Review of Methods of Testing at High Strain Rates

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Abstract.
The subject area covered by this review is a large and important one and to do it full justice would require a larger format than is available here. However, an attempt is made to outline the history of some of the more important developments and to include most major techniques. Taylor impact, Hopkinson bar testing in its various forms and 1-D plate impact are all considered in some detail. High-speed photography, particularly when used in association with optical techniques, is a key area and recent advances are discussed. This review updates an earlier one published in 1994 (Field et al. 1994).

1. Historical Foundations of High Strain-Rate Testing

As the 19th century progressed, there was an increasing awareness that the properties of materials under impact differed from those under static loading (Young 1807; Hopkinson 1872a, b; Dunn 1897; Hatt & Marburg 1899; Symposium on Impact Testing of Materials 1922; Clark 1954).

Experimental investigations were hampered by lack of suitable instrumentation (Hatt & Marburg 1899), but considerable theoretical progress was made in the understanding of the propagation of stress waves in bounded media such as circular rods (Pochhammer 1876; Chree 1886, 1889, 1890; Love 1927; Love 1944). It is generally considered that John Hopkinson in 1872 made the first experimental demonstration that metals can withstand a larger impulsive tensile load than they can under static tensile loading (Hopkinson 1872a, b). However, Dunn (1897) was credited by J.F. Bell (1973) with constructing the first true high strain-rate testing machine. Bell also discusses in his book the contribution of H. Tresca (1878).

After John Hopkinson's tragic death in an Alpine climbing accident along with three of his six children, his son Bertram Hopkinson was elected to carry on his father's work as Professor of Engineering at Cambridge (Ewing & Larmor, 1921; Hopkinson & Ewing, 1947). He invented an ingenious ballistic pendulum method for determining the shapes of pulses caused by the impact of bullets or the detonation of explosive charges at one end of a long rod (Hopkinson 1905, 1914). By using momentum traps of different lengths, he was able to build up a picture of how much momentum passed down the rod as a function of time for different classes of event (assuming that these types of event are repeatable). Because he performed the pioneering work on determining the shapes of impulses travelling down rods, the device consisting of a long rod to convey a force pulse to a force transducer became known as the Hopkinson pressure bar. This was rapidly put to use in the First World War (Landon & Quinney 1923), and is still used to this day in its original configuration in blast wave loading studies (see, for example, Davies et al. (1950) and several of the papers in Bulson (1994)). These achievements of the Hopkinsons were reviewed by G.I. Taylor in a lecture he gave in 1946 (Taylor 1946).

With the development of the continuous strip mill in the 1920s there was renewed interest in determining the dynamic properties of steels both in tension and in torsion, particularly at high temperatures (Guest 1930; Luerssen & Greene 1933, 1934; Mason 1934; Itihara 1935a, b, c, d; Itihara 1936a, b; Luerssen 1935; Mann 1935, 1936; Symposium on Impact Testing 1938; Clark & Dätwyler 1938; Davis 1938; Greene & Stout 1940; Manjoine & Nadai 1940; Brown & Vincent 1941; Nadai & Manjoine 1941; Fehr & Parker 1943; Fehr et al. 1944; Manjoine 1944; MacGregor & Fisher 1945; Warnock & Brennan 1948; Warnock & Taylor 1949). Very little work seems to have been performed on dynamic compressive loading before the Second World War, although G.I. Taylor had been thinking of a method of estimating the dynamic strength of materials in compression towards the end of the 1930s (Taylor 1946). His method consists of firing a solid cylinder of the material against a massive and rigid target. The dynamic flow stress of the cylinder material can be estimated by measuring the overall length of the impacted cylinder and the length of the undeformed (rear) section of the projectile (Taylor 1948; Whiffin 1948) by means of the following simple formula:

$$\sigma = \frac{\rho V^2 (L - X)}{2(L - L_1)\ln(L / X)} \qquad (1)$$

where σ is the dynamic yield stress of the material of the projectile, ρ its density, V its impact velocity, and L, X are defined in figure 1.

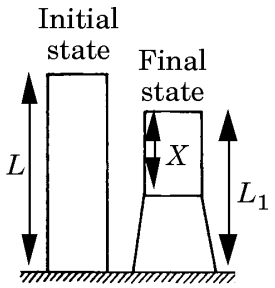

Figure 1. Schematic diagram of initial and final states of a Taylor impact specimen (from Taylor 1948)

One of the assumptions made in deriving this expression was that the rear of the projectile undergoes constant deceleration. Taylor & Whiffin knew that this assumption is not true, but an analysis taking account of the variation in acceleration yields a set of expressions that are transcendental in the yield stress and in which the plastic wave speed acts as a free variable. Taylor and Whiffinís method of solving these equations consisted of numerically determining the plastic wave speed consistent with both the measured deformation and their theory. This then allowed the yield stress to be determined. In order to use this more exact method routinely, Taylor presented it as a set of graphs yielding multiplicative correction factors to equation (1). Whiffin showed that the correction factor was velocity dependent, being ca. 1.12 at about 100 m $s^{-1}$and ca. 1.06 at about 800 m s^{-1} for mild steel cylinders.

The publication of this method occurred just before Kolskyís famous paper on the use of two Hopkinson pressure bars to measure the dynamic properties of materials in compression (Kolsky 1949). This device became known as the split Hopkinson pressure bar (SHPB) and soon became the standard technique for obtaining high strain rate properties of materials, having the advantage over the Taylor test of loading the material under nearly uniform stress and strain rate. To date, there are well over 1000 papers in the literature on SHPB testing of metals, ca. 200 on polymers, ca. 120 on ceramics and rocks, ca. 100 on composites (both polymer and metal matrices), ca. 40 on concrete, and ca. 15 on energetic solids.

However, the Taylor test, or variants on it such as rod-on-rod impact (Erlich et al. 1982; Erlich & Shockey 1984; Erlich 1985; Erlich & Chartagnac 1985), has been used and developed to the present day (there are about 230 papers in the literature on this topic). It has not often been used to obtain dynamic yield stresses of materials but for studying (a) the propagation of plastic waves, (e.g. Duwez & Clark 1947; von Kármán & Duwez 1950; Perzyna 1959; Plass Jr. & Wang 1959; Kolsky & Douch 1962; Critescu 1963; Bell 1968) and (b) for checking constitutive models by comparing the shapes of recovered cylinders with computer predictions, (e.g. Wilkins & Guinan 1973; Hashmi & Thompson 1977; Woodward & Lambert 1981; Johnson & Cook 1983, 1985; Zerilli & Armstrong 1987, 1988, 1990, 1997; Johnson & Holmquist 1988; Holmquist & Johnson 1991; Partom 1992; Holt et al. 1994; Nemat-Nasser et al. 1994; Woodward et al. 1994; Zukas 1994; Jones et al. 1995; Kawata & Tashiro 1995; Allen et al. 1997; Rule 1997; Couque 1998; Jones et al. 1998; Kothari & Anand 1998; Worswick & Pelletier 1998; Maudlin et al. 1999a, b). It has also been used for its original purpose in obtaining the dynamic properties of (a) polymers at room temperature (Briscoe & Hutchings 1976, 1978; Hutchings 1978; Kukureka & Hutchings 1981; Vartanov et al. 1990; Lee et al. 1996; Turgutlu et al. 1996), (b) metals at elevated temperatures (Hawkyard et al. 1968; Gust 1982; Erlich & Chartegnac 1985) and (c) energetic materials (Napadensky et al. 1970; Fugelso et al. 1982; Quidot 1988; Chou et al. 1995).

Other methods for obtaining dynamic stress-strain curves that have been developed include the cam plastometer (Loizou & Sims 1953), hydraulically-driven mechanical testing machines (Briggs & Campbell 1972), drop-weight towers (Baraya et al. 1965; Samanta 1969) and the expanding ring test (Hoggatt & Recht 1969; Warnes et al. 1985; Gourdin 1989; Gourdin et al. 1989; Al-Maliky & Parry 1996). With the exception of the expanding ring test, these other methods produce somewhat lower strain rates than the SHPB (102 s-1or less) as opposed to 103 s-1or greater. A summary of the major developments in high strain rate testing up to the invention of the SHPB is given in Table 1.

Table 1 - Developments in high strain-rate testing (excluding shock studies)

Date	Major developments	Reference
1807	Elastic waves in solids and fracture strength	Young (1807)
1800s	Interest in dynamic fracture strength of rail steel	Hatt & Marburg (1899), Symposium on Impact Testing of Materials (1922)
1872	Dynamic loading of wires	Hopkinson (1872a, b)
1870s-1880s	Dispersion of elastic waves in rods	Pochhammer (1876), Chree (1889)
1897	First high strain-rate mechanical testing machine built	Dunn (1897)
1905	Rapid loading of metals	Hopkinson (1905)
1914	Determination of pulse shapes due to bullet impact and explosions using long rods and momentum traps	Hopkinson (1914)
1920s-1930s	Interest in impact loading of steels in tension and torsion at high temperatures due to the development of the strip mill	Guest (1930), Luerssen & Greene (1933, 1934), Mason (1934), Itihara (1935a, b, c, d, 1936a, b), Luerssen (1935), Mann (1935, 1936), Symposium on Impact Testing (1938), Clark & Dätwyler (1938), Davis (1938), Greene & Stout (1940), Manjoine & Nadai (1940), Brown & Vincent (1941), Nadai & Manjoine (1941, 1944), Fehr & Parker (1943), Fehr et al. (1944); MacGregor & Fisher (1945), Warnock & Brennan (1948), Warnock & Taylor (1949)
1940s-1950s	Use of long rods as mechanical wave guides in various military applications	Prowse (1936), Shear & Focke (1940), Bancroft (1941), Hudson (1943), Cooper (1947), Arenberg (1948), Hughes et al. (1949), Davies et al. (1950), Holden (195), Redwood (1960), Miklowitz (1973)
1940s	Early modern attempts at compressive dynamic loading	Greenfield & Habib (1947), White & Griffis (1947, 1948), Habib (1948), White (1949)
1940s	Taylor test developed	Taylor (1946, 1948), Carrington & Gayler (1948), Whiffin (1948)
1940s	Early use of strain gauges in dynamic tensile testing	Fehr & Parker (1943), Fehr et al. (1944)
1948	Davies analyses the propagation of waves in the Hopkinson pressure bar and develops an electrical capacitance method for measuring stress pulses in rods	Davies (1948a, b)
1948-9	Volterra and Kolsky develop the SHPB	Volterra (1948), Kolsky (1949)
1950	Development of the cam plastometer	Loizou & Sims (1953)
1950s	Experimental checks of the St Venant hypothesis and hence legitimation of the use of surface strain gauges to measure stress pulse propagation	Davies (1948b), Boley (1955, 1960), Horvay & Mirabel (1958), Clausing (1959), Graham & Ripperger (1959), Flynn & Frocht (1961), Kuo (1961), Hauser (1966)

2. Development of the Split Hopkinson Pressure Bar (SHPB)

The development of Hopkinsonís pressure bar into a transducer for measuring the dynamic properties of materials (Volterra 1948; Kolsky 1949) depended on several factors, perhaps the most important being the design and construction of electronic amplifiers with sufficient bandwidth to amplify signals with MHz frequency components without significant distortion. There had also been renewed interest in the problem of the dispersion of elastic waves travelling down solid rods during the early 1940s as it was desired to use them as mechanical waveguides and delay lines in various applications such as blast measurement and radar, (e.g. Prowse 1936; Shear & Focke 1940; Bancroft 1941; Hudson 1943; Cooper 1947; Arenberg 1948; Hughes et al. 1949; Davies et al. 1950; Holden 1951; Redwood 1960; Miklowitz 1973). As experience had been gained during the Second World War in using microphone technology to interconvert mechanical and electromagnetic waves, Kolsky used condenser microphones to detect strain pulses in his pressure bar (Kolsky 1949), though wire strain gauges had already been used in impact tension test machines (Fehr & Parker 1943; Fehr et al. 1944).

Another reason for using condensers was that there was some concern whether a strain pulse measured by a gauge on the surface of a bar was representative of the wave travelling down its interior (Ripperger 1953; Graham & Ripperger 1959), particularly if the specimen has a diameter significantly different to the pressure bar (Davies 1948b; Clausing 1959). For this reason (and also because they were concerned about stress equilibrium within the specimen), early workers used thin wafers of materials with a diameter only just less than that of the bars (aspect ratios of ca. 10) (Kolsky 1949; Hauser et al. 1961; Conn 1965) or they used alternative techniques to study dynamic properties such as the propagation of plasticity down long rods, e.g. (Malvern 1951a, b; Campbell 1952, 1953; Ripperger 1960; Kolsky & Douch 1962; Rajnak & Hauser 1963; Bell 1968). However, the use of thin wafers in the SHPB has a number of disadvantages: (i) friction and radial inertia produce stresses similar in magnitude to the expected strain rate effect (Davies & Hunter 1963), (ii) materials can only be tested that have a lower yield stress than the bar (Tabor 1951; Gorham et al. 1992), and (iii) the strain that can be imposed is small (Campbell 1953). However, the work of Davies & Hunter (1963) and Lindholm (1964) opened the way for the use of specimens with smaller aspect ratios (ca. 1).

Strain gauges started to be used in SHPBs in the mid 1950s to early 1960s (Petersson 1953; Campbell & Duby 1956; Hauser et al. 1961; Chiddister & Malvern 1963; Lindholm 1964). These have the advantage over capacitance methods in that their signals do not require differentiation to obtain particle velocities (Hauser et al. 1961) but the disadvantage that they do not average the strain over the whole section of the bar.

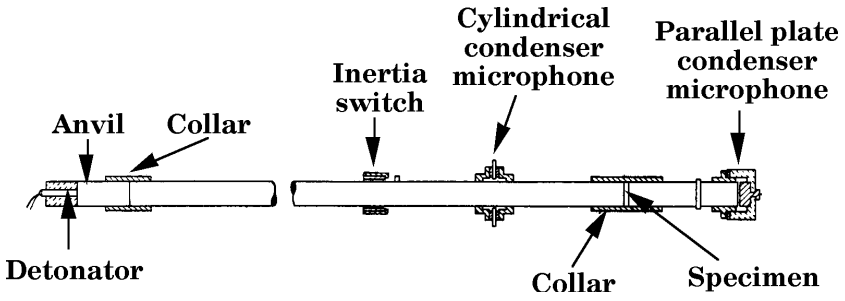

Figure 2. Schematic diagram of original SHPB (from Kolsky 1949)

In order to calculate a stress-strain curve for a cylindrical specimen deforming between the two instrumented bars, it is necessary to know the displacements of the ends of the specimen and the forces acting on these ends. A simple one-dimensional wave analysis, whose derivation may be found in a number of places, (e.g. Kolsky 1949; Krafft et al. 1954; Lindholm 1964; Follansbee 1985) shows that if the forces on the two ends of the specimen are equal, then

$$\dot{\varepsilon}(t) = -\frac{2c_b}{l_s}\varepsilon_R(t) \tag{2}$$

$$\sigma(t) = \frac{c_b Z_b}{A_s}\varepsilon_T(t) \tag{3}$$

where $d\varepsilon/dt$ is the strain rate and σ is the stress in the specimen, c_b is the elastic wave speed and Z_b the mechanical impedance of the bar material (usually identical bars are used), $\varepsilon_R(t)$ is the strain wave in the input bar caused by reflection from the specimen, $\varepsilon_T(t)$ is the strain wave in the output bar caused by transmission through the specimen, and l_s is the instantaneous length and A_s is the instantaneous cross-sectional area of the specimen. Knowing the time taken for elastic waves to travel from the specimen to the gauges on the input and output bars, the reflected and transmitted pulses can be time-shifted to coincide at the specimen. Then by integrating equation (2) (making use of the definition that $\varepsilon=\ln(l_0/l_s)$, where l_0 is the initial length of the specimen) we can find $\varepsilon(t)$ and $l_s(t)$. Assuming the volume of the specimen does not change during the deformation, this information gives $A_s(t)$ and hence $\sigma(t)$ from equation (3). The stress-strain curve can then be constructed by eliminating time as a variable.

A number of problems with this procedure have been identified over the years.

First, do the forces at the ends of the specimen become equal, and if they do, how long does this take (Bell 1966; Jahsman 1971; Bertholf & Karnes 1975; Briscoe & Nosker 1984; Dioh et al. 1993; Wu & Gorham 1997)? This issue was raised right back at the beginning by Kolsky in his original 1949 paper where he reported results obtained for rubber (Kolsky 1949). The time taken to achieve stress equilibrium can be determined by comparing the results of the classical 1-wave Hopkinson bar analysis (given in equations (2) and (3) above) with a 2-wave analysis where the stress at the specimen-incident bar interface is calculated from the incident and reflected wave pulses (Follansbee & Frantz 1983) (the classical analysis is termed ë1-waveí because it uses only one wave, the

transmitted pulse, to calculate the stress in the specimen). If the specimen is in stress equilibrium, the two analyses will yield the same answer, though dispersion effects generate larger oscillations in the results of the 2-wave analysis. This problem of oscillation can be mitigated to some extent by using a 3-wave analysis where you make no assumption about stress equilibrium in the specimen and effectively calculate the average of the stresses on the front and back faces (Gray III 1999a). Gray III and co-workers from Los Alamos National Laboratory (LANL) have recently demonstrated the importance of carrying out this procedure if the high strain rate properties of low sound-speed, dispersive materials such as polymers and energetic composites are being determined (Gray III et al. 1997, 1998a, b).

Second, might the details of the strain-rate history during the loading phase affect the microstructural state of the material and hence the measured flow stress (Klepaczko 1967, 1975; Campbell & Briggs 1975; Follansbee & Kocks 1988)?

Third, because many high strain-rate applications require stress-strain curves to be known out to large strains, the original specimen diameter must be significantly smaller than the pressure bar diameter (this allows a large deformation to be imposed before the specimen diameter equals the bar diameter and equations (2) and (3) become invalid). This means in turn that the elastic wave pulse close to the bar end is not one-dimensional as assumed in the above analysis. The question thus arises as to whether the pulse becomes planar, and if does how far from the bar ends should the surface strain gauges be placed placed (Kennedy & Jones 1969; Gorham 1980; Klupershlyak-Yuzefovich & Shkerbin 1981; Safford 1988; Gorham et al. 1992)?

Fourth, how much error in the stress-strain curve is introduced by assuming the measured strain pulses can be simply time-shifted back to the specimen position? For we know in fact that these pulses are distorted by wave dispersion effects as they travel down the bars (Sharpe Jr. & Hoge 1972; Engström 1974; Yeung Wye Kong et al. 1974; Parnes 1982; Follansbee & Frantz 1983; Gorham 1983; Follansbee 1986; Safford 1992; Gorham & Wu 1996; Mason 1999). Work is in still in progress to improve the correction algorithms and make them more routine (Gorham & Wu 1996; Wu & Gorham 1997; Wu et al. 1998).

Fifth, how much effect do (i) friction between the specimen and bar ends and (ii) radial inertia have on the assumption that the stress in the specimen is uniaxial and can these two effects be allowed for or made negligible (Davies & Hunter 1963; Sato & Takeyama 1979; Bolshakov et al. 1982; Briscoe & Nosker 1984; Gorham et al. 1984; Walley et al. 1989, 1997; Gorham 1991b)?

The main driving force behind the development of the high strain rate testing techniques in recent years has been the need to obtain values for the parameters in the various material constitutive models used in the numerical modelling of the impact or shock response of structures (Macdougall & Harding 1999; Noble et al. 1999). Thus SHPBs have not only been constructed to load specimens in uniaxial compression but also in uniaxial tension (Harding et al. 1960), torsion (Duffy et al. 1971; Lewis & Campbell 1972), and simultaneous torsion-compression (Lewis & Goldsmith 1973). Torsion is perhaps the best method from a materials point of view as friction and inertia play no role (Fleck et al. 1990) but the specimens are difficult to make. SHPBs have also been used to load notched specimens either to measure shear strength (Campbell & Ferguson 1970; Harding & Huddart 1980; Ruiz et al. 1991) or fracture toughness, (e.g. Klepaczko 1980; Kishida et al. 1984; Bacon 1993a; Bacon et al. 1994). With brittle or low strength materials, failure may occur during the initial loading ramp, so such specimens often have gauges attached directly to them (Wasley et al. 1969; Cosculluela et al. 1991).

Reviews of SHPB testing may be found in Sato & Takeyama (1978), Follansbee (1985), Muzychenko et al. (1986), Muzychenko & Postnov (1986), Nemat-Nasser et al. (1991), Field et al. (1994), Al-Mousawi et al. (1997), Gray III (1999a, b), Gray III & Blumenthal (1999).

Temperature has proportionately a much greater effect on material strength than strain rate. But though its effects on high strain-rate deformation have long been studied, it has not really been given the attention it deserves. Some work has, however, been performed on temperature effects at high rates of strain using SHPBs (Krafft et al. 1954; Chiddister & Malvern 1963; Lindholm 1968; Muller 1971; Eleiche 1975; Eleiche & Duffy 1975; Rosenberg et al. 1986b; Kishida et al. 1987; Lennon & Ramesh 1998; Peterson 1999), drop-weight towers (Maiden & Campbell 1958; Baraya et al. 1965; Samanta 1969), cam plastometers (Alder & Phillips 1954-55) and hydraulic testing machines (Briggs & Campbell 1972). The existence of temperature gradients in the input and output bars potentially introduces further distortion into the measured signals (Stanford 1950; Datta 1956; Sur 1961; Chiddister & Malvern 1963; Lindholm & Doshi 1965; Whittier 1965; Francis 1966, 1967; Lindholm & Yeakley 1968; Lee 1974; Eleiche 1975; Eleiche & Duffy 1975; Bacon et al. 1991; Bacon 1993b), but some authors have found this effect to be small even for conventional steel bars so long as the test temperature is no more than 300 °C removed from room temperature (Krafft et al. 1954; Campbell & Dowling 1970; Campbell & Ferguson 1970; Samanta 1971; Senseny et al. 1978; Kishida et al. 1987).

If the temperature gradient is large enough that it cannot be ignored, various approaches have been used to compensate for it: (i) the bars can be tapered to maintain the mechanical impedance constant along their length (Eleiche 1975; Eleiche & Duffy 1975; Bacon 1993a) (this method has the disadvantage that a bar of a particular profile can only compensate for one particular temperature gradient); (ii) the effect of the temperature gradient can be measured (Bacon et al. 1991; Bacon 1993b); (iii) the effect of the temperature gradient can be calculated (Chiddister & Malvern 1963; Lindholm & Yeakley 1968). All three approaches assume that the temperature gradient is in a steady state. If, however, it is desired to heat a specimen rapidly by, for example, induction

heating (Rosenberg et al. 1986a, b) or radiant methods (Macdougall 1998) to ensure that the microstructure of the specimen is the same when you test it as when you made it, none of these methods can be used. Two methods have been devised to test at higher temperatures or with unsteady temperature gradients: (i) up to +600 °C, the bars can be made from one of the Inconel alloys (Kandasamy & Brar 1994) whose mechanical impedance is only a weak function of temperature; (ii) the specimen can be kept thermally insulated from the bars. Two ways of doing this have been devised. The first is to place thermal insulation between the specimen and the bars (Lankford 1977, 1981). The second is to construct a mechanical device that brings the (cold) bars into contact with the heated specimen a fraction of a second before the stress pulse arrives at the end of the input rod (Tsoi et al. 1980; Frantz et al. 1984; Lennon & Ramesh 1998). The latter approach is probably the only practical method of testing materials at high rates of strain above 1000 °C.

Temperature effects come into the problem another way in that high strain-rate deformation results in work being dissipated as heat faster than it can flow away (Chou et al. 1973). Thus the temperature of a rapidly deforming specimen rises, sometimes by many hundreds of degrees (Dao & Shockey 1979; Lataillade et al. 1984; Swallowe et al. 1986; Hartley et al. 1987; Dawson et al. 1991). This can lead to mechanical instability and the localization of deformation into very narrow sheets of material, so called ëadiabatic shear bandsí (for recent overviews of this topic, see Bai & Dodd (1992), Armstrong et al. (1994)). This temperature rise has to be taken into account when checking constitutive models, for strictly speaking, comparisons of the strength of a material at different strain rates are only valid if the material is in the same thermodynamic state (Dorn et al. 1949). For this reason some authors have sought to allow for the temperature rise and compute isothermal high strain-rate stress-strain curves (Dawson et al. 1991; Dixon & Parry 1991; Tugcu & Neale 1994; Nemat-Nasser & Isaacs 1997).

The widely reported upturn in flow stress at strain rates in excess of 10^4 s^{-1} (often explained in terms of viscous drag on dislocations (Kumar & Kumble 1969; Follansbee & Weertman 1982; Follansbee et al. 1984; Johnson & Tonks 1992)) has been called into question recently for a number of reasons.

First, the upturn looks to occur at a strain rate suspiciously close to that where radial inertial stresses start to increase rapidly (compare figures (3) and (4)).

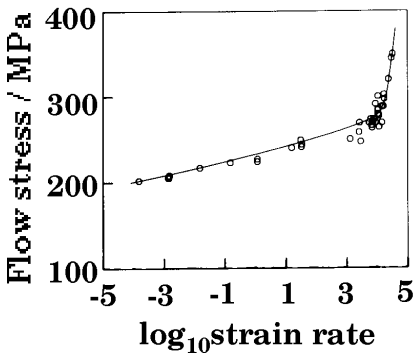

Figure 3. Flow stress of annealed 0.9999 copper at a strain of 0.15 as a function of strain rate (from Follansbee et al. 1984)

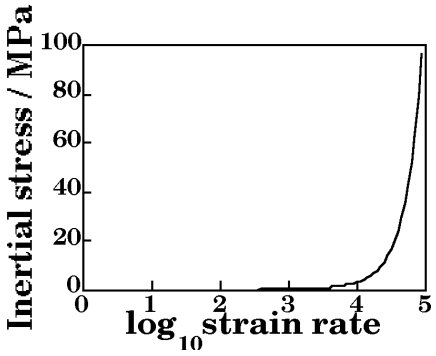

Figure 4. Inertial stress as a function of strain rate calculated using the formula given in (Gorham 1991a) for copper specimens 3.8mm in diameter and 2.3mm thick (the smallest specimen size used in Follansbee et al. 1984).

A criterion computed by Bertholf & Karnes (1975) shows that for inertial stresses to be acceptably small in an SHPB test, the following inequality must hold: $D.d\varepsilon/dt < 50\ m\ s^{-1}$ where D is the bar diameter. Gorham considered the matter again and found that for copper the radial inertial stress would be half the flow stress if $d.d\varepsilon/dt = 42\ m\ s^{-1}$ where d is the specimen diameter (Gorham 1991a). He pointed out that several authors tested specimens with dimensions that were too large for the strain rates they were working at. One way legitimately to obtain very high strain rates in compression is to use a miniaturised SHPB as suggested by Lindholm (1978) and implemented by Gorham (1980). However, it should be noted that an increase in rate sensitivity at very high strain rates has also been observed in torsional experiments where radial inertia plays no role (Yen & Yew 1969).

Second, flow stresses at different strain rates have usually been compared at equal strains, and strictly speaking this is invalid as strain is not a state variable (Hollomon 1947). This is because the microstructure, which is a true state variable, may depend on the loading path which brought the specimen to that strain (Hartley & Duffy 1984; Klepaczko 1988; Klepaczko 1989). For example, twinning is observed in iron at high strain rates but not at low strain rates (Yen & Yew 1969; Behler 1988; Chiem 1988). However, since it is not usually possible to characterise the microstructural state during deformation, much effort has gone into finding a mechanical state variable that is measurable (Follansbee 1986, 1989; Regazzoni et al. 1987; Follansbee & Kocks 1988). Also following on from work performed at low strain rates, there has been some work done on determining how much effect strain and strain-rate history have on mechanical properties by means of strain-rate change tests where part of the loading history occurs at high rates of deformation (Campbell & Briggs 1975; Klepaczko 1975, 1989; Eleiche & Campbell 1976; Senseny et al. 1978).

Third, recent modelling work by Dioh and colleagues has shown that the upturn may be due to the specimen never reaching stress equilibrium due to the slow speed of propagation of plastic waves (Dioh et al. 1995). However, their work indicates that a downturn in stress is just as likely as an upturn, and this is confirmed by recent work on polymers (Walley & Field 1994; Swallowe et al. 1997; Al-Maliky et al. 1998).

Radial inertia sets a limit to the strain rate that can be achieved by compression testing under uniaxial stress conditions. For in order to achieve a strain rate of $10^5 s^{-1}$ and keep inertial stresses negligible the specimen diameter must be less than about 0.5 mm. Specimens this small will not have mechanical properties representative of the bulk unless they are amorphous or at least almost nanocrystalline (Armstrong 1961). Conventional SHPBs, with bar diameters of 10 mm or larger, are not suitable for testing such very small specimens: the disparity of area creates too big an impedance mismatch. Also the rise time of the loading pulse increases as the wave travels down the input bar due to dispersion effects, lowering the strain rate achieved. Because the speed of propagation of a given frequency component depends on the amount of radial motion associated with that frequency, bars made from a material with a low Poisson's ratio would produce little dispersion, but suitable materials such as beryllium with a Poisson's ratio of 0.05 or diamond with a Poisson's ratio of 0.07 either cannot yet be fabricated into rod form (diamond) or are toxic (beryllium). Both diamond and beryllium are brittle. However, beryllium has been used as a Hopkinson bar in two applications that we know of (Jones 1966; Bateman et al. 1996).

A number of workers made the suggestion that another way around this problem of dispersion was to dispense with the input bar and impact the specimen directly (Dharan & Hauser 1970; Wingrove 1971; Wulf & Richardson 1974). However, Wulf & Richardson ís claim to have achieved strain rates of 105s-1is probably doubtful as they used bars 12.5 mm in diameter. Direct impact Hopkinson pressure bars of these kind of dimensions have subsequently been used to obtain the dynamic fracture properties and compressive strength of propellants and polymers (Fong 1983, 1985; Ho & Fong 1987; Walley et al. 1989, 1991, 1992; Ho 1996) at more modest strain rates (103s-1). Direct tension Hopkinson bars have also been constructed (Albertini & Montagnani 1974; Staab & Gilat 1991).

In order to be able to obtain uniaxial compressive stress-strain curves at strain rates close to the limit of Hopkinson bar techniques, Gorham developed in our laboratory a miniaturised version of the direct impact Hopkinson pressure bar (Gorham 1980; Gorham et al. 1992). The pressure bar is 3 mm in diameter and is intrumented with miniature (0.64∞0.15 mm) semi-conductor strain gauges. It can routinely test pinhead size specimens (1mm in diameter and 0.5 mm thick) at strain rates between 10^4 and $10^5\ s^{-1}$. Since there is no input bar whose gauge record would normally give the strain rate and hence the strain, high-speed photography was initially used to record the diametral expansion and hence determine the strain. However, it was soon realised that this was not routinely necessary (Pope & Field 1984) (see figure 5), though useful as a check (Gorham et al. 1992). If for any reason, such as shear banding, the specimen does not remain cylindrical during the test, high-speed photography of the expansion of one plane section will not give an accurate measure of the strain from the time that this happens.

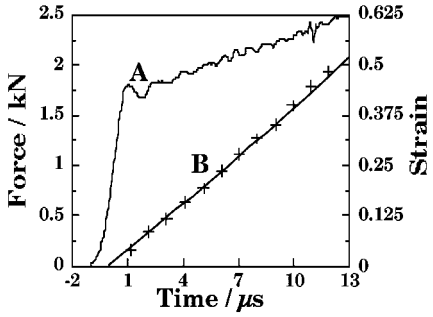

Figure 5. Plot showing the close agreement between strain measured sing high-speed photography (indicated by + signs) and that calculated (line B) from the force pulse (line A) recorded from the output bar or a work-hardened W-Ni-Fe alloy. From (Pope & Field 1984; Gorham et al. 1992)

Two further advantages of miniaturisation are (i) that the range of frequencies which can be propagated without dispersion is increased (because a bar only becomes strongly dispersive at wavelengths commensurate with its diameter (Gorham et al. 1992; Safford 1992), and (ii) the bar can be made from a hard, relatively brittle material like tungsten carbide allowing very strong materials such as tungsten to be tested (our 3mm diameter WC bar has not yet broken, though it has been used many hundreds, if not thousands, of times, whereas we have found that a conventional SHPB made from 12.5mm diameter WC rods breaks after fewer than 100 tests). If it can be used, WC has another advantage in that its Poisson's ratio is smaller than that of many metals (0.22 as opposed to ca. 0.3 for steels, 0.32 for titanium and 0.28 for tungsten) which means that the frequency at which dispersion effects become important is higher for a bar made of WC than for one made from such metals (Bancroft 1941) i.e. it can transmit stress-wave pulses with less distortion.

One common drawback of conventional SHPB systems is that specimens are loaded repeatedly by stress-wave reflections within the bars making microstructural investigations relatively pointless. However, a recent innovation by Nemat-Nasser and colleagues allows ë soft recovery of specimens that have been loaded once and once only (Nemat-Nasser et al. 1991). This can now be achieved in compression, tension and torsion (Chichili & Ramesh 1999).

Other recent developments of note have been:

(i) the construction of polymer Hopkinson bars for testing materials of low mechanical impedance such as the polymer foams used in crash-test dummies (Wang et al. 1992, 1994, 1995; Gary et al. 1995a, b, 1996; Zhao & Gary 1995; Sawas et al. 1996; Rao et al. 1997; Zhao 1997, 1998; Zhao et al. 1997; Bacon 1998, 1999). The mathematical analysis of wave propagation in polymer bars is much more complex than for metallic bars because polymers are strongly viscoelastic. The added complications of temperature gradients make it doubtful whether polymer bars can be used for testing soft materials at non-ambient temperatures, which it is essential to be able to do if a full constitutive equation for the test material is to be constructed and checked. It should be pointed out that the standard Hopkinson bar equations cannot be used for foams or other porous materials as the specimen volume is not constant during the test.

(ii) the use of magnesium, aluminium and titanium bars to test low impedance materials (magnesium has the lowest mechanical impedance of the chemically stable common metals). These have the advantage over polymer bars that they can be used at non-ambient temperatures (Chen et al. 1999; Gray III 1999a, b; Gray III et al. 1999; Gray III & Blumenthal 1999).

(iii) the construction of large (a metre or so in diameter and hundreds of metres in length) Hopkinson bar systems for testing coarse composite materials such as concrete and engineering structures such as car panels (Albertini et al. 1985, 1986, 1988, 1989, 1991, 1992, 1993, 1995, 1996, 1997; Albertini & Montagnani 1992).

(iv) the development of wave separation techniques to extend the effective length of Hopkinson bars and to carry out tests at lower strain rates (Zhao & Gary 1997; Bacon 1999).

A summary of major developments in SHPB testing is given in Table 2.

Table 2 - Progress in SHPB testing

Date	Major developments	Reference
1949	Kolsky and Volterra develop the SHPB	Volterra (1948), Kolsky (1949)
1957	First report of dynamic biaxial testing	Gerard & Papirno (1957)
1960	Harding develops the tensile SHPB	Harding et al. (1960)
1971	Duffy and co-workers develop the torsion SHPB	Duffy et al. (1971), Lewis & Campbell (1972)
1973	Biaxial (torsion-compression) SHPB developed	Lewis & Goldsmith (1973)
1980	Gorham develops the miniaturised direct impact Hopkinson bar	Gorham (1980)
1980	First (published) use of microcomputer with SHPB	Signoret et al. (1980)
1985	Albertini develops large SHPB for testing structures and concrete	Albertini et al. (1985)
1986	Rosenberg suggests induction heating as a method of heating metallic SHPB specimens quickly	Rosenberg et al. (1986b)
1991	Nemat-Nasser develops one pulse loading SHPBs (compression, tension) and soft-recovery techniques	Nemat-Nasser et al. (1991)
1992- 8	Development of polymer Hopkinson bar for testing foams and polymer-based materials	Wang et al. (1992, 1994, 1995), Gary et al. (1995a, b, 1996), Zhao & Gary (199), Sawas et al. (1996), Rao et al. (1997), Zhao (1997, 1998), Zhao et al. (1997\), Bacon (1998, 1999)
1993	Use of torsional SHPB to measure dynamic shearing properties of lubricants	Feng & Ramesh (1991, 1993)
1997-	Use of wave separation techniques to extend the effective length of a Hopkinson bar system	Zhao & Gary (1997), Bacon (1999)
1998	Development of magnesium Hopkinson bar for soft materials	Gray III et al. (1999)
1998	Development of radiant methods of heating metallic SHPB specimens quickly	Macdougall (1998), Lennon & Ramesh (1998)
1999	Development of one pulse torsion SHPB	Chichili & Ramesh (1999)
1999	Use of torsional SHPB for dynamic sliding friction measurements	Rajagopalan et al. (1999)

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