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# Laser Shock Waves: Fundamentals and Applications

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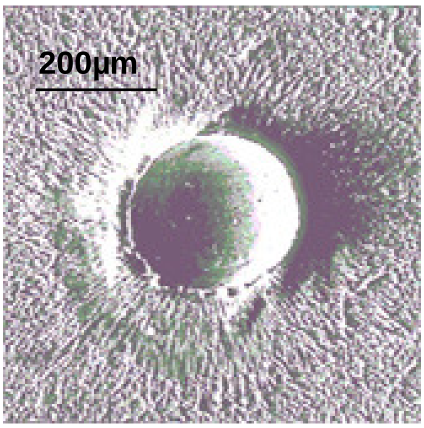
**Abstract :**
High power pulsed laser (above 1GW/cm²) interaction with matter yields to very high amplitude pressure loadings with very short durations, initiating into solids a strong short shock wave. Compared to the conventional generators of shock (launchers of projectiles, explosives), these particular characteristics offer the possibility to study the behaviour of matter under extreme dynamic conditions, with a possible recovery of the shocked samples presenting the effects of the passage of the shock in most cases. This article introduces the principle of laser shock generation, the characterization of these shocks, principal mechanisms and some effects associated with their propagation in the solids (spallation, Laser Adhesion Test, geological applications).
**Keywords** : Laser, shock wave, high pressure, rupture, spallation, debonding, impact

## 1. Introduction

Shock waves in the solids, a strong sudden discontinuity of the pressure and of the associated parameters [1], belong to our environment since the dawn of times. The impact of meteorite, such as the major impact of Chixculub-Mexico probably at the origin of the extinction of the dinosaurs and of large predatory, leaving the way open to the advent of humanity, is certainly the most important shock wave ever carried out.
Many other examples of shock waves in nature exist, such as recently the disastrous

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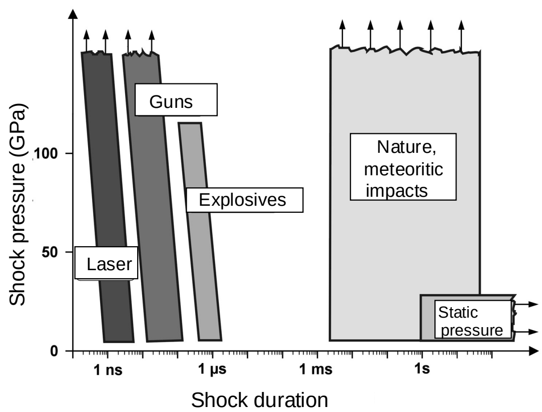


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Figure 1. a-Crater generated by laser impact at 70TW/cm$^2$, with a duration of 25ns focused on 90µm
b-characteristic shock ranges according to shock generators

tsunami at the end of 2004. Mankind has sought to use the effects associated with the shock phenomena, such as to carry out the synthesis of new materials requiring the combination of strong temperatures and pressures, or for defence purposes with the development of new shock generators such as nuclear weapons, guns and explosives.
It is only in the eighties that high power pulsed lasers came to be added in the panoply of shock generators, making it possible to induce pressures much higher than the precedents, but in extremely shorter times [2] (cf fig. 1). These particular properties opened up a new field of investigation in scales of time and pressure hitherto inaccessible.
Thus, research in this field brought complements of knowledge on equations of state of materials, their phase diagrams, their behaviour under dynamic stress and in particular the effects of rupture related to shock propagation . These new laser facilities, whose power is in constant evolution followed by a parallel development of diagnostics, also make it possible to reproduce and analyze in laboratory the behaviour of the matter under extreme conditions and in safer conditions.
After a brief description of laser shock principle and main features, a review of some studies and applications related to their propagation into solids (spallation, debonding test, geological applications) is given.

## 2. Laser shock generation

When a laser pulse of short duration (nanosecond) and high density of power (above $10^9$ W/cm$^2$) is focused on the surface of a solid target, the laser energy absorption of the target surface generates a plasma whose expansion induces by reaction a shock wave.
Two modes of interaction are distinguishable (fig. 2) according to whether the plasma expands freely (direct interaction) or is retained by a transparent medium confining the plasma.

### *2.1 Direct ablation*

Many theoretical [3-4] and experimental [5-6] studies provide the order of magnitude of the shock pressure induced according to the conditions of irradiation. The shock profile roughly follows the temporal characteristics of the laser pulse.
Theoretical studies establish primarily scaling laws connecting the incident laser intensity to the shock pressure; they are parameterized by the characteristics of the pulse

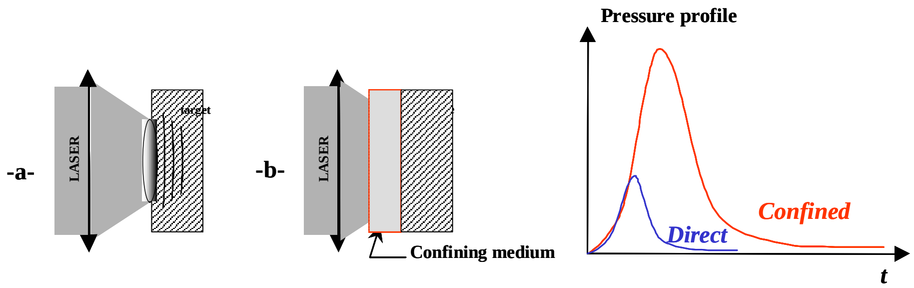


Figure 2. Shock generation in direct irradiation (a) or confined interaction (b) and associated mechanical loadings

(wavelength, pulse duration, nature of material, dimension of the focal spot) and geometry of the interaction (planar or spherical expansion of plasma).
They are based on experimental measurements of pressure according to various methods, such as the measurement of the pulse transmitted to the target, or velocity measurement of induced shock [7].
These laws are defined on ranges of incident intensity and very often associated with specific characteristics of the irradiation (wavelength, duration,…).

### *2.2 Confined ablation*

The confined ablation consists in covering the target by a transparent medium to the laser radiation (water, glass, air), slowing down the plasma expansion [8].
The confining medium results in two major effects on the pulse communicated pressure to the target (fig. 2.b):
- an increase of ablation pressure by a factor 5 to 10 compared to direct ablation,
- an increase of shock duration by a factor 2 to approximately 3.

However, the pressure generated by this mode of ablation saturates above a level of incident density of power, associated with the breakdown observed on the surface of the medium of confinement. This threshold depends on the laser wavelength, the confining medium and the pulse duration [9].

## 3. Some applications of laser shocks

### *3.1 Dynamic fracture : spallation*

By propagation of a non-sustained shock wave into a solid, it is possible to produce strong levels of traction leading to the damage of the material [10].
The laser driven shock wave propagates into the material and reverberates on the back surface (free surface) into a release wave which interacts with the incoming release wave due to the quick laser unloading. The crossing of these two release waves results in traction inside the material, all the more, the closer to the back face, the shorter pulse duration. If the amplitude and the duration of this traction are sufficient, there can then

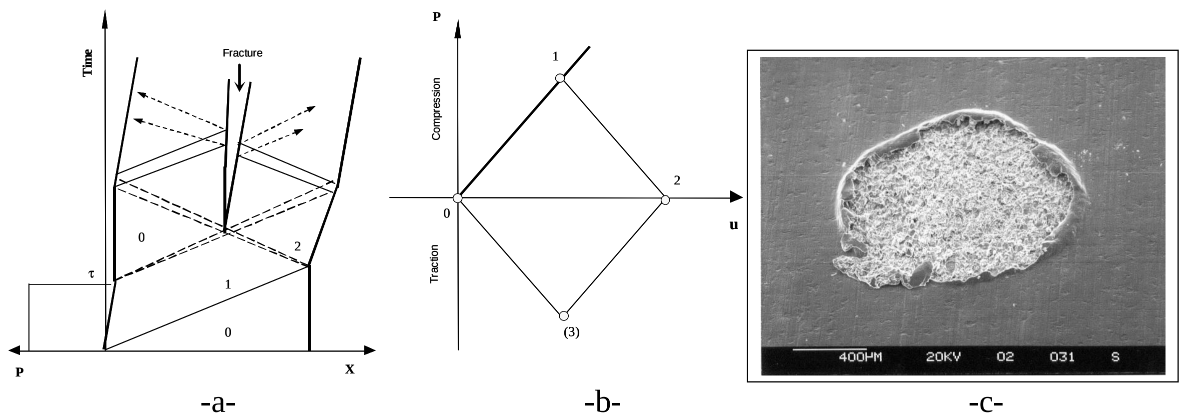


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Figure 3. Principle of traction generation by shock loading of a target
- (a) : Space (X) time (t) diagram for shock wave propagation (plain line) and release (dash line))
- (b) : successive pressure (P), particule velocity (u) states
– (c) : spallation of the back face of an aluminum target laser irradiated on the opposite face

be rupture of material and formation of a spall (fig. 3).
The shortness of the laser shocks and their strong amplitude allow studying the rupture of materials at extreme strain rates of about $10^7 s^{-1}$, much higher than under conventional shocks. It is then possible to gather data on the dynamic rupture of materials in an unexplored field.
The exceptional brevity of these shocks authorizes the recovery of targets for post-mortem observations, which is much more difficult to achieve with the conventional shock techniques. Thus, the effects of damage are observable after shock and the rupture data (facies, position,…) coupled with the free surface velocity measurements performed during the experiments allow a validation of the damage models in this range [10]. Laser shocks afford the possibility to study damage of a wide range of materials, including very brittle materials whose post shock recovery is also possible thanks to the very short deformation holding duration.

### *3.2 The Laser Adhesion Test (LASAT)*

The adhesion test of coatings on substrates constitutes a major industrial challenge, in particular in the field of metallurgy. Indeed, a great number of machine elements are coated, aiming to protect them from aggressions of ambient conditions (case of aeronautical turbines blades) or from a premature wear due to frictions from surfaces in contact. Various methods of control of adhesion are used in industry or research laboratories. Most of these techniques are based on tensile tests (pull-test) or on scratching (scratch-test) but few of them provide a measurement of adhesion. Besides, they are generally rather heavy to implement, not fully automatic and rather difficult to interpret.
Shock waves appear as an alternative to these methods, known as static, to test thin coatings adhesion by submitting them to a dynamic and uniaxial tensile stress [11].
The principle is close to that of spallation in a monolayer target. A laser shock applied to the substrate allows inducing controlled traction conditions at the coating – substrate interface (fig. 4-a). According to the adhesion level of the interface, one can determine the laser loading conditions leading to debonding (fig. 4.b).

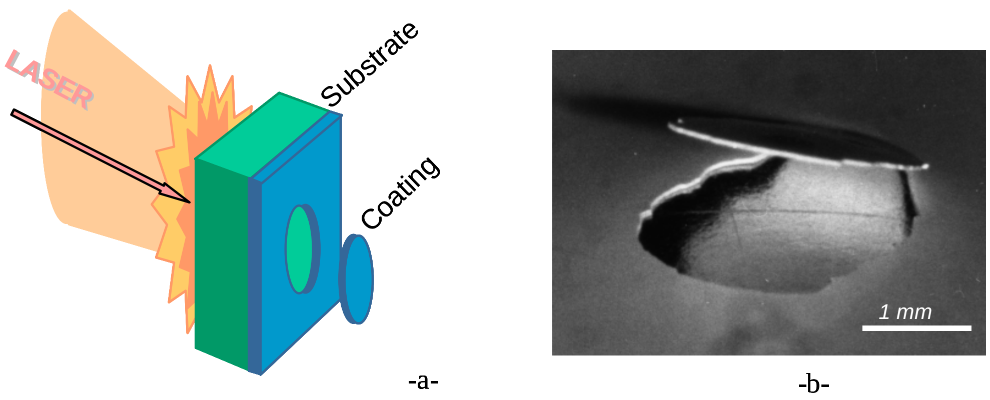


Figure 4. (a) Principle of the Laser Adhesion Test, (b) debonding of a painting 45µm thick on aluminum substrate 1mm thick by laser shock of the aluminum

Coupled with a non-destructive control such as ultrasonic inspection, laser shock can then be considered as non-destructive tool for testing the adhesion of thin layers.

### *3.3 Laser application of shocks in geology*

Hypervelocity impacts (50km/s) are current phenomena in the solar system. They are at the origin of the formation of planets and their geological evolution. The effects of these collisions go from the macroscopic scale by the formation of craters [12], down to the microscopic size (formation of defects in the minerals).
On the ground, it is often difficult for geologists to locate secular sites of impacts masked by strong erosion. Thus, the discovery of the greatest impact in Chixculub (Mexico) dates only from the Nineties. Another means of location lies in the observation of microscopic defects produced in the matter consecutively in the passing of the shock wave. The reproduction in laboratory of these signatures then becomes helpful to the identification of natural sites of impact [13].
Shocks in laboratory are generally produced by techniques using launchers or explosives. The use of lasers makes it possible to consider very high amplitudes with very short maintaining times. Contrary to natural impacts, such experiments allow quenching the transformations by preserving them of the post shock thermal hydro modifications.
Laser shocks are also an interesting laboratory tool for the study of the behaviour of orbital spatial structures submitted to risks of high velocity debris impacts. The high pressure and short duration loading driven by a laser are very close characteristics to those induced by small size debris at high velocity, and the results of damage on structure is therefore directly comparable as in figure 5. The damage caused to a multi layer of a solar wing of Hubble is due to the shock wave propagation and its resulting traction within the layers, phenomena which can be understood and quantified through laboratory experiments in order to define the best shielding conditions.

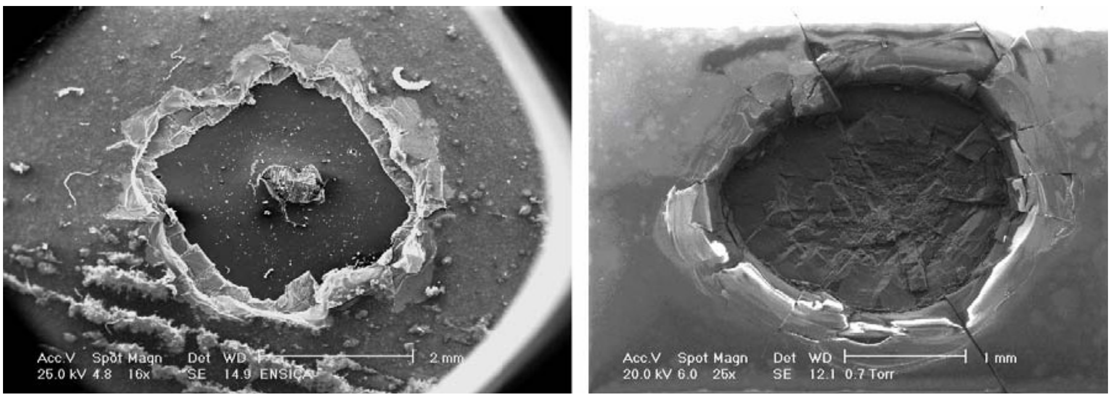


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Figure 5. -a- Rear view of a silicate glass multi layered part of Hubble submitted to a laser shot on the opposite face, b- same material from Hubble impacted by an unknown high velocity debri into space

## 5. Conclusion

This brief review of shock waves in solids illustrated by some research applications using high power pulse lasers is only one abstract of the vast investigation open field. Research widens always more with the construction of new laser sources of great quality and the development of highly time resolved diagnostics (laser Doppler interferometry, streak cameras, spectroscopy resolved in time,…). The field of ultra-short pulses (femtosecondes) is still a quasi-virgin ground from the point of view of the shock effects. With high power lasers, limits in fields towards the infinitely small in time and the infinitely great in pressure are pushed back day after day, draining the development of industrial applications suspended to the only industrial development of the adapted laser sources.

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