Plate impact experiments and simulation on porous graphite

D Hébert, G Seisson, I Bertron, J M Chevalier, C Thessieux, J H Quessada and S Tastet
CEA CESTA, 15 avenue des Sablières, CS60001, 33116 Le Barp Cedex, France
E-mail: david.hebert@cea.fr

Abstract. We present some plate impact experiments on a commercial grade of graphite. The dynamic loadings range between 0.3 and 14 GPa under shock, and reach 23 GPa under reshock in the samples, which were approximately 20% porous and macroscopically isotropic. Material velocity at the sample rear surface is measured and recorded optically with Visar or Perrot-Fabry interferometers. These experimental results are then compared to hydrodynamic simulations, where we use a model that takes porosity into account. Our model is also compared to previously published experimental data. The overall agreement is good.

1. Introduction
A better understanding of the dynamic behavior of composite materials is of major importance for many applications in aerospace industry. With the increasing performance of computers, mesoscale simulations are now becoming possible [1], but they require validated models for the elementary components, such as carbon. Previous papers have been published describing hypervelocity impacts (HVI) [2,3] and laser shocks [3,4] on EDM3, a commercial grade of polycrystalline graphite [5], macroscopically isotropic and with an average density of 1760 kg/m$^3$. In this paper, we present some plate impact experiments on EDM3 and their simulations with the equation of state (EOS) and constitutive relations used elsewhere [2-4]. In the first step, we will discuss the choice of a porous model on the basis of experimental Hugoniot states. In a second step, we will describe three plate impact experiments on EDM3 samples that also give access to off-Hugoniot (reshock and release) states. In the last sections, we will present the simulations and a discussion of the results.

2. Choice of a porous model

2.1. Thouvenin model
We will first consider the very simple model proposed by Thouvenin [6], that consists in parallel slabs of solid (i.e. dense) material. The ratio between the slab thickness and the empty spaces between them is related to the macroscopic porosity of the samples. Assuming that the dense graphite can be described with SESAME 7832 table, this model allows us to compute the D-u curve for EDM3. The result is shown on figure 1, along with the SESAME model and experimental points corresponding to EDM3 or other graphite samples of similar porosity [7]. A relatively good agreement is found below the graphite-diamond phase transition, which corresponds to particle velocities between 1.5 and 2 km/s in the dense material. However, a strong disagreement is observed above this transition. Indeed, the model assumes that the Hugoniot and release isentrope of the solid material are symmetric, which may not be the case above the phase transition. Moreover this model is not valid at low pressure, since it cannot account for acoustic velocities or partial compaction.
2.2. POREQST model

Those extreme conditions (very low and very high pressures) can occur in HVI or laser shock experiments, so a more complete model is needed. We chose POREQST [8], that provides both EOS and strength models. The SESAME 7832 table, which takes the graphite-diamond phase transition into account (see figure 1), has been used for dense material EOS. The compaction curve is deduced from oedometric (static) compression measurements [2,3] and shown on figure 2. The corresponding Hugoniot of EDM3 also lies on figure 1, showing a good agreement on the whole range.

In order to check the validity of this model off Hugoniot states we performed plate impact experiments that are described in the following section.

3. Plate impact experiments

Three plate impact experiments have been performed on SYLEX gas gun at CEA/CESTA, operated in its single-stage, 110 mm bore version. One shot (#909) has been fired with powder propellant and two
shots (#908 and #910) with light gas (He). Particle velocity measurements are made with Perrot-Fabry (DLI) or Visar laser interferometers. Several records were available for each shot, providing complementary results on identical impact conditions. The impactor and target assembly (i.e. materials and thicknesses) are described in table 1, as well as the names and locations of the velocity records. Most velocity measurements are made through transparent (window) materials, either LiF or PMMA, that have a thin vapor-deposited aluminum mirror on their front face. On shot #908, the rear face of the copper driver plate has been optically polished, allowing the measurement of its free surface velocity.

For two shots (#908 and #910), the impact velocity is given by magnetic coils; records on the rear face of the copper driver plate are used to reduce uncertainties and to validate the copper model. For shot #909, impact velocity is given by piezoelectric pins with more uncertainty.

The experimental results are shown on figure 3, figure 4 and figure 5.

| shot | impactor | impact velocity (m/s) | target | record |
|------|----------|-----------------------|--------|--------|
| #908 | Al 6061T6 / Cu (5mm) / (2mm) | 1440 ± 20 | Cu (2mm) | DLI 2 |
|      |                      |          | Cu (2mm) / EDM3 (4mm) / LiF (15mm) | DLI 3 |
| #909 | PMMA / steel (5mm) / (0.5mm) | 2094 ± 150 | EDM3 (1mm) / LiF (15mm) | DLI 2 |
|      |                      |          | EDM3 (5mm) / LiF (15mm) | Visar 3 |
| #910 | PMMA (5mm) | 485 ± 15 | PMMA (10mm) | DLI 1 |
|      |                      |          | Cu (2mm) / PMMA (15mm) | DLI 2 |
|      |                      |          | Cu (2mm) / EDM3 (3mm) / PMMA (15mm) | Visar 3 |

4. Simulation results

The POREQST model has been implemented in Hesione hydrocode developed at CEA. 1D simulations have been performed on a lagrangian mesh using a VNR scheme [9]. The impactor, driver plate and window materials are described with validated equations of state and strength models: SCG for 6061-T6 aluminum, 304 steel, PMMA and LiF [10], PTW for copper [11].

Complete densification of the graphite is expected to occur on the first shock for shots #908 and #909, since the stress levels are 8 and 14 GPa respectively, much above the static consolidation point (cf. figure 2). The loadings on these shots reach respectively 13 and 23 GPa after the 2nd shock due to the reflection on the higher impedance LiF window. We note that shot #910 corresponds to a lower impact velocity, and that the stresses reached in the EDM3 sample remain below 1 GPa. Thus, in this shot, the loading path consists essentially in following the compaction curve shown on figure 2.

Simulation results are shown on the following figures, along with experimental signals, and discussed below.

5. Discussion

As indicated in the curve legends (cf. figure 3, figure 4 and figure 5), a slight translation has been applied to some of the experimental signals along the horizontal (i.e. time) axis. These corrections correspond to a small tilt (less than 2°) of the projectile when it hits the front face of the target plane and allow an excellent agreement between experiments and simulations as regards the first shock travelling time through the samples. Since the shock waves considered here are not stationary (see for instance the wave profiles for shot #909 corresponding to samples of 1mm and 5mm thickness), this result is complementary to the shock velocity plotted on figure 1. We note that an excellent agreement is also found for the amplitude of the first wave in all shots.
However, the simulation of shot #909 for the 1mm-thick sample (DLI 2 record on figure 4) significantly overpredicts the interface velocity corresponding to the first release state. Indeed, we were unable to correctly reproduce the experimental signal unless we added a 120 µm-thick void between the two impactor plates in the simulations. This can be attributed to premature failure of glue during the launching. We note that this modification of the impactor assembly has almost no effect on the simulation of the thicker sample on this shot (Visar 3 record on figure 4).

Figure 3. Comparison of experimental and simulation results with POREQST model for shot #908. The time origin corresponds to the impact of the projectile on the target assembly.

Figure 4. Comparison of experimental and simulation results with POREQST model for shot #909. The time origin corresponds to the impact of the projectile on the target assembly.
We will focus now on shot #910 (cf. figure 5). The simulation of DLI 2 shows that errors less than 2% are obtained after the wave has travelled 4 times back and forth in the copper driver plate. This result confirms the validity of our models for copper and PMMA. The comparisons show that a reasonable agreement is also found for the EDM3 sample (Visar 3) until approximately 5 µs, although the experimental signal exhibits a smoother aspect than the simulation. As can be seen on figure 5, a viscoplastic model of PMMA [12] does not affect much the simulation result, suggesting that this feature is probably related to the porous graphite model. However, to a first approximation, our model correctly reproduces the experiment, suggesting that the dynamic compaction curve is close to the static one in this regime, where stresses remain below 0.3 GPa. A stronger disagreement is found after 5 µs: the sudden rise observed on the Visar 3 signal is poorly reproduced by the simulation. However, lateral release waves begin to affect the rear surface velocity between 5 and 6 µs, so it is expected that the 1D simulations may not be valid any longer.

6. Conclusion
In this paper, we have used the POREQST model to describe the dynamic behaviour of a porous graphite. First, we have shown that this model, using a SESAME table for the dense material, fits the available Hugoniot data. New plate impact experiments have also been presented in order to compare the model with off-Hugoniot (i.e. reshock and release) states. Complete densification is achieved for two shots where the samples are loaded between 8 and 23 GPa. Another shot gives information on the dynamic compaction process for stresses below 0.3 GPa. Despite the relative simplicity of the model, simulations show a good agreement with the experimental results.

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