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FINE STRUCTURE OF COMPRESSIVE AND RELEASE WAVE SHAPES IN
ALUMINUM MEASURED BY THE VELOCITY INTERFEROMETER TECHNIQUE

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ABSTRACT

A new laser interferometer technique has been developed to measure the velocity history of a reflecting surface of a shock-loaded specimen. The velocity interferometer configuration overcomes the formerly reported distance interferometer limitation of being able to monitor only relatively small velocities.

Some preliminary results are included on wave shapes in 6061-T6 Aluminum shocked to various pressures up to 90 kbar. It was found, for example, that the maximum strain rate in the plastic wave front increases from $0.13 \times 10^6 \text{ sec}^{-1}$ for a 20 kbar experiment to $1.5 \times 10^6 \text{ sec}^{-1}$ for a 37 kbar experiment. The shape of the elastic release wave is found to be considerably more smeared-out than expected, and computer analysis of the measured results indicates the influence of a strong Bauschinger effect on the unloading behavior of the aluminum.

INTRODUCTION

The propagation characteristics of large amplitude plane shock waves have been used for the past dozen years to determine the dynamic loading behavior of materials from the kilobar to the megabar pressure range.¹ The corresponding unloading behavior which governs the propagation characteristics of a following release wave is in many respects as important as the loading behavior. However, the unloading behavior has thus far escaped accurate measurement, although several papers have been devoted at least in part to its determination (See, for example, References 2 - 8). It appears that refinements in the determinations of dynamic unloading behavior require greater experimental precision than has been available in measuring release wave shapes. Refinements also require more elaborate analysis than is necessary to determine loading behavior because of the numerous stress wave interactions which influence the results of an experiment.

In this paper, a new interferometer instrumentation technique which is being successfully applied to the determination of dynamic unloading behavior is first described. The new interferometer, known as the velocity interferometer, measures the velocity history of a reflecting surface of a shocked specimen. The limitation of measuring only relatively slow surface velocities in a previously reported interferometer technique⁹ is overcome in the velocity interferometer configuration. After analyses of the interferometer and the fused quartz "window" used in the experiments, the experimental results showing the fine structure of compressive and release wave shapes in 6061-T6 aluminum are presented. Finally, the measured results are used to deduce the dynamic unloading behavior by means of computer analyses of the stress wave propagations and interactions in the experimental configurations.

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EXPERIMENTAL CONFIGURATION

A schematic of the experimental configuration is presented in Fig. 1, which shows a flat projectile plate about to impact the target specimen. A previous paper¹⁰ describes the gas gun which accelerates the projectile plate, the methods of achieving a good impact, and techniques of measuring the impact parameters. The free surface of the target must be polished to a mirror finish, and the finish must be retained during the time of observation after shock arrival. Apparently many materials meet this requirement even at impact pressures exceeding 100 kbar.¹¹

The light source is a single-frequency gas laser of the type used in long path-length difference interferometry (Spectra-Physics Model 119 or equivalent). Such a laser is necessary both to eliminate the amplitude modulation of the laser output due to multiple active longitudinal modes, and to provide good fringe contrast regardless of the length of the delay leg of the interferometer.

The lens L1 brings the laser beam to focus at the target free surface, and L2 recollimates the beam. The effect of tilting of the free surface (due to the small but unavoidable tilt between the impacting plates) on the misalignment of the interferometer is minimized by focusing the laser beam on the free surface.

The first of the two beam splitters sends half of the beam around a delay leg by way of the 90° reflecting (Porro) prism. Delay legs of about 300 cm or less total length have been used. The second beam splitter recombines the two beams so that the photomultiplier sees a brightness which depends on the relative phases of the recombined beams. It will be shown in the analysis that the interferometer produces fringes at the photomultiplier tube in proportion to the velocity attained by the target free surface, and the fringe frequency is proportional to the acceleration. Thus, by recording the photomultiplier output oscillographically with a suitable time base, one can obtain the free surface velocity history simply by plotting the number of oscillations (fringes) of the photomultiplier output as a function of the time.

Figure 2 illustrates how an oscillograph recording of the fringes might look, and how the oscillograph corresponds to the velocity vs time of the reflecting surface. It can be seen that a wave shape containing a large and extremely rapid change in velocity might still produce a burst of fringes

Figure 1:
Velocity Interferometer Instrumentation

exceeding the frequency response capability of the recording system. The ability to control the velocity-per-fringe constant can eliminate the problem, but even if the fringe frequency should exceed the recording capability for a short time, it would be certain that the number of fringes between two peaks on either side of the blurred region would be an integer. If the integer were not large, and if a little were known in advance about the material and the shock strength, one could ascertain with confidence the exact number of fringes in the blurred region even though they were not individually countable.

The response time of the velocity interferometer is equal to the time for light to travel around the delay leg of Fig. 1, and hence can theoretically be made arbitrarily small simply by shortening the delay. However, the response time of the electronics of the photomultiplier-oscilloscope recording system limits our present experimental configuration to frequencies below about 600 MHz.

Figure 2: Oscillograph Data and Corresponding Surface Velocity History

ANALYSIS

The relation between the reflecting surface velocity and the number of fringes counted can be derived as follows. Let the delay leg be defined as the optical distance traveled by the light in going from the first beam splitter to the second along the path through the 90° reflecting prism as shown in Fig. 1, minus the straight-through distance between the beam splitters. Let the length of the delay leg be $N\lambda$, where λ is the wavelength of the laser light. If N is an integer, the delayed beam will arrive at the second beam splitter in phase with the straight-through beam, thus reinforcing the light to the photomultiplier tube. If the length of the delay leg is held constant, but λ is decreased slightly so that N increases by $\frac{1}{2}$, the two beams arrive at the second beam splitter out of phase, and the photomultiplier sees no light. Extension of this reasoning shows that the photomultiplier senses, as light fringes, the total change ΔN in the number of wavelengths contained in the delay leg due to changes in wavelength.

When the free surface of the target starts moving as the result of the arrival of a shock wave, the reflected laser light suffers a doppler shift in wavelength according to the formula

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$$\Delta\lambda(t) = -\frac{2\lambda}{c} u(t)$$

(1)

where $u(t)$ is the velocity of the free surface at time t , and c is the velocity of light. The length of the delay leg can be written

$$N\lambda = c\tau \quad (2)$$

where τ is the time for light to traverse the delay leg. Differentiating (2), we have

$$\Delta N(t) = -\frac{c\tau}{\lambda^2} \Delta\lambda(t) \quad (3)$$

Substituting for $\Delta\lambda$ in (3) from equation (1), and solving for the free surface velocity, we obtain

$$u(t) = \left(\frac{\lambda}{2\tau}\right) \Delta N(t) \quad (4)$$

Thus, the proportionality constant between the surface velocity and the number of fringes $\Delta N(t)$ counted up to the time t is simply $\lambda/2\tau$, which is easily and accurately determinable. As an example, if we choose a delay leg such that $\tau = 10$ nsec, and if we use a He-Ne laser with $\lambda = 632.8$ nm, then $\lambda/2\tau = 31.64$ m/sec per fringe.

It should be noted that the effective "rise-time" of the velocity interferometer is equal to the time τ for light to traverse the delay leg. This is easily shown by considering a step function change in free surface velocity. The doppler shifted frequency resulting from the new velocity would beat against the old frequency for the time τ before the new frequency traveled around the delay leg. Thus, the signal resulting from a jump in velocity would be spread over the time τ . The rise-time can be made less simply by shortening the delay leg; however, consideration must also be given to the desired velocity-per-fringe constant in selecting the optimum τ .

Equation (4) can also be derived from an interferometry point of view. Consider that the photomultiplier in Fig. 1 "sees" the mirrorized surface of the target specimen as both mirrors of an interferometer: It sees the reflecting point once looking straight through the two beam splitters, and it sees the same point as a second mirror by the optical path around the delay leg. Although the two mirrors are physically one and the same, they are nevertheless separated in time, from the photomultiplier's point of view, by the time τ which it takes light to travel around the delay leg. Thus, when the specimen surface is stationary, the two mirrors are superimposed, but when the surface attains a velocity, they become separated, as indicated in Fig. 3. One mirror lags the other in position by $S(t)$, the distance traveled by the mirror during the time for light to traverse the delay leg. The equation for the separation of the two mirrors at a time t is $S(t) = \lambda/2 \Delta N(t)$, where $\Delta N(t)$ is the number of fringes registered by the photomultiplier tube up to time t . $S(t)$ is also equal to the average velocity of the surface during the time interval τ , times τ : $S(t) = \bar{u}(t)\tau$.

Figure 3: Schematic of Specimen Surfaces considered as both Mirrors of an Interferometer

Eliminating $S(t)$ between these two equations results in equation (4). Thus, as one would expect, both the doppler shift and the interferometric points of view lead to identical results.

It has been implicitly assumed in the derivations of equation (4) that the doppler change in wavelength is a monotonous function of the time, i.e., that the specimen surface velocity history is monotonous. The reason for this assumption is that both increasing and decreasing velocities are registered simply as fringes by the photomultiplier tube, so that the results of an experiment can become ambiguous if it is not known that the velocity history is monotonous. On the other hand, if it is known that the acceleration of the reflecting surface will change directions, and approximately what time the change will occur, one can usually distinguish the reversal point in the data. At the expense of added complexity of the technique, one might entirely eliminate the possibility of ambiguity by a method of quadrature similar to that described by J. W. Campbell¹² but such refinements are not considered here.

In order to be a useful technique, the velocity interferometer must remain sufficiently well aligned to provide data even though the specimen surface moves a small distance during the time of measurement and may tilt slightly as a result of a slight tilt between the impacting surfaces. The interferometer is designed to be self-compensating for the tilt, as discussed below. Later, the combined effects of tilt and motion are treated.

If we imagine the target surface in Fig. 1 to tilt slightly about an axis through the point which reflects the focused laser beam, the direction of the reflected beam going to the recollimating lens L2 will change by twice the angle of the tilt. However, as long as the reflecting point only tilts but does not translate, the reflected light still comes from the focal point of the lens L2. Thus, after passing through L2, the beam remains parallel to its original direction, only shifted slightly to the side. If θ is the tilt angle and f_2 is the focal length of the lens L2, the amount of the lateral shift is $D = 2\theta f_2$. As an example, if $\theta = 10^{-3}$ radian (usually attainable in impact experiments) and $f_2 = 100$ mm, the lateral shift D is 0.2 mm. The beam diameter may be 3 mm, so in this case the lateral shift due to tilt would not be enough to cause a significant loss of fringe contrast. Furthermore, the alignment is completely self-correcting as long as the beam remains parallel to its original direction, as can be seen by tracing the path of the shifted beam through the beam splitters and the delay leg of Fig. 1.

In the idealized configuration, the laser beam is brought to focus exactly at the target surface so that the foregoing argument holds. In the real situation, however, the surface moves relative to the lenses L1 and L2 during the time of observation. Then the output beam is no longer collimated, but continues diverging slightly (Fig. 4), and furthermore, the direction of the beam is changed slightly. The amount of the directional change ϕ is given by $\phi = y/f_2$, where y is the apparent shift of the beam center at the focal plane of L2. One contribution to y comes from the motion of the reflecting surface through the distance x , and the other comes from the rotation (tilt) of the reflecting surface through the angle θ . Let the contribution from the former be Δy_x , and from the latter Δy_θ (See Fig. 5). The direction of Δy_x is fixed by the experimental configuration, but because the orientation of the tilt between the impacting plates is random, the direction of Δy_θ is random. For purposes of this analysis, we shall

assume the worst condition, i.e., that Δy_θ is in the same direction as Δy_x . Let γ be the angle of incidence of the center of the incoming beam onto the original untilted surface. Then, for small values of γ and θ , we have from Fig. 5

$$y = \Delta y_x + \Delta y_\theta = 2x(\gamma + \theta)$$

In an actual experiment, we may have $\gamma = .03$ radian, $\theta = .001$ radian, and $x = 0.5$ mm. If the focal length $f_2 = 100$ mm, the outgoing beam is shifted in direction by the angle $\phi \approx 3 \times 10^{-4}$ radian. Note that the tilt in this example contributes only 1/30 as much as the motion of translation to the angle ϕ . Thus, for tilt angles no greater than about 10^{-3} radian, we can neglect the tilt as a significant factor in the misalignment which occurs as the surface moves.

To evaluate the effect of the small change in direction on the alignment of the interferometer, we refer to Fig. 6. Here, by "unfolding" the path around the delay leg, it can be seen that the delayed beam is shifted with respect to the straight-through beam by approximately the delay leg path length times the angle ϕ . If the delay leg is 2.5 m, the present example gives a shift D between the emerging beams of 0.75 mm. This could begin to affect the contrast between light and dark fringes for a beam diameter of 3 mm.

Figure 4: Schematic Denoting the Motion and Tilting of the Reflecting Surface

Figure 5: Geometry for Analyzing the Effects of Translation and Tilting of the Reflecting Surface

The lateral shift D which causes the interferometer to become misaligned is proportional to both the length L of the delay leg and the distance x moved by the reflecting surface of the specimen:

$$D = L \phi = Ly/f_2 \approx 2\gamma xL/f_2 \quad (5)$$

For a given f_2 and γ , and a maximum acceptable D , one can solve for the maximum permissible delay length L which would allow the observation of a displacement x . If it is desired to observe the motion of the surface only after it has already moved through a sizable displacement, equation 5 can be used to deliberately misalign the original configuration by an amount $-D$, such that the interferometer will be aligned at the time of interest. This procedure can also be used to double the range x over which data can be obtained.

Figure 6: Delay Leg Geometry

Next, the effect of the angular change ϕ in beam direction on the number of fringes counted must be determined. To do this, we must calculate the change in phase between the beams emerging from the interferometer, which is equivalent to calculating the change in the delay path length L . Let L_0 be the delay length in the aligned interferometer, and L_ϕ be the delay length after the incoming beam direction is shifted by the angle ϕ . Let perfect optical components be assumed, and (See Fig. 6) let δ = separation of the cube beam splitters; and d = distance between beam splitters and reflecting prism; p = length of the hypotenuse of the 90° reflecting prism; and n = index of refraction of the prism.

The delay length of the aligned interferometer is $L_0 = 2d + np - \delta$. The delay after a change in direction ϕ is approximately $L_\phi = L_0 \sec \phi - D \tan \phi$. This approximation neglects the change in direction inside the prism because of its index of refraction. It is a good approximation as long as $d \gg p$, which is true for our present configurations. The term $D \tan \phi$ enters because the straight-through light must travel this distance after exiting the second beam splitter before it is abreast of the delayed beam at its exit point. Using the fact that ϕ is small and $D = L_0 \phi$, the change in the delay length is

$$\Delta L = L_\phi - L_0 = -\frac{1}{2} \phi^2 L_0 \quad (6)$$

Equation (6) shows that the effective delay length becomes shorter with increasing ϕ . As an example, if $\phi = 3 \times 10^{-4}$ and $L_0 = 2.5$ m, then $\Delta L = 112.5$ mm. For a wavelength $\lambda = 632.8$ nm, $\Delta L = 0.18 \lambda$. Thus, the number of fringes counted is in error by 0.18 when ϕ reaches 3×10^{-4} radians.

To see exactly how this affects the data, recall that the doppler shift shortens the wavelength of the light as the reflecting surface moves toward the lenses in Fig. 1; thus, more wavelengths are needed to fill the delay leg. An increasing angle ϕ produces an apparent decrease in the delay length, as just calculated. Since the decrease in length means that fewer wavelengths are needed to fill the delay length, this acts the same as a decrease in velocity superimposed on the actual velocity. Of course, if the alignment is deliberately offset originally so as to collect data at some desired position x , there will be superimposed on the real motion first an apparent increase in velocity as ϕ decreases, i.e., as the interferometer comes into alignment, and later a decrease in velocity as ϕ increases again.

To better show how ΔL depends on the other parameters, we combine equations (5) and (6) and obtain

$$\Delta L = - 2L_0 x^2 \gamma^2 / f_2^2 . \quad (7)$$

This equation shows the sensitivity of ΔL to the variables over which we have some control.

One might entirely eliminate the ΔL problem by replacing the mirror to the right of the specimen surface in Fig. 1 by a beam splitter which would reflect half of the light onto the surface at normal incidence, thus making $\gamma = 0$ in (7). Half of the light reflected back from the specimen surface would then go straight through the beam splitter after which it could be reflected and recollimated, etc. This procedure would result in a loss of 75% of the laser light, however, even assuming a perfectly non-absorbing beam splitter. The low intensity of the light from single-frequency lasers has prevented the use of this configuration.

Finally, there is the effect of imperfect optical components. If the components were very poor, one would be unable to obtain a single fringe at a time on the output beam because of variations in path length in the optics for different parts of the beam. Also, when the beam moves to a different path through the optics as a result of the reflecting surface motion, an error in the number of fringes counted will be present in addition to that already calculated if the L varies because of imperfect optics.

THE FUSED QUARTZ WINDOW

It is often advantageous to observe the velocity history of the interface between the specimen and a transparent material placed on the specimen surface, rather than observing the motion of the specimen's free surface. Because a free surface reflects compressive waves as rarefaction waves, and vice versa, its motion is always simultaneously affected by both the compression and rarefaction characteristics of the specimen material. Placing a "window" material with a shock impedance similar to that of the specimen on the specimen surface causes most of the incident stress wave to propagate on into the window material. The reflection off the specimen surface is therefore greatly reduced, and the compressive and release characteristics of the specimen are much better isolated

for individual study. A related advantage of using a window is that it prevents spall¹³ from obscuring the bulk of large release waves which carry information about the release characteristics of the specimen. Proper choice of the thicknesses of the driver plate, the specimen plate, and the window can cause the spall condition to occur in the window material after the desired motion of the sample-window interface has been recorded.

The advantages of using a window on the specimen surface are gained at the cost of added complications in analyzing the experimental results. The stress waves which enter the window cause its index of refraction to change. The index of refraction and the variation of the index of refraction with the change in density associated with the stress wave must be accounted for in a new calculation of the velocity-per-fringe constant of Equation (4). Also, the measured motion of the interface between the specimen and the window is influenced by the dynamic properties of the window material as well as the specimen, so that one must have a knowledge of the window material's dynamic properties in order to properly analyze the experimental results.

High quality fused quartz was chosen as the window material for the experiments to be described later for several reasons: (1) The shock impedance of fused quartz differs from that of the aluminum under study by only about 25% or less; (2) The shock Hugoniot of fused quartz is available in the literature,¹⁴ and (3) It is known that fused quartz does not luminesce when shocked to stresses below 65 kbar, and that luminescence at higher stresses occurs only outside the region of uniaxial strain.¹⁵ The following analysis was used to interpret the measured fringe data in view of the change of index of refraction with pressure in the quartz.

Let us approximate the motion of the interface between the sample and the fused quartz window by a series of jumps in velocity; the velocity of the interface u is assumed constant between the jumps. Each jump in velocity Δu causes an additional compressive or release shock to propagate into the quartz; the shock velocity U depends on the stress level, whether it is a compressive or a release shock, etc. The velocity of any one shock is assumed to be constant inside the quartz. Each shock carries with it a change in material velocity Δu equal to the interface jump in velocity which originated the shock. Fig. 7 shows a sample approximation, and defines the regions corresponding to the various subscripts. The undisturbed quartz ahead of the first shock front is assumed to have a density ρ_1 , an index of refraction n_1 , and a material velocity $u_1 = 0$. The shock velocities U are relative to the material velocity ahead of the shock, so that the shock velocity relative to the laboratory is $U_1 + u_1$.

We shall use the concept that the velocity interferometer measures the change in the number of half-wavelengths separating the two mirrors at the specimen-quartz interface which are really one and the same mirror except for the delay time τ in the time between their position histories. Before the motion starts, the mirrors occupy the same position. When the first shock crosses the interface, one of the two mirrors starts moving at the constant velocity u_2 , and the shock whose velocity is U_1 runs into the quartz changing the index of refraction from n_1 to n_2 , while nothing happens to the other mirror until a time τ later.

Figure 7: A Wave-Shape, Approximated by Jumps in Stress, Entering the Fused Quartz Window from the Specimen

Then the identical thing happens to the second mirror. After the time τ and before the second shock enters the quartz, both mirrors are moving with the same velocity, and the shock is changing the index of refraction of the quartz at the same rate for each mirror. Therefore, the mirror separation appears constant, and no further fringes are produced until the next shock enters the quartz. The same logic holds for each successive shock: The mirror spacing appears to vary only during the time τ after each shock enters the quartz.

We now wish to relate the number of fringes ΔN_x , which results from the entry of the m^{th} shock into the quartz, to the change in interface velocity $\Delta u_x = u_{x+1} - u_x$. Our region of interest in laboratory coordinates extends a distance $(U_x + u_x)\tau$ to the right of the position occupied by the interface at the instant of shock entry into the quartz. If the shock amplitude were zero, the change in the total number of wavelengths of light in this region (considering that the light travels through the region once in each direction) during τ would be $-2n_x u_x \tau / \lambda$; this is the condition for $\Delta N_x = 0$, since the mirror spacing would remain constant for a shock of zero amplitude, i.e., no shock at all. The actual fringe count ΔN_x will be equal to the difference between the actual change in the number of wavelengths in the region of interest and the change calculated above, because this difference is the number of half-wavelengths change in mirror spacing.

The original number of wavelengths in the region of interest is $(2n_x \tau) / \lambda (U_x + u_x)$, while the final number is $(2n_{x+1} \tau) / \lambda (U_x + u_x - u_{x+1})$. The actual change in the number of wavelengths is the difference of these quantities. Subtracting the condition for $\Delta N_x = 0$ gives

$$\Delta N_x = \frac{2\tau}{\lambda} \left| n_{x+1} (U_x - \Delta u_x) - n_x U_x \right| . \quad (8)$$

The absolute value signs are used in (8) because otherwise the righthand side could be either positive or negative, whereas ΔN_n , being a number of fringes counted, might be considered as intrinsically positive. However, the variation of the index of refraction with respect to density in shock experiments is such that equation (8) holds for fused quartz, and perhaps for all real materials, if the absolute value signs are removed, a minus sign is inserted in front of ΔN_n , and ΔN_n is defined to have the same sign as Δu_n . Making these changes and solving (8) for Δu_n gives

$$\Delta u_n = \left(\frac{\lambda}{2n_{n+1} \tau} \right) \Delta N_n + \left(\frac{\Delta n_n}{n_n} \right) u_n, \quad (9)$$

where $\Delta n_n = n_{n+1} - n_n$.

Equation (9) is valid even if successive shocks enter the quartz at times less than τ apart, for, referring to equation (8) and dividing by τ we have the equation for the frequency of fringes during the time τ after m^{th} shock enters the quartz. Further, this frequency is constant under the assumption of step changes in u . If the $m+1^{th}$ shock enters the quartz before τ has expired for m^{th} shock, it can be shown that the fringe frequency produced by the following shock, $\Delta N_{n+1}/\tau$, would be added to $\Delta N_n/\tau$ until τ expires for the first-entering shock. Thus, the sum $\Delta N_n + \Delta N_{n+1}$ is unaffected, and in view of our definition of ΔN_n , equation (9) can be considered valid regardless of how closely we space the successive shock approximations to the real wave shape.

Since the spacing of the successive shock steps is immaterial, we can approximate any real wave shape by a very large number of very small jumps in u . Equation (9) then reduces to the differential form

$$du = \frac{\lambda}{2n\tau} dN + \frac{dn}{n} U. \quad (10)$$

In order to proceed further, we must know how the index of refraction of the fused quartz varies with the changes in density which accompany the shocks which enter the quartz.

A simple model of index of refraction pictures photons as traveling through matter with the velocity of light in free space, but occasionally suffering atomic capture and subsequent reemission. The average velocity in a material is smaller than the free space velocity because of the delays between capture and reemission. This model gives the Gladstone-Dale relation between material density and index of refraction:

$$\frac{d\rho}{\rho} = \frac{dn}{n-1} \quad (11)$$

This equation has been confirmed by experiment for gases and vapors¹⁶ and is in fair agreement with experiment for solids. It predicts the behavior of the index of refraction of some liquids,¹⁷ of plexiglas,³ and of fused quartz better than the Lorentz-Lorenz formula.

An experiment was performed to test the agreement of (11) with fused quartz. One disk of fused quartz was impacted against another at a velocity of 182 m/sec, producing a stress of 11.7 kbar. The index of refraction in the shocked region was measured by interferometry looking through the two pieces of quartz along the direction of shock propagation. It was found that

$$\frac{\Delta \rho}{\rho} = \frac{1.146 \Delta n}{n - 1} \quad (12)$$

Let us assume that the index of refraction of fused quartz can be described in terms of the density by the equation

$$\frac{d\rho}{\rho} = [1 + \epsilon(\rho)] \frac{dn}{n - 1} \quad (13)$$

where $\epsilon(\rho)$ is assumed to be a slowly varying function of the density. The assumption seems logical since apparently, $\epsilon(\rho)$ should be zero for gaseous quartz,¹⁶ and at the several orders of magnitude greater density of fused quartz $\epsilon(\rho)$ has a measured value of only 0.146 (c.f. equation 12). Solving (13) for dn/n , and using the equation $d\rho/\rho = du/U$ which expresses the conservation of mass, we obtain

$$\frac{dn}{n} = \frac{n - 1}{n(\epsilon + 1)} \frac{du}{U} \quad (14)$$

Substituting (14) into (10) leads directly to

$$du = (1 - c) \frac{\lambda}{2\tau} dN \quad (15)$$

where $c = \frac{\epsilon(n - 1)}{1 + n\epsilon}$.

Note that this equation becomes equation (4) if the quartz is eliminated, i.e., if $n = 1$, and also that the factor correcting for the presence of the quartz, c , is zero if $\epsilon = 0$. Let it be assumed that ϵ is a constant over the few percent change in density of the quartz involved in the shock experiments considered here. Using $n = 1.45706$ at ambient conditions and at $\lambda = 632.8 \text{ nm}$,¹⁶ and letting $\epsilon = 0.146$, the correction factor in (15) at zero stress is $c = 0.0550$. Our measurement at 11.7 kbar in the quartz gave $n = 1.46341$; this makes the correction factor at 11.7 kbar equal to 0.0557. Thus, c varies only slowly with the stress level. Assuming c to be a constant 0.058 undoubtedly makes equation (15) a good deal more accurate than 1% at stresses up to 100 kbar, providing our assumption of constant ϵ is valid. Additional experiments are necessary to test this assumption.

Letting $c = 0.058$ over the range of u 's of interest, equation (15) can be integrated to give

$$u(t) = 0.942 \frac{\lambda}{2\tau} N(t) \quad (16)$$

Thus, equation (16) replaces equation (4) for interpreting the results of experiments in which a fused quartz window was used.

EXPERIMENTAL RESULTS

The first application of the velocity interferometer technique has been primarily to the study of release wave shapes in 6061-T6 aluminum. Some interesting details of the compressive wave shapes of impact loaded aluminum are also being obtained as a by-product of the experiments. In this section we shall first show the raw and the reduced data for a particular experiment. The collective results of several compressive wave shape measurements is presented next, followed by the measurements of the release wave shapes. Finally, the measured wave shapes are compared with computer solutions of the shock experiments, assuming various elastic-plastic models of material behavior.

Data From Shot 929:

It is customary at this point in a paper to present the results of a "typical" experiment. However, this author cheerfully admits that the data from Shot 929 was selected not because it is typical, but rather because it is the best-looking data obtained thus far. It is hoped that this decision is justified first by the fact that "typical" is difficult to define from the few experiments already conducted with the new technique, and second because the experimental results have improved as we gained experience so that there is every reason to expect that the "best" of today will become the "typical" of tomorrow.

Shot 929 consisted of a 6.48 mm thick projectile plate striking a 12.52 mm target plate at a velocity of 467 m/sec. Both plates were of 6061-T6 Al. The experimental configuration was the same as that shown in Fig. 1; no quartz window was used in this shot. The time for light to traverse the delay leg was 4.369 nsec, which made the velocity-per-fringe constant equal to 0.0724 mm/ μ sec. Three oscillographs of the photomultiplier output are shown in Fig. 8. The time marks below each data trace are spaced at intervals of 0.2 μ sec. In Fig. 8 (a), the first jump in the data trace is about 2/3 of a fringe which results from the jump in free surface velocity at the time of arrival of the elastic wave front. The apparent decay in the trace amplitude during the next 0.2 μ sec is really another 1/2 fringe indicating a gradual increase of the free surface velocity. The burst of fringes recorded next corresponds to the large increase in free surface velocity at the arrival of the plastic wave front. Following this, no further fringes are observed, indicating a constant free surface velocity. Fig. 8 (b) shows a magnified view of the fringes at the time of the plastic wave arrival. The oscillograph of Fig. 8 (c) was taken at a slower sweep speed than Fig. 8 (a). The elastic and plastic wave arrivals are seen on the left, while the fringes on the right indicate the slowing down of the surface which results from the arrival of the release wave from the rear surface of the projectile plate. As stated previously, this type of experiment without the window results in spallation of

Figure 8: Oscillographs from Shot 929

the target plate. The release wave created by the sudden release of tension at the spall plane reaches the free surface as a compressive wave front, causing a sudden increase in free surface velocity. This reversal in acceleration can be seen as the cusp in the data trace just before the last fringe is registered.

The velocity history of the free surface during the arrival of the compressive wave front was measured from the oscillographs of Fig. 8 (a) and 8 (b), and is shown in Fig. 9, curve A. The small hump in the velocity record just ahead of the plastic wave at about 0.275 μsec is caused by the first reverberation of the elastic wave between the free surface and the on-coming plastic wave. Curve B of Fig. 9 shows the complete velocity history until just after spall occurs. The reason for the loss of further data fringes just after spall was probably that the stress waves coming from the rather jagged spall surface ruined the mirror finish of the free surface.

Figure 9:
Free Surface Velocity
vs
Time of Shot 929

Compressive Wave Shapes:

The compressive wave velocity histories of a number of experiments are presented in Figure 10. The specimens were all approximately 12.5 mm thick. The fused quartz window was used in all experiments except the 9.5 kbar data, which has been corrected to the quartz window condition for comparison with the other data. The 9.5 kbar data was obtained using the earlier Michelson interferometer technique.⁹ The curve shown represents an interpolation to a specimen thickness of 12.5 mm from four experiments of varying specimen thicknesses, all of which had impact stresses of about 9.5 kbar.

Figure 10: Velocity Histories for Four Different Impact Stress Levels

Figure 10 shows that the acceleration approaches zero smoothly rather than abruptly after the bulk of the plastic wave has arrived. This is evidence that strain rate effects are playing a part in the stress wave propagation.⁷ The initial amplitude of the elastic precursor is apparently not affected by the peak stress of the impact. Probably the most interesting part of the data is the measurement of the maximum strain rate occurring in the plastic wave fronts. Each doubling of the impact stress appears to increase the strain rate by more than an order of magnitude. A log-log plot of the impact stress vs the maximum strain rate in the plastic wave is fit by a straight line, as indicated in Fig. 11. If the line is extrapolated to about 1000 kbar, and if the maximum possible dislocation velocity is approximately equal to the shear wave velocity,¹⁸ the mobile dislocation density necessary to accommodate the plastic part of the strain rate exceeds 3×10^{13} cm/cm³, which seems prohibitively large. The problem of what happens in a material when the shock wave becomes so strong and so thin that dislocation motion cannot account for the plastic strain rate appears interesting and deserving of further study.

Release Wave Profiles:

Three shots which produced release wave shape data using the quartz window are summarized in Table I. In all cases, the release wave resulted from the

Figure 11:
Impact Stress vs
Maximum Strain Rate
in the Plastic Wave
Front

reflection of the impact shock off the rear surface of the projectile plate. The relatively high stress of 90 kbar in Shot 926 was obtained by using a tungsten carbide projectile nose plate and the maximum velocity capability of our gas gun. The measured velocity histories of these three experiments are shown in Fig. 12. The release wave data are characterized by a lack of structure compared to the elastic-plastic structure of the compressive wave shapes. The mis-match of shock impedance between the tungsten carbide driver plate and the aluminum target in Shot 926 causes the initial release wave from the rear surface of the tungsten carbide to release only a part of the impact stress in the aluminum. The release wave data of Shot 926 stops at 0.44 mm/ μ sec because only the first release wave from the tungsten carbide was monitored.

Table I

Summary of Shots Showing Release Wave Shape

Shot No.	Projectile Material	Projectile Thickness (mm)	Target Thickness (mm)	Impact Velocity (mm/ μ sec)	Peak Stress (kbar)
922	Al	6.46	12.51	.274	21.4
926	Tungsten-Carbide	3.20	12.53	.635	90.3
927	Al	6.50	12.23	.481	37.6

Computer Fits of the Data:

Because of the numerous shock wave and stress wave interactions which influence the measured surface motion, particularly by the time of observation of the release wave, it is impossible to obtain the release character of the material by simple hand calculations. Instead, one must assume various models of material behavior in computer solutions of the impact conditions, and deduce the correct material behavior by comparing the computer-predicted surface motion with that which was measured.

The SWAP 7 program¹⁹ (Stress Wave Analyzing Program) for solving problems of one-dimensional strain is being used to fit the results reported here. It

uses a method of characteristics approach, assumes the material behaves independently of the strain rate, approximates smooth stress wave shapes by a number of small jumps in stress (shocks), and individually solves the numerous interactions which occur as the stress waves propagate back and forth in the shocked materials. The chief virtue of the SWAP 7 program is that the computer running time required for the solution of impact problems is much less than that required by the more common finite differences codes. Typical running times of one or two minutes per problem on a CDC 3600 computer makes it easy to conduct parameter variation studies to match measured data, whereas such studies are much more difficult if running times are an hour or more per problem.

The Hugoniot for fused quartz reported by Wackerle¹⁴ gave computed interface velocities which were consistently higher than those measured. Although such a discrepancy could result from errors in the Hugoniot of aluminum or in the index of refraction's effect on the velocity-per-fringe constant, it was decided to revise Wackerle's quartz Hugoniot to produce a better computer match to the measured peak interface velocities. The main reasons for this decision were that there is considerable scatter attributed to experimental errors in Wackerle's data in the stress range of interest, and that the predicted Hugoniot based on Bridgman's hydrostatic measurements¹⁴ seems to fit the present data better than does Wackerle's Hugoniot. As for the release path, Wackerle's data suggests that the fused quartz remains elastic to 98 kbar. Since the present experiments resulted in a maximum stress of about 75 kbar in the quartz, elastic behavior was assumed, i.e., the release stress-strain path was assumed to be the same as the compressive stress-strain path. It was found that although the peak interface velocity depended on the choice of a Hugoniot for the fused quartz window, the shape of the velocity history was affected only slightly by changes in the Hugoniot and by the assumed release characteristics of the quartz, i.e., the measured surface motion was much more sensitive to the release behavior of the aluminum than the quartz. Letting σ denote stress and ϵ strain, the simplified stress-strain path used in the computer solutions had a slope $d\sigma/d\epsilon = 754$ kbar from $\sigma = 0$ to 12.8 kbar; above 12.8 kbar, $d\sigma/d\epsilon = 710$ kbar was used.

A Grüneisen equation of state, assuming a linear shock velocity vs particle velocity Hugoniot,²⁰ was used for the hydrostatic component of the stress in the 6061-T6 Aluminum. The Grüneisen parameter γ was assumed to be constant at 2.0. A trial run with $\gamma = 3.0$ showed the results to be insensitive to γ . The shock velocity-particle velocity equation used to construct the Hugoniot was $U = 5.27 + 1.37u$, where U and u are measured in mm/ μ sec. Poisson's ratio was also assumed to be a constant 0.336, independent of the stress. Only the yield strength behavior, which governs the deviatoric component of the stress, was varied in matching the measured results.

The Hugoniot of the tungsten carbide driver plate used in Shot 926 has been measured by C. H. Karnes.²¹ For the computer solutions of this shot, Karnes' data was approximated by an elastic stress-strain path with slope $d\sigma/d\epsilon = 7500$ kbar up to $\sigma = 50$ kbar, and thereafter by a "work hardening" stress-strain path with slope $d\sigma/d\epsilon = 6570$ kbar to the 90 kbar impact stress. The release path was assumed to be elastic with a slope of 7500 kbar all the way to zero stress.

Figure 12: Measured Velocity Histories and Comparisons with Computer Predictions

The computer comparisons with the measured data are also shown in Fig. 12. The stair-step shapes of the computer fits are due to the SWAP 7 program's approximations of smooth wave shapes by jumps in stress. The customary hydrodynamic calculation based on the assumption that the material behaves as a fluid is omitted in these figures since other investigators have already amply demonstrated that the hydrodynamic model is a poor one in the range of stresses under consideration.^{2-6,8}

Two elastic-perfectly-plastic fits are shown in Fig. 12, one based on a constant yield strength of 2.4 kbar (dotted lines) and the other on a yield strength which increases with pressure (dashed lines) according to the equation $Y = 2.4 + 0.05 P$, where P is the hydrostatic component of the stress in kbar. The latter seemed to agree fairly well with measurements on 2024 Al according to Erkman.⁵ However, although either of these calculations approximates the present data much better than a hydrodynamic model would, both predict much more structure in the release wave than was observed. The release wave takes on the measured form only if the reverse yield strength on unloading is assumed to be initially small, but to increase at first rapidly and later more slowly with reverse plastic straining. This amounts to a pronounced Bauschinger effect on reverse yielding, which has been previously detected in aluminum impact experiments at the 10 kbar stress level.⁷ The solid line fits shown in Fig. 12 were obtained by letting the compressive yield strength increase from an initial value of 2.4 kbar to 3.0 kbar along a "work hardening" stress-strain path. The tensile yield strength y_t , along the release stress-strain path was assumed to increase from zero to nearly 4 kbar according to the equation

$$y_t = 4[1 - \exp(-800 \epsilon_p)] ,$$

where ϵ_p is the plastic component of the strain along the release stress-strain path. These yield strength assumptions seem to fit all the shot data about equally well although the yield strength is not a function of the hydrostatic component of the stress. This casts serious doubt on the existence of any large dependence of the yield strength on pressure, at least for 6061-T6 aluminum.

The stress vs strain hysteresis paths for loading and unloading of the aluminum according to the three models discussed above are shown in Fig. 13 for Shot 927. It is apparent that relatively small changes in the stress-strain path produce pronounced differences in the predicted velocity profiles. Thus, the error in the stress-strain path incorporating the Bauschinger effect is probably small, provided that the assumption of strain-rate independence is good. Since the strain rate associated with any stress level in the wave shape varies according to the distance of propagation, the stress-strain curve incorporating the Bauschinger effect must represent an average stress-strain path even if strain rate effects are significant.

CONCLUSIONS

The new velocity interferometer has already proved itself to be an extremely valuable tool for measuring the velocity history of either a free surface or an interface between a specimen and a transparent window material. Its accuracy, its response time of as little as two nsec or even less, and its ability

to measure release wave shapes are among its chief attributes. The main limitation of the technique may prove to be the requirement for a mirror finish on the specimen surface, since some materials will not take a mirror finish, and since sufficiently strong shocks appear to degrade or destroy the reflectivity of the surfaces of certain materials.^{11,22} At present it is known only that the technique is usable on aluminum to at least 90 kbar, iron to at least 50 kbar, and tungsten carbide to at least 300 kbar. The fused quartz has served well as a window material to 75 kbar, but there are indications from the failure of two shots generating 90 kbar in the quartz that it may lose its transparency between 75 and 90 kbar.

In the study of 6061-T6 aluminum, it has been found that the maximum strain rate in the plastic wave-front increases very rapidly with increasing stress. The release wave structure was much more smeared out than might have been expected, indicating a strong Bauschinger effect on reverse yielding in the shock loaded aluminum.

Previous work⁷ has shown aluminum to exhibit a small strain-rate effect in its response to shock loading. The strain rate effect is responsible for the rounding of the plastic wave front near the peak velocity in the measurements shown here, for example. It is undoubtedly also a factor in the smearing of the release wave shape, although this part of the data can be fit reasonably well by strain rate independent calculations assuming the Bauschinger effect. The influence of strain rate might be evaluated by studying the release wave shape vs its distance of propagation, which has not yet been done.

Figure 13: Loading and Unloading Stress-Strain Paths for Shot 927 According to Three Models of Material Behavior

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