Dynamic pressure measurements to 300 kilobars with a resistance transducer

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Abstract. A method has been developed for measuring the pressure–time profiles of the stress waves produced in solids by explosives. The system uses the linear variation of resistance with pressure in a manganin wire. Various pressure profiles are presented, illustrating a range of shock phenomena; in particular a two-wave structure has been detected in glass and granite between pressures of 100 and 200 kb. A large rounded pressure wave observed in glass is attributed to the adiabatic compressibility initially increasing with increasing pressure, a variation opposite to that usually found in solids. A simple treatment is given by which the pressure–volume relationship can be found in this region from measurements of the pressure–time profile. The resulting curve for glass is not inconsistent with measurements by conventional methods in the high pressure single shock region.

1. Introduction

In most materials intense compressions are propagated as shock waves. The material properties on either side of the shock are conventionally described by a 'Hugoniot Equation of State', that is a relation between pressure and volume applicable to the shock process. Shock and free surface velocities can be measured, and particle velocity inferred from the latter. A pressure–volume point is obtained by substituting these values in the Rankine–Hugoniot equations (Rice *et al.* 1958). This technique has been used satisfactorily up to at least 5 Mb.

Recently however, interest has focused on compression waves in geological materials at pressures below 100 kb. With such materials at these pressures, compression characteristics often depart from the simple form required for the propagation of a single shock. Such departures have been reported for marble (Dremin and Adadurov 1959), granite (Lombard 1961) and quartz (Wackerle 1962); they have been attributed to either polymorphic transitions or large elastic waves. The more complex pressure–time profiles of stress waves under such conditions were found to cause existing methods for the measurement of shock and free surface velocities and their subsequent interpretation to yield misleading or erratic results. It was therefore decided to attempt to devise a pressure transducer which would enable the pressure profile generated by a substance to be recorded directly. It is shown how this was achieved, and how in some cases a pressure–volume adiabat can be calculated from the pressure–time profile.

2. The pressure transducer

The resistance of most metals decreases with pressure (Bridgman 1952) and increases with temperature. When a metal is subject to an isothermal compression the resistance alters due to two effects, the change of dimensions and a variation of resistivity, the latter effect predominating. In a dynamic experiment the pressure impulse is accompanied by a temperature rise, which for the more incompressible metals is of the order of a few hundred degrees Celsius. Bridgman (1949) has shown that the temperature coefficient of resistance for metals is nearly independent of pressure, and recent data over larger ranges (Kaufman *et al.* 1962) has tended to confirm this observation. The pressure and temperature in a dynamic experiment affect the resistance in opposite directions, but in practice with common metals the temperature effect is dominant and the resistance increases.

The basic form of the transducer is a thin wire embedded in an insulating material, mounted parallel to the plane shock front and fed from a constant current supply. A typical schematic arrangement is shown in figure 1. Any resistance change as the wire is compressed is detected by recording the voltage across the wire on a high speed oscillograph. Since in practice the transit times across the wire for stress waves are shorter than the time resolution of the system, the pressure in the wire is assumed to have become equal to that in the surrounding insulator at the time the measurements are made. The voltage across the wire is made sufficiently large to be recorded without amplification, but to avoid electrical overheating it is only applied a few microseconds before the stress wave reaches the wire.

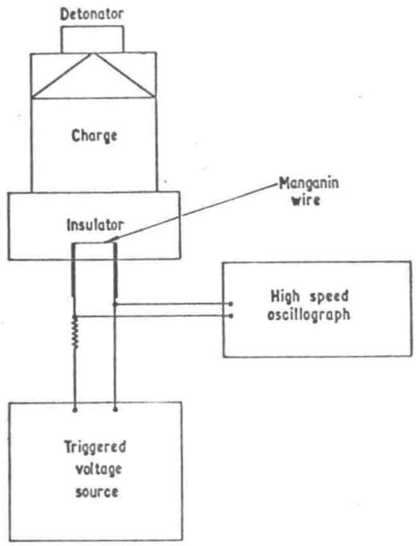

Figure 1. The general arrangement. For simplicity only one wire is shown, but in practice four wires with separate circuits are normally used.

2.1. *Transducer material*

An ideal metal for use as a transducer should have the following qualities:

(i) when it is dynamically compressed the change in resistance due to pressure is much larger than the corresponding change due to temperature;
(ii) the change in resistance is large enough to measure easily;
(iii) the resistivity is sufficiently high for a suitable resistance to be obtained from a reasonably short wire.

As the temperature effect predominates in common metals, only those alloys with abnormally low temperature coefficients are likely to be usable. Some information is available on the resistance under pressure of constantan (Bridgman 1957) and manganin (Bridgman 1949 pp. 70–76, 1950). Constantan is not very suitable for whilst the temperature effect is small the pressure effect is also small, being only a 3% decrease in resistance at 100 kb.

The behaviour of manganin however is more satisfactory, the resistance variation being very small over a wide temperature range, and the pressure coefficient of resistance constant and positive; Bridgman measured a 6% increase in resistance at 30 kb.

2.2. *Insulator material*

The next problem is to find an insulator that retains a high resistivity at the required shock pressures and temperatures. In addition the insulator should be a liquid or a castable solid so that air is not trapped round the wire, where it would ionize and conduct when the system is compressed. There is little relevant information in the literature on the behaviour of insulators when shocked. David and Hamann (1960) have shown that the resistivities of water and some insulating liquids fall rapidly with increasing shock pressure.

The resistivity of several insulating materials was measured under shock compression. Of these, epoxy resins showed the best performance; for example the resistivity at 250 kb was found to be not less than 1500 ohm cm for a duration of about 1 μsec after the shock front had passed. The Hugoniot for epoxy resin was calculated from velocity measurements so that the relationship between pressure and shock velocity could be found.

In order to estimate the effect of conduction in the insulator on the resistance of the pressure transducer, some measurements were made using an electrolytic tank analogue. The data obtained, together with the shock resistivity results, showed that a 3 ohm manganin wire in epoxy resin with the geometry employed can be used up to 300 kb without appreciable shunting due to the insulator.

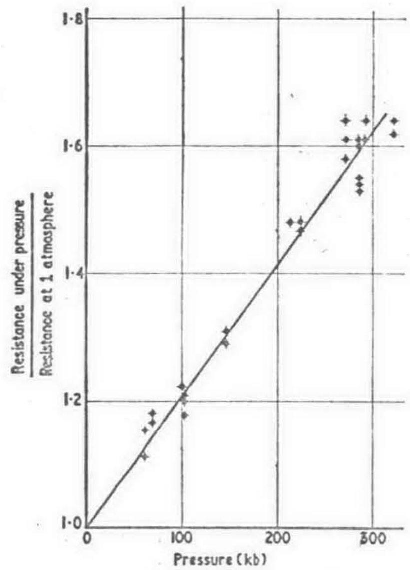

Figure 2. Dynamic resistance–pressure calibration of the manganin wire transducer.

2.3. *Calibration*

The final form of the transducer consisted of a 0·0046 cm diameter manganin wire of 3 ohm resistance soldered between the ends of two parallel 0·132 cm diameter brass tubes mounted 1·43 cm apart in epoxy resin. A series of experiments was carried out in which the resin transmitted shock pressures ranging from 0 to 300 kb. In each experiment the shock velocity in the resin, measured by concentric shock-actuated switch pins, gave the shock pressure using the known Hugoniot curve. Some of the points previously published (Fuller and Price 1962) have been revised, and new points have been added. The results are shown in figure 2. It will be seen that Bridgman's linear result to 30 kb has been extended to 300 kb. The pressure coefficient of resistance is +0·002 10 per kb, with a standard deviation of 0·000 03, for manganin of composition 86% copper, 12% manganese and 2% nickel. This was obtained by linear least squares fit, minimizing errors in resistance and constraining the line to pass through the point ($P = 1$ atm, $R/R_0 = 1{\cdot}000$).

3. Applications

3.1. *Pressure profiles*

The transducer has proved capable of giving reproducible pressure–time profiles of a variety of shock systems. Some examples are shown in figures 3 and 4. Multiple pressure waves have been recorded from a shock reverberating in an acetone layer between a steel plate and the epoxy resin block. Two pressure waves have been recorded from the

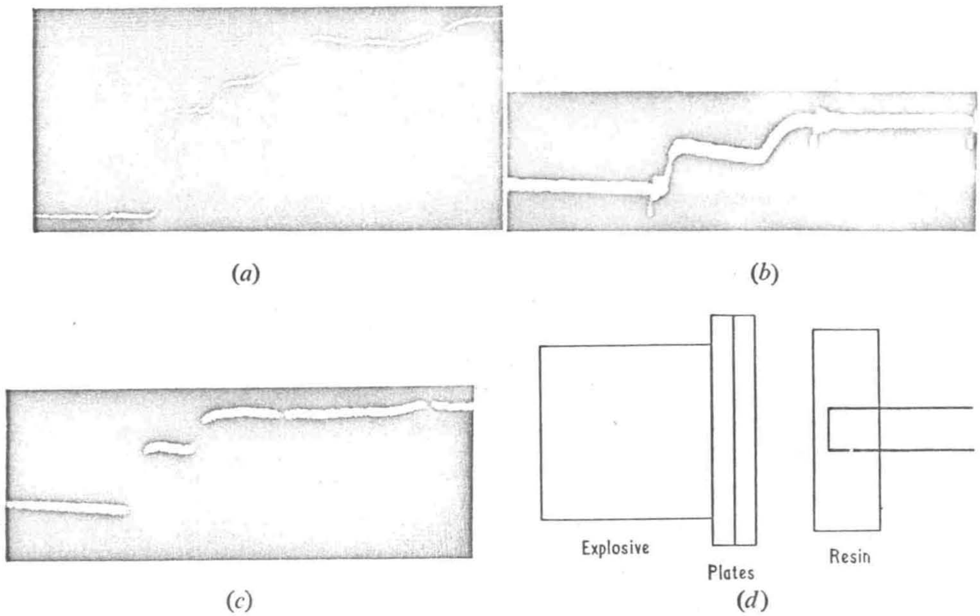

Figure 3. Pressure–time profiles (with time marker pulses 0·5 μsec apart). (*a*) Multiple shocks in epoxy resin from reverberations in a thin acetone layer; first shock 100 kb. (*b*) Shocks in epoxy resin from the successive impact of two flying plates; first shock 65 kb. (*c*) A similar profile from a single tin plate showing that lateral splitting has occurred; first shock 135 kb. (*d*) Arrangement of transducer (not to scale) for (*b*); the arrangement for (*c*) was similar with a single plate.

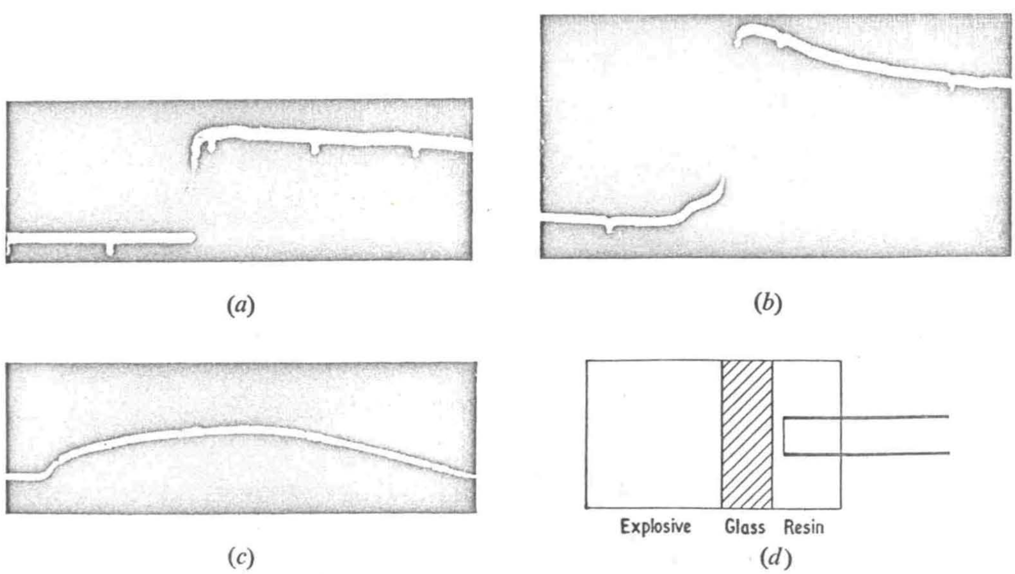

Figure 4. Pressure profiles of two-wave structures in glass. Recorded by wires in epoxy resin, pressures quoted corrected to glass. (*a*) A shock of 280 kb peak pressure; (*b*) a simple compression wave followed by a shock to 200 kb peak pressure; (*c*) a simple compression wave, 50 kb peak pressure; (*d*) arrangement of transducer (not to scale).

successive impact of two flying plates, and this work has led to the detection of the lateral splitting ('scabbing' or 'spalling') of an explosively accelerated tin plate. In addition two pressure waves, the first showing a gradual rise in pressure rather than a step, have been recorded in glass and granite. Further investigation of the wave propagation effects in glass have shown that the high pressure elements of the first compression wave travel slower than the low pressure elements, and that for a large range of pressures this wave may be followed by a shock (Duvall 1962 p. 337).

In all the above examples the pressure recorded is that induced by the particular explosive system in a block of epoxy resin cast round the transducer. The pressure profile in the epoxy resin qualitatively follows the profile in any preceding material in contact with it. To yield quantitative information about this material it is necessary to know its equation of state, so that pressures in it can be calculated from those in the resin. However, even in the absence of such information polymorphic transitions or unusual compressibilities are qualitatively recognizable from the pressure profiles observed.

For materials such as granite and glass, which remain adequate electrical insulators at high pressures, the technique can be extended to measure the actual pressure in the material and to deduce pressure–volume relationships.

3.2. *Pressure–volume measurements*

Glass has been used to illustrate the technique because it is obtainable in a suitable form and is more homogeneous than granite. Manganin wires were sealed between glass plates with epoxy resin. As glass is still a good insulator at high pressures, the manganin wire was placed in contact with the glass. The maximum thickness of the resin layers was therefore the diameter of the wires, about 0·0046 cm. It is assumed that pressure reverberations in this space quickly change its pressure to that in the glass, so that the transducer moves at the particle velocity of the glass and the profile recorded is at the true glass pressure. The velocities of pressure elements of the first simple compression wave were measured from pressure profiles taken at successive points as the waves passed through a glass block. Typical records are shown in figure 5 and the results in figure 6.

The wave velocity at zero pressure D_0 calculated from these experiments is $5 \cdot 5$ km sec^{-1} which agrees with the velocity of sound measured with an ultrasonic tester at $5 \cdot 47$ km sec^{-1}.

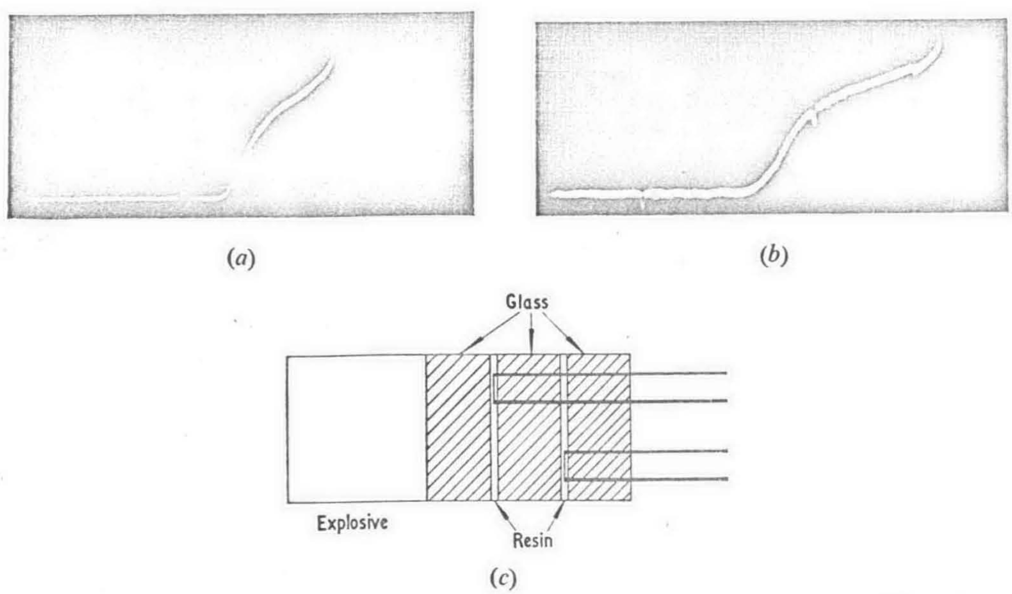

Figure 5. Pressure profiles of a simple compression wave of 100 kb peak pressure, followed by a shock (not shown), produced and recorded in glass. (*a*) After 0·846 cm, (*b*) after 1·48 cm travel, (*c*) arrangement of transducer (not to scale).

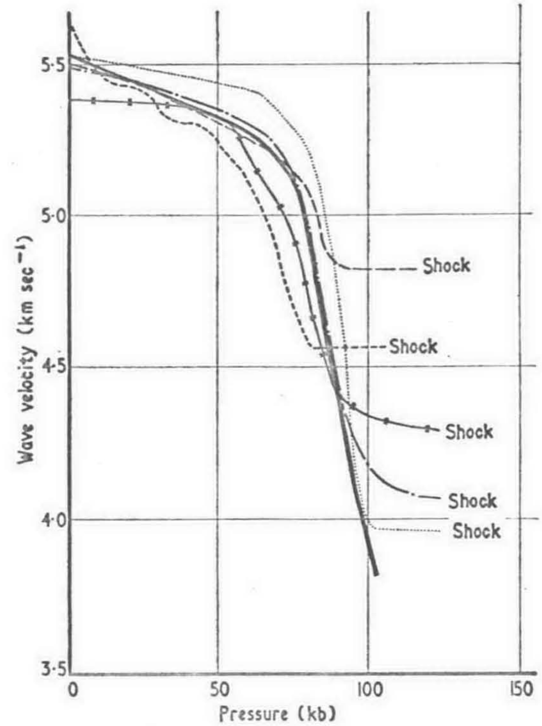

Figure 6. Velocity–pressure curves for simple compression waves in glass, calculated from successive pressure–time profiles such as are shown in figure 5. Round 1 – – – –, round 2 ········, round 3— — —, round 4 —×—×—, round 5 — · — mean ———.

The velocity D of any increment of a compression wave at pressure p and density ρ is given by

$$D^2 = \frac{\partial p}{\partial \rho}. \tag{1}$$

From experiment D is measured as a function of p, $D = g(p)$ say, so that integrating equation (1) gives

$$\rho_1 - \rho_0 = \int_{p_0}^{p_1} \frac{dp}{[g(p)]^2}.$$

This integral can be evaluated numerically to give the pressure as a function of the density

$$p = h(\rho). \tag{2}$$

The particle velocity u can be found by considering the Riemann integral, expressing conservation of momentum

$$\int_{u_0}^{u_1} du = \int_{p_0}^{p_1} \frac{dp}{\rho D}.$$

Using (1) and (2) and putting $u_0 = 0$

$$u_1 = \int_{\rho_0}^{\rho_1} \frac{[h'(\rho)]^{1/2}\, d\rho}{\rho}$$

where the prime represents differentiation with respect to ρ. Therefore from an experimental relationship $D = g(p)$, densities and particle velocities can be evaluated. This

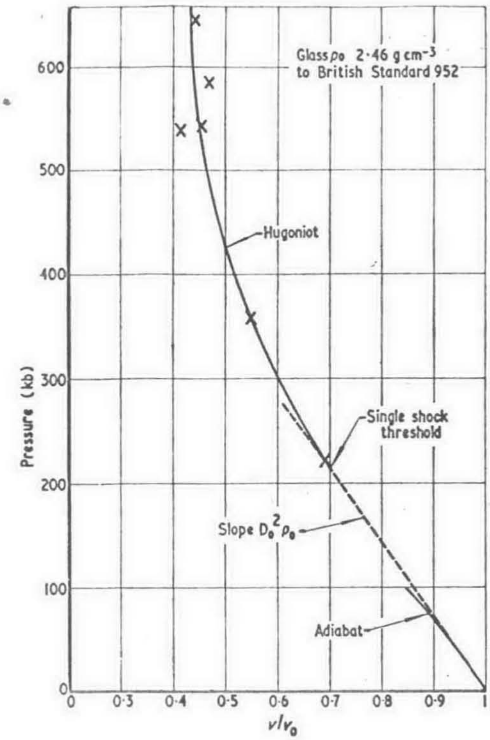

Figure 7. The pressure–volume relation for glass to BS 952, showing the adiabat calculated from the velocity–pressure curve and the high pressure Hugoniot measurements.

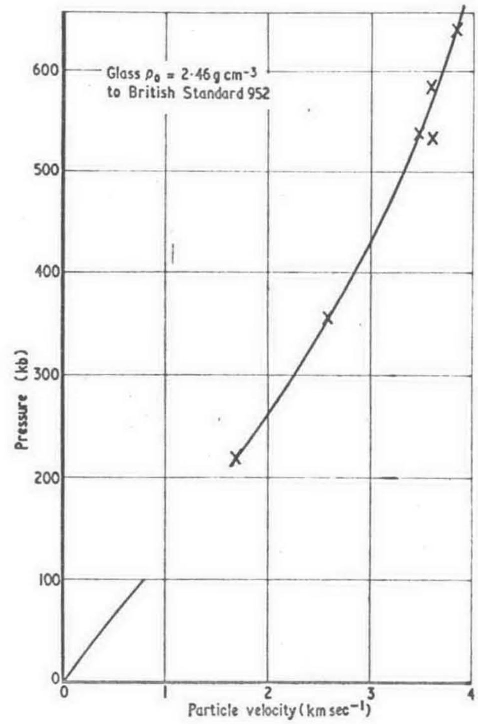

Figure 8. The relation between particle velocity and pressure for glass to BS 952.

calculation was carried out taking $D = g(p)$ to be the mean of the curves shown in figure 6, ignoring any particular curve after a shock had been detected.

The initial adiabatic portion of the pressure–volume curve has the opposite curvature to that usually found in solids. A similar curvature for the isothermal compression of several glasses has been found by Bridgman (1944–48). When the peak pressure in an experiment exceeded about 230 kb only a single shock was seen. Six points were measured on the glass Hugoniot in this high pressure single shock region, using the conventional switch pin technique. In figures 7 and 8 the simple compression measurements are compared with the Hugoniot data. The agreement is seen to be quite satisfactory in the sense that the two sets of data appear to represent different regions of a common curve. A line drawn from $p = 0$, $v/v_0 = 1$ with slope $- D_0^2\rho_0$ divides the pressure–volume plane into two areas; above the line single shocks exist and below it a simple compression wave can separate from the shock. This line cuts the Hugoniot measurements at about 220 kb, agreeing with the single shock threshold as determined from pressure profiles. In addition the shape of the pressure–volume relationship obtained implies that when two waves are seen, the peak pressure of the simple compression wave should decrease with increase in peak shock pressure. This has been observed consistently in numerous experiments.

4. Conclusions

A pressure transducer has been developed using the linear increase in resistance of a manganin wire, and is capable of measuring the pressure–time profiles of pressure pulses generated in an epoxy resin block by a variety of explosively driven systems. Pressures in non-conducting under dynamic conditions, and in this case simple compression and/or Hugoniot pressure–volume data can be obtained. Currently the technique is being extended to avoid this restriction.

Acknowledgments

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