International Journal of Impact Engineering 50 (2012) 76–82

Contents lists available at SciVerse ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Optical techniques for measuring the shock Hugoniot using ballistic projectile and high-explosive shock initiation

F.R. Svingala [a,*], M.J. Hargather [b], G.S. Settles [a]

[a] The Pennsylvania State University, Gas Dynamics Lab, Department of Mechanical and Nuclear Engineering, 301D Reber Building, University Park, PA 16802, USA
[b] New Mexico Institute of Mining and Technology, Department of Mechanical Engineering, Brown Hall 14, Socorro, NM 87801, USA

ARTICLE INFO

Article history:
Received 15 May 2012
Received in revised form
29 July 2012
Accepted 1 August 2012
Available online 31 August 2012

Keywords:
Shock hugoniot
Shadowgraphy
Polyurea
Polyurethane
High-speed videography

ABSTRACT

The shock Hugoniot is a fundamental relationship between pressure, volume, and energy for a given medium. Accurate knowledge of the Hugoniot for a material is critical in order to determine its response to shock waves and high-velocity impacts. Traditionally, the shock Hugoniot is measured on a point-by-point basis by a series of high-velocity impact experiments. Observations are typically confined to pointwise pressure or velocity measurements at the free-surfaces of the sample. In this work, shock waves are initiated in transparent polyurethane and semi-opaque polyurea samples using exploding bridgewires, aluminum ballistic projectiles, and gram-scale explosive charges. Shock waves and material motion are observed optically by shadowgraphy using a high-speed-digital camera recording at up to 10^6 frames/s. Ballistic impact, producing a constant-strength shock wave, is combined with these optical techniques to obtain a single shock Hugoniot point per test. A gram-scale explosive charge produces a shock wave in the material sample that is initially strong, but attenuates to near the bulk sound speed as it transits the polymer sample. With optical access to the entire sample, multiple shock and particle velocity combinations may be observed in a single test, allowing the measurement of a shock Hugoniot curve in fewer experiments than by traditional methods. These techniques produce data in general agreement with an extrapolation of published Hugoniot data for polyurethane and polyurea.

1. Introduction

Shock waves are sharp discontinuities in pressure, density, and internal energy in any continuous material. They can result from a localized rapid release of energy, as in an explosion, or from high-velocity impacts. The behavior of a material under shock loading is defined by the Rankine–Hugoniot equations, which represent conservation of mass, momentum, and energy across a shock wave. These equations define a locus of possible pressure-density-energy states that a material may attain across a shock wave. The steady-state form of these relations are given in equations (1)–(3)

$$\frac{\rho_2}{\rho_1} = \frac{U_s - U_{p1}}{U_s - U_{p2}} \tag{1}$$

$$P_2 - P_1 = \rho_1 (U_{p2} - U_{p1})(U_s - U_{p1}) \tag{2}$$

$$e_2 - e_1 = \frac{1}{\rho_1}\frac{(P_2 U_{p2} - P_1 U_{p1})}{(U_s - U_{p1})} - \frac{1}{2}\left(U_{p2}^2 - U_{p1}^2\right) \tag{3}$$

where, ρ represents density, U_s represents shock wave velocity, U_p represents the velocity of the material through which the shock passes, and e represents internal energy. Variables with a subscript of 1 represent values in the unshocked material while 2 represents the shocked values (Fig. 1).

Knowledge of material shock behavior is critical for the design of systems which may be subjected to explosive or projectile loading, e.g., infantry helmets, ship hulls, building facades, etc. Recently, there has been a push to develop systems to protect people and equipment from relatively low-pressure shock waves, i.e., those with overpressures in the kPa–1 MPa range. These waves typically induce particle velocities (U_{p2}) on the order of 10–300 m/s, and can be produced by air blasts in the mid-to-far-field. Soldiers in Iraq and Afghanistan often encounter shock waves of this magnitude, which can result in mild to severe traumatic brain injury (TBI), and long-term medical problems [1]. Thus, many recent experimental [2–4] and computational [5,6] works have centered around the response of polymer and polymer-composites to these types of threats.

* Corresponding author. Tel.: +1 8452421687.
E-mail address: frs122@psu.edu (F.R. Svingala).

0734-743X/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijimpeng.2012.08.006

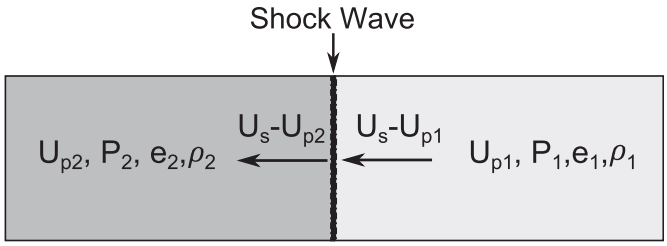

Fig. 1. Reference diagram for steady Rankine–Hugoniot equations. Coordinate frame is fixed to the shock wave and material moves from right to left.

However, shock Hugoniot data for polymers that are available in the literature are typically confined to shock waves inducing particle (U_{P2}) velocities greater than 500 m/s [7]. Simple materials, such as common metals, generally exhibit a linear U_s–U_{p2} relationship, allowing high-velocity data to be simply extrapolated to lower particle velocities. More-complex materials, however, may undergo a primary or secondary phase transition in this region, altering the shape of the U_s–U_{p2} curve and making a blind extrapolation misleading and inaccurate. Measurements of the polymethyl methacrylate (PMMA) shock Hugoniot, for example, reveals a significant downward curvature below a particle velocity of $U_{p2} \cong 300$ m/s [8]. Porter and Gould suggest that this more-complex behavior in polymers is due to a combination of the collapse of ring groups and the long molecular relaxation times associated with high-molecular-weight polymers [9]. To accurately predict the shock response of polymers and other complex materials in this region it is therefore important to rely on experimental data rather than extrapolations of higher-velocity shock Hugoniot data.

Experimentally defining a shock Hugoniot requires the initiation of a shock wave in the material of interest, and simultaneous measurement of any two variables in the shocked state, i.e., U_{p2}, P_2, U_s, e_2, or ρ_2. In practice, U_{p2}, P_2, and U_s are the most readily observed. These measurements must be made in the region of 1-D strain immediately behind the shock wave in order to satisfy equations (1), (2), and (3).

There are many methods of initiating a shock wave in the laboratory, the most common being a ballistic projectile accelerated up to as much as several km/s by a light gas gun [10]. U_s and U_{p2} may be measured by laser interferometry at the back surface of the sample or P_2 may be measured with single-use manganin gages [11,12]. Each of these tests produces a constant-strength shock, allowing a single point of the shock Hugoniot curve to be measured. Determining the entire shock Hugoniot in this manner thus requires an extensive series of impact experiments.

In the present work, optical methods for determining the shock Hugoniot of transparent and opaque materials are explored. The passage of a shock wave changes the local material density, which results in a change in the local index of refraction [13]. If the material of interest has at least some transparency, the refractive index field within the material can be visualized by the schlieren or shadowgraph technique [13]. The shadowgraph technique was previously explored by Yamada et al., who measured the shock Hugoniot for PMMA optically, using shadowgraphy and a high-speed-film streak camera in 1978 [14]. This previous work observed a single shock velocity and inferred the particle velocity from the motion of the back surface of the sample.

The present work further develops this technique in two main ways: optical measurement of the shock Hugoniot is extended to opaque materials, even those which exhibit spallation or void formation that alters motion of the sample's free-surface, and the measurement of multiple points of the shock Hugoniot of transparent materials in a single experiment with an explosively-driven shock wave. Using these techniques, the shock Hugoniot of two polymers of interest for ballistic and blast protection (a polyurethane and a polyurea) are experimentally extended for shocks inducing $U_{p2} < 250$ m/s.

2. Experimental methods

2.1. Apparatus and materials

The stress and shock wave properties of two polymers are investigated here: a clear polyurethane (Ultralloy Ultraclear 435) and a semi-opaque polyurea (Air Products Versalink P1000 combined with Dow Chemical Isonate 143L at a 4:1 ratio). Stress waves are also examined in a polycarbonate bar obtained from McMaster-Carr.

Wave motion was visualized by a 100 mm diameter, f/9.6, lens-type shadowgraph system with a Photron SA-5 high-speed-digital camera recording at up to 10^6 frames/s (Fig. 2). Shadowgraph illumination was provided by a 200 W Hg-Xenon arc lamp. A principal advantage of this system is the lack of complicated triggering requirements; typical high-speed optical methods used in shock physics often require the use of an argon flash, streak camera or both [15]. Both require very precise triggering with respect to the shock event and each other in order to successfully observe the event of interest. By using a continuous arc lamp and a high-speed digital camera with a recording time on the order of 5 s, triggering problems are eliminated, making this experimental apparatus much less difficult to set up and use.

2.2. Stress wave visualization and sound speed measurement

Shadowgraph stress wave tracking was performed on 25 mm × 25 mm × 25–60 mm rectangular bars of transparent polyurethane and polycarbonate and semi-opaque polyurea. Stress waves were initiated by the explosion of 0.4 mm diameter copper exploding bridge-wires (EBW) by a 125 J capacitor discharge.

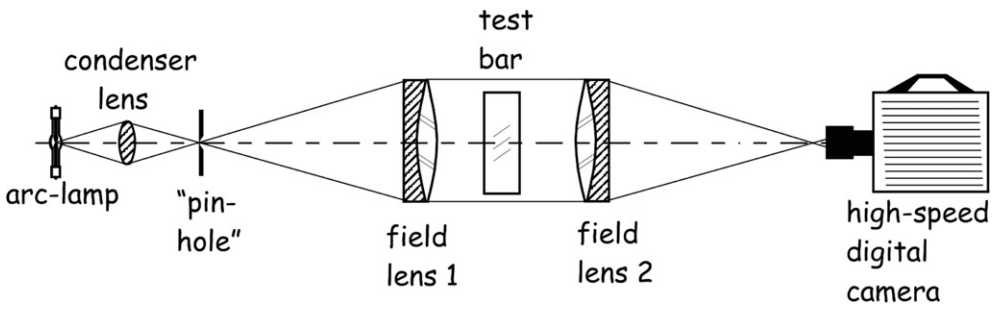

Fig. 2. A schematic diagram of the shadowgraph system used in this investigation.