# SHOCK WAVES IN SOLIDS[1]

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## INTRODUCTION

Shock waves have been important in military and industrial technology at least since the invention of blasting powder. Theorizing about them dates as far back as Rankine's classical memoir of 1870.[2] Yet only now, with improved techniques and instrumentation, are the interactions between shock waves and matter beginning to play a serious research role. The reasons for such long delay in exploiting a potent research avenue are not difficult to understand.

Requirements on instrumentation for shock-wave research are rigorous indeed; and carrying out work with high explosives calls for both isolation and considerable expense (Fig. 1). But probably the most serious barrier has been the paralysis that overtakes the inexperienced mind when it is faced with an explosion. This prevents the novice from recognizing an explosion as the orderly process it is. Like any orderly process, an explosive shock can be investigated, its effects recorded (Fig. 2), understood, and used. The rapidity and violence of an explosion do not vitiate Newton's laws, nor those of thermodynamics, chemistry, or quantum mechanics. They do, however, force matter into new states quite different from those we customarily study. These provide stringent tests for some of our favorite assumptions about matter's bulk properties.

## BROAD ACCOMPLISHMENTS AND APPLICATIONS

Although the laboratories devoted to shock-wave work are very few, their research accomplishments in the last dozen years already are impressive, and the range of applications opened to further development is very broad. Transient pressures as high as 9 million atmospheres have been achieved; this is three times greater than the pressure at the earth's core, and about 18 times higher than the pressure that can be reached in static pressure-generating equipment (Tilsen, 1962). Shock pressures of such magnitude drastically change electronic energy levels in solids, rearrange atoms in lattices, and alter the equilibrium partition of energy in substances.

Thus, such pressures—applied almost instantaneously, and under controlled conditions—have yielded fundamental thermodynamic data (known as equation-of-state data) essential to every science for over two hundred materials at pressures where data could not be obtained by any other means. Changes in crystal structure (such as the familiar graphite-diamond transition)—permanent in some materials, transient in others—have been induced by shock.

Shocks change electrical conductivity too, almost magically making conductors out of such insulators as sulfur and paraffin. Shocks also release electrical charges from piezoelectrics, ferroelectrics, and many insulator materials, producing measurable currents in an external circuit; this effect is already the basis of new developments in transducer materials and applications.

Shocks harden metals and create and alter

[1] *Editor's note:* This article, which provides an excellent introduction to shock waves, is a revision of an article published in *International Science and Technology* for April, 1963 (no. 16, p. 45–52), when the author was affiliated with Poulter Laboratories of the Stanford Research Institute. We are deeply grateful to Conover-Mast Publications, Inc., and to Robert Colborn, Editor of *International Science and Technology,* for permission to republish the article in this volume. Thanks are also due to Professor Duvall for undertaking, on short notice, an extensive revision and updating of the original article for publication here.

[2] Some general references are cited at the end of the article.

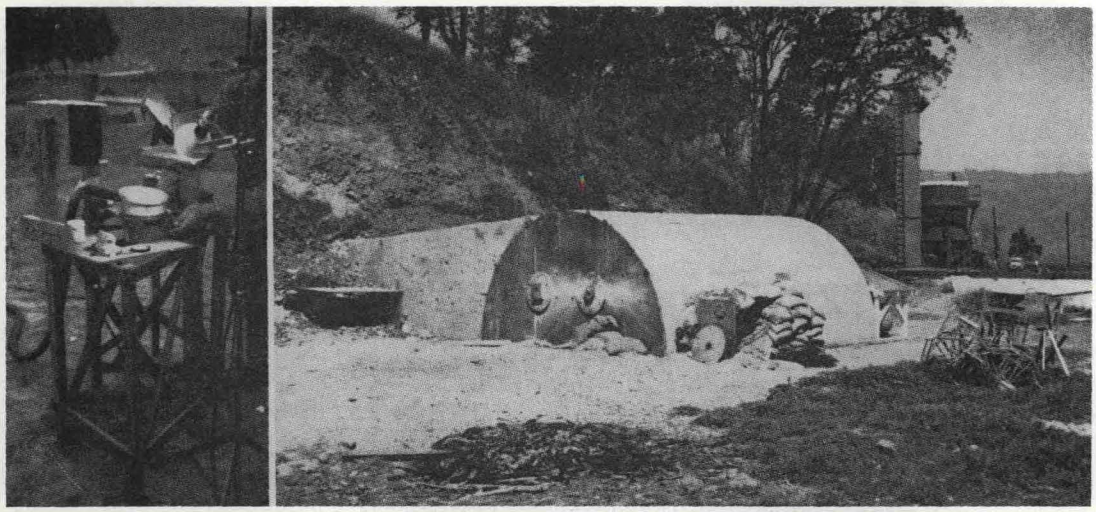

Fig. 1. Typical shock experiment uses firing mount at left, placed in front of armor-plated instrument bunker at right. Streak camera inside bunker views mirror at top of mount through glass ports. Light source for camera is in rectangular box next to mirror. Just below it is specimen assembly, in cylinder with hose attached to vacuum line; below this is second cylinder with explosive and plane-wave generator. The shot reduces entire firing mount to rubble.

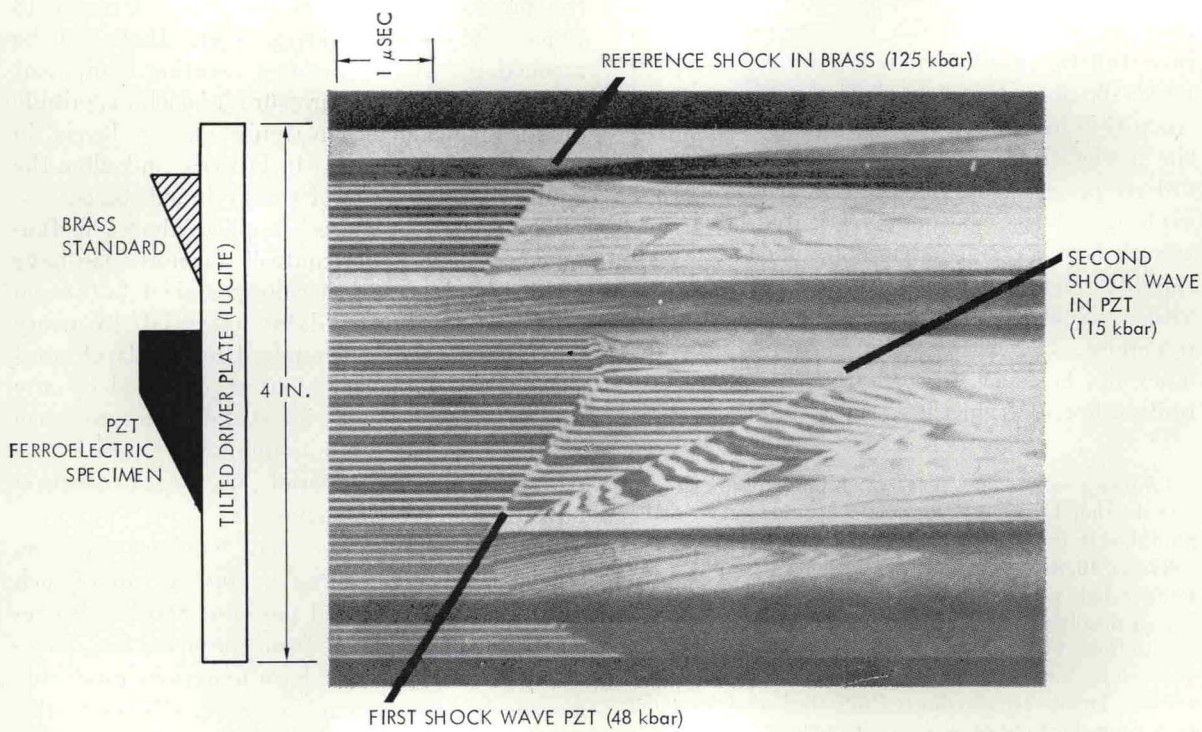


Fig. 2. Streak camera record shows shock arrival preceded by an elastic wave. Reference shock in brass gives needed data on state in the driver plate. Record of this kind yields either shock velocity or the velocity of free surface on specimen. Either one can be used to determine the material's (here PZT) equation-of-state.

vacancies and dislocations in lattices. Shock-induced impact bonding of metals is now commercial (Park, 1962).

In geophysics, shock-wave research in the laboratory has provided some of the first data ever gained on phase changes that may occur deep in the earth's mantle; and in chemistry shock waves have contributed uniquely to understanding kinetics of fast reaction in gases.

But applications and accomplishments thus far, though impressive, are modest and tentative, compared with what shock research may accomplish—if certain of its inherent difficulties can be overcome.

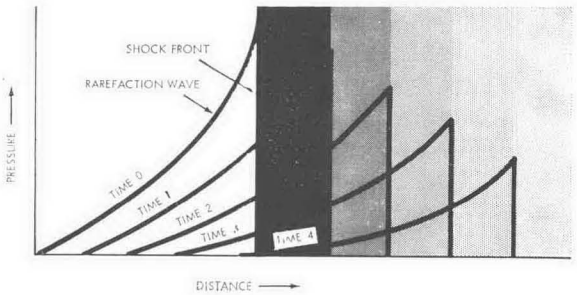


Fig. 3. Rarefaction phase of shock wave—where pressure tails off to ambient from its peak value in shock front—travels faster than shock front itself, progressively overtakes it. This causes entire shock wave to decay in amplitude.

## SOME DIFFICULTIES

There are several serious obstacles to the rapid expansion of shock-wave research. One is the shortage of skilled personnel at all technical levels in the field. Another is the violence of strong shock waves—particularly in solids and liquids. Shocks are usually generated by explosives, and the resulting hazards and noise traditionally force operations to remote sites. Ingenuity and forethought may relax this condition; for example, gas guns for producing shock by impact have already been successfully used near office areas, and enclosed shooting chambers may, in the future, permit the detonation of high explosives in relatively populous areas.

Older techniques for measuring details of shock-wave structure have been limited to time resolutions of about $10^{-8}$ seconds. New electro-optical methods are being developed which promise resolutions approaching $10^{-9}$ seconds (Barker, 1967). Details of shock structure provided by such resolution are expected to provide important new insights into parameters of dissipation and relaxation in solid materials.

Last, shock-wave research on solids and liquids is relatively expensive. A minimum installation for making quantitative, dynamic measurements probably costs on the order of $100,000, aside from the cost of a remote location. Because experimental assemblies are complicated and require precision manufacture and assembly, the cost of each fully instrumented shot is at least about $1000, including data analysis. Moreover, the thought of an elegant and precise assembly being destroyed in each experiment is almost more than some scientists can bear, and this approach to experimentation calls for a psychological readjustment on the part of many experimenters.

Applications depend largely on the effects a shock wave has on the material through which it passes. However, the material reciprocally affects the structure of the shock wave itself, altering and complicating it. One of the chief goals of basic shock-wave research is to unravel the connections between the original structure of a shock, the properties of the material through which it travels, and the effects upon the shock of its brief journey through the material. The better we understand these relationships, the more likely become applications that we cannot now foresee.

## CHARACTERISTICS OF SHOCK WAVES

We all know what a shock wave is, in a sense—it is the boom from a supersonic aircraft, the crack of a bullet, or the blast from an explosion. Yet a more precise definition of a shock wave is not so easy to formulate. We commonly use the term to refer to any almost-instantaneous increase in the value of stress or pressure in a material, so long as the velocity with which the stress transition travels through the material is greater than the velocity of sound in the substance. Also essential to our definition is the idea that the stress transition retains its characteristic abruptness as it travels through the medium. As shown in Figure 3, the abrupt transition itself is

called the shock front, or shock; it is the compressive phase of the entire shock wave. Behind this, where pressure tails off rapidly from its peak value to its pre-shock ambient value, is the wave's rarefaction phase.

Immediately ahead of the shock front at any instant, the material through which the shock is propagating remains undisturbed, blissfully unaware of what's to come. But an infinitesimal distance behind the shock front the material is in the shocked state: it's compressed to a higher density, and its constituent particles are accelerated. This additional particle velocity behind the shock, added to the wave's propagation velocity, permits the rarefaction portion of the shock wave to travel faster than the shock front itself. Therefore, the rarefaction part of the wave gradually overtakes the shock front and, as suggested by Figure 3, the entire shock wave simultaneously lengthens and decreases in amplitude as it travels. In a sense, the shock front—by accelerating particles as it passes—sets in motion the cause of its own ultimate undoing.

The details of shock-wave structure depend upon how the wave was generated, how far it has propagated, geometry of generation and of the medium, and upon the material properties of the medium itself. It is this last which is most often of interest, and in consequence, the attempt is made to generate incident shocks so that their detailed structure can be related to properties of the medium. This requires that the experimental geometry be simple and calculable: therefore shock waves for dynamic measurement are most often generated in plane geometry where the direction of propagation and the lapse of time since propagation are the two independent coordinates. This can be done in several ways.

## HOW TO MAKE PLANE SHOCK WAVES

This may be accomplished by shaping the detonation in an explosive to form a plane wave or by accelerating a flat-faced projectile in a gun and allowing it to impact on the plane face of the target.

In the first case the explosive may be placed in direct contact with the target, as in Figure 4B, or it may be used to drive a flyer plate which produces a plane shock in the target on impact, as in Figure 4A. The flyer plate produces higher pressures than the contact explosive because it accumulates momentum from the explosive during its entire flight across the gap and delivers it to the target in a very much smaller time. Flying plate pressures up to nearly 10,000 kilobars have been reported by Russian scientists (Kormer *et al.*, 1962); flier plates are commonly used at pressures as low as 300 kilobars. The price paid for flier plate data is high in dollars and in loss of quality, but when high pressures are required, they can be achieved in this way.

When explosive is in contact with the driver plate, as in Figure 4B, a point initiation is again converted into a plane wave by a lens. This plane detonation wave impinges directly on the driver plate, inducing in it a shock pressure which increases with its mechanical impedance. This factor, as we shall see, determines the peak pressure that can be induced in the driver plate and hence in the specimen.

Since the detonation wave in the explosive is itself a shock wave—driven by expansion of the chemically reacting gases behind it—one might reasonably ask, why not use this shock wave directly? Why interpose between this detonation shock and the specimen all the impedimenta shown in Figure 4—especially the explosive slab and the driver plate? In essence, the answer is that the driver plate smooths irregularities in the detonation front, improving resolution.

Moreover, introduction of the driver plate and explosive slab into the array gives us three independent parameters for controlling the shock pressure finally induced in the specimen: (1) the kind of explosive used; (2) the material of the driver plate; (3) the ratio of driver-plate thickness to explosive-slab thickness. Thus, for example, the range of pressures that can be produced in a single material with the kind of setup in Figure 4B is about four to one. Pressures attainable are in the 100–1500 kbar range, intermediate to those obtainable with the flying plate or gun-launched projectile discussed below.

The use of guns to drive projectiles against flat target plates, thus producing shocks by impact, has been increasing in recent years. The reasons for this are several: the initial investment in a

gas gun is probably somewhat less than required for an explosive site, better shock amplitude control is achieved through control of projectile velocity with gas pressure and volume, the gun is better adapted to laboratory operation, and safety problems are perhaps somewhat less than

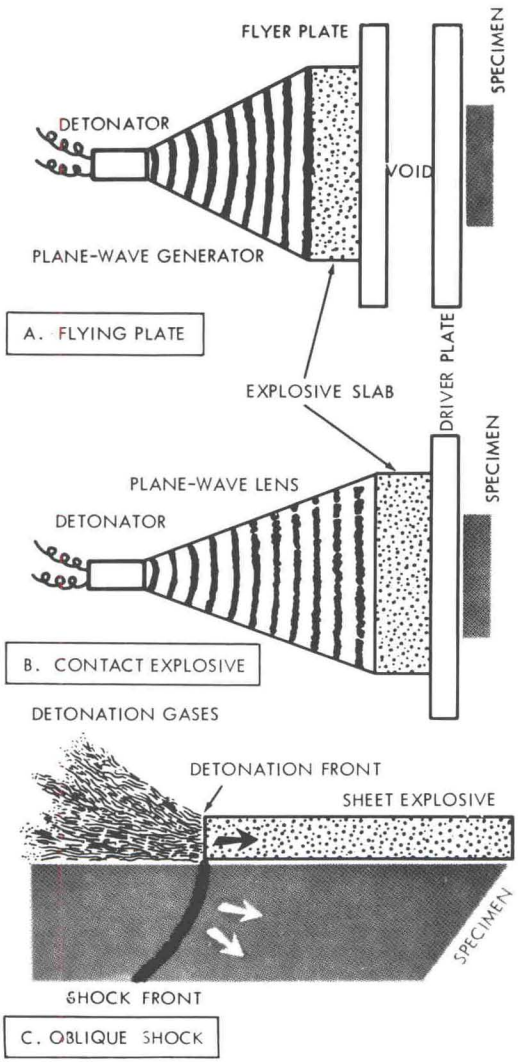


Fig. 4. Explosive methods to deliver shock to a specimen differ in cost, pressures they can attain, and ease of interpretation: (Top) Flying plate is most difficult, usually most costly, but attains highest pressures; contact explosive reaches intermediate pressures at comparable or slightly lower cost; Oblique shot is least expensive of methods shown, achieves only low pressures, requires large sample, and geometry complicates interpretation.

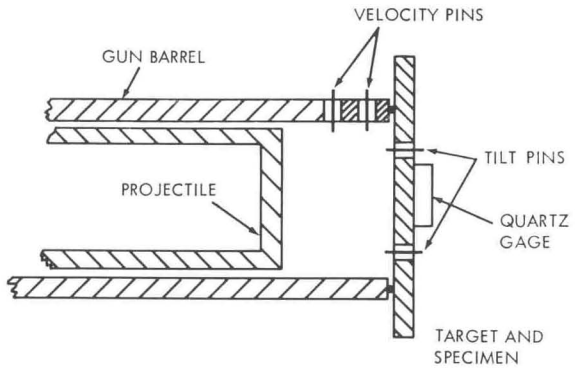


Fig. 5. Schematic arrangement for a shock experiment using a gas-driven projectile.

with explosive handling. Early gun models were limited to low projectile velocities and shock pressures of a few tens of kilobars. The art of gun design has improved and pressures of several hundred kilobars can be obtained with single stage gas guns, while pressures of several megabars have been produced by two-stage guns (Jones *et al.*, 1966).

A gun experiment is shown schematically in Figure 5. The shock detector at the right may be a quartz or manganin gage or one of the systems commonly used in explosive experiments (Linde and Schmidt, 1966).

## PRODUCTION OF OBLIQUE SHOCK WAVES

A fourth shock-generating method, the method of oblique detonation shown in Figure 4C, differs from the others in geometry, yielding a curviplanar shock instead of a one-dimensional one. The chief advantages of this method are: first, it offers lower pressures than any other explosive method (18 kbars in aluminum, for instance), making it useful in attempts to correlate shock work with static high-pressure studies; second, it offers a continuous record of both pressure and density from a single experiment, making it valuable for equation-of-state measurements; third, it is the least costly way to make shocks, because large, precise plane-wave generators are not required to initiate detonation. Disadvantages arise from the more complex geometry of the shock wave, which makes data interpretation more difficult than in other methods.

We now know what shock waves are, and how to generate them. Next, let's trace the energy delivered from explosive to specimen further along its path to dissolution.

## THE SHOCK EQUATIONS

Back in Figure 4B, for example, when the plane shock wave in the driver plate reaches the interface between driver plate and specimen, part of the wave is transmitted into the specimen, and part is reflected back into the driver plate. In order to determine the amplitude (and ultimately the energy) of the transmitted wave, we must use the equations which describe the effects of shock transition on both the mechanical and the thermodynamic states of the medium.

These equations express the fact that mass, momentum, and energy are conserved in the shock transition:

$$u_1 = (p_1 - p_0)/\rho_0 U \tag{1}$$

$$U^2 = V_0^2(p_1 - p_0)/(V_0 - V_1) \tag{2}$$

$$u_1 = [1 - (\rho_0/\rho_1)]U \tag{3}$$

$$E_1 - E_0 = \tfrac{1}{2}(V_0 - V_1)(p_1 + p_0) \tag{4}$$

In these equations, which apply precisely to a shock which connects two uniform states—indicated by the subscript (0) for an initial unshocked state, and (1) for a subsequent shocked state—$p$ is the component of compressive stress parallel to the direction of shock propagation. Density is denoted by $\rho$, and its reciprocal—the specific volume—by $V$. The velocity of propagation of the shock relative to the unstressed material just ahead of it is $U$. As mentioned earlier, the shock compresses material to a higher density, and simultaneously increases its particle velocity by $u_1$. The work done on a unit of mass by the force driving the shock thus shows up as an increase in the internal energy per unit mass of the shock, $E$, along with an increase in kinetic energy. Equation (4) represents this energy conserved with kinetic energy eliminated by means of Equations (1) and (3).

Equation (4), known as the Rankine–Hugoniot relation, plays a key role in shock theory. Its particular importance depends on the fact that it contains no velocity terms—only thermodynamic quantities.

When the Rankine–Hugoniot relation is combined with the equation of state of any material, a unique relation between $p$ and $V$ is obtained. This relation is called the Rankine–Hugoniot (R–H) curve of the material (see Fig. 6). This curve expresses the locus of all states ($p_1$, $V_1$, $E_1$, and so on) that can be reached from an initial state ($p_0$, $V_0$, $E_0$) by shock compression. In an analogous way, the ordinary adiabat or adiabatic curve may be defined as the locus of all states that can be reached from the initial state by adiabatic compression.

At the point B, which represents initial unshocked conditions in the material ($p_0$, $V_0$, $E_0$), the R–H curve and the adiabat through point B have the same slope and curvature, but only at that point; at all higher pressures the R–H curve lies above the corresponding adiabat, because unlike adiabatic compression, shock compression dissipates energy, and is, therefore, irreversible.

As shown in Figure 6, the increase in internal energy in a shock whose pressure amplitude is $p_1$ is represented by area ABCD. Loss of energy in a shock can be illustrated by comparing this area thermodynamically with that associated with a weaker shock, area ABC′D′, for example. It can also be shown by simple calculation that just as

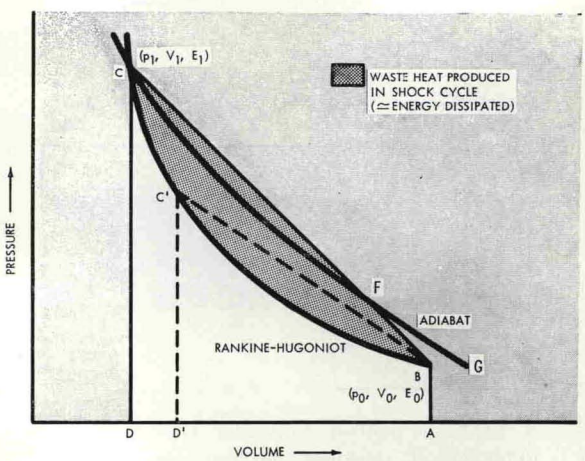


Fig. 6. The Rankine–Hugoniot curve defines states that can be induced in substance by shock compression in terms of pressure ($p$), specific volume ($V$), and internal energy ($E$). Shock compression from initial state B to shocked state C follows the straight line BC. Expansion follows the adiabat CFG. The energy dissipated in shock is approximately equal to the gray area.

the internal energy increases or decreases as the shock is stronger or weaker, so the entropy of the final shocked state also increases with the shock strength. Although such calculations are valuable in computing the entropy of the shocked state, they are insufficient for calculating the total energy dissipation resulting from passage of the shock wave. However, referring again to Figure 6, the gray area (BCC'B)—bounded below by the Rankine–Hugoniot curve and above by the straight line connecting the initial, unshocked point B with the final shocked state C—is a fair approximation to the energy dissipated in the shock cycle, sometimes called the waste heat of the cycle. It is difficult to determine an exact expression for energy dissipated because thermal stresses are left behind in the material, even after the shock pressure has been relieved. Therefore, a precise calculation of the true energy dissipation in a decaying shock must account for hard-to-evaluate effects of thermally induced after-flow in the material. In practice we settle for the waste heat approximation.

We are now prepared to intelligently conclude our discussion of how a shock wave gets across an interface between two media—as from driver plate to specimen in Figure 4. Such transmission phenomena determine the magnitude of shock we finally get in the specimen, for a given combination of explosive and driver plate characteristics. They are also basic to determining the equation-of-state for unknown materials, using shock data.

## PROPAGATION AND TRANSMISSION OF SHOCKS

Every unique Rankine–Hugoniot curve derived from relations between pressure and specific volume—as in Figure 6—transforms to an equally unique relationship between pressure and the velocity of particles in the material. Figure 7 shows such curves for both the shock incident in the driver plate (OA), and the shock transmitted into the specimen (OB).

However, there is an all-important third wave in shock interactions that we also must consider. This is the wave *reflected* back into the driver plate from its interface with the specimen. This can be either a compression or a rarefaction. The

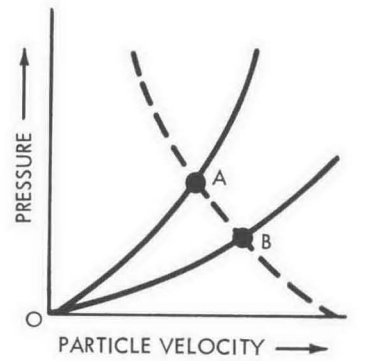


Fig. 7. Matching of interface conditions.

difference is critical because if it is compressive the shock transmitted to the specimen will be even stronger than that originally incident in the driver. But if, instead, the reflection is a rarefaction, the transmitted shock will be weaker than the incident.

The nature of the reflected wave, therefore, is part of the answer to an important practical question—what experimental conditions are necessary for achieving in a specimen a shock of specified pressure?

In Figure 7, the reflected wave is represented by cross-curve (AB), approximately the mirror image of the R–H curve (OA). Such a cross-curve plays the same role for reflected waves as do R–H curves for direct waves: it defines conditions that exist in a material as a result of a wave's passage.

For a given experimental arrangement, if conditions of pressure and particle velocity in the wave reflected back into the driver lie above point A on cross-curve (AB), the reflection is compressive. If, on the other hand, the reflection lies below point A, it is a rarefaction. Point B represents conditions common to both driver plate and specimen (at their interface only), and it is evident that the reflection illustrated is a rarefaction, and that the transmitted wave is weaker than the incident one.

This would be the case for a set up that combined a relatively harder driver—steel, for

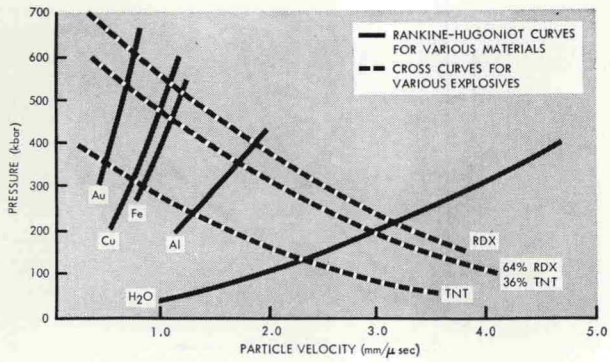


Fig. 8. Representative pressures that can be generated in various materials by different explosives are shown by points where curves cross. For example, a detonation wave in an explosive made up of 64% RDX·36% TNT, incident on aluminum, yields 360 kbar pressure.

instance—with a relatively softer specimen such as lucite. Reversing the relative hardness of driver and specimen would, of course, reverse the relative strength of transmitted and incident shocks.

These transmission concepts underlie the curves of Figure 8. This figure shows plane shock-wave pressures that can be reached in various materials with various explosives. The pressure that is attainable for a given combination of material and explosive lies at the intersection of the curve for the material with the curve for the explosive. For example, a plane detonation wave in an explosive made up of 64% RDX and 36% TNT, incident normally on aluminum, induces a shock pressure of about 360 kbars in the aluminum; in water, the same explosive would induce a pressure of only about 190 kbars.

All well and good; now let's get some idea of the data that come out of a shock experiment, and of how to get these data.

## VELOCITY MEASUREMENTS

We return to the experimental setup of Figure 4B. As the shock passes from driver plate to specimen, either the shock's velocity, or the free-surface velocity in the specimen, or both, are to be measured. How?

One method uses the familiar principle of the optical lever. As the incident shock wave produces small rotational displacements in an inclined polished surface on the specimen, reflections of light—incident on the same surface from point sources—are displaced a greater amount via appropriate reflection geometry. Reflections are recorded on film by a streak camera as a series of light streaks, against a base whose abscissa is time and whose ordinate is distance. Figure 2 shows such a record. Wave arrivals at points on both specimen and reference standard are indicated by abrupt displacements of successive traces.

The speed of the shock along the free inclined surface of the specimen is obtained from such a record by measuring the slope of the line that connects the same wave break in adjacent light traces.

An interesting feature of this record (Fig. 2) is that the first deflection of light traces in PZT is produced by an elastic wave that precedes the main shock wave. Since this elastic precursor travels with constant velocity, regardless of its amplitude, the first break in the light traces forms a straight line. But in the shock wave that follows it, the velocity is continually changing; and a trace-by-trace measurement must be made to determine the local slopes and velocity values in the decaying shock.

Another light-reflection technique for recording motion of shocked surfaces is based on the apparent change of reflectivity of polished or mirrored surfaces when they are struck by a shock wave. Figure 9 shows a streak camera record obtained from such a setup.

This technique allows the specimen's free-surface motion to be monitored continuously; hence, it is particularly useful where the wave in the sample consists of more than one shock front, as is the case in Figure 9. But the method is sensitive to both tilt and nonplanarity of the shock, so that good plane-wave generators are essential to its successful use.

Non-optical methods also can be used for measuring shock and free-surface velocities in specimens that are electrical conductors. One such is called the pin method, in which motion of a shock-accelerated surface closes a gap and strikes a pin. This short-circuits an RC network, which discharges through an oscilloscope. If the pin position is accurately known and the RC

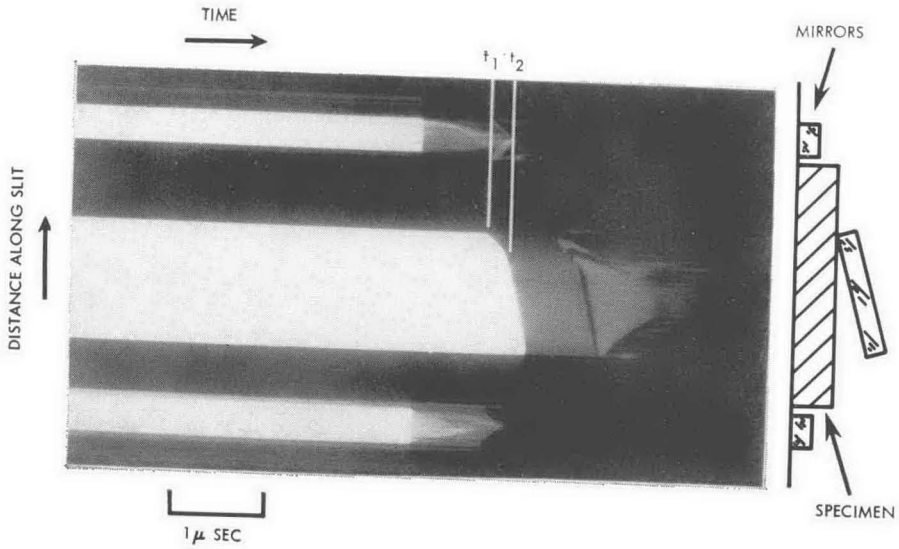


Fig. 9. Streak camera photograph of two shocks in $BaTiO_3$ (arrival times $T_1$ and $T_2$) affords both shock and free-surface velocities by measurement of the slope of successive light traces.

discharge recorded, the time at which the shock-accelerated surface reached that position is known. If several pins are used on a single specimen, an $(x, t)$ plot of its motion can be made and its velocity obtained by differentiation. Such a pin record from a raster oscilloscope is shown in Figure 10.

But none of these data-taking methods is ideal; all are relatively delicate to arrange; and all involve rather complex subsequent reduction of the data.

## PRESSURE TRANSDUCERS

There are a number of variations to the techniques described above for measuring shock parameters (Deal, 1962), all being suited for some particular material or application. A different approach is to use a transducer to record pressure or stress directly. Two philosophies are used in the use of transducers: one is to imbed a sensing element in the material, minimize the perturbation it causes, and ignore it. This approach is commonly used in sound field measurements. The other is to let the perturbation be as big as it need be, but calculate it. The latter approach has been successfully used in shock measurements. The transducer is made as large as the specimen with its flat face in contact with the specimen face. Reflection of the shock occurs at the specimen-transducer interface, and the change in shock amplitude is calculated by the procedure indicated in Figure 7. Two such transducers have been successfully used: the single-crystal quartz

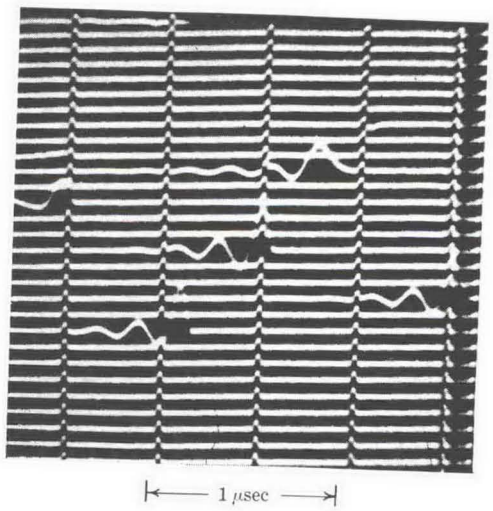


Fig. 10. Pin method for measuring shock and free-surface velocities in specimen uses motion of its shocked surface to close a gap and strike a pin, short-circuiting an R–C network which discharges through a raster oscilloscope to yield record.

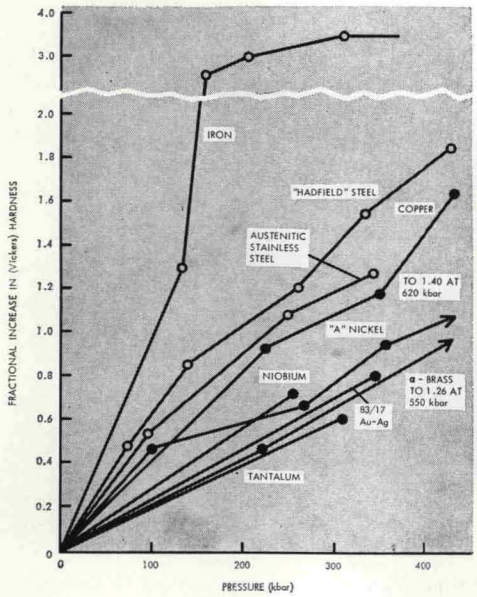


Fig. 11. Increase in hardness of shocked metals relative to their hardness in pre-shock, annealed condition is impressive. Curves cannot be extrapolated upwards indefinitely, however, because rapid rise in heat induced by shock would also have annealing effect. This would eventually surpass hardening effect, reversing slope of the curves.

transducer which produces a piezoelectric signal proportional to the difference in pressures at its two faces (Neilson *et al.*, 1962) and the manganin wire transducer which records pressure-induced changes in resistivity near the interface (Bernstein and Keough, 1964). Both these devices have their deficiencies, but both are useful under special circumstances. Contact pins of polar or ferroelectric materials, in which a thin wafer is compressed by the moving surface, thus generating a voltage, are also being used.

Work is in progress toward the development of a manganin gage which can be imbedded in the medium under study, but its successful development may be long in coming (Keough and Williams, 1967).

## MORE APPLICATIONS AND SOME AFTERTHOUGHTS

At this point in our discussion, it will surprise nobody to hear that shock waves can alter the electrical and electronic properties of matter, often permanently. But studies of such effects have been less vigorously prosecuted than studies of mechanical effects.

Electrical effects which have been observed in shock include changes in electrical conductivity, polarization of insulators, depolarization of ferroelectrics, anomalous Peltier coefficients, and shifts of Curie temperatures (Doran and Linde, 1967). Most of the observed effects appear explicable on the basis of volume compression and deformation. The extent to which the rapid transient effects in the shock play a role is not yet known.

Shock-induced luminescence has been observed and usually appears to be due to compression of gases to high temperatures, to internal electric fields, or to triboluminescence. Here again the role of shock transients has not been delineated (Doran and Linde, 1967).

The most-used mechanical effect of shocks has been simple volume compression which provides basic data for high pressure equations of state (Kormer *et al.*, 1962). However, the stress produced in a plane shock wave is anisotropic. In consequence the shock is often preceded by an elastic precursor, whose amplitude is a measure of dynamic yield, and the shear stresses in either the precursor or the shock wave may produce material effects such as martensitic transformation, twinning, and dislocation multiplication. These effects are observed in microscopic exam-

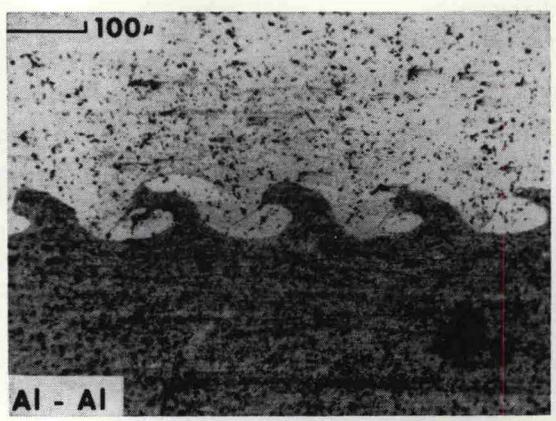


Fig. 12. Both size and shape of ripples at interface between explosively bonded aluminum alloys depend on velocity and impact angle in contact, aid diffusion of atoms across interface by straining surfaces at high rate, provide interlock.

ination of shocked specimens; they also influence macroscopic properties.

Figure 11 illustrates how the Vickers hardness of many metals increases as a function of shock pressure. Although hardness in the pressure range shown increases monotonically with pressure, it would be misleading to leave you with the thought that this can be extrapolated *ad infinitum*. Ultimately the curves must reverse in slope because of the annealing effect that would be produced by a rapid rise in heating induced by shock.

Another lively area of application of the shock wave art is one we mentioned earlier, bonding of dissimilar metals. Figure 12 shows an interface between hardened and annealed aluminum alloys, which was produced by firing the upper plate against the lower. Both atomic diffusion and simple mechanical locking probably play a role in this kind of bond.

The appearance of these Proceedings and the work which led to it are evidence that the application of shock wave techniques to geological studies is of far greater importance than was realized five years ago. It is not likely that the Conference reported here will be the last such. It and others to follow will be firm evidence of the broad utility of new techniques in science which extend our abilities to influence the states of matter.

Besides these geological applications, it may be expected that shock wave research will continue to contribute to the understanding of solid state and metallurgical processes which are influenced by rapid changes in stress, volume, and temperature. The applications of such research will be limited only by the imagination and pocketbook of the scientist and by the hard facts of nature.

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