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Investigating strength of materials at very high strain rates using magnetically driven expanding cylinders

Zev Lovinger[1,2,a], Ron Nemirovsky[3], Eyal Avriel[1,2], Avraham Dorogoy[2], Yehezkel Ashuach[1], and Daniel Rittel[2]

[1] Rafael- Advanced defence systems, Haifa, Israel
[2] Faculty of Mechanical Engineering, Technion – Israel Institute of Technology
[3] Solid State Institute and Physics Department, Technion – Israel Institute of Technology

Abstract. Dynamic characterization of strength properties is done, in common practice by the means of a Split-Hopkinson Pressure Bar (also named Kolsky-Bar) apparatus. In such systems, strain rates are limited up to $\sim 5 \cdot 10^3$ sec^{-1}. For higher strain rates, the strain rate hardening is assumed to be the same as that measured at lower rates, with no direct measurement to validate the assumptions used for this extrapolation. In this work we are using a pulsed current generator (PCG) to create electro-magnetic (EM) driving forces on expanding cylinders. Most standard techniques for creating EM driving forces on cylinders or rings, as reported in the literature, reach strain rates of 1e3-1e4. Using our PCG, characterized by a fast rise time, we reach strain rates of ~1e5, thus paving the way to a standard technique to measure strength at very high strain rates. To establish the experimental technique, we conducted a numerical study of the expanding cylinder set up using 2D hydrodynamic simulations to reach the desired high strain rates.

1. Introduction

It is well known that strain rate is an important factor influencing the strength and failure properties of materials. For most materials, the dynamic behavior is significantly different from their behavior in the quasi-static regime. Furthermore, at high strain rates, new phenomena which were not relevant or with a weak influence at lower strain-rates can arise and change significantly the behavior of the material. In the work of Follansbee & Kocks [1], examining the flow stress dependence on strain rate in copper, it was shown that the flow stress increases significantly when strain rates rise above $\sim 5 \cdot 10^3$ sec^{-1}. Such behavior, evident in many materials, is related to a change in the dislocation mobility mechanism. In the low rate regime, dislocation glide is controlled by thermal activation, while at the high rate regime the dynamics are controlled by viscous effects such as the mechanism of phonon drag. Experimental techniques today reach strain rates of up to 10^9 sec^{-1} (e.g. loading by thin layer ablation using high energy lasers [2]), extending the behavior shown in [1] to higher strain rates with a general two slope behavior which meet a transition at some rate between 10^3–10^4 sec^{-1}. Dynamic characterization of strength properties is done, in common practice by the means of a Split-Hopkinson Pressure Bar (SHPB, also known as Kolsky-Bar) apparatus. In such systems, strain rates are of the order of $\sim 10^3$ sec^{-1}. Higher rates could be reached in plate impact experiments and in laser driven experiments with characteristic strain rates of $\sim 10^6$ and $\sim 10^9$, respectively. While plate impact tests are common, no agreeable method for measuring strength exists for those tests. Furthermore, in such experiments very high pressures evolve, affecting dramatically the strength of the material aside the high strain rates. The pressure dependence is usually the main parameter one seeks to investigate in such experiments [3,4]. In the laser experiments, strength is measured from the evolution of instabilities ([2]). Such experiments require a high-end facility making them to be very complicated and expensive to conduct. In addition, these experiments again, incorporate combined conditions of very high pressures and ultra-high strain rates. Without any experimental data taken at very high strain rates, modeling strength at this regime can only take into account the rate sensitivity measured at lower rates using SHPB and make the needed extrapolation to higher rates. In order to validate the model at high rates, usually Taylor tests are conducted. In a Taylor test, a short rod is accelerated into a rigid wall which causes the rod to deform plastically, flowing in a mushroom-like geometry. The impacted end is characterized by high strains and by strain-rates which reach values of about 10^5 sec^{-1}. For model validation, the profile of the projectile is traced and compared with that obtained from the simulations (e.g. Ref. [5]).

For different applications there is a true need for a strength model which could represent properly the strain rate hardening of materials in hydrodynamic simulations. Such models must take into account a large span of strain rates since different parts of the problem can reach either low or very high strain rates, at least for a certain period of time. For example, simulations of an EFP (Explosively formed Projectile) formation show that different areas of the deforming liner are characterized by very large strains and strain rates which span between 10^3–10^5 sec^{-1} [6].

[a] Corresponding author: cvloving@gmail.com

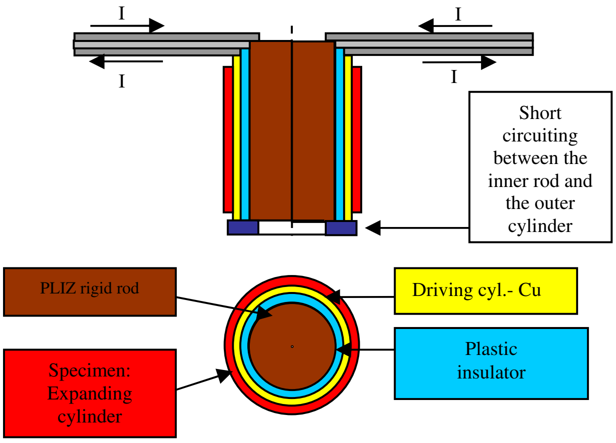

Figure 1. Schematic of the expanding cylinder test for strength measurements.

In this work, we seek to develop a simple and reliable experimental technique which will provide direct measurements of strength at strain rates above 10^4 in expanding cylinder experiments. The experiments are conducted with a pulse current generator (PCG) providing magnetic pressures as the driving force. Expanding cylinders were used in various works in the literature to measure strength [7] or fragmentation [8,9] at high rates, yet these experiments reach at most values of 10^4 sec^{-1}. Using our PCG, characterized by a fast rise time of about 1 μs [10], we manage to reach strain rates of ∼1e5, with no significant temperature rise, thus paving the way to a standard technique to measure strength at very high strain rates.

2. Experimental set-up

The pulsed current generator uses a capacitor bank system charging 20–30 kVolts which are released using high voltage dischargers allowing fast and simultaneous discharge into the conductor system, achieving current flows of about 1 MA. The PCG was further detailed in [10]. The experimental set-up for expanding cylinders using the PCG is shown in Fig. 1.

The conductor system is made of two plates, each attached to an opposite pole, separated by an isolating layer. The specimen is an assembly of coaxial cylinders: an inner rigid rod is attached to the upper plate, the outer cylinder is attached to the bottom one and an isolating plastic cylinder is put in between them. The tested specimen is driven by the expanding outer cylinder. On the bottom side of the specimen, the cylinders, each attached to an opposite pole, are short-circuited. When the voltage is discharged, an electrical current flows from one pole, through the upper plate and the inner rod, to the outer cylinder and to the bottom plate. As a result, a high current flows through the rod and outer cylinder, but in *opposite* directions, creating repulsive magnetic forces between them, causing the expansion of the outer cylinders. The main diagnostics is velocity interferometry measurements of the expanding specimen. The strength is calibrated and detrmined as an *inverse problem*, through hydrodynamic simulations, using different strength models. A main demand for such calibration is to provide accurate loading conditions in the experiment. The boundary magnetic pressure is extracted from current flow measurements. The current flow is calculated from Bdot measurements and calibrated under the assumption of an ideal RLC circuit.

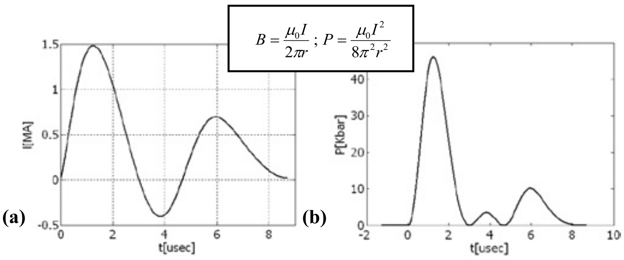

Figure 2. Typical histories derived from B-dot measurements on the PCG (from [10]): (a) measured current-flow history, (b) calculated boundary pressure.

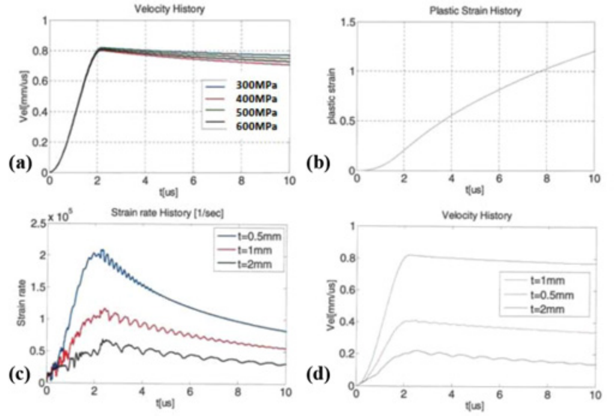

Figure 3. Simulation results of an expanding cylinder: (a) velocity history with different values of strength (b) plastic strain history, (c) vtrain rate and (d) velocity histories as function of the cylinder wall thickness.

A typical Bdot signal and calculated pressure boundary condition in such a test are shown in Fig. 2. Typical pressures are 20–40 kbars with a rise time of ∼ 1 μs.

3. Initial results

To design the experimental set-up, we conducted numerical simulations, specifically, we calculated the particle velocity sensitivity to changes in the strength of the material and the strain rates that are expected to evolve.

We carried out 2D simulations of the expanding cylinder with axial symmetry. Cylinder dimensions and pressure boundary conditions were chosen to be the same as those of the collapsing cylinder experiments we conducted on the PCG [10]. The cylinder is made from copper and has an inner diameter of 7 mm with a thickness of 0.5 mm. We used a simple EPP strength model with strengths of 300-400-500 and 600 MPa. The pressure boundary condition is a half sine function with a duration of 2.2 μs and a peak pressure of 2.5 GPa. The results are shown in Figs. 3a–3c. The strain rates achieved are (1–2) $\cdot 10^5$ sec^{-1}. The particle velocity sensitivity to strength changes is ∼ 10 m/s per 100 MPa. From former measurements done with our interferometry system, 10 m/s is estimated to be the limit resolution, thus determining that *our PDV measurements is sensitive to changes of 100 MPa in strength*.

The expected velocities using the above mentioned boundary conditions are ~ 800 m/s. Furthermore, we examined the strain rates and velocities as function of the wall thickness as shown in Figs. 3c,d, showing that we reach strain rates above 1e5 $\sec^{-1}$ with cylinder thicknesses under 1 mm.

4. Summary

In this work we present an experimental set up of an expanding cylinder, using a pulsed current generator to produce the magnetic driving forces. This new set-up enables to measure strength at very high strain rates, above 1e5 $\sec^{-1}$, where a significant rise in the material strength is expected. Presenting the geometry of our initial specimen, we demonstrated by numerical simulations, that we manage to reach strain rates of $\sim$1e5, with no significant temperature rise, thus paving the way to a standard technique to measure strength at very high strain rates. Initial tests are currently conducted on copper specimens.

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