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Christian Kettenbeil, Zev Lovinger, Suraj Ravindran, M. Mello, and G. Ravichandran

Pressure-shear Plate Impact Experiments at Very High Pressures

Christian Kettenbeil,[1, b)] Zev Lovinger,[1, a)] Suraj Ravindran,[1, c)] M. Mello,[1, d)] and G. Ravichandran[1, e)]

[1] *Division of Engineering and Applied Science, California Institute of Technology, Pasadena, CA, 91125, USA*

[a)] *Corresponding author: lovinger@caltech.edu*
[b)] *ckb@caltech.edu*
[c)] *surajrav@caltech.edu*
[d)] *mello@caltech.edu*
[e)] *ravi@caltech.edu*

Abstract. Recent modifications of a powder gun facility at Caltech have enabled pressure shear plate impact (PSPI) experiments on materials at very high strain rates (>10^7 s^{-1}) and pressures (>20 GPa), that have not been reached before. The high strain rate/pressure regime expands significantly the advantages of this well-studied technique. However, it requires overcoming several challenges including requiring a new approach for analysis of the experimental measurements, to extract the material's strength. At high pressures, standard anvils such as steel and tungsten carbide (WC) do not remain elastic, and their inelastic behavior needs to be accounted for in the analysis. The methodology presented here extracts the strength of the material using a hybrid method, combining numerical simulations to simultaneously match both the normal and transverse free surface velocity measurements. First, the inelastic response of the anvils is measured using symmetric PSPI experiments and a material model is calibrated to best match the experimental measurements. Then, measuring the response including the material of interest in a sandwich PSPI configuration, the anvil's material model is used for the analysis and the extraction of the strength of the material of interest. The methodology is demonstrated for soda-lime glass with WC anvils and pure magnesium with steel anvils. The proposed methodology has the potential to expand the PSPI experiments to higher pressures and strain rates.

INTRODUCTION

The Pressure shear plate impact (PSPI) experiment, developed and pioneered by R. J. Clifton over 40 years ago at Brown university enables to probe the dynamic strength of materials at high pressures and strain rates ([1-3]). Traditional PSPI experiments assume that the flyer and anvil plates remain linear elastic under the imposed dynamic loading conditions. Characteristic relationships derived from the 1-D wave equation transform normal and transverse particle velocity profiles measured at the rear surface of an anvil plate to the corresponding velocity histories at the boundary of a thin, material specimen sandwiched between two impacting plates [3]. Simple elasto-dynamic relationships are invoked to infer the normal and shear stress developed within the specimen, under the assumption of an equilibrated and uniform state of stress. Material strength properties may also be extracted by assuming a flow rule. Traditional PSPI experiments were mostly conducted on single-stage gas guns, which restricted the terminal projectile velocity to approximately 500m/s [6] and thus limited the corresponding pressures which could be achieved. The use

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of standard anvils like hard steel or Tungsten Carbide (WC) limits such experiments to the materials' HEL, typically up to 3-6 GPa. Other materials, with a much higher HEL such as Sapphire (15 - 20GPa) [4], Zirconia (~17GPa) [5] and Diamond (60-80 GPa) may be used as anvils to reach higher pressures. The application of these higher strength materials has been recently explored in PSPI experiments [4] and magnetically applied pressure-shear experiments [5] albeit with limited success. In this work, we extend PSPI experiments to significantly higher pressures, using the powder gun facility at Caltech. The high-pressure and high-velocity impact regimes introduce several experimental challenges which must be overcome: (1) *the inelastic behavior of the anvils* at high pressures precludes traditional elastic analysis to extract the material's strength; (2) *slip* between impact faces as a result of elevated temperatures and shear forces on the impact surfaces due to higher velocities and pressures; (3) *accurate measurement of the transverse velocity at large displacements* as a result of the higher velocities and maintain the transverse optic measurements, at the target free surface. New experimental capabilities have been introduced to overcome each of these technical challenges, which include a new all fiber-optic interferometer system [8]. New analysis methods which account for the inelastic response of the flyer and anvil plates have also been developed for the accurate extraction of material strength properties from PSPI experiments. The new PSPI capabilities have been demonstrated using D2 tool steel and WC anvils for measuring the strength of soda-lime glass and magnesium.

EXPERIMENTAL SET-UP

The PSPI experimental set up is depicted in Fig.1(a). Figure 1(b) shows the target plate assembly, which has a diffraction grating patterned onto its rear surface. The fiber-optic interferometer system includes a photonic Doppler velocimeter (PDV) [7] which measures the normal particle velocity from optical phase carried by the 0^{th} order beam. A heterodyne transverse velocity interferometer (HTV) measures the transverse particle velocity through the mutual interference of the symmetrically diffracted 1^{st} order beams. Three collimating fiber-optic probes which collect the 0^{th} order and +/- 1^{st} order beams were specifically designed to counter the effects of large normal displacements and undesired tilting of the diffracted beams (Fig. 1(d)). The structure of the 400 lines per mm grating is also tailored using e-beam lithography to generate slightly broadened diffraction lobes which serve to maximize the light return for longer sustained measurement times. The 2d diffraction pattern shown in Fig. 1(e), is demonstrated using visible red laser light. A detailed discussion, characterization, and analysis of the optical interferometry schemes utilized in these experiments are found in [8].

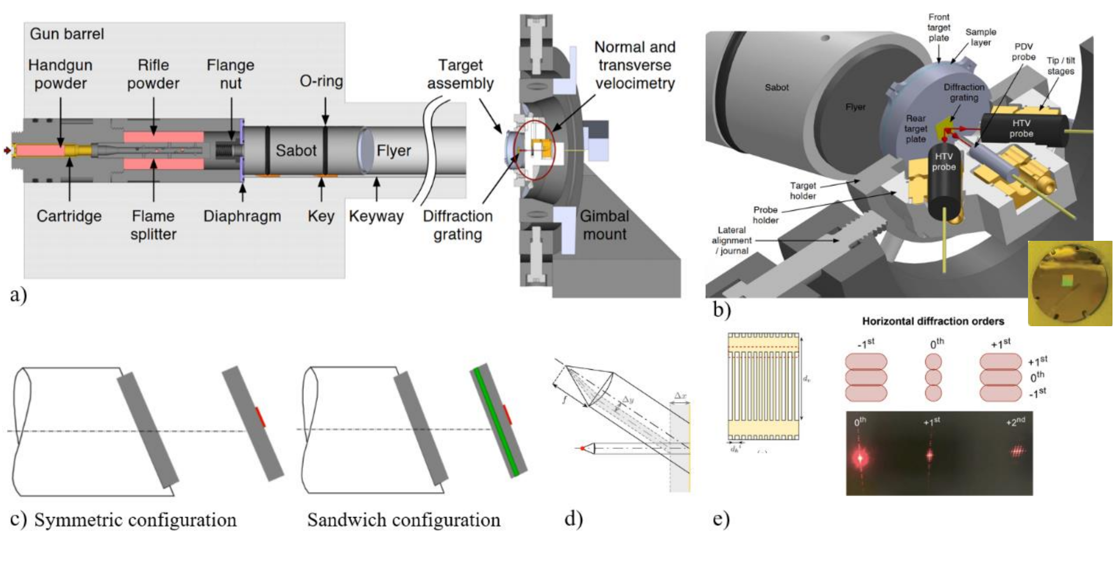

FIGURE 1. High-pressure PSPI experimental setup: (a) powder gun and target setup, (b) target assembly with all-fiber optical setup for simultaneously measuring normal and transverse free surface velocities, (c) two types of PSPI configurations, (d) collimated probe scheme, (e) modified diffraction grating and diffraction spots.

The experimental set up includes two types of configurations as shown in Fig. 1(c): a symmetric one for which the flyer and target are thick plates and both normal and shear wave probe the target material, sweeping through its thickness. The second scheme is a sandwich configuration, where the material of interest is a thin film, confined between two thick anvil pates. For this case, the measurements are affected both by the anvil plate and the material that is investigated, and are dependent on their relative thicknesses and relative strength.

NEW APPROACH FOR PSPI ANALYSIS

As the anvils do not remain elastic under the high pressures, reaching pressures above their HEL, the simplified straight forward expressions to compute the material strength from the particle velocity records [3], are no longer valid. To that end, a new hybrid numerical/experimental approach has been developed, using direct numerical simulations and comparing the simulated free surface velocity signals with the experimentally measured ones. The approach consists of four steps:

1. Conducting symmetric PSPI experiments on the anvil material.
2. Calibrating an inelastic material model for the anvil to reproduce the measured signals.
3. Conduct experiments on the material of interest using the sandwich configuration, and
4. Extracting the strength of the material of interest, simulating the experiments in step (3) and using the anvil's material model from step (2), with only the material of interest to be calibrated to best match the measurements.

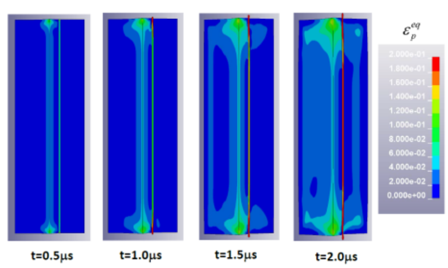

FIGURE 2. Numerical modeling of a PSPI experiment at 10 GPa with steel anvils and a magnesium sample (sandwich configuration, Fig. 1(c)). The simulations were done with LS-DYNA [9], showing significant plastic strains in the anvils.

EXPERIMENTAL AND NUMERICAL RESULTS

The above methodology was applied to two types of anvils and test specimens: (1) tungsten carbide (WC) with soda-lime glass (SLG) and (2) D2 steel (as received) with pure magnesium (Mg). The results from one such numerical simulation are shown in Figure 2, which depicts the plastic strain developing during the impact of a D2 steel flyer at 298 m/s on a sandwiched target with a 300 μm Mg sample, reaching a normal stress of 5.6 GPa. The WC, for the ~15GPa shots, undergoes inelastic strain of up to 5%. A separate series of experiments relied on as received D2 Steel (with no heat treatment) with increased ductility, to examine the results in cases during which the anvils underwent large plastic strains. Specific cases of note include a test shot with normal stress approaching 5.6 GPa, where the plastic strains reached ~12%, and 10.2 GPa shot, where the anvils reached plastic strains of 22%. A comparison between the experimental measurements and the calibrated numerical simulations results are discussed in the following section. The calibrated material models are discussed in [10-11].

Measuring the strength of SLG using WC anvils at 15 GPa

Figure 3(a) presents results of a symmetric WC PSPI experiment conducted at 319 m/s with an impact angle of 18^0. In a symmetric shot, the target is a thick plate and both the normal and transverse waves are probing its material bulk response. The coupled measurement sets a strong constraint when calibrating a material model, requiring a simultaneous match of both transverse and normal velocity profiles. The material model used for WC incorporates strain and strain-rate hardening [10]. In Fig. 3(b), the results of a sandwich configuration are presented, using the same WC material for the anvil plates, which sandwich a 100μm glass film. The transverse response is dominated by the glass behavior, and the best-calibrated model resulted in the shown fit with the experimental measurements. The calibrated WC model was used to produce the close fit between the synthetic and experimental curves depicted in Fig 3(b). The normal stress in the experiment was 15 GPa and the SLG film was subjected to an average strain rate of 8×10^{5} s^{-1}. The calibrated strength for the SLG was 2.8 GPa with damage softening starting at a strain of 0.21. The material model is described in detail in [10].

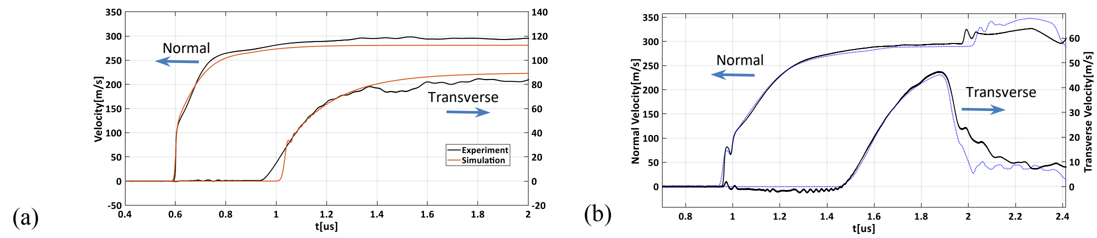

FIGURE 3. Measuring the strength of SLG with WC anvils by comparing experimental measurement and calibrated simulation: (a) for a symmetric shot with WC plates at 319 m/s with normal stresses of 14.1 GPa, (b) for a sandwich configuration of WC anvils and a 100 μm SLG film at 330 m/s with normal stresses of 14.5 GPa.

Measuring strength of pure magnesium using steel anvils at 10 GPa

Figure 4(a) shows results of a symmetric D2 steel shot at 539 m/s with an inclination angle of 18^{0}. The plasticity model calibrated for steel incorporated strain and strain rate hardening. In Fig. 4(b), the results of a sandwich configuration experiment are presented, using steel anvils, sandwiching a 300 μm pure magnesium film. The normal shock loading was aligned with the extrusion direction, whereas the shear was aligned normal to the extrusion, in the radial direction of the material. Figure 4(b) also shows results for simulated free surface velocities of a shot at 548 m/s with a normal stress of 10.2 GPa. The model captures closely the experimentally recorded signals including the recompression wave arriving at 2.4 μs, reverberating back from the steel-Mg interface. A stress-strain curve was derived for the magnesium, reaching a maximum value of 380 MPa and failing at a plastic strain of 0.15. The calibrated stress-strain curve reflects significant crystal plasticity features, expected for this textured material. The material models for Mg and D2 steel are described in [11].

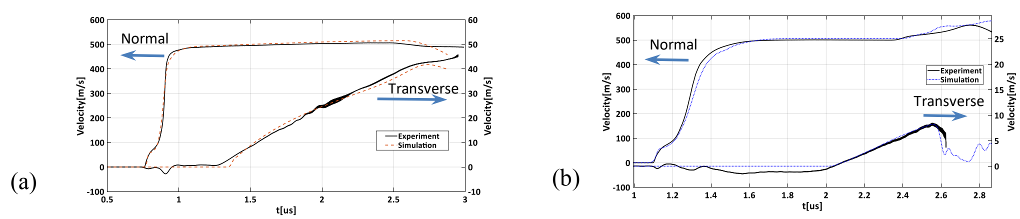

FIGURE 4. Measuring strength of Mg with D2 Steel anvils by comparing experimental measurement and calibrated simulation: (a) symmetric shot with D2 steel plates at 539 m/s with normal stress of 10.2 GPa, (b) sandwich configuration of D2 steel anvils and a 300 μm magnesium film at 548 m/s with normal stress of 10.5 GPa.

SUMMARY AND CONCLUSIONS

An experimental powder gun facility at Caltech was modified to enable PSPI experiments at high pressures in excess of 20 GPa. The all-fiber optic set up [8] was proved to be a robust technique, simultaneously measuring normal and transverse free surface over 15 successful PSPI experiments. A new hybrid methodology using numerical simulations was established to extract the material strength of the materials of interest, accounting for the inelastic behavior of the anvils at high pressures. The analysis was demonstrated for SLG with WC anvils and pure Mg with steel anvils. Additional challenges of slip, not reported here, were addressed at higher velocities and pressures, and currently using reduced impact angles allow conducting PSPI experiments beyond 30 GPa.

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