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Extended Abstract+

High Strain-rate Shear and Friction Characterization of Fully-Dense Polyurethane and Epoxy

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1. Introduction

The characterization of polymer behavior at high strain-rates is a critical area of research driven by the use of polymers as adhesives, structural components, or as binders for energetic systems. Previous investigations have successfully defined Hugoniot equations-of-state for many relevant polymers such as epoxy, polycarbonate, and polyether ether ketone [1]–[4].Several studies have also explored the ramifications of polymer viscoelasticity at high strain-rates and pressures. This has been observed as nonlinearities in both propagating stress wave structure and Hugoniot state spaces [5]–[7]. The mechanisms driving such behavior is hypothesized as the breakdown and extended time interaction of polymer-chains but is yet to be fully understood.

The majority of high strain-rate polymer characterizations were achieved through uniaxial (plane strain) flyer plate impact experiments using light-gas guns. Such testing is well suited for Hugoniot development, however is limited as a method for evaluating strength. In many cases, strength may be quantified through the Hugoniot elastic limit (HEL) observable in the elastic wave preceding a shock. Polymers lack an observable elastic precursor, and so strength can only be inferred from the material shear stress response. To observe shear in uniaxial tests embedded transverse stress gages must be implemented [4]. More so, the loading-path in this configuration is fixed (plane strain) and so implications of combined loading on material strength are unobservable.

Given these limitations, it is of interest to consider alternative experimental methodologies which expand high strain-rate characterizations to include other phenomena. Oblique impact experiments consist of an angled projectile propelled toward a target set at the same angle via gas gun. Upon impact, both normal (pressure) and shear stress waves are generated and propagate away from the impact surface. Often term pressure shear plate impact experiments (PSPI), targets are subjected to combined loading and analysis results in direct measurement of material strength [8]. The technique has been used to successfully evaluate the yield strength behavior of a metals, granular materials, and a few polymers [9]–[12]. It has additionally been used to observe dynamic friction behavior between tribological pairs [13]–[15].

In this study, two fully dense thermosetting polymers, polyurethane (PUR) and epoxy, were subjected to rapid (high strain-rate) pressure-shear stress loading via oblique impact and the material responses were observed. Two experimental variations were utilized to observe both strength and friction phenomena. Impact speeds were varied to consider the effects of increasing pressure on polymer strength, and the roles of surface roughness and polymer-adhesion were considered. Constitutive and equation-of-state models, informed by experiment, were implemented into the CTH hydrocode [16] to demonstrate the applicability of such a characterization.

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2. Methodology

2.1. Polymer Description

Polyurethane and epoxy were the chosen materials of interest. This was due to their prevalence in most polymer applications, ease of acquisition, and the availability other dynamic characterization data with which to compare. The polyurethane was 1512 two-part liquid plastic purchased from *Polytek*. Relevant mechanical properties include a mix viscosity of 400 cP, a shrinkage of about 5×10^{-3} in/in, a quasi-static yield strength of approximately 46 MPa, and a 20-minute pot life available for mixing and molding. Post-mold densities were on average 1.135 g/cc. The epoxy-of-interest was the F110 formulation from *Atom Adhesives* and was also two-part resin/hardener system. Specifications include a mix viscosity of 310 cP, negligible shrinkage, a yield strength of 36 MPa, and a 30-minute pot life. Density was nominally 1.155 g/cc. Each had degradation temperatures around 100 deg-C. The presence of air bubbles post-molding was a significant concern, and so samples were degassed during pot life with a vacuum less than or equal to 29 inHg. This was sufficient to remove most bubbles from the mixed polymer with the remainder being crushed by the return of ambient pressure, any remaining microbubbles were considered negligible.

Mechanical testing was done measure relevant properties and establish a baseline for polymer behavior. Sound speed measurements using *Olympus* ultrasound through transmission equipment resulted in nominal longitudinal and shear wave speeds of 2.30 and 0.99 mm/us respectively for polyurethane, with 2.64 and 1.24 mm/us for epoxy (±0.04 mm/us). Quasi-static/low strain-rate shear strength was measured conducting the ASTM-D143 standard test with an Instron machine. Results were consistent with manufacturer specifications and confirmed strain-rate dependence – a few megapascals increased strength for an order of magnitude increasing rate. Thin-film specimens exhibited very brittle behavior compared to larger counterparts. From this comparison, toughness was observed to be very dependent on specimen geometry. Uniaxial plane-strain impact experiments were conducted at the High-Pressure Particulate Physics (HP3) facility at Eglin AFB. Results demonstrate that the selected polyurethane and epoxy have similar Hugoniot behavior to others observed in literature [6][7].

2.2. Oblique Impact Experiments

Experiments were conducted using a two slotted-bore light-gas guns, including a 2.5” bore 6 ft barrel gun at Eglin AFB and 2” bore 12 ft barrel gun at Marquette University. Two configurations of oblique impact were utilized referred to as constant-pressure pressure shear plate impact (CPPSPI) experiments and dynamic friction impact experiments respectively. Figure 1 presents a schematic of both tests and labels relevant components and their orientation before impact. In both cases, upon impact, a normal (pressure) and shear stress wave are produced and propagate into the target package and impactor respectively.

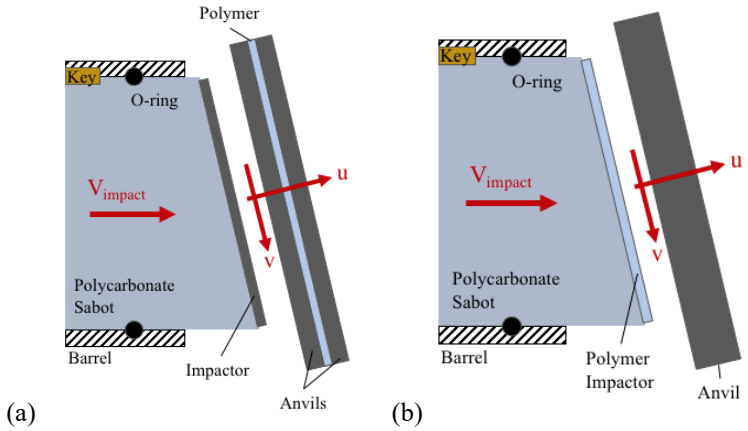

Fig. 1. Oblique impact experiment configurations (a) A CPPSPI experiment which consists of an angled projectile planarly impacting a target package set at an angle of obliquity. The target package consists of a front anvil, polymer sample, and rear anvil respectively. Note a key is shown which maintains projectile orientation down the slotted-barrel. (b) A dynamic friction impact experiment, wherein the same angled planar impact is facilitated, however the polymer of interest serves as the impactor.

For the CPPSPI experiment, the target package consisted of a front and rear anvil confining the polymer of interest. The front anvil thickness was set such that the normal stress wave arrives at the polymer sample and reverberates between anvils bringing the polymer to an equilibrium (constant) pressure state prior to the arrival of the slower moving shear wave. This ensures the effect of shear stress is temporally distinct from that of normal stress and is more readily distinguished within observed wave profiles. Samples were kept thin, nominally 0.5 millimeters, so reverberation did not take more than approximately a microsecond. After propagating through the polymer, waves continued through the rear anvil and their behavior was observed via free surface particle velocity traces measured through transverse photon Doppler velocimetry (PDV) [17][18]. Anvil materials and impact conditions were chosen such that the yield strength of all components, except the sample, was never exceeded. This was necessary to ensure only anvils could sustain shear loading and enables the use of one-dimensional elastic wave theory for analysis, wherein particle velocity is directly proportional to stress [19]. Impactors and anvils consisted of 7075-T6 aluminum with the polymer sample being either the PUR or epoxy of interest. The measurement of both normal and shear stress states resulted in the characterization of the polymer stress response to the imparted loading conditions. If no yielding occurs, the expected observable shear stress magnitude is known based on impact conditions and material properties. As such, any deficiency in shear stress is assumed to be representative of polymer yield – i.e. shear strength.

For dynamic friction experiments, the polymer of interest served as the angled projectile impacting a 7075-T6 aluminum anvil target, the yield strength of which was again not exceeded. Given its role as impactor, the polymer simultaneously experiences both normal (pressure) and shear stress unlike the CPPSPI configuration. Stress waves propagate elastically through the anvil and were observed using the same PDV methods. A coefficient of friction (COF) for the anvil/polymer interface was then quantified through the ratio of shear to normal stress [13][15]. Slip occurring at the interface was indicative of polymer yield, on the level of surface roughness asperities, and so shear stress in these experiments was also assumed to be representative of shear strength. Notably, loading in this configuration is pressure-*and*-shear as opposed to pressure-*then*-shear and the polymer is not confined so strength behaviors are not directly comparable to those obtained in CPPSPI testing [20].

3. Results & Discussion

Six CPPSPI and two dynamic friction experiments were conducted on fully dense polyurethane, while seven CPPSPI and one dynamic friction experiment were done for epoxy. Impact velocities were varied allowing for different pressures. Anvil surface roughness Ra (average roughness) was tracked using a *Pocket Surf* ® sapphire stylus profilometer. Roughness was allowed to vary between approximately 0.2 and 10 μm, in an effort to identify possible ramifications. Notably, over said range roughness had no observable effect on bulk stress wave profiles -which was further corroborated by mesoscale simulations. Coefficient of friction values were successfully calculated from dynamic friction experiments, with values of 0.18 and 0.42 for PUR and epoxy respectively each with a 7075-T6 aluminum tribological partner.

Normal and shear stress values were measured for all experiments (both configurations). These shear strengths can then be plotted against pressure to evaluate any dependence, which has been seen at lower strain-rates [21]. Figure 2a shows these results plotted alongside literature data [11][15] and the Mulliken-Boyce viscoelastic model [22].

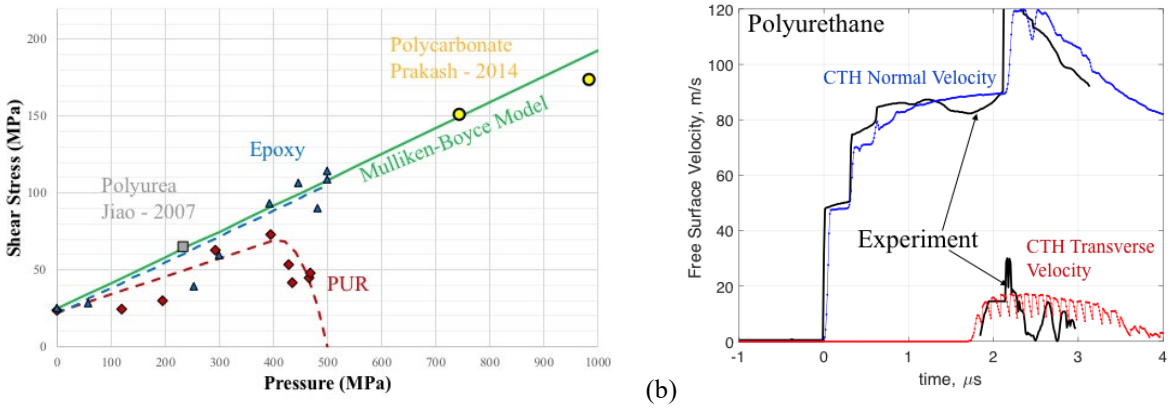

Fig. 2. (a) Shear strength as a function of pressure. The tested PUR and epoxy are shown alongside other literature data for different materials as well as the theoretical Mulliken-Boyce viscoelastic model. (b) CTH simulations, with data-based constitutive models, compared against experimentally observed PDV.

Results show shear strength to have a strong dependence on pressure for both polyurethane and epoxy. This persists even with respect to the dynamic friction case, which is under different loading conditions. For polyurethane specifically, this trend eventually decays reminiscent of a Drucker-Prager cap [23]. Observed epoxy data does not suggest the same behavior, however it is hypothesized a similar trend would be evident if the tested pressure regime were extended. Strength data is used to formulate a *Geo-Yield* constitutive model for each polymer in CTH. Along with Hugoniot information, CTH is able to recreate experimental wave profiles quite well for both normal and shear stress waves, shown as particle velocities in Figure 2b. This suggests pressure-dependence to be a dominate mechanism governing polymer strength. Viscoelastic effects are known to be another crucial factor and, despite the good agreement between simulation and data, are notably not implemented – nor readily isolated in this methodology. Temperature degradation was a concern, and while not measured directly, values were inferred from CTH simulations. CPPSPI experiments did not appear to induce temperatures exceeding degradation, however localized surface asperities in simulated dynamic friction experiments did, providing another reason for which the two configurations should be compared with caution.

As a last consideration, polymers in CPPSPI were adhered to confining anvils, as such it was initially unknown whether strength being measured was that of the polymer or that of interface-bond. However, post-mortem of CPPSPI targets revealed that adhesion survived the impact event suggesting that the observations were indeed of the polymer itself. A more precise evaluation of the adhesive bond is of particular interest for future work.

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