals, δ is the initial phase of the signals, and θ is the phase difference between signals, which by virtue of the $\lambda/8$ plate is about 90° . The constant k is related to the velocity per fringe constant,^{18,22} which for free surfaces, can be written as

$$k = \frac{4\pi \tau (1 + \delta)}{\lambda}$$

where λ is the wavelength of light used, τ is the delay time of the interferometer and $\delta = 0.034$ for the experiments reported here. If the recorded spot exhibits a distribution of particle velocities, $w(u)$, such that $\int_{-\infty}^{\infty} w(u) du = 1$, the interferometer equations ($i = 1, 2$) become^{3,21}

$$y_i = A\{1 + C_1 C_0 \sin [ku_0 + \delta + \theta_i] + C_2 C_0 \cos [ku_0 + \delta + \theta_i]\} \quad (3)$$

(3)

where $\theta_1 = 0$, $\theta_2 = \theta$ and

$$C_1 = \int_{-\infty}^{\infty} w(u - u_0) \cos [k(u - u_0)] du,$$

$$C_2 = \int_{-\infty}^{\infty} w(u - u_0) \sin [k(u - u_0)] du.$$

If the distribution function, $w(u - u_0)$, can be defined by two parameters such as the mean velocity, u_0 , and the width in a normal distribution, the two fringe measurements and the measured beam intensity (see Fig. 2) are sufficient to define these parameters.

On the basis of physical grounds it might be expected that a symmetric distribution may often describe the response of surfaces where material is not ejected.³ On the other hand, an asymmetric distribution function is probably necessary to define the spread in particle velocities if material is actually ejected from shocked surfaces. Kennedy²¹ has recently derived a complete set of relations which relate the measured contrast and phase of interference signals to parameters occurring in various distribution functions.

Interferometer Measurements on Aluminum and Lead

Fig. 4 shows examples of both a loss of contrast and signal intensity in interferometer experiments conducted on free surfaces. The two results shown were obtained on free surfaces of 6061-T6 and 1100 aluminum alloys which were shocked to about 30 GPa in separate plate impact experiments. In both cases, the experimental conditions were sufficient to produce a spalled piece in the aluminum specimen. A feature which is common to both results is that when the shock first arrives at the free surface, a burst of about 25 fringes occurs. The fringe change is not observable on these records, due to frequency limitations. There is also an abrupt decrease in signal intensity in both cases. The intensity of reflected light remains nearly constant thereafter, until lateral edge effects arrive. The primary difference between the two results is that the interference signal on the 6061-T6 sample undergoes a loss of signal contrast, whereas that on the 1100 sample does not. This is apparent from the observation that ringing in the spall piece is clearly defined by changes in the interference signal for 1100, but just barely resolvable for 6061-T6. If we make the reasonable assumption that the distribution in particle velocity occurring in the experiment on 6061 is exponential with a decay parameter a , then we can use Kennedy's result to relate the spread in velocity to the signal contrast after shock arrival.* Kennedy shows that Eq.(3) for an exponential distribution becomes

$$y_i = A[1 + \sqrt{C_1^2 + C_2^2} \sin(ku_o + \delta + \theta_i + \varphi)],$$

*A normalized distribution function which describes an exponential dependence for the particle velocity distribution is $w(u) = \frac{1}{a} \exp(-u/a)$

Fig. 4. Results of interferometry experiments conducted on free surfaces of 6061-T6 aluminum and 1100 aluminum alloys. Time increases to the right and the time marks superimposed on the signals occur at 0.2 μ s intervals.

where

$$C_1 = 1/(1 + k^2 a^2),$$

$$C_2 = ka/(1 + k^2 a^2),$$

$$\tan \varphi = ka.$$

This relation allows an estimate of a , which is found to be 0.13 km/s for a measured free surface velocity of about 2.7 km/s. Thus, these results suggest that the maximum velocity of material ejected from the surface is on the order of 15-20 percent larger than the free surface velocity.

The results shown in Fig. 4 are fairly typical in that contrast loss has been observed in a large number of interferometer experiments conducted on 6061-T6 alloy for either impact loading, as reported here, or for experiments in which electron beams were used to generate stress waves.¹¹ However, a loss of signal contrast is usually not observed for free surface experiments conducted on 1100 alloy. Perry and Mix¹⁰ have recently proposed that the loss of contrast observed on 6061 specimens may result from development of unstable perturbations on the free surface which have wavelengths comparable to the spot size recorded by the interferometer and which grow at a rapid rate. However, we will present evidence later which suggests that the loss of contrast observed in the present experiments arises from material ejection and that the difference observed between 6061 and 1100 aluminum samples results from a difference in ejecta particle size for the two cases.

Experimental data obtained in the present experiments on different materials show that the loss of light intensity varies fairly

systematically with shock pressure. The relative reflected light intensities obtained on three different materials are presented in Fig. 5. For the aluminum alloys, a significant decrease in light intensity occurs over the range of 8.5 to 13 GPa (130 kbar), which is near the elastic over-drive stress for aluminum. For higher shock pressures in 1100, the light intensity reflected from the surfaces remains relatively constant at about 40 percent of the initial value. For 6061-T6, the intensity continues to decrease, such that at 40 GPa, it is about 15 percent of the initial value. We have also found that these results are not strongly dependent on surface conditions. The specimens of 1100 aluminum were all lapped and then polished to a $1\text{ }\mu\text{m}$ finish with diamond paste. The surfaces of the 6061 samples studied here were not as well controlled. For pressures up to about 30 GPa, 6061 sample surfaces were first lapped and then touched up with $1\text{ }\mu\text{m}$ diamond paste to slightly enhance the reflectivity. The two experimental results near 40 GPa were obtained on 6061 surfaces which were lapped to approximately a $17\text{ }\mu\text{m}$ finish and not polished. These differences in surface preparation may account for the slight decrease in intensity observed for 6061 between 30 and 40 GPa. However, this slight variation observed in reflected intensity with shock pressure is not thought to be significant, even though surface conditions were varied by a large degree.

The results illustrated for lead were obtained on pure specimens polished to a $1\text{ }\mu\text{m}$ finish. In this material, the elastic over-drive pressure is about 3.0 GPa, so that the lowest shock pressure studied corresponds to a single plastic shock acceleration of the surface. It is found in this material that the reflected light intensity is on the order

Fig. 5. Dependence of the relative light intensity vs. shock pressure for two aluminum alloys and lead.

of 10% or less of the initial value, and that it remains relatively constant as shock pressure increases. This large light loss essentially precludes interferometer measurements on free surfaces of lead at high shock pressures.

There are several possible interpretations of the results shown in Fig. 5. One possibility is that increased surface roughness due to either shock-induced perturbations or surface break-up could cause the surfaces to become more diffusely reflecting and therefore cause a reduction of reflected intensity. However, the close agreement obtained between results for initially diffuse surfaces to those for initially specular surfaces suggests that this is probably not the case. An alternative explanation may be that the loss of reflected intensity results from scattering and absorption processes occurring in a cloud of material ejected from the shocked surface.²³ In this case, a larger light loss would correspond with a larger amount of mass ejected from the surface. We will present evidence in the next section which tends to support this hypothesis.

III. EJECTION OF MASS FROM SHOCKED SURFACES

Experimental Technique for Measuring Ejected Mass

Based on the present work and also on previous work performed at Los Alamos Scientific Laboratory² and at Lawrence Livermore Laboratory,²⁴ the loss of light intensity observed in interferometer experiments on aluminum and lead was thought to result as a consequence of microjetting from the free surfaces. Although this effect has been known for several years, there have been no systematic studies of surface conditions, material properties or stress ranges which influence localized mass ejection. For this reason several experiments were performed to determine whether this effect could

provide a plausible explanation for the observed degradation of interferometer experiments conducted on shocked free surfaces. Another motivation for this work was to obtain quantitative information about the mass and velocity of material which may be ejected from surfaces under impulsive conditions.

Several techniques have been developed for measuring particle distribution of micron-sized hyper-velocity particles.²⁵⁻²⁹ However, most of these techniques are not compatible with the instrumentation requirements necessary for plate impact experiments. We initially thought that the loss of contrast occurring in interference signals could be used to characterize the velocity distribution of ejected material through the use of Eqs. (3) and (4). However, it was found that a loss of contrast did not always occur when ejected material was actually observed. The results obtained on 1100 aluminum are a particular case in point. For this reason a more conventional technique was used.

Figure 6 illustrates the method used in the present work to measure the mass and velocity of material ejected from shocked free surfaces. Basically, material ejected after shock wave reflection at the free surface was collected with a thin foil which was placed a specified distance from the surface. The momentum transferred to the foil was then determined with a VISAR by measuring the foil velocity as a function of time. Either aluminum or steel foils were used here and foil thicknesses ranged from 4 μm to 75 μm . The gaps between the free surface and the foils employed in different experiments ranged from about 0.5 mm to 7 mm. The technique shown in Fig. 6 has been used previously to collect ejected material from shocked surfaces;³⁰ however, the time-resolved interferometer technique employed in the present work allows much better mass sensitivity for detection of ejected material than was possible in prior studies.

Fig. 6. Experimental technique for measuring the mass and velocity of material ejected from impulsively loaded free surfaces.

One of the main objectives of this work was to determine the mass-velocity distribution of ejected material. In order to accomplish this, several simplifying assumptions were made for reduction of the interferometer data. The basic assumptions were: (i) that all ejection of mass occurs over a sufficiently small time during shock reflection at the free surface that the ejection can be approximated as instantaneous. This assumption also allows estimation of the velocity of a given mass increment across the gap from the measured arrival time at the foil; (ii) that the foil is sufficiently separated from the free surface that the lateral spatial distribution of mass is uniform; in this case the foil motion would be one-dimensional; (iii) that the collision of mass with the foil is inelastic with no foil penetration or splashing of the foil upon impact; and (iv) that the foil is sufficiently thin that its motion can be analyzed as a rigid body motion. Some of these assumptions can be partially justified on the basis of the data we have obtained, and these qualifications will be mentioned in various parts of this section. However, all of these assumptions have not been satisfactorily verified. In particular, ejection of mass at late times and splashing of the foil upon impact of ejected mass are thought to be the primary limitations. Both of these effects would cause the calculated ejected mass to be larger than the mass actually ejected from the surface. For these reasons, the results presented later should be viewed as semi-quantitative.

The foregoing assumptions can be combined with the conditions which express conservation of momentum and mass incrementally during the measured foil history and thereby allow an estimate of ejected mass and velocity. Equating the momenta of the foil and a given increment of ejecta, Δm , just before collision with the foil to the final momentum of the foil after

impact provides the relation

$$v\Delta m + M'V = (M' + \Delta m)(V + \Delta V) , \quad (5)$$

where v is the velocity of the increment in ejected mass, V is the foil velocity before impact, ΔV is the incremental change in foil velocity and M' is the total mass of the foil, including any previously accumulated ejected mass. Note that all masses are per unit area. This equation can be further expressed in differential form as

$$\frac{dm}{dt} = \frac{M'}{v - V} \frac{dV}{dt} . \quad (6)$$

Conservation of mass applied to a given increment travelling with velocity v gives the relation

$$\rho(t) = \frac{1}{v - V} \frac{dm}{dt} , \quad (7)$$

where $\rho(t)$ is the instantaneous density of ejected mass at the foil. This relation can be further re-arranged to provide the increment of mass in a given velocity interval between v and $v + dv$ as

$$m_v = \frac{dm}{dv} ,$$
$$m_v = \frac{t}{v - V} \frac{dm}{dt} , \quad (8)$$

where t is transit time of the mass increment across the gap. This relation allows an estimate of the mass-velocity distribution of material ejected from shocked surfaces. Since it is necessary to differentiate the experimental data, $V(t)$, in order to obtain m_v , some smoothing of the data was required. Young has developed a smoothing technique for treating these data³¹ and this program was used in all of the data analyses.

Figure 7 illustrates the sequence of steps required to reduce the experimental data in order to estimate the mass-velocity distribution of the ejecta. The particular results presented in the figure were obtained on a lead specimen shocked to about 37 GPa. A steel foil, 0.0478 mm thick and separated from the surface by 4.748 mm, was used to collect the ejected mass. The initial time ($t = 0$) was defined to represent reflection of the shock wave at the free surface. Complete gap closure by the free surface is indicated by the dashed vertical lines. Since the ejecta velocity for an increment of mass can be determined from the measured transit time across the gap (foil motion is accounted for), application of Eq. (6) gives the second result illustrated in Fig. 7. This graph represents the total mass, $m(t)$, accumulated on the foil as a function of time. In keeping with the terminology established at Los Alamos,² the ejected mass has been referred to as "fluff." In this experiment, a total fluff mass of approximately 10 mg/cm² was ejected from the surface. The last graph gives the fluff mass-velocity distribution. As illustrated by this figure, a small amount of mass travels with a velocity about 60% higher than the free surface velocity. However, the bulk of ejected material has a velocity only slightly higher than the free surface value. The latter two diagrams in Fig. 7 illustrate the parameters of primary interest in this work. Both of these parameters, the total fluff mass and the fluff mass-velocity distribution, will be important to later discussions.

Mass Ejection Occurring Naturally in Aluminum

The two aluminum alloys discussed earlier were the first materials to which this technique was applied. The 1100 aluminum is commercially pure with a total metallic impurity concentration of about 0.7% by weight. The principal metallic impurities occurring in this alloy are silicon and iron.

Fig. 7. Sequence of data reduction steps required to estimate the total ejected mass accumulated on a foil and the mass-velocity distribution of ejected material. These results were obtained on a lead specimen shocked to 37 GPa.

Most of the experiments on 1100 were performed on annealed specimens which were prepared by first cross-rolling plate stock to 30% reduction and then annealing at 620 K for $\frac{1}{2}$ hour. This mechanical and thermal history produced a relatively soft material with a grain dimension on the order of 0.2 mm in width and about 1 mm in length. The samples were lapped with $17\text{ }\mu\text{m Al}_2\text{O}_3$ and then polished with $1\text{ }\mu\text{m}$ diamond paste. They were cleaned with acetone and ethyl alcohol and most were cleaned further by RF sputtering the surface to be studied with 400 ev argon ions. This procedure effects removal of a few thousand Angstroms of the surface. Because of the soft condition of the surface (O temper), a fairly large density of surface scratches developed during polishing. These can be seen in Fig. 8, which shows a typical surface condition obtained on the 1100 samples. This figure is only representative, since the density of scratches and other surface defects was found to vary substantially from one sample to another.

6061-T6 aluminum is a precipitation-hardened alloy with a total concentration of about 3% of metallic elements other than aluminum (primarily Fe, Cu, Mg, Mn and Cr). Although most of the Mg and Si is in solid solution, there is a relatively large concentration of Mg and Si in the form of inclusions with diameters on the order of a few μm . For most of the experiments conducted on this alloy, the surfaces were prepared with the same technique used for the 1100 samples. However, the polished surfaces of 6061 specimens tended to contain more surface defects than those for 1100. Figure 9 illustrates several photomicrographs of a representative surface of 6061. The top part of the figure shows the surface conditions obtained on a surface that was polished to a final finish of about $1\text{ }\mu\text{m}$. After polishing, many small micron-sized pits are observable, as shown by the magnified scanning electron microphotograph (SEM) on the right. A large number of polishing

Fig. 8. Photomicrograph of an 1100 aluminum sample studied in the present experiments (Exp. F-22).

Fig. 9. Representative photomicrographs obtained on different areas of a 6061-T6 aluminum specimen. The two photos at the top were obtained on specimens that were polished to a $1\text{ }\mu\text{m}$ finish only. The bottom part of the figure illustrates the effect of RF sputtering the polished surface.

scratches on the surface are also apparent. The white regions are inclusions, primarily either Mg or Si. The bottom part of the figure illustrates the effect of RF sputtering the surface with argon ions. In the process of cleaning the surface, ion bombardment removes a few thousand Angstroms of aluminum, as mentioned earlier. This process (ion milling) causes a substantial decrease in the density of both observable scratches and the smaller pits. In addition, the remaining larger pits exhibit much more shallow dimensions with rounded sides. Careful examination of SEM photographs taken from different viewing angles illustrates that RF sputtering preferentially removes aluminum, leaving small inclusions protruding from the surface.

Table I tabulates the impact parameters for experiments conducted on aluminum for the purpose of the mass ejection studies. In all experiments, the specimen thicknesses were nominally 3.9 mm, with the exception of the last two experiments in which specimen thicknesses were 2.5 mm. The impactor thicknesses were chosen in most experiments so that the aluminum specimen did not spall before impact with the foil. All experiments were performed in an evacuated chamber at pressures of nominally 70 MPa (50 μ m Hg).

Impact pressures and free surface velocities were determined in each experiment by using the measured impact velocities and the known equations of state of the impactors and aluminum.³² The resulting uncertainties in Hugoniot pressure and free surface velocity are estimated to be about 2%.

It is well known²⁰ that shock waves produced by plate impact are usually extremely sharp (i.e., small risetimes) if the elastic over-drive stress is achieved (~ 13 GPa in aluminum). In this limit, viscous effects in the material which effect a smearing of the shock are nearly completely overridden by material nonlinearities which tend to steepen the shock. Measurements of shock risetimes from free surface VISAR measurements on aluminum

TABLE I

IMPACT PARAMETERS FOR MASS EJECTION
EXPERIMENTS IN ALUMINUM

Exp. No.	Material	Surface ^a Condition	Impactor	Impact Vel., km/s	Hugoniot Pressure GPa	Free Surface ^b Velocity, km/s	Total Ejected ^c Mass, $\mu\text{g}/\text{cm}^2$	Maximum Ejecta Velocity, km/s
F12	1100	P,RF5	Cu	1.833	24.1	2.56	3.2(2.379)	4.9
F13	6061-T6	P,RF5	Cu	1.868	24.6	2.61	2.8(2.399)	5.2
F18	1100	P,RF5	WC	1.483	22.2	2.41	<0.05(2.477)	---
F19	1100	EP	WC	2.143	35.8	3.53	0.5(2.599)	4.1
F20	1100	P,RF	WC	2.166	36.2	3.55	0.8(3.769)	5.2
F21	1100	P,RF	Cu	2.150	29.2	3.00	1.5(2.546)	3.5
F22	1100	P,RF	WC	2.185	37.0	3.61	0.2(6.067)	---
F23	6061-T6	P	WC	2.144	35.8	3.49	11.4(5.301)	5.8
F24	6061-T6	P	WC	2.142	35.8	3.49	13.1(4.024)	8.2
F25	6061-T6	P,RF15	WC	2.152	36.0	3.53	4.8(4.501)	6.4
F27A ^d	6061-T6	IP16	Cu	1.864	24.5	2.61	13.5(7.288)	9.4
F27B ^d	6061-T6	IP17	Cu	1.864	24.5	2.61	9.0(7.288)	11.3

a. Surface conditions are identified as P - polish to 1 μm finish; EP = electropolish for 10 min. RF5 = surfaces RF sputtered with argon for 5 min; RF15 = surfaces sputtered for 15 min; IP16 = Ion implant of 10^{16} argon ions/cm² on polished surface; IP17 = Ion implant of 10^{17} argon ions/cm² on polished surface.

b. Calculated from the equations of state of impactor and aluminum. The free surface velocity was assumed to vary linearly from twice the particle velocity in aluminum near zero pressure to 1.5 percent higher than $2u$ at 37GPa.

c. The numbers in parentheses indicate the foil spacing from the free surface in mm.

d. These results were obtained on different regions of the specimen in a single experiment.

indicated that the risetime was smaller than the electronic risetime of the recording system. This observation places an upper limit on the risetime of about 7 ns, which implies that the minimum acceleration experienced by the free surface was at least $3.5 \times 10^{11} \text{ cm/s}^2$ for impact pressures ranging from 25-37 GPa.

In all experiments reported in Table I, aluminum foils, 4.31 μm thick, were used to collect the ejected mass. The areal density of these foils is 1.168 mg/cm^2 , and for the quoted accuracy of VISAR measurements¹⁸ ($\sim 0.002 \text{ km/s}$ in the present experiments), Eq. (6) indicates an absolute accuracy for ejected mass of about 0.5 $\mu\text{g/cm}^2$ in the present work. However, this is a conservative estimate in that it is possible to detect changes in ejected mass of about 0.05 $\mu\text{g/cm}^2$ with the foil thicknesses used.

Uncertainties in the reported maximum fluff velocities are harder to estimate. Timing measurements could be made easily to within 1%. However, the sensitivity of detecting ejected mass undoubtedly determines the apparent maximum fluff velocity. This conclusion was partially substantiated in 1100 aluminum by using another technique to detect the ejected mass. It was found that a more sensitive indication of fluff arrival was to replace the aluminum collecting foil with a flat specularly reflecting fused silica window with a 200 nm thick aluminum mirror on the front surface. Micro-impacts of ejected material with the mirror caused a loss of intensity in the light reflected from the mirror, and this could be easily recorded with a photomultiplier. This particular experiment illustrated that the maximum fluff velocity occurring in 1100 was also in the range of 7 to 8 km/s when the free surface velocity was 2.52 km/s. Thus, it is thought that the high fluff velocities observed for 6061 also occur in 1100, although the amount of mass travelling at this velocity in 1100 is smaller. Figure 10 summarizes the experimental results obtained on these two alloys.

Fig. 10. (a) Ratio of maximum ejecta velocity to free surface velocity vs. shock pressure for 1100 and 6061 aluminum, (b) Total mass ejected as a function of shock pressure. The notation used for different surface preparations is the same for both graphs.

There are several points regarding Fig. 10 which are relevant to surface break-up and mass ejection effects. First, it is noted that in all cases, more mass is ejected from surfaces of 6061 samples under similar conditions than for 1100 aluminum. This conclusion supports the earlier observation illustrated in Fig. 5 that the intensity of laser light reflected from free surfaces tends to be lower for 6061. This difference would be expected if the loss of intensity results from scattering and absorption processes occurring in ejected material. Secondly, the amount of ejected mass in 1100 tends to be relatively independent of impact pressure over the range of 22 to 37 GPa. This observation also agrees with the earlier result which showed that the relative intensity for 1100 is essentially independent of impact pressure in the range of 13 to 30 GPa. As a final point, the data indicate a slight tendency for the total mass ejected from 6061 surfaces to increase with impact pressure. This is also consistent with the earlier observation that the relative intensity of laser light reflected from shocked surfaces of 6061 tends to decrease with impact pressure. However, this correlation may not be a realistic one as indicated by problems in reproducibility, which will be discussed later.

One of the important observations illustrated in Fig. 10 is that there is a definite difference between sample surfaces which are only polished versus those which are polished and then RF sputtered. This observation is apparent for the 6061 samples and has important implications regarding the mechanism of material ejection. As shown in Fig. 9, the main difference between these two surface conditions is that sputtering reduces the number of pits and scratches. Also, the remaining pits tend to be more shallow and with smoother contours. Sputtering at these accelerating voltage levels and ion concentrations does not change the grain structure nor the density of impurities and

inclusions near the surface. Therefore, this observation suggests that one of the main mechanisms for mass ejection in these experiments might be microjetting at surface defects, such as scratches and pits.

The mechanism of microjetting would also provide a plausible explanation for the maximum fluff velocities observed in these experiments since it is known that jets from shaped cavities can exceed average free surface velocities by large factors.^{1,33} Furthermore, this mechanism would explain why smaller amounts of ejected material travelling with high velocities are observed in 1100 since the surfaces of this material contain, in general, a significantly smaller number of pits. Of course, a jetting mechanism for mass ejection from pits and scratches suggests that the shock risetime should be even smaller than the upper limit given earlier. In order to form jets from these cavities, it would be expected that the shock risetime would be on the order of the transit time across a pit or scratch. For a pit that is 5 μm deep, the upper limit for the shock risetime would therefore have to be about 0.7 ns in order to satisfy this criterion. This may not be unreasonable in plate impact experiments, where the main limitation to shock risetime results from viscous effects associated with dislocation motion. It is known that viscous effects are minimal in aluminum at these stress levels.

Microjetting may not be the only contribution to the total ejected mass measured in the aluminum alloys studied here. Magnesium is one of the major inclusions in 6061 and this element has a lower mechanical impedance than aluminum. Therefore, inclusions of magnesium near the surface may spall during shock wave reflection. Consideration of the differences in mechanical impedance between aluminum and magnesium indicate that spalled magnesium particles could travel at a velocity about 20% higher than the free surface velocity of aluminum. Therefore, these particles could contribute to the

total mass travelling at relatively low ejecta velocities. Furthermore, these inclusions tend to be larger than the wave length of light ($0.5145 \mu\text{m}$) used in these experiments, as shown in Fig. 9. Therefore, ejection of these particles could easily account for the particle velocity spread of 15-20% observed in free surface interferometer experiments conducted on 6061-T6 aluminum. However, the silicon impurity occurring in 1100 does have a lower mechanical impedance than aluminum. As for the case of magnesium, silicon impurities could also spall from the surface with a velocity about 20% higher than the average free surface velocity, and it is thought that this material accounts for much of the ejected mass observed for this alloy. The main difference with the 6061 results is that electron microprobe analyses indicate an average size for the silicon impurity which is less than $0.5 \mu\text{m}$. Therefore, these particles would not cause much back-scattering of laser light, and, consequently, no loss of contrast in interferometer signals reflected from the free surface. Therefore, we propose that the process of microspalling produces the relatively low velocity ejecta observed in both alloys and that the size of the spalled particles determines whether a loss of signal contrast occurs in interferometer signals.

As a further specification of surface conditions, Auger spectroscopy measurements were made and these indicated an oxide layer thickness of about 6 nm on the free surfaces of the 1100 and 6061 aluminum samples. The amount of mass in such a layer is comparable with the total ejected mass observed for 6061. However, ejection of oxide probably does not contribute to the total fluff mass observed in these experiments for two reasons. First, the impedance of Al_2O_3 is much larger than that of aluminum, so that a simple spalling mechanism would not result in ejection of an oxide film. Second,

the oxide concentrations are comparable for both 1100 and 6061, which implies equal amounts of ejecta for both materials if this mechanism dominated. As shown in Fig. 10, the total mass ejected in 6061 is at least a factor of three larger than that for 1100. Thus this mechanism is probably not operative in aluminum.

As illustrated in Fig. 10, we varied the surface preparation somewhat in order to study how different surface conditions influenced the total amount of ejected mass. As mentioned earlier, it was found that RF sputtering reduced the amount of ejected material from 6061 surfaces over those that were only polished. One specimen of 1100 aluminum was electropolished for 10 minutes in which about 50 μm of material was removed. The objective of this experiment was to determine whether the work-hardened layer near the surface caused by lapping and polishing contributed to the ejection of mass. As illustrated in Fig. 10, there was essentially no difference in the amount of fluff observed in this experiment over that for surfaces that were polished and sputtered.

Two experiments were performed on 6061 specimens that were first polished and then implanted with 10^{16} and 10^{17} argon ions/ cm^2 . It is known³⁴ that implanting argon ions to these densities produces considerable damage near the surface for depths up to about 100 nm. Since gradients in strain can occur near the surface, it was suggested³⁵ that ejection of material from shocked surfaces might be affected for large densities of implanted ions. This hypothesis was checked by studying two regions of an aluminum specimen, which were polished only and then implanted to the argon densities given above. The specimen was shocked to 24.5 GPa and the mass ejected from these two regions was analyzed with two different interferometers. The

results are shown as the solid squares at 24.5 GPa in Fig. 10. The lower data point in Fig. 10b represents the 10^{16} surface density implant. Although the higher surface density of argon ions gives a total ejected mass about 30% larger than the lower density region, this difference is not thought to be statistically different. Furthermore, the difference between implanted and sputtered specimens is about the same as that obtained between polished and sputtered specimens. This would be expected if mass ejection results primarily from surface defects such as pits and inclusions, since there was no difference in surface roughness due to implantation.* For this reason, the results for the two implanted specimens have been grouped together with results for specimens that were polished only.

Not enough work has been done to this point to accurately estimate the reproducibility of these measurements. The work on 1100 aluminum suggests that variation in total ejected mass can easily be on the order of $\pm 0.5 \mu\text{g}/\text{cm}^2$. This degree of fluctuation is a relatively large proportion of the average total ejected mass observed for this material. The two cases where direct comparisons can be made in 6061 and the one case of different surface densities of ion implants suggests that sample-to-sample variation is not greater than about 30%. Although these estimates are not conclusive, they do suggest, first, that the sample surfaces can be prepared to similar finishes and, second, that the sites for material ejection are relatively uniform on the scale monitored by the interferometer. This latter observation suggests that the assumption regarding spatial uniformity is probably reasonable for the foil separations employed here.

* There could be an increased contribution in ejected mass due to micro-spalling, since implanted regions may have an effectively smaller impedance than bulk aluminum.

Mass Ejection Occurring Naturally in Lead

The ejected mass observed under shock loading in aluminum is thought to result primarily from jetting at surface defects, such as scratches or pits. In this case, macroscopic thermal effects, such as the ambient temperature of the surface, would probably not be important to mass ejection. However, it is possible that the average temperature attained on the free surface by shock compression could dominate at high shock pressures. For example, the increased temperature caused by irreversible shock compression could cause localized melting of the surface. Since melting would result in a loss of shear strength and therefore reduce binding forces, material could be ejected at such sites.

Temperature increases during shock loading can be determined through the differential equation³⁶

$$\frac{dT}{de} - \frac{\gamma T}{1 - e} = -c_v f(e) \quad , \quad (9)$$

where γ is the Grüneisen ratio, c_v is specific heat at constant volume, T is temperature and e is engineering strain, which is defined in terms of initial and final densities as $e = 1 - \rho_0/\rho$. The function $f(e)$ can be related to the pressure along the Hugoniot, $P(e)$, as

$$f(e) = \frac{1}{2\rho_0} \left[P(e) - e \frac{dP}{de} \right] \quad , \quad (10)$$

where ρ_0 is the initial sample density. If T_s is the temperature achieved during shock compression to the final pressure, the resulting final temperature attained after release at the free surface can be estimated by the differential equation describing isentropic flow;

$$\frac{dT}{de} = \gamma \frac{T}{1 - e} \quad . \quad (11)$$

Application of equations (9) and (11) to the results on aluminum indicate that the final temperature achieved was about 500 K at the maximum pressure. This is well below the ambient melt temperature of 931 K. Thus, it would be expected that melting of the surface would not contribute to ejection of mass in those experiments. On the other hand, it is relatively easy to induce free surface melting in lead. This observation is apparent from the phase diagram for lead, which is illustrated in Fig. 11.³⁷ Three shock (solid) and release (dashed) paths are shown in the figure to illustrate the response predicted by Eqs. (9) and (11). For shock pressures greater than approximately 25 GPa, incipient melting on the free surface occurs and for pressures greater than about 37 GPa melting should be complete. For a pressure of 53 GPa, the final temperature state is about 300 K greater than ambient melt, if thermodynamic equilibrium is maintained. Therefore, the effects of melting on material ejection in lead can be investigated at relatively low shock pressures. In order to investigate these effects, a series of experiments were conducted on lead for shock pressures ranging from about 9.5 GPa to 53 GPa.

The lead specimens studied in the present experiments were approximately 99.99 percent pure with principal metallic impurities of Mg, Si, Bi, Al, Cu, Ag, and Cu. The average sample density was 11.35 g/cm³ and the grain size was about 0.05 mm. The specimens were polished to a final finish of 1 μ m (there was no variation of surface finish in these experiments). A photomicrograph of a typical surface is shown in Fig. 12. Steel foils were used in most cases to collect mass ejected from the shocked surfaces because of penetration of aluminum foils in the higher pressure experiments. However, aluminum foils were used in some of the low pressure experiments. The foil thicknesses ranged from 0.025 to 0.076 mm, and these different cases are

Fig. 11. Phase diagram for lead showing the shock and release paths followed for three shock pressures. The primed states represent the final temperatures attained after release.

0.1 mm

Fig. 12. Photomicrograph of a lead specimen studied in the present experiments.

identified in Table II, which summarizes the experimental results obtained on lead.

Figure 13 illustrates the foil velocity histories obtained for four different experiments conducted on lead. Through the use of Eq. (6) it is possible to convert these measured velocity histories into total masses accumulated on the foils, and these results are shown in Fig. 14a. It is found that for shock pressures on the order of 10 GPa, the total mass ejected is approximately 1 mg/cm^2 . For shock pressures greater than about 21 GPa, a rapid increase in total ejected mass is observed. As illustrated in the figure, this increase occurs in the vicinity of incipient melting. The ejected mass for shock pressures greater than about 40 GPa has not been included, since the free surface is not well defined in these cases. In these experiments, the foil velocity increases rapidly at times near those expected for free surface arrival. Thus, a discontinuous increase in foil velocity due to arrival of the free surface does not occur at the higher pressures, but is observed at lower pressures (see Fig. 13).^{*} The second part of Fig. 14 shows the relation between the maximum ejecta velocity, v_m , and the free surface velocity, u_{fs} , in lead. The maximum ratio of v/u_{fs} observed in these experiments is intermediate between the values measured in 1100 and 6061 aluminum alloys. Furthermore, the results obtained on lead show that this ratio remains relatively constant near 1.5 as shock pressure increases.

As indicated earlier, Eq. (8) provides an estimation of the mass-velocity distribution of ejected material. Distributions estimated with this technique

*The experiment conducted for a shock pressure of 36.6 GPa in Fig. 13 illustrates how the foil velocity increases rapidly near free surface arrival at the higher shock pressures.

TABLE II
IMPACT PARAMETERS FOR MASS EJECTION
EXPERIMENTS IN LEAD

Exp. No.	Impactor	Impact Vel. km/s	Foil Sep., mm	Hugoniot Pressure, ^a GPa	Foil Thick. mm	Free Surface Velocity, km/s	Total Ejected Mass, mg/cm ²	Maximum Ejecta Velocity, km/s
PB1	Al	1.321	6.331 ^b	14.8	0.0259	1.09	0.8	1.8
PB2	Al	1.839	4.078 ^b	22.1	0.0508	1.45	3.2	2.3
PB4A ^d	Cu	1.740	4.784	36.6	0.0478	1.97	11.5	3.1
PB4B						1.97	10.1	3.1
PB5B	WC	1.80 ^c	6.390	53.0 ^c	0.0762	2.52 ^c	--- ^e	3.8
PB6A	Al	0.893	7.562 ^b	9.5	0.0259	0.73	1.4	1.1
PB6B						0.73	1.5	1.1
PB7A	Al	1.540	6.325	30.8	0.762	1.77	11.1	2.9
PB7B						1.79	12.4	3.1

a. Determined from impedance matching.

b. Aluminum foil.

c. Estimated.

d. Experiments denoted by postscripts A & B were made with two independent measurements of foil velocity, using two different VISARs.

e. Determination of total mass was not possible.

Fig. 13. Foil velocities obtained for several representative experiments on lead. The origin of time is taken to be time of shock arrival at the free surface in each experiment. The dashed vertical lines represent free surface arrival at the foil.

(a)

(b)

Fig. 14. (a) Total mass vs. shock pressure in lead, (b) Ratio of maximum ejecta velocity to free surface velocity vs. shock pressure.

are presented in Fig. 15 for several representative experiments obtained on lead. Since the free surface velocity increases with shock pressure, the fluff velocity, $\dot{v}$, has been normalized by the free surface velocity, u_{fs} in each experiment. The scale for the abscissa is identical for all experiments. However, the ordinate scale differs for the different cases. The solid and dashed curves represent two independent interferometer measurements of the collecting foil on a given experiment (denoted by suffix A and B in Table II).

The results in Fig. 15 show how the mass-velocity distribution varies with shock pressure in lead. At the lower pressures, the ejected mass tends to be more or less uniformly distributed with fluff velocity. The distribution is nearly centered about a velocity approximately 25 percent higher than the free surface value at the lowest pressure studied. In contrast, there is a large amount of mass travelling with a velocity only slightly higher than the free surface velocity at 30.8 GPa. As shown in Fig. 14, approximately 50 percent conversion to liquid should occur in this experiment. Figure 16 compares more directly how these distribution functions vary with shock pressure.

Another point established by the lead experiments is that there is no significant difference in the mass-velocity distribution observed in experiments conducted with either steel or aluminum foils, providing that shock pressures are similar. This observation suggests that splashing of the foil after ejecta impact may not be a significant problem, and therefore, that assumption (iii) discussed earlier may be reasonable. Furthermore, the similar results obtained with two different VISAR systems on a given experiment imply that the earlier assumption regarding uniformity of ejected mass may also be reasonable. As a last point, the smooth variation of the

Fig. 15. Mass per unit velocity interval, m_v , vs. the normalized fluff velocity, v/u_{fs} . In experiments where two curves are shown, the solid and dashed lines represent results obtained in experiments identified with letters A and B, respectively.

Fig. 16. This figure illustrates how the form of the mass-velocity distribution changes with shock pressure. The highest pressures represented here correspond to complete melting of the free surface (see Fig. 11).

experimental results with shock pressure suggests that there is no significant dependence of measured mass on foil separation. This observation is a further indication that the ejecta velocity remains relatively constant during propagation across the gap, as assumed for data reduction.

As a brief summary of the results obtained on lead, the first point established by these experiments is that the total mass ejected from shocked surfaces is at least two to three orders of magnitude larger than that observed from aluminum surfaces for similar impact pressures. Secondly, it is found that the total amount of ejected mass increases rapidly for shock pressures sufficient to cause melting on the free surface. Experiments conducted to date suggest that this increase is fairly abrupt, but it appears to start for shock pressures somewhat lower than those representing the onset of equilibrium melting. Such an effect would not be unreasonable, since it is unlikely that temperature equilibrium occurs in nanosecond time intervals after shock compression. Thus, temperature fluctuations on the free surface could cause localized melting or even vaporization for states well below those required for equilibrium conditions. Another observation is that the shape of the mass-velocity distribution is found to change in the vicinity of shock pressures where melting occurs. The major change is that the distribution functions tend to become weighted towards the free surface velocities, and thus the free surface of the specimen appears to lose precise identification. A final point is that the ratio of maximum ejecta velocity (as observed with a mass sensitivity of about $.03 \text{ mg/cm}^2$ in the lead experiments) to free surface velocity remains relatively constant as shock pressure increases.

Mass Ejection from Aluminum Surfaces with Artificial Defects

The experimental results obtained on the two aluminum alloys and on lead demonstrate different aspects of material ejection from shocked surfaces. First, it was found that the amount of ejected mass varies by about three orders of magnitude between aluminum and lead. Secondly, there is a significant difference between the pressure dependence of total ejected mass for aluminum and for lead. Thirdly, the apparent maximum ejecta velocities which are observed experimentally vary from about 20% greater than free surface velocities in 1100 aluminum to about four times the free surface velocity in 6061-T6.

These different observations suggest that different mechanisms may contribute to the mass ejection observed in the different cases. For example, Fig. 17 illustrates some of the mechanisms for shock-induced mass ejection which have been proposed by different investigators.^{2,30,38} First, it has been known for many years that shock wave interactions with an irregular cavity can cause jetting of mass.^{1,33,39} In macroscopic cavities, maximum jet velocities observed experimentally are typically about two to three times the free surface velocity.² If jet formation processes are not strongly influenced by time-dependent effects, then microjetting could also occur from microscopic cavities such as pits or scratches on the free surface. In particular, such effects could occur in both the aluminum alloys and in lead, since pits and scratches due to polishing are observed in all specimens. Secondly, local hot spots on the free surface caused by shock compression could cause localized melting or even vaporization and thus provide another mechanism for ejection of material. As a specific possibility, the increased strain energy associated with grain boundaries could result in local concentrations of thermal energy after shock compression and hence

Fig. 17. Different mechanisms which could contribute to ejection of mass from shocked surfaces.

provide sites for ejection of mass. In addition, internal dissipative processes occurring at slip bands within grains during shock compression could provide yet additional sites where thermal energy may be concentrated. It would be reasonable to expect that these latter two effects would be enhanced for thermal states where incipient equilibrium melting should occur. As a third possibility for mass ejection, shock wave interactions occurring at relatively large inclusions or precipitates near the free surface may cause local break-up or microspalling of the surface and hence ejection of relatively large particles. Such an effect could occur, for example, in the aluminum alloys studied, since inclusions and precipitates a few microns in size are observed near the free surface.

These considerations suggest many different mechanisms which could contribute to mass ejection. Furthermore, the situation may be complicated by the presence of several mechanisms operating simultaneously. Thus it is difficult to sort out these effects in order to study the importance of different mechanisms under shock loading. For these reasons a series of experiments were conducted on aluminum specimens which had artificially induced defects. The objective of this work was to determine whether theories which describe jet formation could be used to describe mass ejection from microscopically shaped cavities; in particular, to determine whether results obtained on macroscopic cavities scale to the microscopic regime.

The defects studied in the present work were in the form of parallel wedged grooves on the free surface of aluminum samples. The interaction of shock waves with wedge-shaped grooves on a surface has been known for some time; Fig. 18 illustrates a simplified case of how a jet can be formed under such circumstances. The figure shows the case of a plane shock wave incident normally on a wedged cavity running normal to the plane of the paper. The

Fig. 18. Conditions for jet formation from a wedged cavity. The initial half angle of the groove is α' and the final half angle after collapse is β . The dark shaded strip around the cavity represents a liner for shaped lined charges.

initial half-angle of the cavity is defined to be α' and β is the collapse angle after shock wave interaction. Under certain conditions of shock wave collision, a jet can be formed from the apex of the cavity and this is shown to travel with velocity v in the figure.

Various theories have been developed to describe cavity collapse and subsequent jet formation. The problem was first treated by Birkhoff et al.,⁴⁰ in which jet formation was calculated by assuming that flow near the cavity was incompressible and hydrodynamic. For the simplifying assumption of steady jet formation, Birkhoff et al. were able to develop analytic relations for the jet velocity. They found the jet velocity, v , was given in terms of shock velocity, U , and angles α' and β as

$$\frac{v}{U} = \frac{\sin(\beta - \alpha')}{\cos \alpha'} \left\{ \csc \beta + \cot \beta + \tan\left(\frac{\beta - \alpha'}{2}\right) \right\} . \quad (12)$$

Since this relation was developed for the assumption of steady jet formation, it applies strictly only to those cases where the flow fields on either side of the cavity are independent of both time and lateral dimension. This condition is not realized for the interaction of a plane shock wave with a wedged cavity, because of gradients in particle velocity caused by interaction of rarefaction waves from the cavity with the shock. In most previous experimental investigations, the requirement for uniform flow was approximated by using an explosive with a shaped cavity, rather than an inert material, and lining this cavity with a thin layer of metal. This particular case is illustrated in Fig. 18 by the shaded area of thickness δ which represents the liner.* It is usually assumed that the liner is sufficiently thin that shock wave interactions can be ignored so that the particle velocity fields

*In this case, U becomes the detonation velocity for the explosive.

in the liner are uniform and time-independent. In this case, Eq. (12) should apply, and it is found experimentally that maximum jet velocities from shaped charges are in agreement with predictions of steady jetting theory. However, it is also known from experimental measurements⁴¹⁻⁴³ that gradients exist in the implosion velocity of the liner which cause a gradient in jet velocity; i.e., the tip of the jet travels faster than the tail. This effect is a consequence of the fact that flow of the liner does not remain steady during the entire collapse process. A modification to the steady jetting theory has been developed to account for these effects.⁴¹

Jet formation is usually assumed to result from hydrodynamic response of materials, assuming negligible rate-dependent (viscous) properties of materials. However, Godunov et al.³³ have recently shown that viscous effects associated with jet formation can also modify the predictions of steady jetting theory. For the assumption of Newtonian viscosity, they show that for jetting from lined wedged cavities, Eq. (12) is modified to

$$\frac{v}{U} = \frac{\sin(\beta - \alpha')}{\sin \beta \cos \alpha'} \left\{ 1 + \frac{\cos \frac{(\beta + \alpha')}{2}}{\cos \frac{(\beta - \alpha')}{2}} \cdot \chi \right\}, \quad (13)$$

where

$$\chi = \sqrt{1 - \frac{2\nu}{\delta U} \frac{(1 - \sin \beta) \cos \alpha'}{\sin \beta (\sin \beta - \sin \alpha')}}.$$

ν is the kinematic viscosity and δ is the liner thickness shown in Fig. 18. For inviscid materials, $\nu = 0$ and Eq. (13) reduces to Eq. (12). Eq. (13) predicts critical angles β^* at which jetting is suppressed. Such cut-off angles have also been predicted from other theories,¹ which treat flow near the cavity as compressible, inviscid and hydrodynamic.

The predictions of these various theories have been verified reasonably well in a number of cases. However, it has never been shown whether the

results of jetting theory (time-independent) apply to the microscopic regime. The justification for using these theories for small cavities is not obvious because of possible time-dependent, or viscous, effects associated with jet formation. The presence of a spatial dimension (scale length) in Eq. (13) for lined cavities suggests that this conclusion may be true in the more general case. Because the results obtained on aluminum, in particular, suggested that microjetting could contribute to ejected mass, a series of experiments were performed on aluminum surfaces which contained grooves on the free surface, as illustrated in Fig. 18. A theory has not yet been developed to predict the complete collapse of unlined cavities due to plane shock loading and subsequent jet formation. As mentioned earlier, this problem is complicated by possible time-dependent processes and gradients in the flow field near the cavity. Notwithstanding all of these qualifications, we have compared the maximum jet velocities observed from these grooves with the predictions of steady jetting in order to determine whether Eq. (12) can be used to estimate maximum fluff velocities from grooved defects.

Aluminum samples (6061-T6 alloy) were used in this work, since material ejected naturally during shock loading was known from the previous work. The specimens were first polished to a surface finish of $1\text{ }\mu\text{m}$. Parallel, straight grooves of the shape illustrated in Fig. 18 were then machined on the surfaces of different specimens. In all cases, the spacing and depth of grooves were maintained relatively constant and only the groove angle was varied. The groove half angle ranged from a minimum value of 7.5° to a maximum of 45° . Figure 19 presents normal and cross-sectional views of one specimen that was studied. The specimen had a diameter of about 60 mm and approximately 300 parallel 45° grooves (total angle) were machined on the specimen. The lateral dimensions of the machined area were chosen so that

Fig. 19. Photomicrographs of the free surface of the grooved specimen used in Experiment AF2, X100. The total groove angle ($2\alpha'$) is 45° .

one-dimensional response of the collecting foil occurred during times of interest. Table III tabulates the geometrical configurations and impact data for all of the specimens studied.

As shown in Fig. 19, there were some variations in groove dimensions on a given experiment. The most significant variation was rounding of the wedge angles near the apex of the groove. This effect is due to pulling of aluminum by the carbide tool bit used for machining. It is estimated that the radius of curvature of the apex is no more than 0.005 mm in most cases. There is also some variation in groove angle as shown in Fig 19. However, duplicate interferometer measurements were made on each sample in order to average out most of these variations. In addition, the foil separations and recording areas for the interferometers were chosen in order to further average the fluff properties from a given sample. Foil separations were maintained at approximately 6.3 mm in each experiment and the lens focal length shown in Fig. 6 was chosen to be 580 mm. Because of the angular divergence of the laser, the illuminated area of the foil was therefore about 0.3 mm in diameter. This spot size provided some averaging of the foil response, since the groove separation was on the order of 0.1 mm.

The impact configuration used for the artificial fluff experiments is basically identical to that used in the earlier experiments and is illustrated in Fig. 6. Tungsten carbide (WC) impactors were used in all experiments, and the projectile velocity was maintained relatively constant between experiments so that nearly identical impact pressures of 29.5 GPa were produced.

Figure 20 presents the particle velocity histories measured on the different samples. Steel foils, 0.076 mm in thickness, were used in most

TABLE III

ANGULAR CONFIGURATION OF GROOVED SAMPLES

Exp. No.	Proj. Vel. ^a km/s	Sample Thickness, mm	Total Groove Angle ^b	Groove Sep., mm	Groove Depth, mm	Gap Sep. mm
AF1 ^c	1.833	3.16	30°	0.1271	0.07112	6.300
AF2	1.840	3.16	45°	0.1271	0.0559	6.320
AF3	1.836	3.17	90°	0.1271	0.0483	6.355
AF4	1.831	3.15	30°	0.1302	0.0480	6.365
AF5	1.834	3.14	15°	0.1271	0.0542	6.359

a. Tungsten carbide projectiles were used as impactors in all experiments.

b. Total angle, $2\alpha'$. The angular deviation of the tool kit used to machine the grooves was maintained to within 30' of arc. However, visual observation of the grooves suggests a larger variation than this.

c. An aluminum foil, 0.025 thick, was used in this experiment.

Fig. 20. Foil velocities obtained for samples containing grooves on the free surface. The solid and dashed lines represent results obtained for experiments designated A and B, respectively, in Table III. The time origin has been normalized to shock arrival at the free surface of the specimens. The dashed vertical lines represent arrival of the free surface at the foil.

cases except for Exp. AF5 (15° grooves), where the foil thickness was 0.025 mm and Exp. AF1 (30° grooves), where an aluminum foil, 0.025 mm thick, was used. In general, reasonable agreement was obtained between the two VISAR measurements (identified by letters A and B). As before, the dashed lines represent free surface arrival at the foil. The velocity measurements represented in Fig. 20 indicated no loss of fringe contrast in most cases, which indicates a relatively uniform foil velocity. However, a loss of contrast was observed in Exp. AF5. This began during the first arrival of fluff at the foil and persisted for about $0.8 \mu\text{sec}$. Such an effect could arise from a spatial distribution of the ejected material, which would therefore cause local variations in foil velocity. An estimate of these local variations was made by assuming a Gaussian distribution of particle velocity. Equation (3) then allowed an estimate of the mean velocity, u_m , and also the spread in velocity, a , ($1/e$ value). Results obtained on two different interferometers gave a maximum velocity spread of 0.13 km/s ($\pm 0.065 \text{ km/s}$). The average foil velocity was approximately 0.3 km/s ; therefore, these results indicate that highly localized particle velocities occurred on the foil during its initial motion. Since these variations arise from impact of ejected mass, the results show that microjets from 15° grooves remain fairly coherent over the propagation distances employed here.* The lack of observable particle velocity distributions in the other experiments suggests that coherency is not maintained in the jets from larger groove angles for propagation distances greater than 6 mm.

* Because of the observed nonuniformity of ejected mass for Exp. AF5, the calculation of total ejected mass using the relations presented earlier may be in appreciable error. However, the interferometer measurement of foil motion should still allow an accurate determination of the maximum fluff velocity.

The foil velocities illustrated in Fig. 20 were converted to total fluff masses, using Eq. (6). These results are tabulated in Table IV and illustrated graphically in Fig. 21a. The results show that the total amount of ejected mass increases as the total groove angle α (equal to $2\alpha'$) increases. Note that the amount of mass ejected from grooved specimens is about two to three orders of magnitude larger than that occurring naturally in aluminum so this latter contribution can be neglected. Similarly, the maximum fluff velocity shown in part b of the figure decreases as the groove angle increases. The maximum velocity varies from about three times the free surface velocity for 15° grooves to about twice the free surface value for 90° grooves.

The mass-velocity distributions for each experiment were calculated from the foil histories shown in Fig. 20, using Eq. (8), and are presented in Fig. 22. The mass per unit velocity interval, m_v , has been plotted versus the normalized velocity, v/u_{fs} . In conformity with the results shown in Fig. 21b, the maximum normalized velocity decreases as the groove angle increases. A particularly significant feature of these results is that there is a definite concentration of mass near the maximum fluff velocities in all experiments. This peak is followed by a range of velocities where the mass density is relatively low, particularly for the smaller groove angles. Although there is some indication of a larger proportion of the mass travelling at a velocity near the free surface velocity for the 90° grooved sample, there is a significant difference between these results and those obtained in lead, where most of the fluff mass observed at high pressure travels with a velocity near the free surface value. This can be clearly seen by comparing Fig. 22 with Fig. 15.

The results shown in Fig. 20 also allow an estimation of the density and average pressure exerted by fluff on the foil. Equation (4) indicates that

TABLE IV

MASS EJECTION FROM GROOVED SAMPLES OF ALUMINUM

Exp. No.	Groove ^a Angle	Impact Pressure, GPa	Free Surface ^c Vel., km/s	Maximum Fluff Vel., km/s	Total Mass Ejected, mg/cm ²	Mass per unit Groove Length mg/cm
AF1 ^d	30°	29.4	----	8.1	----	-----
AF2A	45°	29.6	2.97	7.2	2.33	0.030
AF2B	"	"	3.04	7.5	2.07	0.026
AF3A	90°	29.5	2.95	6.3	2.60	0.033
AF3B	"	"	2.95	6.3	3.06	0.039
AF4A	30°	29.4	2.93	8.3	1.60	0.021
AF4B	"	"	2.94	---	1.58	0.021
AF5A	15°	29.4	2.96	10.1 ^e	1.46	0.019
AF5B	"	"	3.00	9.8 ^e	1.57	0.020

a. Total angle, 2α .

b. Calculated from impedance matching techniques. Al: $P = 14.28u + 3.71u^2$; WC: $P = 78.8u + 17.0u^2$ GPa, u in km/s.

c. Measured from free surface arrival at foil.

d. Aluminum foil used in this experiment.

e. There was a possible timing error in this experiment which could affect the calculated maximum fluff velocities. This source of uncertainty puts a lower bound on the velocities of 8.6 km/s for AF5A and 8.4 km/s for AF5B

Fig. 21. (a) Total fluff mass versus total groove angle α ($= 2\alpha'$) for grooved specimens, (b) maximum fluff velocity versus total groove angle. The solid line was calculated from steady jetting theory.

Fig. 22. Mass-velocity distributions for the different grooved specimens. The solid and dashed lines represent results obtained on experiments listed in Table IV with suffixes A and B, respectively.

maximum fluff density for the peak of the distribution for Experiment AF3 is about 0.04 g/cm^3 . The average pressure, P_f , exerted on the foil can be estimated from the relation

$$P_f = \rho(v - V)^2 \quad . \quad (14)$$

These calculations indicate that the peak pressure produced in Experiment AF3 is about 1.0 GPa, although a value of 0.05 GPa is more typical of the average pressure exerted on the foil.

As mentioned earlier one of the objectives of this work was to determine whether the results of jetting from samples with microgrooves could be correlated with the predictions of steady jetting theory, which is known to describe the tip velocities of macroscopic jets from lined cavities. If the initial collapse angle β were determined independently in the present experiments, Eq. (12) would allow an estimation of the maximum jet velocity, since the shock velocity, U , is known from the equation of state. The calculated velocities could then be compared with experimental values in order to determine whether Eq. (12) applied to the present case. Since β was not measured in these experiments, the approach taken here was to use the measured maximum jet velocities to estimate the initial collapse angle through Eq. (12). Angles estimated in this way could then be compared with collapse angles measured experimentally in earlier investigations.

The maximum fluff velocities recorded in the experiments are tabulated in Table IV. Since the shock velocity in aluminum is 7.31 km/s for an impact pressure of 29.5 GPa, the parameters listed in the table allow determination of β for different initial groove angles. Values of the collapse angle determined in this way are shown in Fig. 23. For illustrative purposes, the quantity $\beta - \alpha'$ has been plotted versus α' . It is found experimentally that

Fig. 23. Experimental relationship between initial groove angle and initial collapse angle after shock arrival.

this quantity increases initially but then tends to level off at a value of about 20° . Two direct measurements of β obtained for macroscopic, lined cavities^{42,43} are also shown in the figure for comparison. The agreement between the results obtained on microgrooves and on shaped lined cavities for a total wedge angle near 45° is excellent considering (1) the difficulty of these measurements, (2) the three to four orders of magnitude difference in cavity dimensions, and (3) the fact that steady jetting theory is not strictly applicable to the present groove configuration. This agreement suggests that Eq. (12) may be useful in describing the maximum jet velocities from wedged grooves of the type shown in Fig. 18, if a suitable relation between α' and β is determined experimentally. For the present work, we have used the approximate relation $\beta - \alpha' = 20^\circ$ to describe this relationship. Calculations using Eq. (12) and this empirical relation provide a good estimation of the maximum jet velocity as shown by the solid line in Fig. 21b.

It has been shown both theoretically,³³ experimentally,¹ and with numerical calculations,^{44,45} that critical collision angles exist in lined shaped cavities for which jets will not be formed. The critical collapse angle, β^* , is about 12° ^{1,46} in aluminum for the stress amplitudes employed here. Collapse angles less than this produce a jetless configuration. Examination of Fig. 23 shows that the collapse angles obtained in the present experiments exceed β^* , although the results obtained from 15° grooves begin to approach this limit ($\beta = 23^\circ$).

The maximum jet velocities and therefore the initial collapse angles were determined from the first detectable fluff arrival on the foil. These velocities correspond to the maximum values of v shown in Fig. 22 and are not always well defined. Thus, the calculated collision angles, β , are subject to uncertainties from this source of experimental error. This

uncertainty can be estimated by using a lower bound for the maximum fluff velocities; i.e., the velocities corresponding to the peak mass concentration presented in Fig. 22. Values of β determined from these values range from 2° lower for 90° grooves to about 5° lower for 15° grooves. Thus, the calculated collision angles are not sensitive to small uncertainties in the measured maximum fluff velocities.

Steady jetting theory and modification to this theory provide analytical expressions for the amount of mass contained in jets formed from lined cavities. Such relations have not been developed for nonlined cavities, as studied here. Therefore, the experimental measurements of total ejected mass presented in Fig. 21a cannot presently be compared with analytic predictions. However, computer simulations of groove collapse, similar to the calculations performed by Harlow and Pracht⁴⁴ and Chou et al.⁴⁵, would shed some light on how the jet accumulates mass from the cavity walls. A comparison of computer calculations of the mass and velocity distributions in a jet with experimental measurements would also allow a good test of the constitutive behavior of aluminum under these conditions. In this regard, the present data allow the first direct comparison of experimental and calculated mass - velocity distributions occurring in jets.

IV. DISCUSSION

The combination of results obtained for naturally occurring fluff in aluminum and lead and for fluff from artificial grooves allows some deductions about material ejection from shocked free surfaces. First, the range of maximum fluff velocities obtained on 6061-T6 aluminum free surfaces correlate well with those obtained from grooved surfaces of aluminum. This

observation indicates fairly strongly that at least part of the mass ejection observed naturally from aluminum surfaces can be interpreted as a jetting phenomenon. Furthermore, the micron-size pits observed on aluminum surfaces may provide sites for free surface jetting (this hypothesis has recently been partially verified⁴⁷ by using holography to observe the local microscopic deformations occurring on a collecting foil). Second, the total amount of mass ejected from aluminum surfaces is observed to remain relatively constant over the pressure range of about 25 to 40 GPa. Since free surface melting should not occur for these shock pressures, the mechanisms causing material ejection should not change. This conclusion suggests that it might be ultimately possible to separate the total mass ejected for a particular loading condition into several different mechanisms. Such an approach would be beneficial if mass ejection were ever described statistically. Third, the form of the mass-velocity distribution functions observed from grooved samples of aluminum suggest that it may be possible to describe mass ejection from scratches and pits on the surface of samples in terms of a convolution of functions which describe the mass-velocity distribution for a given pit geometry. Last, the rapid increase of total mass ejected from surfaces of lead near the onset of free surface melting suggests that a different mechanism becomes important in this range. The form of the mass-velocity distribution in this case is different from that for lower pressures in that a large portion of the total ejected mass travels at a velocity only slightly higher than the free surface velocity. In particular, the definition of a free surface in lead becomes ambiguous for impact pressures where complete melting of the surface occurs.

The above discussion suggests that, in general, the mass-velocity distribution observed on a given material could result from the superposition

of several different physical mechanisms. As a particular example of how the distribution function could be decomposed into separate contributions, the present work suggests that at least three mechanisms could contribute to ejection of mass. These are (1) microspalling of impurities and inclusions near the surface, (2) jetting from surface defects such as scratches or pits, and (3) ejection due to localized melting or vaporization. The mass-velocity distribution could be separated into three functions which describe the dependence on material properties:

$$m_v(P, v) = m_s(P, P^*) + m_j(\eta, \alpha, \dot{P}) + m_M(P) \quad (15)$$

where the function m_s describes mass ejection due to microspalling from the surface, m_j describes ejection by jetting from existing surface defects and m_M refers to ejection caused by localized melting or vaporization. Since m_s relates to spalling it would probably depend at least on the shock pressure and the magnitude of bonding strength, P^* , of impurities to the matrix. The function m_j may well be independent of shock pressure, as suggested by the results obtained on aluminum. However, it would depend on surface properties such as defect density η , angular geometry α , and also on shock risetime, $\dot{P}$. Since m_M would depend on the final free surface temperature attained after shock compression and release, it would depend on the shock pressure directly and the constitutive properties of the material. If localized melting occurs at slip bands or grain boundaries, m_M could also depend on yield properties, since these would influence the dissipative energy deposited near the free surface.⁴⁸ Since shock compression is highly irreversible whereas continuous loading, as occurs during release, is nearly reversible, m_M could also depend on wave risetime or falltime. These additional effects have not been included in Eq. (15). In fact, there may be

other phenomena contributing to m_v which are also not discussed here. However, it may be possible to separate out these various functions on a given material by performing mass ejection experiments for different surface conditions, shock pressures and shock risetimes. The present results suggest that m_s and m_J are important to natural occurring mass ejection in aluminum, m_M and possibly m_J are important in lead and m_J applies to grooved surfaces of aluminum.

There are some further observations about the present results which also relate to physical mechanisms. The results obtained on the grooved specimens suggest a possible interpretation for the observed decrease in the ratio of maximum fluff velocity to the surface velocity with shock pressure in 6061-T6 aluminum (see Fig. 10a). Because of the results on grooved samples, it is likely that jetting occurs from the small pits which are observed on 6061 surfaces. If Eq. (12) is applicable to the jet velocities, the maximum fluff velocity would be proportional to shock velocity for a given defect geometry. However, the shock velocity varies slowly with pressure for aluminum.* On the other hand, the free surface velocity varies rapidly with pressure. Thus the ratio v_m/u_{fs} should decrease with increasing shock pressure. This effect is observed experimentally, as shown in Fig. 10.

The total mass ejected from lead surfaces is about three orders of magnitude larger than that observed on aluminum. However, as illustrated by Figs. 9 and 12, the density of surface imperfections on lead is definitely not three orders of magnitude larger. Furthermore, the ratio of maximum fluff velocity to free surface velocity in lead remains relatively constant with shock pressure. These observations suggest that mass ejection due to

* $U = \frac{1}{2} c_o (1 + \sqrt{1 + 4sP/\rho_o c_o^2})$; for aluminum, $\rho_o = 2.70 \text{ g/cm}^3$, $c_o = 5.25 \text{ km/s}$, $s = 1.37$. The free surface velocity is given approximately as $u_{fs} = 2P/\rho_o c_o$.

a jetting process may not be the dominant mechanism in lead. Due to the low melt temperature, an attractive possibility for mass ejection in this material is the localized melting which can occur at grain boundaries or slip bands. In general, these defects would intersect the free surface at arbitrary angles and would not result in an actual surface imperfection, such as a pit or scratch. Thus, conditions for the formation of the extremely fast jets observed in aluminum may not be present, so that maximum fluff velocities may not be governed by Eq. (12). This mechanism could also account for the premature increase in total ejected mass shown in Fig. 14a. Mass ejection due to this mechanism would probably not produce coherent streams of material and, furthermore, the ejection sites would probably be finely spaced. Although ejection of mass in vapor form is easy to visualize, the physical process causing ejection of liquid products is not clear. It may be that development of Rayleigh-Taylor instabilities on the surface lead to liquid ejection, as suggested by the work of Perry and Mix.¹⁰ Thus, holography experiments similar to those used in Ref. 47 might be employed to identify the primary physical mechanism responsible for mass ejection in lead.

For practical applications, the results of this study suggest some techniques for minimizing the amount of material ejected from shocked surfaces. The results obtained on the two aluminum alloys indicate less ejection for the more pure material. Furthermore, experiments conducted on sputtered surfaces of 6061 aluminum suggest that ejection can be reduced by removal of sharp depressions on the surface, such as pits and scratches. Sputtering tends to differentially remove aluminum around impurities and

inclusions, leaving protrusions on the surface (see Fig. 9). However, these apparently don't increase the total ejected mass over that for a surface containing no protrusions and only pits or scratches.

Experiments conducted on aluminum and lead suggest that materials with high melt temperatures may be better in general. With regard to the yield stress of materials, the present results are not conclusive. However, the two aluminum alloys studied here have initial yield strengths which vary by a factor of about 10. The 1100 alloy has the lower yield stress (about 0.03 GPa in the annealed condition) and also produces the least amount of fluff. This behavior might be contrary to the expected dependence of mass ejection on yield stress. However, it is known that 1100 alloy work hardens considerably faster than 6061 under shock compression.⁴⁹ Thus, material near the free surface in both alloys may exhibit comparable yield strengths after shock compression and release.

V. CONCLUSION

In summary, a discussion of interferometer measurements on free surfaces at high pressures has been presented, and it has been shown how these measurements are influenced by surface break-up and subsequent material ejection. It was found in this work that laser light reflected from shocked surfaces of aluminum and lead undergoes abrupt decreases in intensity after shock arrival at the surface. This loss of intensity is interpreted as resulting from scattering and absorption processes occurring in a cloud of ejected material. In some cases (although not all) a loss of contrast was observed in the interferometer signal, and this is thought to arise from light scattering from micron-sized inclusions or precipitates ejected from the surface.

The pressure at which the light signal amplitude decreases abruptly in aluminum correlates reasonably well with the elastic over-drive stress of about 13 GPa in this material. For higher amplitudes, single shock waves with risetimes on the order of a few nanoseconds or less are obtained. In this region, the reflected light intensity from aluminum surfaces is relatively independent of shock pressure and remains at approximately 20-40 % of the original intensity. In general, the observed light levels in aluminum are sufficient to allow interferometer measurements on the free surface. On the other hand, lead surfaces produce a much larger loss of intensity for a given shock amplitude. Because of this, interferometry on lead surfaces is severely degraded for shock pressure greater than about 10 GPa.

An interferometer technique for measuring the mass and velocity of material ejected from free surfaces was also discussed, and results obtained on several materials were presented. There appears to be a rough correlation between the relative intensity of laser light reflected from shocked surfaces and the amount of mass ejected from the surface. Experiments performed on two different alloys of aluminum indicate that more mass is ejected from the less pure alloy. The maximum velocity of the ejected material is on the order of two to four times the free surface velocity in 6061-T6 aluminum and this range is compatible with jet velocities obtained from shaped cavities. Photomicrographs of the 6061 surfaces studied in this work show a high density of micron-sized pits. These may provide sites for the formation of microjets, which would explain the high ejecta velocities observed from this material.

Mass ejection experiments conducted on lead indicate that the total amount of ejected mass is approximately three orders of magnitude larger than that for aluminum surfaces. The ratio of maximum ejecta velocity to

free surface velocity in lead is found to remain relatively constant at 1.5 as shock pressures vary from about 10 GPa to over 50 GPa. However, a rapid increase in the total amount of ejected material is observed at pressures near those required to cause melting of the free surface. There is also a change in the mass-velocity distribution function near the melt transition. At higher shock pressures, the relative amount of ejected material travelling at a velocity only slightly higher than the free surface velocity increases substantially. This has the effect of producing an ill-defined free surface at high shock pressures in lead.

As a final part of this work, experiments were conducted on aluminum specimens which contained parallel, wedge-shaped grooves on the free surface. These data showed that the amount of mass ejected from the grooves increased with groove angle; whereas the maximum velocity of ejected material decreased with groove angle. These results are in qualitative agreement with the predictions of steady jetting theory. Further, we have found that the collapse angles of the grooves, as estimated with steady jetting relations, agree quite well with independent measurements of the collapse angle made in large shaped cavities. This observation suggests that rate effects associated with jet formation may be minimal in aluminum.

For future work, it would be beneficial to verify whether different mechanisms contribute to mass ejection and, if so, to characterize the parameters influencing each. A particularly useful experiment would be to extend the results on aluminum to much higher shock pressures where free surface melting can occur. This would allow determination of whether the amount of ejected mass remains constant, as suggested by the trends observed presently in aluminum; or whether there is a significant increase in ejected mass near the melt point, as suggested by the work in lead. It

would also be useful to determine whether the degree of free surface acceleration (shock risetime) significantly influences material ejection, since this would allow a practical way of minimizing mass ejection in some applications.

As a final recommendation, the work initiated on samples with artificial defects should be continued. For example, the pressure dependence and effects of shock risetime on mass ejection can easily be studied in these cases, since only one mechanism for mass ejection is likely to occur. Furthermore, the effects of different defect geometry should be studied. The results of such studies would aid in constructing statistical theories to describe mass ejection occurring naturally from shocked free surfaces.

ACKNOWLEDGMENTS

I would like to thank R. J. Lawrence and F. C. Perry for helpful comments about the results presented here. D. E. Munson and B. M. Butcher offered continual support and made this project possible. Many conversations with L. D. Bertholf regarding jetting theory are greatly appreciated. C. Witten was responsible for the successful preparation of samples with microgrooves. R. Kinchen, D. Baldwin and D. Cox aided in various aspects of target construction. R. Hardy and C. Konrad operated the powder gun facility used for these experiments. And, finally, E. G. Young provided invaluable aid in development of computer routines necessary to reduce the experimental data.

REFERENCES

1. J. M. Walsh, R. G. Shreffler and F. J. Willig, J. Appl. Phys. 24, 349 (1953).
2. D. Venable, Los Alamos Scientific Laboratory, private communication.
3. J. R. Asay and L. M. Barker, J. Appl. Phys. 45, 2540 (1974).
4. J. W. Taylor in Metallurgical Effects at High Strain Rates, ed. by R. W. Rohde, B. M. Butcher, J. R. Holland and C. H. Karnes, Plenum Press, NY (1973).
5. G. Birkhoff, Amer. Math Soc. 92, 13 (1962).
6. R. Bellman and R. H. Pennington, Quart. Appl. Math 11, 151 (1955).
7. J. F. Barnes, P. J. Blewett, R. G. McQueen, K. A. Meyer and D. Venable, J. Appl. Phys. 45, 727 (1974).
8. Ye Ye Meshkov, "Instability of a Shock Wave Accelerated Interface Between Two Gases," NASA Tech. Pub., NASA TT F-13, 074 (1970).
9. R. F. Rolsten, J. Appl. Phys. 46, 4784 (1975).
10. F. C. Perry and L. P. Mix, Appl. Phys. Lett. 27, 194 (1975).
11. F. C. Perry and M. Widner, J. Appl. Phys. 47, 127 (1976).
12. M. J. Clauser, Phys. Rev. Lett. 35, 848 (1975).
13. J. R. Freeman, "Stability Calculations for Laser and Electron Beam Driven Pellets," Sandia Laboratories Report RS 5241/073, 1975.
14. S. E. Bodner, Phys. Rev. Lett. 33, 761 (1974).
15. K. A. Brueckner, S. Jorna and R. Janda, Phys. Fluids 17, 1554 (1974).
16. M. J. Clauser and M. A. Sweeney, "Charged-Particle Beam Implosion of Fusion Targets," International Topical Conference on Electron Beam Research and Technology, ed. by G. Yonas, Sandia Laboratories, SAND 76-5122 (1975).

17. G. S. Fraley, W. P. Gula, D. B. Henderson, R. L. McGrory, R. C. Malone, R. J. Mason, and R. L. Morse, "Implosion, Stability and Burn of Multi-shell Fusion Targets," Los Alamos Scientific Laboratory Report LA-5783-MS (1975).
18. L. M. Barker and R. E. Hollenbach, J. Appl. Phys. 43, 4669 (1972).
19. J. E. Kennedy, Sandia Laboratories, private communication.
20. Ya. B. Zel'dovich and Yu P. Raizer, Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena, Vol. I, Ed. by W. D. Hayes and R. F. Probstein, Academic Press, NY (1966).
21. J. E. Kennedy and O. B. Crump, to be published.
22. L. M. Barker and K. W. Schuler, J. Appl. Phys. 45, 3692 (1974).
23. S. B. Kormer, Sov. Phys. Uspekhi 11, 229 (1964).
24. A. Mitchell, Lawrence Livermore Laboratory, private communication.
25. D. K. Dean and D. P. Van Dyke, "Kerr Cell Photography of the Blowoff Plume," Sandia Laboratories Report, SCL-DC-720202 (1971).
26. R. D. Klett, "Trajectories and Temperatures of Small Spheres Fired at Hypersonic Velocities," Sandia Laboratories Report, SC-TM-72 0345.
27. D. Smith and N. G. Adams, J. Phys. D 6, 700 (1973).
28. D. O. Hansen, Appl. Phys. Lett. 13, 89 (1968).
29. M. M. Menon and K. D. Srivastava, J. Appl. Phys. 45, 2094 (1974).
30. B. Craig, Los Alamos Scientific Laboratory, private communication.
31. E. G. Young, Sandia Laboratories, private communication.
32. R. G. McQueen, S. P. Marsh, J. W. Taylor, J. N. Fritz and W. J. Carter, "The Equation of State of Solids from Shock Wave Studies," in High Velocity Impact Phenomena, ed. by R. Kinslow, Academic Press, NY (1970).
33. S. K. Godunov, A. A. Deribas and V. I. Mali, Combustion, Explosion and Shock Waves 11, 3 (1975).

34. N. E. W. Hartley, "Surface Stresses in Ion-Implanted Steel," in Applications of Ion Beams to Metals, ed. by S. T. Picraux, E. P. Eernisse and F. L. Vook, Plenum Press, NY (1974).
35. J. K. Galt, Sandia Laboratories, private communication.
36. J. M. Walsh and R. H. Christian, Phys. Rev. 97, 1544 (1955).
37. Samuel L. Thompson, "CKE052 - An Equation of State Test Program for the Chart D/CSQ EOS Package," Sandia Laboratories Report SAND 76-0175 (1976) (unpublished).
38. George White, Los Alamos Scientific Laboratory, private communication.
39. L. V. Al'tshuler, S. B. Kormer, A. A. Bakanova, A. P. Petrunin, A. I. Funtikov, and A. A. Gubkin, JETP 14, 986 (1962).
40. G. Birkhoff, D. P. MacDougall, E. M. Pugh, and G. Taylor, J. Appl. Phys. 19, 563 (1948).
41. E. M. Pugh, R. J. Eichelberger and N. Rostaker, J. Appl. Phys. 23, 532 (1952).
42. R. J. Eichelberger and E. M. Pugh, J. Appl. Phys. 23, 537 (1952).
43. R. J. Eichelberger, J. Appl. Phys. 26, 398 (1955).
44. F. H. Harlow and W. E. Pracht, Phys. Fluids 9, 1951 (1966).
45. P. C. Chou, J. Carleone and R. R. Karpp, J. Appl. Phys. 47, 2975 (1976).
46. A comparison of the present results with those of Walsh et al.¹ can be made by calculating the effective plate velocity $V_p = \frac{U \sin(\beta - \alpha)}{\cos \alpha}$.
Fig. 14 of ref. 1 gives the critical angle in aluminum as a function of V_p .
47. J. R. Asay, L. P. Mix and F. C. Perry, J. Appl. Phys. Lett. 29, 284 (1976).
48. D. E. Grady, to be published in J. Geophys. Res. (1976).
49. R. J. Lawrence and J. R. Asay, to be published.

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M. Van Thiel, L-504
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PO Box 808
Livermore, CA 94550

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Lawrence Livermore Laboratory
PO Box 808
Livermore, CA 94550

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Lawrence Livermore Laboratory
PO Box 808
Livermore, CA 94550

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Lawrence Livermore Laboratory
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Lawrence Livermore Laboratory
PO Box 808
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D. Kohler
Defense Nuclear Agency
575 Thomas Bldg.
2020 N. 14th ST
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L. R. Hettche
Naval Research Laboratory
4555 Overlook AV, SW
Washington, DC 20390

C. M. Huddleston
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US Naval Surface Weapons Center
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D. R. Curran, G178
Stanford Research Institute
333 Ravenswood Avenue
Menlo Park, CA 94025

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Stanford Research Institute
333 Ravenswood Avenue
Menlo Park, CA 94025

H. E. Read
Systems, Science, and
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Dr. G. R. Fowles
Washington State University
Department of Physics
Pullman, Washington 99163

Dr. George Duvall
Washington State University
Department of Physics
Pullman, WA 99163

Dr. J. J. Dick
Washington State University
Department of Physics
Pullman, WA 99163

Y. S. Touloukian
Aerospace Corporation
PO Box 92957
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Los Alamos Scientific Laboratory
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