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High strain rate testing of plastics

Part 1. *Shock tube technique*

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A technique for subjecting thin walled tubular specimens to a controlled, sudden internal pressurization is described. The technique may be used as an impact test or to obtain stress-strain data over a wide range of strain rates. A shock tube is used to generate a shock pulse, which passes through the tubular specimen mounted essentially as a free body, causing it to fracture when the shock pressure is sufficiently large. It is found that the minimum shock pressure required for fracture varies linearly with tube wall thickness for four thermoplastics tested. The mode of fracture of the tubular specimens is also discussed, following studies of the fracture fragment distribution and fracture surfaces of poly(methylmethacrylate).

1. Introduction

Engineering materials are subjected to a variety of mechanical tests to ascertain their deformation behaviour for design or research purposes. Testing over a wide range of strain rates(10^{-8} to 10^{4} sec^{-1}) is necessary to define the behaviour fully. Standard techniques for the determination and presentation of deformation behaviour at low strain rates (10^{-8} to 10^{-1} sec^{-1}) have been established, which are applied to a wide range of materials [1, 2]. At strain rates greater than 10^{-1} sec^{-1}, inertial forces become increasingly significant, while dynamic effects complicate the measuring techniques and the interpretation of the data obtained. A range of test techniques for high strain rate testing exists [3, 4], but none is, as yet, recognized as a standard technique for all purposes. Methods used divide between those that seek primarily to determine the stress-strain behaviour at high strain rates, fracture not necessarily occurring, and those which seek to characterize fracture by a single variable, such as the energy to fracture. The term impact test is normally reserved for high strain rate tests which seek to determine the fracture toughness* of a material [5, 6], Izod or Charpy impact tests being most commonly employed [7].

Charpy impact testing has been used [8] to study the fracture toughness of plastics, but attempts to normalize the data obtained by reference to different aspects of the specimen geometry were unsuccessful. Similar tests on metal specimens [9] using fully instrumented apparatus have shown that the loading pattern in a Charpy impact test is complex unless the stiffness of the apparatus and specimen are carefully matched. Further complications are the energy losses to the specimen supports and the complex dynamic stress field formed in the notched beam specimen when it is subjected to impulsive loading. Although the standard Charpy impact test is easy to perform, the full analysis of the test is complex. The test remains, however, a useful, rapid method for quality control of materials and their susceptibility to notch embrittlement. Recent research using the Charpy method has sought, with some success, to apply fracture mechanics to polymers deformed at high strain rates [10, 11].

A new approach to the high speed testing of materials, plastics in particular, has been developed at this laboratory. Objectives in developing the technique were (a) to apply a well characterized and controlled impulse to the specimen, (b) obtain the simplest possible stress field in the specimen in which dynamic effects were minimized and in which the stress field was essentially uniform, (c) to monitor

*Fracture toughness here referring to the area under the stress-strain curve as opposed to the K_c of fracture mechanics.

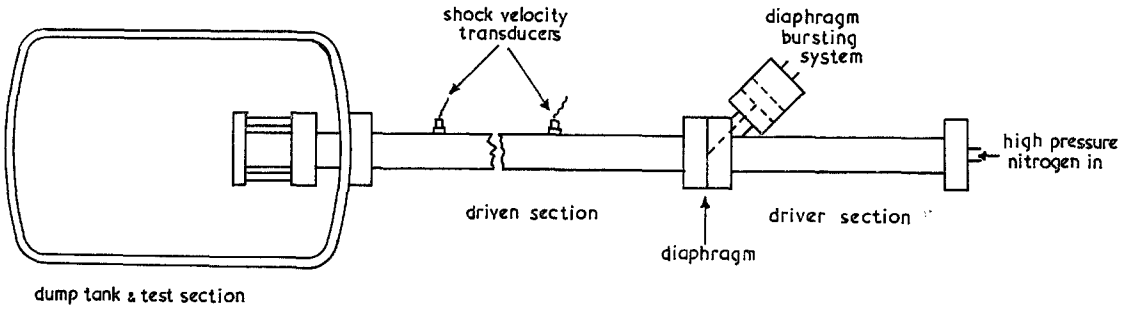

Figure 1 Schematic arrangement of shock tube high strain rate testing facility.

the complete load-deformation behaviour to rupture. Lindholm's review [3] of high strain rate test techniques suggests that the method of impulsively loading thin rings, by applying a uniform radial internal pressure to the ring, provides a uniform hoop tension in which wave propagation effects are minimized. Hollow tubes, filled with liquids having a high bulk modulus, have been pressurized by the impulsive loading of a piston acting on the liquid [12]. Complications arise in this technique from the clamping at the tube ends which locally prevents radial expansion and thus complicates the stress field. Other methods [13, 14] use electrical discharge or explosives to rapidly deform a thin ring which expands in free flight, with no complications arising from specimen clamping. The form of the impulse or the loading rate in these latter methods is not readily variable.

2. Shock tube technique

A controlled impulse can be obtained using a shock tube [15] which is a straight tube divided into two sections, (the driver and driven sections) separated by a diaphragm section as illustrated in Fig. 1. The driver section is filled with high pressure gas, which is initially separated from the low pressure driven gas by a thin diaphragm. On puncturing the diaphragm, the driver gas expands into the driven gas forming a shock wave which travels along the driven section at a constant supersonic velocity. The pressure rise at the shock front is effectively instantaneous. A dump tank is provided at the end of the driven section to collect the gases after testing and contains the test section for impact testing in the present experiments. The pressure distribution along the shock wave is shown in Fig. 2. Features of the shock are the instantaneous pressure rise to the shock pressure (P_2) at the shock front and the period of

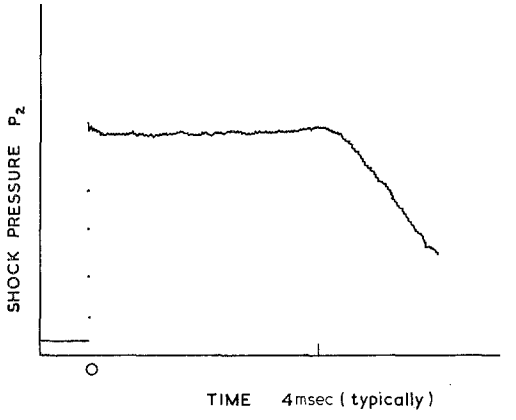

Figure 2 Pressure distribution along a typical shock pulse.

constant pressure following the shock front. Both factors are controllable, so that a shock of known magnitude and duration may be applied to the specimen. Fig. 3 shows the relationship between the shock pressure (P_2) and initial driver pressure (P_4) for various driven pressure (P_1) for a nitrogen/air system. A shock tube has been previously used to determine the high strain rate characteristics of materials in biaxial tension, by placing a disc of the material under test in the path of the shock [16].

The technique to be described here seeks to combine the advantages of the ring testing method with that of the controlled impulse provided by the shock tube. A thin walled tubular specimen is mounted to form a continuation of the driven section, as shown in Fig. 4. The shock travels along the driven section and then through the tubular specimen, subjecting it to uniform internal pressure once the shock front has traversed the full length of the specimen. The specimen, its support frame and the associated instrumentation are contained

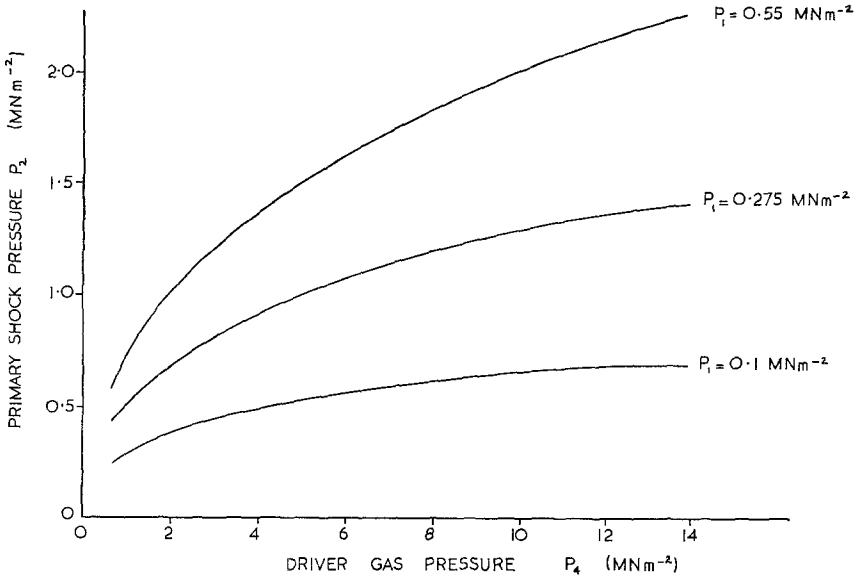

Figure 3 Primary shock pressures (P_2) obtained from different combinations of driver pressure (P_4) and driven pressure (P_1) for a nitrogen/air system.

within the dump tank, which is necessary to maintain the inital driven gas pressure and collect the shock pulse, but also serves to retain the fragments of the broken specimens. End clamping restraints on the specimen have been minimized to allow the whole specimen to expand uniformly under the internal pressure.

The specimen is lightly sandwiched between end plates, one of which is fixed to the end of the driven section, while the other slides on rigidly mounted rods which support its weight (Fig. 4). Knife edges on the end plates locate in chamfers machined into the ends of the specimen so that, when correctly in position, the specimen forms a smooth walled continuation of the driven section. It has been found that this alignment is

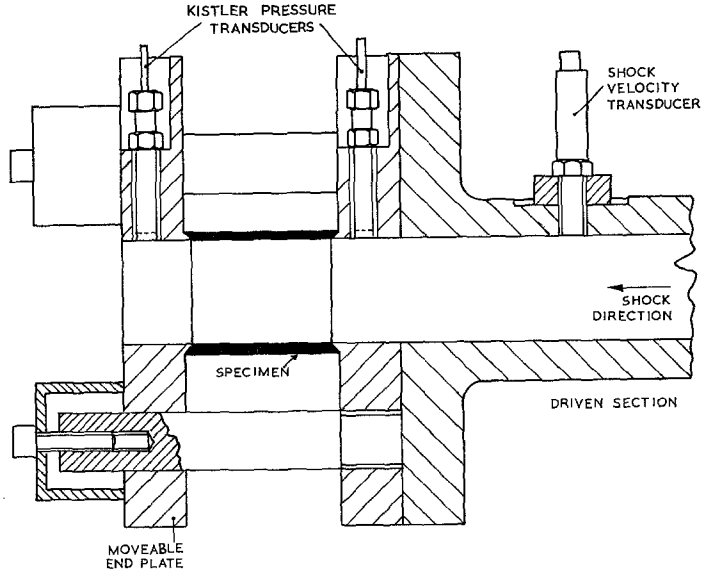

Figure 4 Method of mounting the thin walled tubular specimen and the location of the pressure measuring transducers.

critical, since waves are reflected from any protruding edges and interfere with the shock wave. The movable end plate is slid along the support rods until the specimen is just located and prevented from falling under its own weight before the end plate is fixed in position. The specimen is effectively freely supported and can expand radially over its entire length under internal pressurization. The initial seal at the knife edges is broken when expansion commences, allowing gas to escape around the ends of the specimen. Measurements of the shock pressure at entry and exit of the specimen, however, show that the shock pressure is not significantly reduced by this leakage.

3. Enhancement of the shock pulse and variation of the loading rate

The shock formed on initially bursting the diaphragm is referred to as the primary shock (pressure P_2). Values of P_2 for a nitrogen/air system are shown in Fig. 3. The magnitude of the shock pulse is governed by the initial driver (P_4) and driven (P_1) gas pressures alone, the shock pressure increasing with driven gas pressure for any given driver gas pressure. Fig. 3 shows that, for any given driven pressure, the increase in shock pressure diminishes as the driver pressure is increased, and that values of P_2 are much smaller than P_4. Stronger shocks may be obtained by either changing to different gas systems (e.g. hydrogen/nitrogen) or by working in reflected shock conditions, by blocking the open end of the driven section, causing the primary shock to be reflected back into the already high pressure gas. Values for reflected shock pressures (P_5) are given in Fig. 5 for a nitrogen/air system. Under reflected shock conditions, the specimen is, of course, subjected first to the primary shock (P_2) followed by the reflected shock (P_5), instantaneous pressure rises occurring on both occasions.

The pressure rise time at a shock front is theoretically of the order of two mean free flight times of a gas molecule and therefore instantaneous in the present context. A range of loading rates may be obtained using the same equipment by a further modification. If a nozzle is fixed in the driven section before the specimen and the blanking plate is retained as for reflected shock conditions, the section containing the specimen becomes a closed vessel with gas admission through the nozzle. When the shock passes along the driven section, the high pressure gas is held behind the nozzle and escapes through it at sonic velocity while

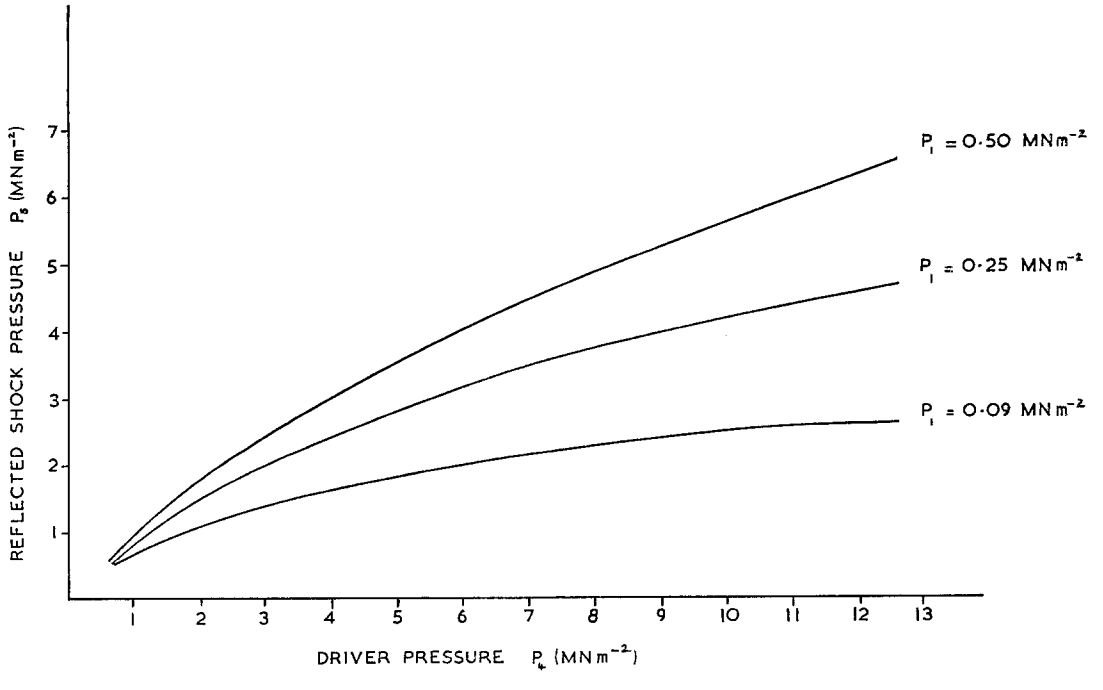

Figure 5 Reflected shock pressures (P_5) obtained from different combinations of driver pressure (P_4) and driven pressure (P_1) for a nitrogen/air system.

the nozzle remains fully choked, i.e. sufficient gas behind the nozzle to maintain full sonic flow. The mass flow rate through the nozzle, and hence the pressurization rate in the closed specimen chamber, is determined by the cross-sectional area of the nozzle. Pressurization rates are varied by changing the nozzle size and are linear until the nozzle becomes unchoked. This facility allows data to be obtained for a range of loading rates using the same equipment, same specimen geometry and loading method, and thus overcomes the problems of correlating data obtained for a range of strain rates from different techniques.

4. Instrumentation

Means of measuring the applied pressure and the resulting deformation are required to determine the stress-strain behaviour. Shock pressures can be determined from the theoretical ideal gas behaviour, but this method is not accurate. Pressure transducer systems have been developed specifically for shock tube research. Kistler pressure transducers were mounted in the end plates supporting the specimen, as shown in Fig. 4, so that the sensing head was flush with the bore of the shock tube. Signals from the transducers are fed, via charge amplifiers, to a double beam oscilloscope fitted with a Polaroid camera. Measurements of the shock pressure are thus made both before and after passing through the specimen.

The predominant strain in thin rings subjected to internal pressurization is the hoop strain, since no external axial restraint or loading is imposed. This strain is measured by small foil gauges bonded to the specimen, the signal from which is again amplified and fed to a second oscilloscope. Since the pressure and hoop strain are recorded at different positions, it is necessary to know the time interval between the shock front's arrival at the different measuring stations in order to synchronize the load strain measurements accurately. Further transducers were arranged along the shock-tube at known intervals and signals from these transducers, as the shock front passed, were fed to a chronometer to determine the time lapse of the shock front passing the transducers. The shock velocity was then calculated and used to synchronize the load-deformation data. One of the additional transducers is also used to trigger the oscilloscopes to start their single sweep just prior to the arrival of the shock at the test section.

5. Tests on thin walled plastics specimens

The shock tube facility has been used to test a variety of materials. Investigations on the application of fracture mechanics to poly (methylmethacrylate) and bone have been previously reported [17, 18]. Preliminary impact test studies on four thermoplastics are reported here; further work on the effect of strain rate on the stress-strain behaviour of the same plastics will appear subsequently.

Since results from standard notched bar impact testing exhibit a dependence on the specimen geometry which is not easily rationalized [8], the preliminary tests were carried out to determine the effect of specimen geometry on the fracture strength and also to study the mode of fracture. Specimens were machined from commercially available extruded tubes or rod. Specimens used for testing were 50 mm long, 37.5 mm i.d. to conform with the shock tube bore, and had wall thicknesses between 0.25 and 1.25 mm. The plastics used were poly(methylmethacrylate), poly(vinyl chloride), a polyacetal copolymer and polycarbonate. The shock tube was arranged for a single primary shock loading of the specimen. Several specimens with a given wall thickness were prepared and each specimen was subjected to a different shock pulse and then discarded, even if the specimen showed no sign of permanent damage. Recent experiments show that this is necessary to obtain consistent results, since a loading history appears to strengthen the plastic tubes. The test performed was a go/no-go test to determine the shock pressure required to just fracture the specimen and observe how this varied with wall thickness.

Results for the four materials are shown in Fig. 6. Tests which resulted in fracture and non-fracture are shown by filled and unfilled dots respectively. In each case a well-defined linear division is found between fracture and non-fracture regions and which is readily reproducible. This ability to reproduce data with a minimum of scatter is extremely encouraging for high strain rate testing, since other techniques are notorious for the scatter in the data obtained from them. Associated studies on the fracture mechanics of the same materials under similar loading conditions [17] have

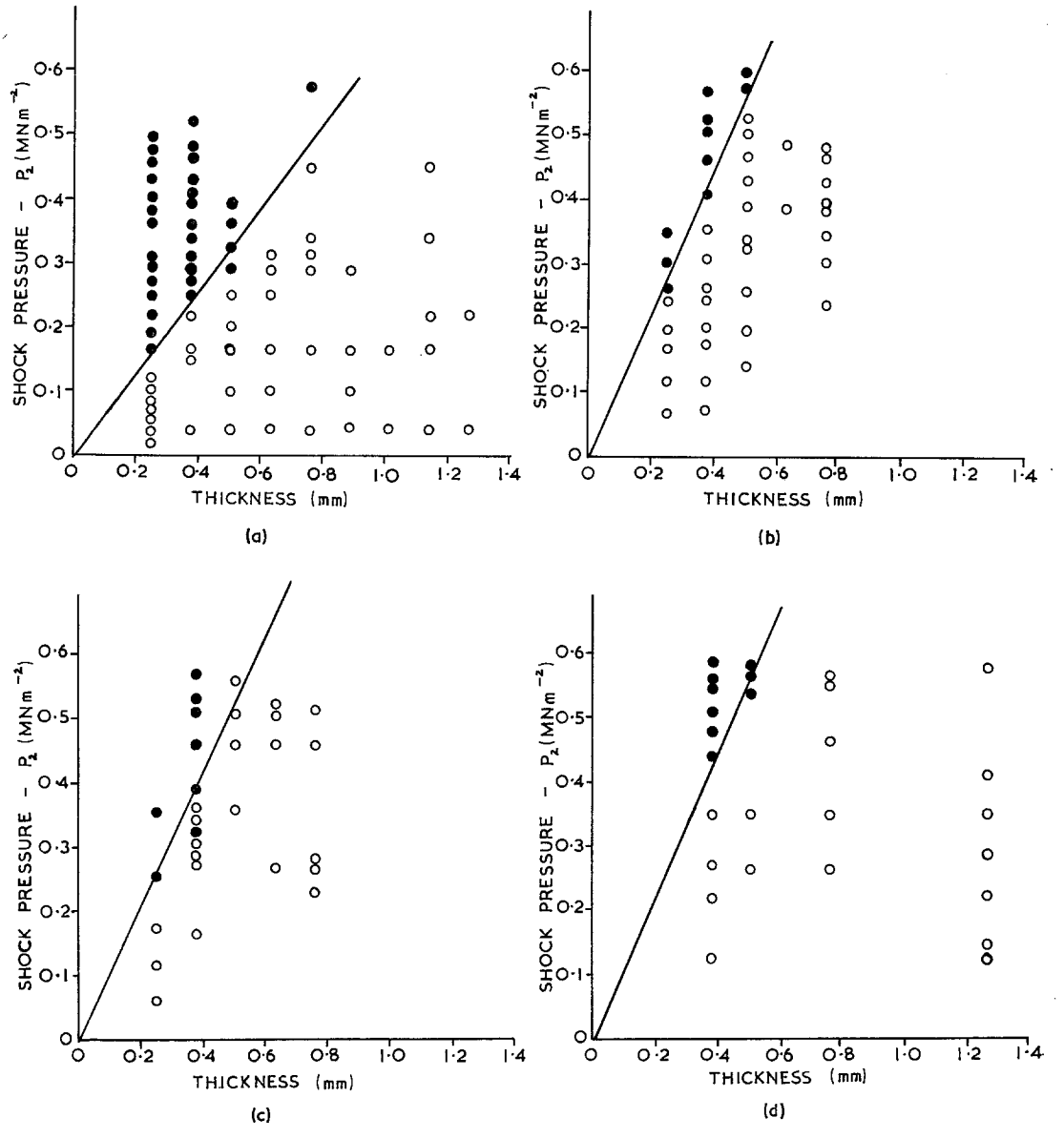

Figure 6 Primary shock pressure required for fracture against tube wall thickness for (a) poly(methylmethacrylate) (b) a polyacetal copolymer (c) poly(vinylchloride) (d) polycarbonate. Filled circles indicate that the specimen fractured, open circles show test conditions which did not cause failure.

shown that the flaw size must exceed approximately 10 mm to significantly change the fracture stress under shock loading. Machine markings are much smaller than this, which no doubt contributes to the reproducibility of the limiting fracture stress. Further studies [19] suggest that, under high speed testing, the tip radius of the flaw is more significant in fracture than the overall flaw length once the latter is less than a critical size. It is thought that the use of the thin ring specimens which, as previously discussed, simplifies the dynamic stress field, also enhances the reproducibility of the test data.

A further interesting feature of the data shown in Fig. 6 is the linear relationship between minimum pressure for fracture and wall thickness, which has since been found to apply also to bone [18]. It is, therefore, possible to predict accurately the effect of modifying the specimen

TABLE I

Material	Fracture stress (MNm^{-2}) at 20°C		
	Shock loading of ring specimens	Quasi-static testing of ring specimens	Uniaxial testing
Poly(methylmethacrylate) PMMA	13.9	38	50
Poly(vinylchloride) PVC	27.0	31	33
Polyacetal co-polymer	23.6	38	51
Polycarbonate PC	23.0	—	—

geometry. Variations in the specimen length do not affect the fracture stress, showing that the specimens are loaded uniformly under test. Hoop stress values associated with a particular pressure are derived using the relationship

$$\sigma = P_2 r/t$$

where r and t are the tube radius and thickness respectively. Although this expression is derived for quasi-static testing of thin tubes subject to an internal pressure, P_2, it has been shown to be equally applicable under shock loading conditions without introducing significant errors [20]. The linear relation between the minimum pressure to just cause fracture (P_2) and wall thickness (t) suggests that there is a threshold critical hoop stress for fracture which is independent of specimen geometry. Values of this threshold stress for the four plastics tested are given in the following table and are compared with the fracture stresses for the same materials tested under quasi-static testing using, firstly, tubular specimens subjected to internal pressurization and, secondly, conventional uniaxial testing.

The fracture stress unexpectedly decreases under shock loading conditions for all four materials tested. This decrease is particularly large in the case of poly(methylmethacrylate) and polyacetal, but is only slight in the case of poly(vinylchloride). The large decreases are attributed to transitions in the molecular mobility [19], which occur in PMMA and polyacetal at strain rates of 10 to 100 sec^{-1} at room temperature. Differences between the quasi-static fracture stress determined by the pressurized ring method and uniaxial testing are negligible in the case of PVC but substantial for the two other materials. Specimens for uniaxial testing were machined from the same stock as the ring specimens where possible, but always with their axes parallel to the extrusion direction. The PMMA and polyacetal uniaxial and ring specimens were prepared from extruded tube, while the PVC specimens were prepared from extruded rod. Preferential molecular orientation is likely to be more severe in extruded tube than rod, with the orientation parallel to the extrusion axis. The difference in quasi-static tensile strengths determined by the two methods is thus primarily attributed to anisotropy in the test materials, applied stress being parallel and transverse to the molecular orientation in the uniaxial and ring tests respectively. The generally low values of quasi-static tensile strength compared with quoted values reflect the particular grades of material used for extrusion. An anisotropic structure in the PVC rod used, resulting from the extrusion machine, has been previously reported [21].

6. Mode of fracture

When fracture occurs in the polymers tested, fragmentation of the specimen occurs. Fig. 7 shows a selection of the fragments from a single specimen, which vary from relatively large fragments to almost dust. Checks have been made that the gross fragmentation is not caused by larger fragments shattering on striking the walls of the dump tank. Padding the walls of the dump tank does not noticeably alter the fragment size distribution. Further checks have been carried out to determine whether the fragment size varies along the length of the specimen. Different coloured circumferential bands were painted along the specimen prior to testing. After fracture, the fragments were sifted into different sizes and then each size was sorted by colour. It was found that fragments of all sizes were obtained from all parts of the specimen, with a tendency for a higher proportion of larger fragments to come from the "upstream" end where the shock first

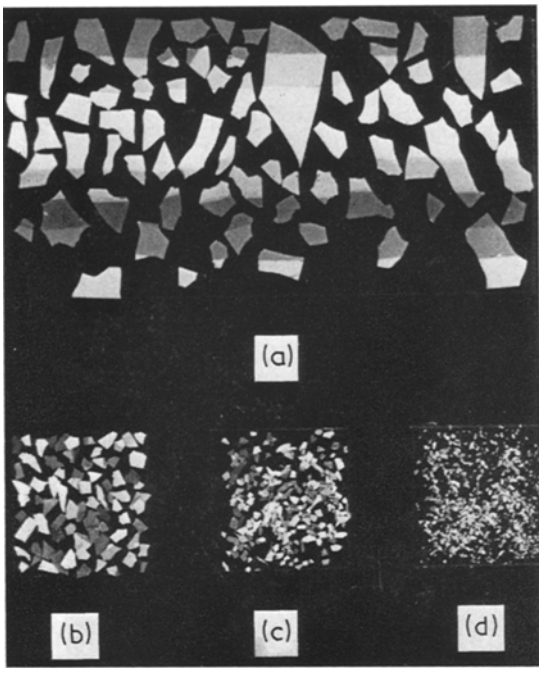

Figure 7 Variation in fragment size obtained from one specimen.

enters and more small fragments from the "downstream" end. The uniformity in fragment distribution shows that all parts of the specimen are subjected to the same loading pattern, and that the stress distribution within the thin walled tube is essentially uniform up to the point of fracture. The slight variation in fragment size concentration along the length of the tube is thought to result from the passage of the shock through the specimen. Since the shock takes a finite time to traverse the specimen (~60 μsec), it is believed that fracture commences at the upstream end, where the shock is first applied, and propagates along the specimen behind the shock front. Evidence of propagating deformation pattern has been obtained from strain measurements at different points on the same specimen. Evidence of bifurcation of the fracture front is also observed in some fragments. The small variation in fragment size concentration is thus attributed to bifurcation of the fracture fronts as fracture propagates along the specimen length.

Analyses of the fragmentation of bombshells [22] suggest that fragmentation initiates at the outer surface where a compressive elastic wave is reflected as a tensile wave. Quasi-static analyses of finite thickness tubes subjected to internal pressure [23] show that the maximum tensile hoop stress occurs at the tube bore. The fracture surface of a PMMA fragment is shown in Fig. 8 and shows the manner in which the crack propagated. The fracture surface shown is through the thickness of the tube and parallel to the axis of the tube. Fracture initiated at the bore of the specimen at the position of highest tensile stress according to the quasi-static analysis, and propagated both axially and radially through the tube wall. Successive positions of the primary fracture front are shown by the fine regularly spaced rib markings in the centre region of Fig. 8. The elliptical form of these markings shows that the fracture velocities axially and radially through the tube wall are different, the axial velocity ($\dot{x}$) being greater than the radial velocity ($\dot{y}$). Measurement of the angle (α) that the tangent of the primary front makes to the tube axis

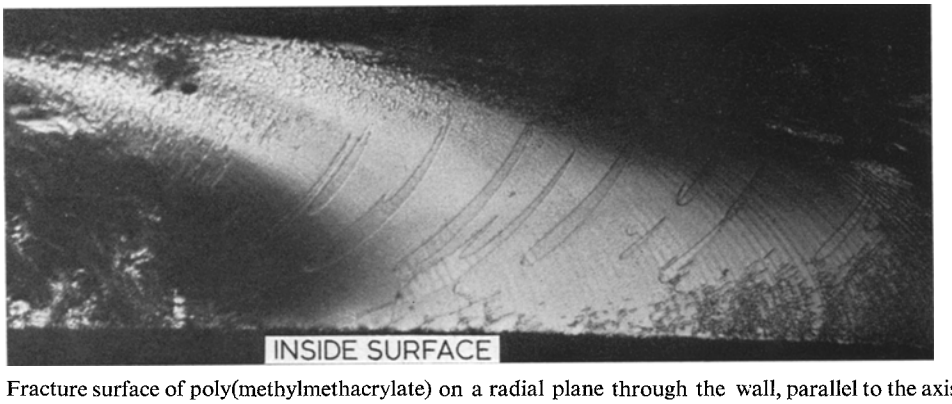

Figure 8 Fracture surface of poly(methylmethacrylate) on a radial plane through the wall, parallel to the axis of the tube.

allows the ratio of these velocities to be determined at any general position since

$$\dot{y} = \dot{x} \tan \alpha \ .$$

If it is assumed that the axial component ($\dot{x}$) is constant throughout the wall thickness and equal to the shock velocity, an absolute value for the radial velocity of the fracture front may be determined. This assumption is plausible since shock velocities used are about 0.45 of the dilational wave speed in PMMA, and crack speeds can achieve velocities of similar magnitude.

Results from this calculation are shown in Fig. 9. A rapid acceleration of the fracture front as it travels through the specimen wall towards the outside surface is indicated. The dashed line on Fig. 9 indicates the transition from mist to hackle regions on the fracture surface, the hackle surface being very uneven and comprises many secondary fracture surfaces. The transition from mist to hackle occurs at a fracture velocity of 460 $msec^{-1}$ which agrees with values predicted by other workers [24-26].

A further most interesting feature of the fracture surface are the closed banana-shaped loops which are clearly visible in Fig. 8. Such features have been previously observed [27] although closed loops are rare, and can be attributed to secondary fractures initiating ahead of the propagating primary fracture front. The curve of the banana shape is due to the acceleration of the fracture front as it propagates through the specimen wall.

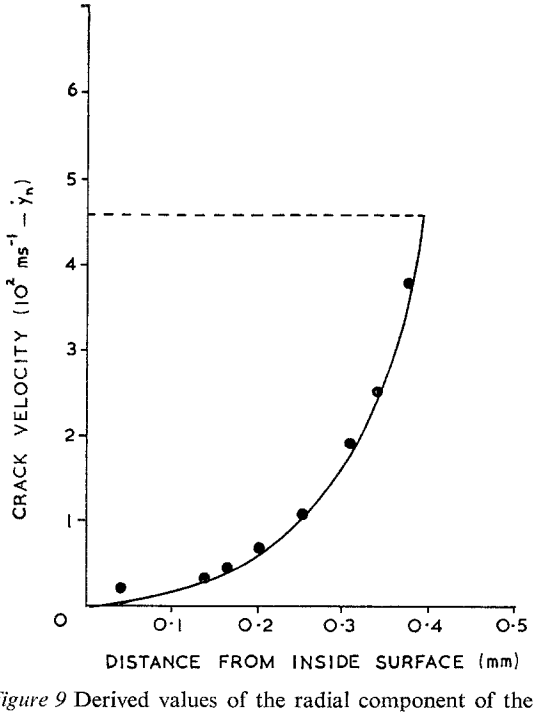

Figure 9 Derived values of the radial component of the fracture front velocity through the tube wall.

7. Conclusion

It is considered that the shock tube technique described offers certain advantages for the study of the high strain rate behaviour of materials. The major advantage is the essentially uniform stress throughout the entire specimen, as evidenced by strain measurements and the uniform fragment distribution on fracture, so that the continuum behaviour of the material at high strain rates may be easily characterized. Minimum interaction between specimen and apparatus is a major factor in simplifying the stress field within the deforming specimen. The reduced scatter in the experimental fracture data renders it more amenable to analysis. A further advantage is the facility to study the material behaviour over a wide range of strain rate using the same apparatus and specimen geometry, thus avoiding the problems of correlating data obtained from different testing techniques. Disadvantages of the technique as a routine testing facility are the size of the apparatus and the lack of energy available to rupture thick walled strong materials. Thin walled specimens have been used mainly to approximate to membrane theory and reduce stress wave effects, but also so that rupture is obtained under reasonable shock pressures. It is considered that the shock tube technique offers a new approach to the high speed tesing of plastics and can lead to further understanding of the behaviour of these materials at high rates of strain.

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