Modeling of laser-driven water-confined shocks into porous graphite

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Abstract. This paper presents a laser-driven water-confined shock experiment into a commercial grade of porous graphite. An intensity of about 3 GW/cm² led to a pressure above 2 GPa on the front surface of the 0.46 mm sample. The rear surface velocity, recorded by a Velocity Interferometer System (VISAR), reached 325 m/s. Two classical models for porous materials are discussed. The first one uses plates of dense graphite spaced out in order to obtain the correct average density. The second one models a continuous material and includes an experimental compaction curve of our porous graphite. They were implemented into hydrocodes and both gave quite correct maximum free surface velocities and shock break-out instants. Nevertheless, the continuous representation appeared to be more efficient to reproduce the experimental free surface velocity ramp. Discussions on the laser-matter interaction modeling are also provided. Finally, a protocol for the simulation of future laser experiments is proposed.

1. Introduction

Because of their low density and high mechanical properties, composite materials based on carbon fibers and/or matrix are more and more used in various applications such as aerospace industry and high-power laser facilities where they are submitted to very specific aggressions, particularly to hypervelocity impacts (HVI). Indeed, meteoroids may impact satellites generating secondary debris which may also hit other man-made space structures [1–3]. Similarly, the various instruments used in the Laser MégaJoule (LMJ) experiment chamber may be struck by a variety of shrapnel originating from the target assembly [4]. In both case, impact velocities reach several kilometers per second and the local pressure ranges from a few to hundreds of GPa during 10 ns to 1 µs. Traditionally, these phenomena were and are still reproduced in laboratory by the mean of explosive launchers [5, 6] but the use of high-power lasers as shock generators continuously increases [7, 8]. When the spot diameter of the laser is widely larger than the sample thickness, it is comparable to plate impact experiment [9]. On the contrary, when the laser spot is smaller than the sample thickness, there are many similarities with HVI [10]. For instance, the behavior under HVI of composites using carbon components has been studied [11, 12] but, it appears there is a lack of knowledge for modeling porous graphite to improve the predictive capabilities of hydrocodes for such materials.
This paper aims to validate a protocol for simulating separately laser-matter interaction and shock wave propagation into a porous graphite with two hydrocodes. We report experiments of a laser-driven shock into a commercial grade of porous graphite and we describe a way to adapt laser characteristics using a reference shot on aluminum. Computations with two porous models for graphite are performed and results are discussed.

2. Experimental
Experiments were carried out at the laser facility of the P’ Institute (Poitiers, France) on aluminum and a commercial grade of porous graphite named EDM3 [13]. Its initial density is 1.75 g/cm$^3$ and its porosity is approximately 20%. Moreover it appears to be macroscopically isotropic. Its main mechanical characteristics have already been published [14]. The wavelength of the laser was 1053 nm. The energy deposited on the samples was 2.2 J with a pulse duration around 25 ns at half-height (triangular pulse). However, the focal spot was not perfectly known but its diameter was near 2 mm. Hence, the maximum intensity expected was 3 GW/cm$^2$. It was necessary to keep a low laser intensity in order to avoid laser absorption in ambient air since the shots were done at atmospheric pressure. However, shock pressure and duration were increased by the mean of water confinement which retains the plasma and decelerates its expansion. The velocity of the rear free surface was recorded by VISAR as shown in figure 1.

Because laser parameters are uncertain, especially the spot diameter and its homogeneity, we performed a repeatable reference shot on a 0.25-mm-thickness 6061T6 aluminum target which is a well-known material. It enabled to determine an accurate laser intensity (cf. Section 3). Then, one shot was carried out into an 0.46-mm-thickness sample of graphite. In both case the 1D-assumption is valid since the thicknesses are respectively eight and four times less than the spot diameter. The velocities of the rear free surfaces are presented in figure 2. Regarding graphite, it reaches 325 m/s, the shock break-out happens at 150 ns and the velocity ramp duration is more than 150 ns.

In this study, we used two different hydrocodes developed at CEA, Hésione and Esther which has laser-matter interaction models for various materials.

3. Esther simulations
Esther is a 1D Lagrangian hydrocode. It solves the laser wave propagation into the plasma dealing with thermal diffusion and hydrodynamic processes. As mentioned previously, there are often uncertainties about the laser parameters, and especially about the intensity. Thus, one assumes that the Esther’s hydrodynamic and plasma models of aluminum and water are rather reliable. It allows us to adopt a laser intensity that makes the numerical rear surface velocity to
Figure 2. Experimental rear surface velocities versus time. From 0.25-mm and 0.46-mm aluminum and graphite targets, respectively.

Figure 3. Calibration on aluminum by comparing experimental and numerical rear surface velocities. Accurate laser intensity equal to 1.8 GW/cm$^2$. Note that the optimization of the elastoplastic model of aluminum was not the purpose of the study.

fit the experiment, \textit{i.e.} 1.8 GW/cm$^2$ (see figure 3). From now we take this value for the next computations.

Thouvenin [15] suggested to model a porous material as a set of plates of dense material, representing the granular state of the solid. The average density of the set was equal to the porous density. The agreement between this model and explosive-driven plate impact experiments on various porous materials was excellent. We adapted his work to laser-driven shocks with 0.25-\textmu m-thickness plates using the 7832 Sesame table for the EOS of graphite. The laser-matter interaction was done in a single plate of thickness equal to the ablated depth (1 \textmu m). The results are presented in figure 4.

The free surface velocity of the same shock into a dense material is also presented. It proves the necessity of a porous model. Indeed, the plate model better reproduces the shock break-out instant (excluding ramp) and the maximum velocity. As expected, the velocity ramp does not exist in simulation. Note that for plates of thickness 0.5, 1, 2 and 5 \textmu m, the results are exactly the same but the signal gets noisy for 2 \textmu m and beyond. Hence, to work properly, the model needs enough plates along the shock width. Moreover, a second shock appears that does not in experiment. To explain this fact, there are two hypothesis: 1-the 1D-assumption is no more valid a this time; 2-the extreme simplicity of the model induces errors in modeling the shock release waves. For these reasons, the Thouvenin’s model is certainly more adapted to strong and long shocks. An improved model for simulating a laser-driven experiment such as ours is needed and available in an other hydrocode named Hésione.
Figure 4. Comparison between experiment and Esther simulation using a dense graphite EOS and a discrete porous model for EDM3 graphite.

Figure 5. Validation of the separated computation of the laser-matter interaction (with Esther) and the shock wave propagation (with Hésione) using the aluminum shot.

4. Hésione simulations

Hésione is a reliable hydrocode available in 1D, 2D and 3D and both in Lagrangian and Eulerian mode. But it has no laser-matter interaction model. Hence, the laser energy deposits was simulated by the mean of Esther. The resulting pressure induced by the plasma on the sample surface was extracted and used as a boundary condition in Hésione 1D Lagrangian computations. It supposes that thermal effects are negligible. Figure 5 verifies this assumption thanks to the shot on aluminum presented before.

We applied the same method for graphite. The laser-matter interaction was simulated by Esther into dense graphite and the resulting equivalent pressure law (2.2 GPa at maximum) is used as an input parameter of Hésione simulation. In the latter, graphite is represented by a continuous porous model based on POREQST [16] and adapted to the mechanical properties of EDM3 using an experimental compaction curve [17, 18]. Figure 6 shows the good overall agreement between computations and experiments, especially concerning the velocity ramp and the shock break-out instant. However, a second shock appears slightly before 500 ns that does not exist in experiment. It could be explained by damage or by the fact that the 1D-assumption is no more valid at this time.

5. Conclusion

A simple porous model such as Thouvenin’s was not sufficient to reproduce the main features of the experiment. Hence, we validated a protocol for simulating laser-driven shocks into porous graphite using separated hydrocodes for the laser-matter interaction and the shock wave...
A reference shot on a well-known material such as aluminum enabled us to select the accurate laser intensity. Thus, the laser-matter interaction was simulated with the dense material model. Neglecting the thermal effects, the pressure induced by the plasma on the target surface was extracted from Esther to serve as a temporal boundary condition in Hésione. In the latter, a continuous porous model taking account of the mechanical properties of porous graphite reproduced correctly the experiment.

Finally, this work suggests that porosity has no such influence on the laser-matter interaction and that thermal effects are negligible. With adaptations, this protocol may probably be used for two-dimensional studies.

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![Figure 6. Comparison between experiment and Hésione simulation using a continuous porous model for EDM3 graphite.](image)
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