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ANALYSIS OF STRAIN WAVE PROPAGATION IN POLYMERIC MATERIALS

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ABSTRACT

Polymeric materials used as binders in energetic materials exhibit interesting and unique material behavior. These include full geometrical recovery after deformation and a rate dependent stress strain relationship which can be categorized as viscoelastic. Taylor Cylinder Impact Tests have been conducted for adiprene-100 polyurethane. These produce time resolved cylinder profiles from which deformation wave speed can be extracted as a function of strain and strain-rate. Using this information and a set of conservation "Jump" relationships applied across the deformation wave front, stress points as a function of strain and strain rate can be extracted. This discretized information then can be used in the development of a constitutive relationship suitable for use in a three dimensional computer code calculation.

I. Introduction

The Taylor Cylinder Impact Test consists of a cylindrical projectile impacting a nearly rigid target in a normal orientation[1]. From this experiment, the time resolved deformation of the cylinder is recorded using high speed photography. The cylinder profiles are extracted from the digitized photographs using image recognition software. These temporal profiles can be reduced into strain and deformation wave speed data. Taylor Cylinder Impact Test can be separated into three temporal phases[2]. The first phase occurs after impact where the shock wave propagates down the cylinder with radial relief waves ringing about the center line. Phase two, a state of near uniaxial stress, features a deformation wave that propagates down the cylinder at constant speed. This deformation wave can be observed as a radial bulge in the cylinder, characterized by the areal strain defined as $e_A = A_0/A - 1$. The quantity A_0/A is the ratio of the initial cross sectional area to the current cross sectional area. The third and final transient phase occurs when stress waves reflect with sufficient frequency off the end of the cylinder to decelerate the projectile. This analysis of the mechanical behavior will focus on phase two under the assumption of steady state deformation in a uniaxial stress state for a polymeric material (adiprene-100).

II. Conservation "Jump" Relations

Consider a phase two deformation wave moving along a Taylor specimen with speed u_w . The analysis proceeds by attaching a inertial control volume at a particular value of strain which also moves with speed u_w . In this control volume analysis, the known quantities are the properties at the inlet out in front of the wave: ρ_0

- density, σ_0 - cauchy stress, u_0 - particle velocity, i_0 - internal energy, e_{A0} areal strain, and ε_{v0} - volumetric strain defined to be $\varepsilon_v = \rho_0/\rho - 1$. For application to the Taylor Cylinder Impact Experiment, the stress, areal strain, internal energy and velocity of the material entering the control volume will be assumed to be zero. The corresponding values of the variables exiting the control volume are unknown. Using the above defined control volume and strain relationships, the conservation "jump" equations can be derived for mass, momentum, and energy[3,4]:

$$\text{Mass: } u_w = \frac{-u}{(\varepsilon_A - e_A \varepsilon_v - \varepsilon_v)} \quad (1a)$$

$$\text{Momentum: } \frac{\sigma}{1 + e_A} = -\rho_0 u_w u \quad (1b)$$

$$\text{Energy: } \frac{1}{2} \frac{\sigma}{(1 + e_A)} (\varepsilon_v + \varepsilon_v e_A - \varepsilon_A) = -\rho_0 i \quad (1c)$$

III. Analysis

System (1) can be combined with experimental information in the following manner to describe the mechanical behavior. The conservation "jump" equations represent 3 equations containing 6 unknowns. If thermal effects are neglected, i.e., no change in internal energy, and the material is assumed to be incompressible ($\varepsilon_v = 0$), this reduces to 2 equations and 4 unknowns. Eliminating the exit velocity between these equations gives

$$\sigma = \rho_0 u_w^2 e_A (1 + e_A). \quad (2)$$

Using time resolved Taylor specimen profiles, an additional relationship can be formed by finding the wave speed u_w as a function of strain and

strain rate[5]. This is accomplished by selecting a value of strain and looking at the time history of the position of the radial bulge associated with that strain. To describe the position of a particular value of strain, a coordinate H is introduced as the Lagrangian distance from the impact interface. A plot of H as a function of time for several areal strains for adiprene-100 is shown in Fig. 1. It is expected that the experimental profiles contain some degree of uncertainty. To minimize the impact of this uncertainty on this analysis, a linear least squares fit of the experimental data was performed, denoted in Fig. 1 by the solid lines.

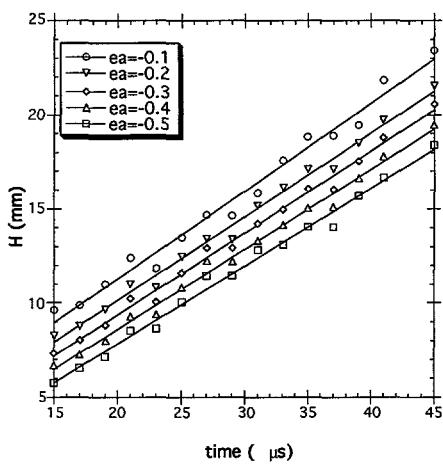


Figure 1 - Lagrangian position of several different values of areal strain on the deformation wave as a function of time. Solid lines are a linear least squares fit of the experimental points.

An examination of the linear fits shows that the lines are diverging, with small strains moving at higher speeds than large strains. Physically this means that the deformation wave is spreading out as it propagates down the cylinder. Recalling the manner in which the control volume was defined, the wave speed can be found for a particular value of strain by taking the derivative of H with respect to time. This gives us a relationship between strain and wave speed. Implicit in this relationship is a strain rate associated with the wave speed, which can also be extracted from the experimental profile data[6]. Combining experimental wave speed with Eq. (2) gives stress as a function of the areal strain $\sigma = f(e_A, \dot{e}_A)$.

IV. Results

Applying the above analysis technique for an experiment using adiprene-100 with an impact velocity of 300 m/s, a relationship between stress versus strain and strain rate is found. Using a one-dimensional method of characteristics code [7], with the Bardenhagen viscoelastic model [8], a long wire analysis

similar in principle to the one by Kolsky [9], can be solved. Figure 2 compares the stress strain relationship using the above control volume/cylinder profiles analysis with the solution to the long wire problem.

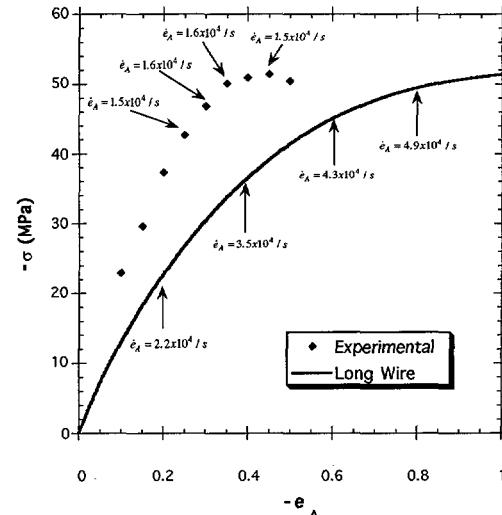


Figure 2 - Comparison of the stress strain relationship generated from the experimental data and the numerical result of a one-dimensional uniaxial stress long wire problem using the Bardenhagen viscoelastic model[7].

Both results approach the same asymptotic stress level (50 MPa), but the two differ in stiffness at smaller strains. This difference in stiffness is due in large part to the fact that the viscoelastic model was characterized from quasi-static strain rate tests. The strain rates from the calculation do have the same order of magnitude as those in the experiment, but in general the strain rates are higher in the long wire result.

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