A Review of the Techniques Available for Obtaining the Mechanical Properties of Materials at High Rates of Strain*

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Abstract

A variety of techniques used to obtain the mechanical properties of materials at high rates of strain (≥ 10 s^{-1}) are discussed. These include dropweight machines, split Hopkinson pressure bars (SHPBs), Taylor impact, and shockloading by plate impact. Their limitations as well as their advantages are outlined.

Keywords:

Dynamic, Strength, Deformation

1 Introduction

Figure 1 presents a schematic diagram of the range of strain rates (in reciprocal seconds) that are typically of interest to materials scientists. They span 16 orders of magnitude from creep (over periods of years) to shock (nanoseconds). Conventional commercial mechanical testing machines cover the low strain rate range up to around 10 s^{-1}. Dropweight machines are also available commercially and standards have been written covering their design and use in the strain rate range 10 - 1000 s^{-1}. Historically, machines for obtaining mechanical data at higher rates of deformation have tended to be confined to government or university laboratories, but recently some companies have been ‘spun-off’ to market items such as split Hopkinson pressure bars (SHPBs) and plate impact facilities.

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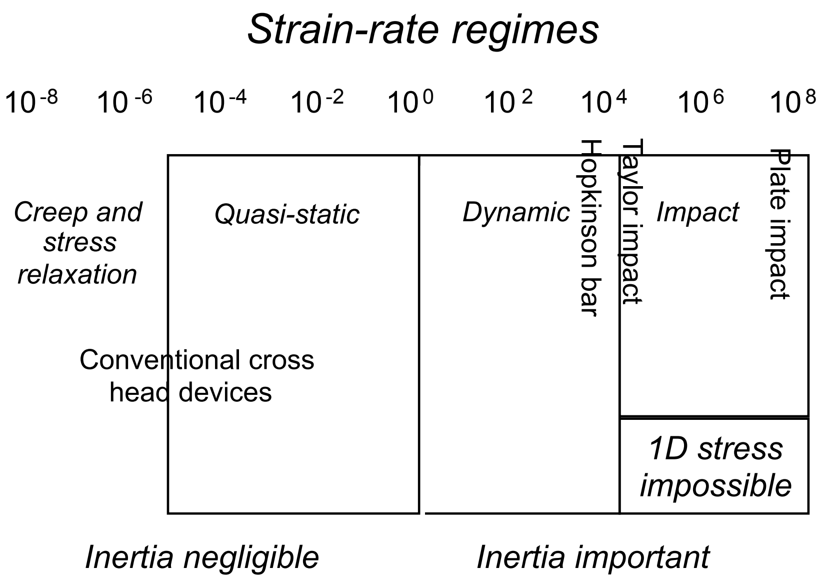

Figure 1: *Schematic diagram of strain rate regimes (in reciprocal seconds) and the techniques that have been developed for obtaining them*

One very important transition that this figure shows is that from a state of 1D stress to 1D strain. The strain rate at which this occurs depends on the density of the material being investigated and the size of the specimen: the larger the specimen and the higher its density, the lower the transitional strain rate [1,2]. Examples of the effect of strain rate on mechanical properties combined with the transition from 1D stress to 1D strain are given in Figure 2.

Because it is necessary to have about 1000 grains or crystals in a specimen for it to be mechanically representative of the bulk [5,6], the coarser the microstructure, the larger the specimen has to be to fulfil this condition and hence the lower the maximum strain rate that can be accessed in 1D stress. Hence, for investigating concrete, for example, very large Hopkinson bars have had to be constructed [7]. By contrast, very fine-grained metals can be deformed in 1D stress at strain rates close to 10^5 s^{-1} using miniaturised Hopkinson bars (3 mm diameter) and 1mm sized specimens [8].

Fuller historical surveys of the development of high strain rate techniques may be found in refs. [9,10]. Recent reviews of the techniques outlined in this paper may be found in ref. [11]. In addition, the DYMAT Association is in the process of publishing test recommendations. Those for compression Hopkinson bars [12] and Taylor impact [13] are already available; that for shockloading by plate impact will be published soon (see the website www.dymat.org).

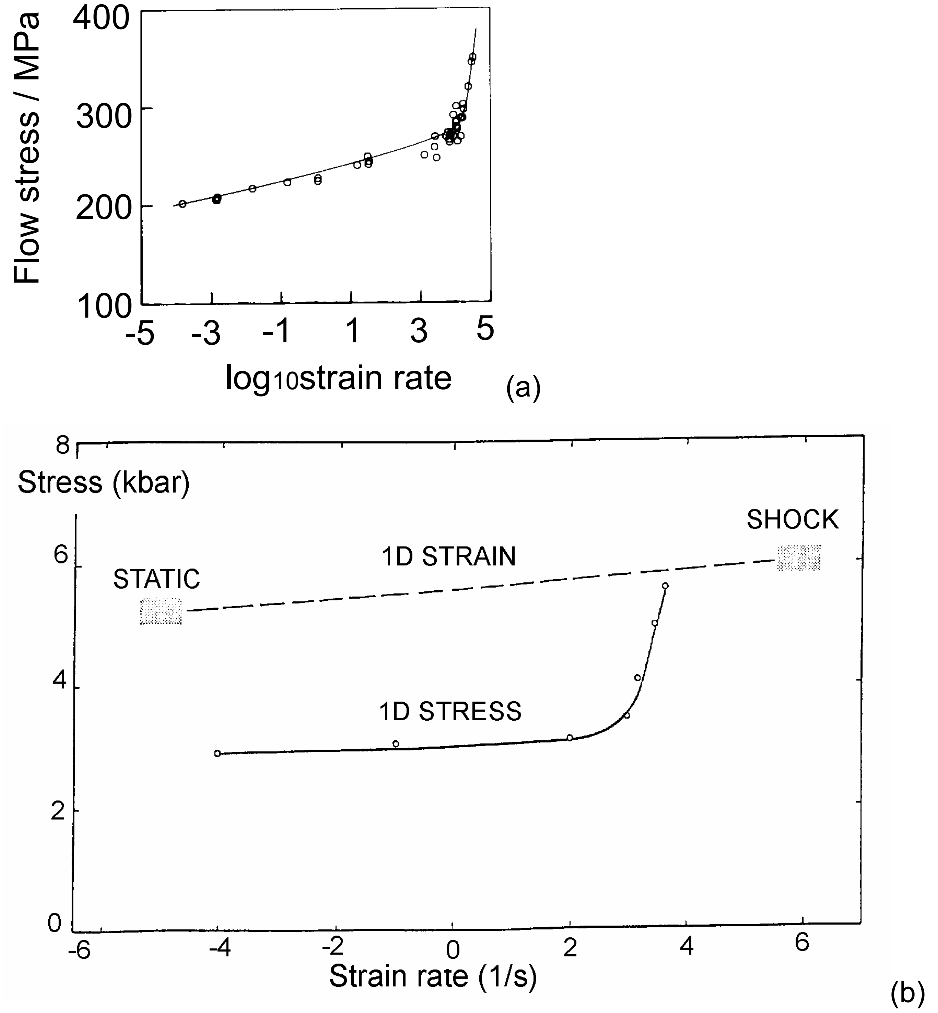

Figure 2: *(a) Plot of flow stress of copper as a function of log10(strain rate); from ref. [3]. (b) Failure stress of limestone as a function both of strain rate and loading state; from ref. [4]*

2 Dropweights

Machines where a falling weight is used to strike a plaque or a structure are widely used in industry both in research and in quality control. The weight is often used to carry darts of various shapes (sharp, rounded) to impact the target. ASTM Standards have been written governing the performance of such tests on sheet materials (ASTM D5420-98a, ASTM F736-95(2001)) and pipes (ASTM G14-88(1996)e1, ASTM D2444-99) (see their website www.astm.org). Dropweights are also used in explosives safety qualification: the higher a standard dropweight has to be dropped onto an energetic formulation before half the drops produce ignition, the safer that formulation is assumed to be.

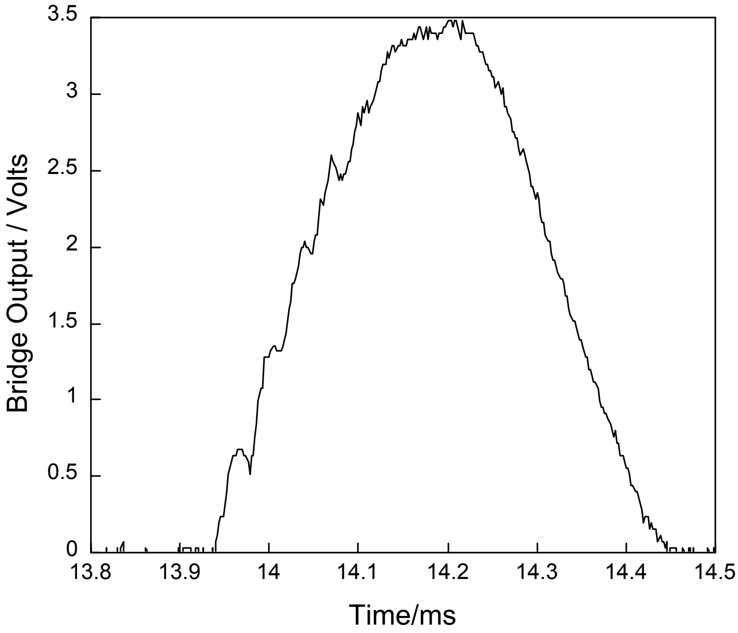

***Figure 3:** Output of the strain gauge bridge for a dropweight force transducer calibration experiment*

The standard way of analysing the output of a dropweight machine assumes the weight behaves as a rigid body and hence that one can simply apply Newton's laws of motion. Thus, in determining the calibration factor k (N/V) of a dropweight force transducer dynamically, we assume we can replace $\int Fdt$ by $m\Delta v$. Thus:

$$k = \int Fdt \,/ \int Vdt = m\Delta v \,/ \int Vdt \qquad (1)$$

where m is the mass of the dropweight, $\int Vdt$ is the integral of the strain gauge bridge output voltage signal, and Δv is the change of velocity of the weight produced by impact on the force transducer (remembering, of course, that velocity is a vector, so that the magnitudes of the impact and rebound speeds must be added). A typical calibration signal is presented in Figure 3. Dynamic calibration has been found to agree well with that performed statically in a calibrated commercial testing machine [14].

In practice, the output signal from a dropweight machine often has oscillations comparable in size to the signal produced by the mechanical resistance of the specimen. This is particularly true if the dropweight itself is instrumented e.g. with accelerometers. The reason is that impact excites the weight below its resonance frequency [15]. Elastic waves therefore reverberate around inside until the momenta of the constituent parts of the weight have been reversed. Rebound then occurs and the specimen is unloaded. Recent work has demonstrated that it is possible to obtain high quality data from such machines (at least for simple specimen geometries) either by the use of a momentum trap in the weight if the weight itself has to be instrumented [16] or by careful design of a separate force transducer placed below the specimen [14]

3 Split Hopkinson Pressure Bars (SHPBs)

Three researchers had the idea of using two Hopkinson pressure bars [17] to measure the dynamic properties of materials in compression [18-20]. Methods of obtaining high rate mechanical properties of materials in tension and torsion had previously been invented [21-24]. However, SHPBs were not widely used until the 1970s (Figure 4). Instead, alternatives such as the propagation of plasticity down rods or the cam plastometer [25] were used for obtaining dynamic mechanical properties in compression. As SHPBs increasingly became the standard method of measuring material dynamic mechanical properties in the strain rate range 103 – 104 s^{-1}, tension [26] and torsion [27] versions were developed.

The basic idea of the SHPB is that the specimen is deformed between two bars excited above their resonant frequency (Figure 5). Note in comparing Figures (3) and (5) the very different shapes and durations of the loading pulses. The material of the bars is chosen so that they remain elastic (small strains) even though the specimen itself may be taken to large strains. This means that strain gauges can be used repeatedly to measure the signals in the bars (strain gauges normally have small failure strains). Dynamic loading is produced either by striking one end of one of the bars (the input bar) or by statically loading a section of the input bar held at some point by a clamp and then releasing the clamp, so that the load propagates to the specimen. Compression bars are nearly all of the dynamically loaded type (though there is no reason in principle why a 'statically' loaded compression SHPB could not be built). Tension SHPBs have been designed of both types [28]. Torsion SHPBs are nearly always statically loaded [29].

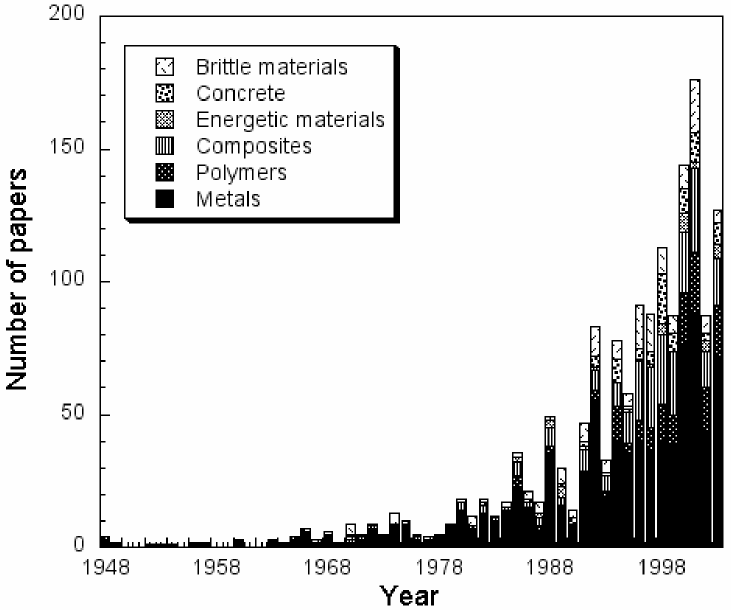

Figure 4: *Histogram of the number of papers published in any given year where an SHPB was used to obtain the high rate mechanical properties of various materials*

The classic elastic wave analysis of the SHPB assumes that the rods are one-dimensional objects (their true three dimensional nature is demonstrated by the oscillations on the recorded signals; see Figure (5)). The aim of the analysis is to relate the elastic strains in the rods (measured by, for example, strain gauges) to the force applied to and the deformation of the specimen sandwiched between them. The full analysis may be found in ref. [30] and results in two equations:

$$\sigma(t)=\frac{AE\varepsilon_t}{A_s} \tag{2}$$

$$\frac{\partial\varepsilon}{\partial t}=\frac{2c_b\varepsilon_r}{l_s} \tag{3}$$

where $\sigma(t)$ is the stress in the specimen, A is the cross-sectional area of the bar, E is the Young's modulus of the bar material, ε_t is the strain pulse measured in the output bar (transmitted pulse), ε_r is the strain pulse reflected from the specimen and measured in the input bar, $\partial\varepsilon/\partial t$ is the specimen strain rate, c_b is the elastic wave speed of the bar material, and l_s is the current specimen length (thickness). The stress-strain curve of the specimen can be found from equations (2) and (3) by eliminating time as a variable. Similar analyses exist for tension and torsion systems. Note that two major assumptions were made in deriving these equations: (i) the forces on the two ends of the specimen are the same, and (ii) the specimen deforms at constant volume. If either of these assumptions are false, the equations are invalid. However, the force-time data obtained may still be used for checking material models.

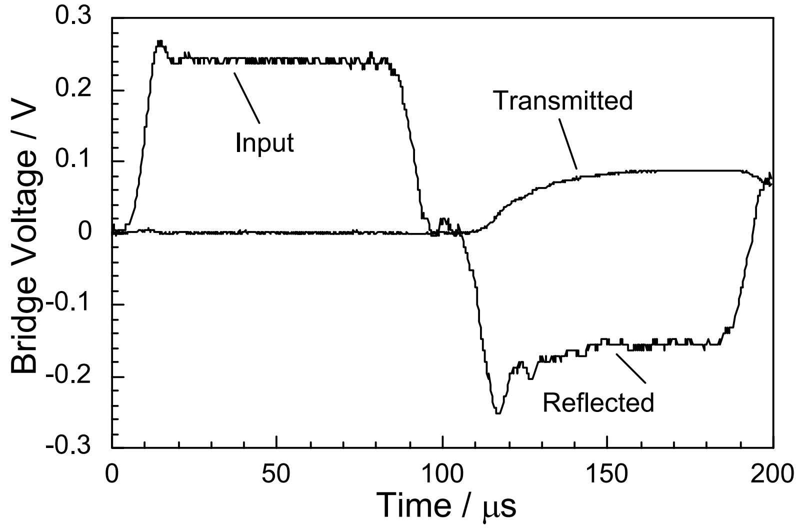

Figure 5: *Input (loading), reflected and transmitted pulses in a dural compression SHPB for a 4mm thick, 5mm diameter polycarbonate specimen (courtesy of C.R. Siviour)*

4 Taylor Impact

The Taylor test was developed by G.I. Taylor and co-workers during the 1930s [18, 31-33] as a method of estimating the dynamic strength of ductile materials in compression. The technique consists of firing a cylinder of the material of interest against a massive, rigid target. The dynamic flow stress can then be found by recovering the deformed cylinder and measuring its change of shape. However, this lacks the accuracy of deforming a disc of material and so Taylor impact is now rarely used for its original purpose.

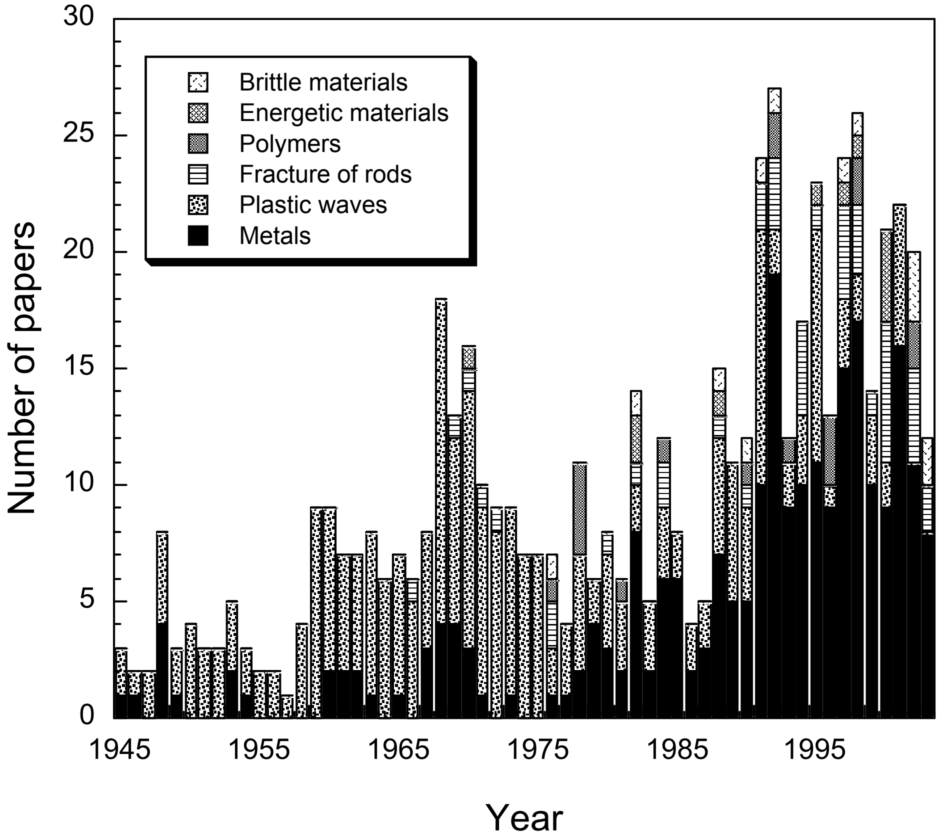

Figure 6: *Histogram of the number of publications published in any given year where Taylor impact or plastic wave propagation was used to investigate various materials*

As mentioned before, a technique that is in some sense intermediate between Taylor impact and the SHPB was popular for about 25 years, namely the study of the propagation of plastic waves along rods e.g. ref. [34]. However, recently there has been renewed interest in Taylor impact or its variants (such as rod-on-rod impact [35]) as a method of 'exercising' constitutive relations [36,37] for a wide range of materials (see Figure (6)). High-speed photography is invaluable in these modern studies and is essential for both brittle [38,39] and viscoelastic materials [40]. One reason this technique is so useful in exercising constitutive models is the wide range of strain rates it covers in one experiment from shockloading at the impact face to quasistatic loading at the rear [39, 41]. It also produces large strains.

5 Shockloading by plate impact

The planar impact of a disc of material onto a target specimen (Figure 7) produces shock waves in both target and impactor materials. The strain rates within the shock are typically in the range 106 to 108 s^{-1}. These are the highest rates of deformation that can be achieved in the laboratory by mechanical means. Higher rates and higher shock pressures can be achieved by, for example, nuclear bombs [42], high intensity lasers [43], and particle beams [44], but these techniques will not be considered further in this review. A fuller review of plate impact techniques may be found in ref. [45].

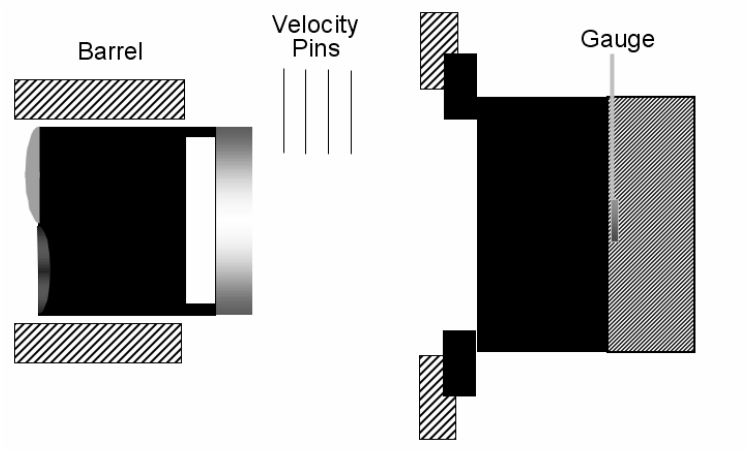

Figure 7: *Schematic diagram of the 'business end' of a plate impact shockloading gun*

As Figure 1 indicates, deformation takes place at these strain rates under 1D strain. This is because the inertia of the material involved in the collision acts (for a period of a few microseconds) to rigidly constrain the material in the centre of the colliding discs. Deformation therefore takes place only in the direction of impact. This state of affairs lasts until release waves reach the centre of the discs i.e. for a time given by r/cs where r is the radius of the disc and cs is the appropriate wavespeed in the shocked (and hense densified) material. Hence, the larger the diameter of the impactor/target, the longer the state of 1D shock strain lasts. However, the costs of manufacture and operation of a laboratory gun increase rapidly with the bore size. So most plate impact facilities use guns in the range 50-75 mm bore. Single stage guns operated with compressed gas have a typical upper impact speed of around 1.2 km/s if helium is used as the propellant. Higher velocities can be achieved with single stage guns using solid propellants, but this has the disadvantage of producing a great deal of residue which has to be cleaned out each time the gun is fired. To achieve impact speeds typical, say, of the impact of space debris on an orbiting satellite requires two- or even three-stage guns [46, 47]. One disadvantage is that each successive stage is of smaller diameter than the one before. Hence, the final projectile is typically only a few millimetres in diameter. For the very highest speeds in such systems, hydrogen is used as the propellant.

Typical applications of the plate impact technique to materials include: (i) obtaining their Hugoniot curves (locus of possible shock states) [48]; (ii) measuring their dynamic spall (or tensile) strengths [49]; (iii) investigating high pressure phase changes [50]; (iv) study of shock-induced chemistry [51]. Evidently, all of these are of interest to the military in applications such as armour, penetrators, shaped charges, explosives etc., but there are many civilian applications as well, including quarrying/blasting [52], shielding of orbiting satellites [53], geophysics [54], explosive welding [55], novel materials synthesis [51] etc.

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