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Dynamic fragmentation of graphite under laser-driven shocks: Identification of four damage regimes

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ABSTRACT

This study presents the results of a large experimental campaign conducted on the Luli2000 laser facility. Thin targets of a commercial grade of porous graphite were submitted to high-power laser-driven shocks leading to their fragmentation. Many diagnostics were used such as high-speed time- and space-resolved imaging systems (shadowgraphy and photography), laser velocimetry (PDV and VISAR), debris collection and post-mortem X-ray tomography. They provided the loading levels into the targets, the spall strength of the material, the shape and size of debris and the localization of the subsurface cracks. The crossed data reduction of all the records showed their reliability and allowed to get a better insight into the damage phenomena at play in graphite. Thereby, four damage regimes, ranked according to their severity and loading level, were identified. It confirms that laser shocks are very complementary to classical impact tests (plates and spheres) since they ally two-dimensional loadings to the possibility of using both, in-situ and post-mortem diagnostics. Finally, the campaign shall be able to provide large and consistent data to develop and adjust reliable models for shock wave propagation and damage into porous graphite.

1. Introduction

From the beginning of their development, high-power laser facilities have always been considered as potential calibrated-shock generators [1]. Indeed, the interaction between the laser and the front face of a solid target generates a plasma whose expansion creates a shock wave into the matter that may lead to its failure. Thus, similarities with plate impact experiments [2–5] or hypervelocity impacts [6,7] have been pointed out. Many efforts have been done to understand and predict the mechanical effects of the laser–matter interaction through the development of empirical laws [8–11] and specific hydrocodes [12,13]. As a consequence, high-power lasers are now commonly used in a large scope of shock studies [14–21].

The present authors have recently studied the dynamic behavior of porous graphite under high or hypervelocity impacts of metallic plates and spheres [22–27]. On the one hand, for plate impact experiments, all the phenomena are one-dimensional. Data, exclusively particle velocities (free-surface or interface), are collected during the experiment and samples cannot be recovered for further post-mortem analysis. On the other hand, hypervelocity impacts of spheres generate two-dimensional phenomena and allow sample recovering for fine post-mortem analysis such as micrography and tomography. However, in-situ dynamic observations are less reachable because of time and space uncertainties about the impact.

Hence, the purpose of this paper is to show how a better insight into the two-dimensional damage phenomena of porous graphite can be obtained with well-calibrated and repeatable laser-driven shocks using crossed data reduction from various in-situ and post-mortem diagnostics. In Section 2, we present the experimental set-up. Then, in Section 3, we discuss the free-surface velocity records in order to estimate the loading levels and the spall strength of our graphite. And finally, in Section 4, we confront, correlate and discuss all the experimental results in order to better understand the damage mechanisms, leading to the identification of four different damage regimes.

2. Experimental set-up

Shock experiments have been conducted with a high-power laser facility onto thin graphite targets leading to their fragmentation and/or perforation. Various diagnostics have been used in order to

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measure the laser spot and pulse, to capture time- and space-resolved images of the fragmentation and to record the particle velocities. In the same time, reference shots have been done onto well-known materials such as aluminum and tantalum.

2.1. Facility and diagnostics

Luli2000 is a high-power laser facility of the *Laboratoire pour l'Utilisation des Lasers Intenses* (LULI) based at the *École Polytechnique* (Palaiseau, France) [28]. This laser generates square temporal pulses tunable from 0.5 to 5 ns and can reach energies up to 1 kJ at the wavelength of 1064 ns.

Fig. 1 gives a simplified scheme of the experimental set-up. During this campaign, the laser was used at the wavelength of 532 ns with energies between 35 and 700 J, of which about 90% were delivered in 5 ns as shown in Fig. 2(a). The targets were placed at the center of the experimental chamber under high-vacuum where two different beams (called SB and NB, i.e. South beam and North beam) were alternatively focused. They formed a negligible angle of 5.5 degrees with the horizontal *x*-axis. They shared the same laser source but had their own amplification chain which allowed larger quantity of shots per day. The focal spot of each beam was spatially shaped just before the experiment chamber by means of phase plates that made the beams axisymmetrical and pseudo-Gaussian (see Fig. 2(b) and 2(c)).

The particle velocities of the rear face of the targets were measured by VISAR [29] which has a good temporal resolution. However, its need of a strong return signal can be an issue when the measured surface gets highly deformed and loses its reflectivity. Hence, we also used photonic Doppler velocimetry (PDV) [30–32] that has a lower temporal resolution but is capable to record multiple velocities despite weak return signals (around a few percents of the original one). Two PDV probes with 1-mm-diameter beams were placed in the *x*-*y* plan, each forming an angle with the *x*-axis (α_1 and α_2 respectively). They were pointed to the back face of the targets measuring its velocity and then the velocity of the ejected fragments.

For some shots, VISAR was replaced by an open cube filled with varagel, a gel derivated from paraffin with a density close to the water one. Placed at a few centimeters from the back face, this collector captured debris without damaging them in order to measure and analyze them by means of tomography [33].

The time- and space-resolved laser shadowgraphy recorded fragments ejected from the targets back face [34]. A 527-nm continuous laser enlightened two amplified cameras that took pictures of the shadow of the ejecta according to the *x*-*z* plan. Each camera made two images at different times with an exposure time of 5 ns. The exact instant of the capture was known thanks to a synchronization system between the laser facility and all the diagnostics.

High-speed photography was obtained by pulsed-laser illumination [35]: two 10-ns pulses of second harmonic YAG laser

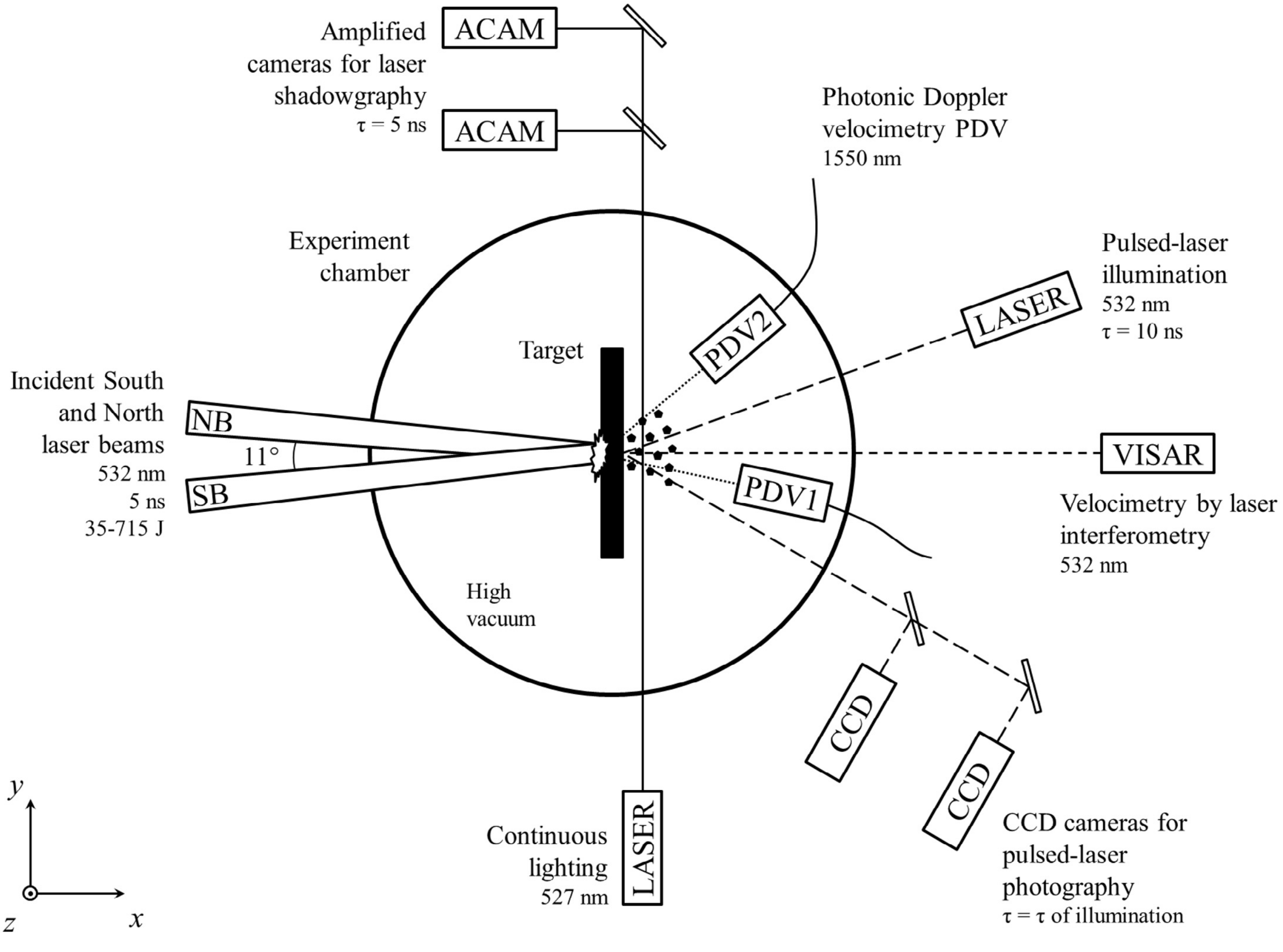

Fig. 1. Simplified scheme of the experimental set-up. Two different types of diagnostic have been used: laser velocimetry, and time-resolved laser imaging.