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A Miniaturized Split Hopkinson Pressure Bar for Very High Strain Rate Testing

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Measurements of material properties at very high rates of strain give an important insight into the structure of these materials, as well as having many industrial uses. This paper describes a miniaturized split Hopkinson pressure bar (MSHPB) for measuring the stress-strain relationships in materials at strain rates up to 10^5 s^{-1}, extending the technique from its usual range of 500 – 10^4 s^{-1}. As well as describing the difficulties of carrying out experiments at very high rates, and how these difficulties are overcome in this system, the paper also shows some data from experiments on copper and polytetrafluoroethylene (PTFE).

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PREFACE

This report was prepared by the Air Force Research Laboratory/Munitions Directorate, Ordnance Division, Energetic Materials Branch (AFRL/MNME), Eglin Air Force Base, Florida 32542-5910, and covers work performed during the period from 01 October 2003 to 01 February 2005. Dr. Jennifer L. Jordan managed the program for the Directorate.

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SECTION I

INTRODUCTION

An understanding of the way materials behave at very high rates of strain is of great importance to both industrial application and academic study. High strain rate deformation can occur in many circumstances, large-scale impacts, such as automobile or airplane accidents are the most obvious examples, but localized deformation at high rates of strain is possible in low speed impacts where a rapid deceleration is transmitted to small components of a system. Academically, high strain rate experiments sample atomic and molecular transitions and movements that occur at very high frequencies and must be understood.

The split Hopkinson bar is a very commonly used apparatus for producing accurate, qualitative measurements of material properties at strain rates between 500 and 10^4 s^{-1} (Reference 1). There are three configurations in general use allowing loading in tension, compression and shear, which share some common features. The specimen sits between two rods, usually made out of metal. These rods are known as the input and output bars and are instrumented with strain gauges halfway down their length. A tensional, compressional or torsional stress pulse, known as the incident wave, is loaded into the input bar and travels to the specimen which deforms under the load. The impedance change at the bar-specimen interface causes some of the incident wave to travel through the specimen, and some to be reflected back into the input bar, to form the transmitted and reflected waves respectively. The magnitude and shape of these waves is measured by the strain gauges, and this information can be used in the Hopkinson bar equations (Reference 1) to calculate the stress and strain in the specimen as a function of time.

In the particular case of the compressional split Hopkinson pressure bar (SHPB) the incident wave is usually produced by a third rod, the striker bar, which is typically accelerated into the input bar using a light gas gun. Changing the firing pressure in the gas gun allows the speed of the striker, and thereby the magnitude of the input pulse, to be controlled, which in turn controls the strain rate in the specimen. The strain gauges on the input and output rods allow these pulses to be measured, and as long as the length of the striker bar is less than half that of the input and output bars, there is no overlap of the waves. A schematic diagram of the system, also showing the three pulses, is given in Figure 1. The essence of the system is that the bars remain elastic during the test, ensuring that the strain gauges are reusable and can be well calibrated, while the specimen deforms plastically. This restriction limits the size of the input pulse that can be used.

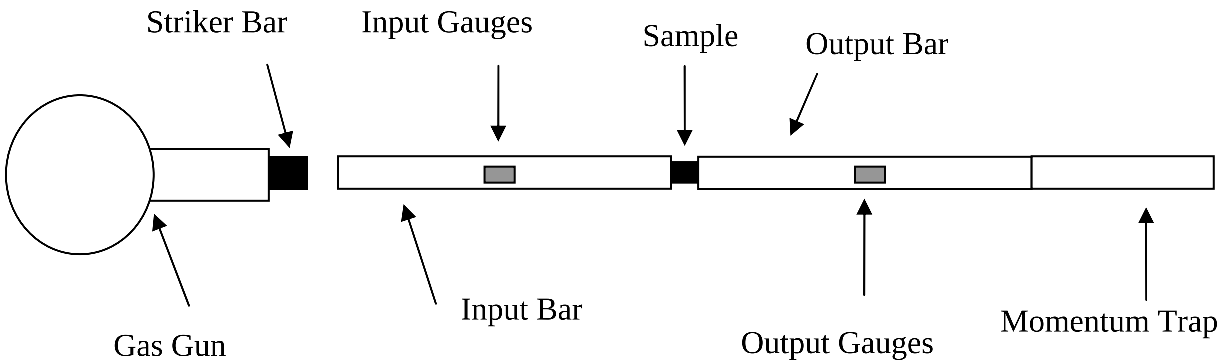

Figure 1a. Schematic of Compression Split Hopkinson Pressure Bar

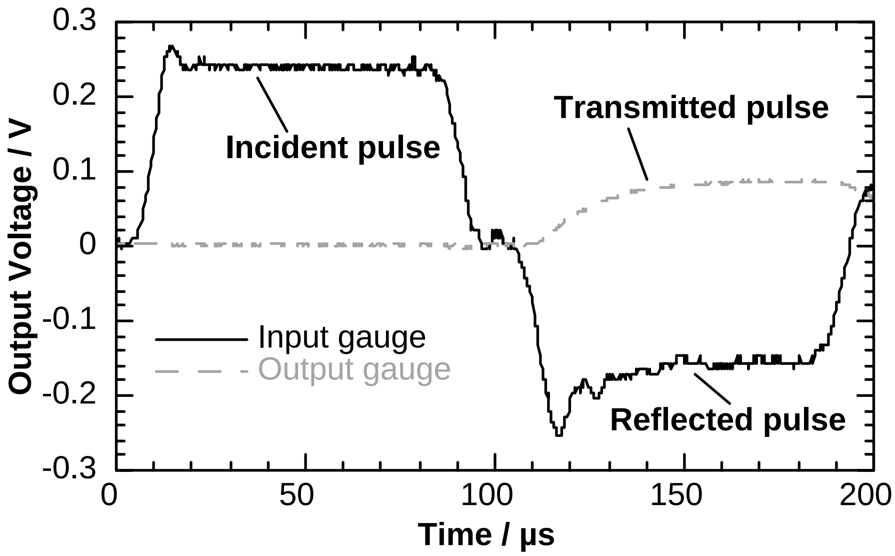

Figure 1b. Voltage-Time Traces of Incident, Reflected, and Transmitted Pulses

The specimen in an SHPB system is a small disc or cylinder, with sides perpendicular to its faces. It is important to ensure that the specimen is large enough to represent the bulk material from which it is made; a commonly used criterion is that the specimen must contain 10 characteristic units of the material structure across all its linear dimensions (Reference 2). The size of the transmitted pulse is also governed by the size of the specimen, and for soft materials a large radius may be required.

As strain rate increases, it is necessary to decrease the size of the specimen in order to limit the effects of inertia. As the specimen is compressed it expands radially, the inertial resistance to this expansion increases the measured stress so that it is greater than the actual strength of the material. Gorham derived an equation to describe the inertial contribution to the stress, and showed that it is proportional to the square of the strain rate (Reference 3). He also showed that it is not possible to correct for this inertia, but that it should be minimized through sensible specimen design, as the strain rate is increased the size of the specimen must be reduced. Unfortunately, as the specimen size is reduced the amount of transmitted force also decreases. It is possible to increase the strain generated by this force by decreasing the area of the bars. Therefore, measurement of mechanical properties of materials at very high strain rates naturally calls for the development of a miniaturized split Hopkinson pressure bar (MSHPB).

The idea of using miniaturized Hopkinson bars for measurements up to 10^5 s^{-1} was first developed by Gorham and Field (References 4, 5, and 6), who described the use of a miniature direct impact Hopkinson bar, where the striker bar impacts the specimen directly without the use of an input bar. By accurately measuring the impact velocity of the striker bar, and the signal in the transmitted bar, it was possible to produce accurate stress-strain curves (Reference 7). A further advantage of miniaturization was that the small bar diameter decreases dispersion of the stress wave.

The main disadvantage of the direct impact system is that it is not possible to measure specimen equilibrium. This is traditionally done in a split system by calculating the stress in the specimen from the force on its front face, using the incident and reflected waves, and comparing this value to that calculated from the force on its rear face using the transmitted wave (Reference 1). These two methods of calculating the stress will be called the one-wave and two-wave analyses respectively, and if the specimen is in equilibrium the two results should be the same. In reality, the two-wave stress tends to oscillate around the one-wave, because of noise on the incident and reflected signals, which are both large compared to the transmitted signal.

By developing a MSHPB, it is possible to measure material properties at rates of up to 10^5 s^{-1}, while minimizing the effects of inertia, and being able to test for specimen equilibrium during the experiments.

This paper describes some of the challenges of making such a system and the essential features of the system that has been produced. Finally results from the high strain rate compression of polytetrafluoroethylene (PTFE) and copper will be presented and compared to those obtained from quasi-static testing. These were carried out with specimen sizes designed to keep inertia effects to a minimum at all the strain rates investigated. It is shown that accurate and repeatable results can be obtained in the system, with good strain gauge signal to noise ratios for both hard and soft specimens. Mechanical equilibrium in the specimens is also confirmed.

SECTION II

EXPERIMENTAL SET-UP AND APPLICATION

The new MSHPB has been designed to measure the properties of materials at strain rates between 10^4 and 10^5 s^{-1}. It uses rods with diameters ranging from 3.0 to 3.2 mm, in order to test specimens with diameters between 0.5 and 1.5 mm. The rods are held at three points along their lengths in PTFE bearings, which are carefully aligned and mounted on a single piece of steel to ensure that the alignment is retained. The input and output rods are 300 mm long, and the striker is 100 mm long. This gives a typical loading pulse of 40 µs. Alignment is confirmed by the complete passage of a stress wave from the input to the output bar when no specimen is present, with no reflection at the interface.

An important consideration when using a miniaturized system is the instrumentation of the rods. With such a small diameter, it is not possible to affix foil strain gauges. It is also important to minimize the gauge length, to reduce the inherent time averaging that occurs along the length of the gauge. As the strain rate increases, accurate time measurements become increasingly important if precise measurements of specimen strain are to be made. Semiconductor strain gauges can offer the advantage of small length (1 mm) and high gauge factor (140). In this system, Kulite type AFP-500-90 strain gauges are placed in a potential divider circuit, with constant voltage excitation. As well as turning the resistance change of the gauges into a voltage change suitable for measurement on an oscilloscope, this linearizes the output in strain, and also compensates for temperature changes. With a suitable choice of series resistor, the temperature dependence can be reduced below 0.25 percent for a change in temperature of ± 10 ˚C.

In order to ensure accuracy of results, the strain gauges are dynamically calibrated *in situ*. A gas gun is used to propel the striker bar, which sits in a sabot with external diameter 12 mm. A sabot stripper ensures that the sabot does not contribute to the input stress wave. The velocity and acceleration of the striker are measured just before it hits the input bar, using a 3-point light gate. This allows accurate calculation of the impact velocity, which is then used to calibrate each set of strain gauges. An accurate knowledge of the striker bar mass and velocity allows its momentum to be calculated. This is compared to the voltage pulse from the strain gauges to give a calibration of the form:

$$F = KV(1 + bV), \qquad (1)$$

where K and b are calibration factors (Reference 6).

Currently two bar materials are used, Tungsten Carbide (WC) and Ti-6Al-4V, whose properties are listed in Table 1. Both materials have the advantage of a high yield modulus, but they have very different impedances, allowing both soft and hard materials to be tested.

Table 1. Selected Properties of the Tungsten Carbide and Ti-6Al-4V Rods Used in the Miniature SHPB

Material	Density (kg/m^3)	Acoustic wave speed (mm/µs)	Impedance ($kg\ m^{-2}\ s^{-1}$)	Yield stress (MPa)
WC	14527	6316	91753540	2600
Ti6Al4V	2709	5039	13652962	1000

SECTION III

SPECIMEN PREPARATION AND TESTING

The results presented here were obtained on as-received PTFE and Hitachi OFE copper. These data are the initial efforts to measure the properties of both of these materials, which will be carried out on carefully annealed and characterized specimens, and were taken as proof of principle for the new apparatus.

Specimen sizes were chosen to ensure that the effect of inertia on the measured stress was minimized. The nominal size of the samples was 1.5 mm length and 0.65 mm diameter. The specimens were carefully machined and in order to ensure accurate results they were examined under a microscope for flat and parallel faces, and individually measured prior to being tested. Future work will examine the manufacture of specimens 0.2 mm long, and 0.5 mm diameter, for experiments at strain rates up to $10^5\ s^{-1}$.

SECTION IV

RESULTS AND DISCUSSION

Figure 2 shows stress-strain curves from specimens of PTFE tested at 1.2 x 10^4 and 3.6 x 10^4 s^{-1} in the Ti-6Al-4V bars. As a comparison, the data obtained by Walley, et al. (Reference 8) at 2.6 x 10^4 s^{-1} are also presented. The strain - time curves are shown in Figure 3, as it is always important to check that a constant strain rate is being obtained. These data show that it is possible to obtain very high strain rate results, using a SHPB system, that are consistent and reproducible. While the results do not agree precisely with those of Walley, this was expected since the grade of material used was not the same. The signal to noise ratio on the stress-strain curves is also very good.

Stress-strain curves from unannealed copper are shown in Figure 4, with corresponding strain-time data in Figure 5. Again, the curves are seen to be very reproducible, while there are some differences on the rising part of the pulse, the flow stress is consistent to within 10 MPa, or 2.5 percent of the actual stress. A comparison of the one and two wave analyses show that the specimens do reach equilibrium before the flow stress plateau, Figure 6. Unfortunately Pochammer-Chree oscillations disguise the point where equilibrium is reached. However, it is expected that equilibrium will be achieved very quickly because of the small specimen size. A commonly used rule of thumb is that the specimen is in equilibrium after the stress wave has had time to traverse the specimen three times. This hypothesis is supported by, for example, the work of Parry et al. (Reference 9). In a copper specimen of this size, three wave transitions within the specimen would take approximately 1 μs, corresponding to 2.4 percent strain at 2.4 x 10^4 s^{-1}.

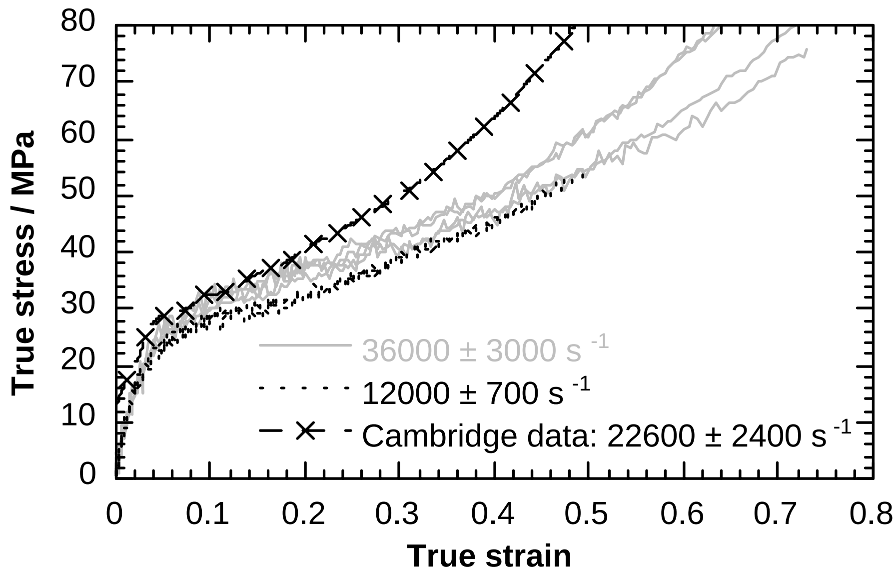

Figure 2. Stress-Strain Curves for PTFE at Two Strain Rates, Compared to Data from Walley (Reference 8)

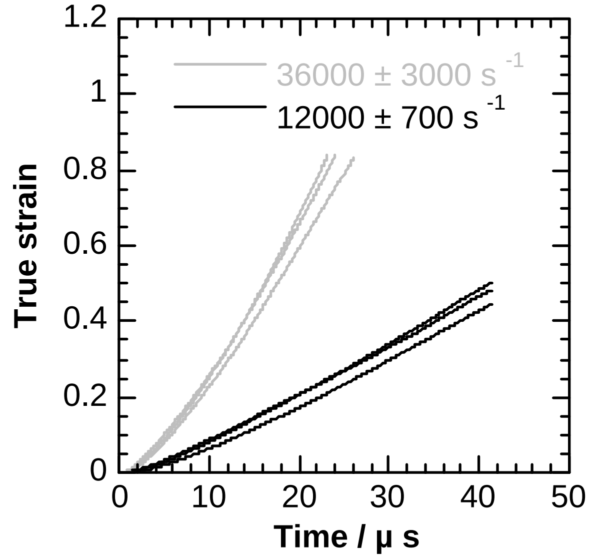

Figure 3. Strain-Time Curves Corresponding to the Stress-Strain Curves in Figure 1

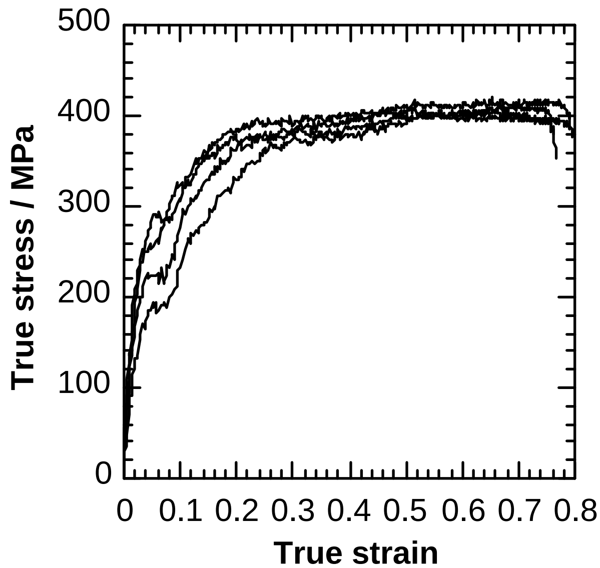

Figure 4. Stress-Strain Curves for Copper Specimens at 20,600 ± 1000 s^{-1}

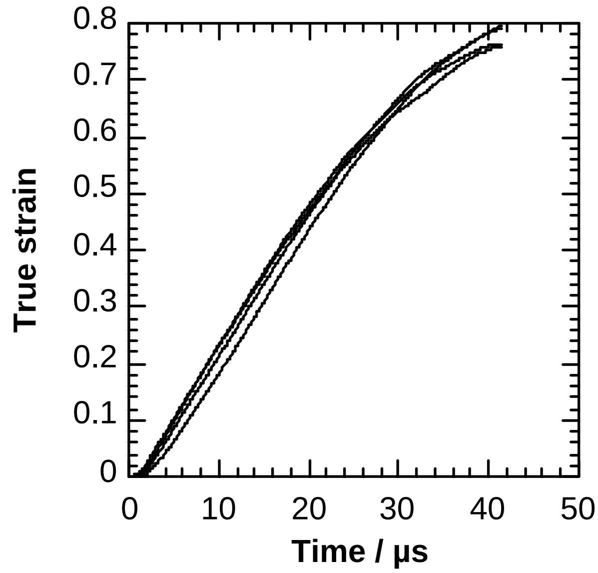

Figure 5. Strain-Time Curves Corresponding to Figure 3

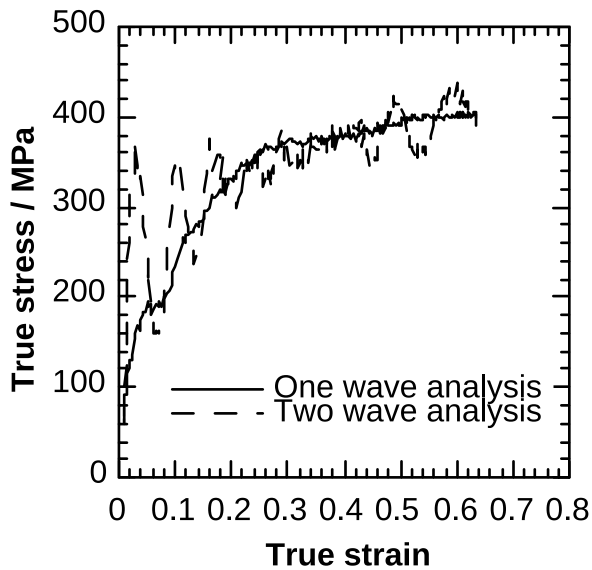

Figure 6. Comparison of One and Two Wave Analyses for a Copper Specimen, Showing that the Specimen was in Equilibrium from a True Strain of about 0.2.

SECTION V

CONCLUSIONS

A MSHPB bar has been used to make measurements of material properties at strain rate up to $3.6 \times 10^4 \ s^{-1}$. These results have been shown to exhibit the necessary features of a Hopkinson bar experiment, with equilibrium reached early during the experiment, a constant strain rate, and good alignment between the striker, incident and transmitted rods. Data have been obtained on PTFE and copper, although the specimens used have not been well characterized. This technique is a useful extension of other dynamic compression testing methods.

Attractive features of the MSHPB are the high strain rates that can be achieved and the small specimen size, which allows sampling of a material on the millimeter scale.

Future work will concentrate on measurements on a range of well-characterized materials, as well as preparation of smaller specimens to achieve higher strain rates.

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