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## SPALLATION UNDER THE ACTION OF A LASER INDUCED SHOCK WAVE

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**Résumé** - L'utilisation des ondes de choc générées par irradiation laser permet d'étendre l'étude de l'endommagement dynamique à des temps de chargement de la cible très faibles, de l'ordre de quelques nanosecondes. Un critère de fracture dynamique à dommages cumulatifs est intégré dans un code hydrodynamique monodimensionnel. Ce logiciel permet de simuler correctement les expériences d'écaillage réalisées sur des cibles d'aluminium de différentes épaisseurs irradiées par une impulsion laser de 2 ns à un flux incident de  $10^{12} \text{W/cm}^2$ .

**Abstract** - The conditions of laser-driven shock wave loading leads to study the dynamic fracture in an unusual range of stress and strain rates : 0.2-2 Mbar and more than  $10^7 \text{s}^{-1}$ . A cumulative damage criteria for spallation process has been included in a one-dimensional finite difference hydrodynamic code. This program correctly fits spallation experiments on aluminum targets of various thicknesses irradiated by 2 ns laser pulse of  $10^{12} \text{W/cm}^2$  incident intensity.

### 1 - INTRODUCTION

The spallation phenomenon is a mechanism of dynamic fracture of solid resulting from the application of intense impulsive loads, due to the impact of a flyer plate or a high explosive in contact with the sample or an energy deposition. The compressive stress waves, induced within a sample, reflect as a rarefaction waves from a discontinuity such as a free surface and produce tensile waves in the interior of the body. The tension or "negative pressure" increases by the interaction of two rarefaction waves until a critical value is reached and fracture occurs. Therefore, the spallation can be defined as a complete or partial separation of material parallel to the wave front as a result of a dynamic tensile stress component perpendicular to this plane. For certain conditions, the layer of material (spall or scab) is split away from the surface and separates from the remaining material, moving away from the surface with a definite speed [1,2].

The spalling studies are of utmost importance in the development of shock wave material-working (shock synthesis, compaction, forming, ...). These industrial processes are often limited in some respects by dynamic fracture. Therefore, all these topics are interested in the evaluation of material characteristics in dynamic range.

A considerable portion of the published spalling experimental works, caused by shock waves produced by conventional dynamic techniques, has been used as input to computer codes with predictive capability [3,4,5]. However, scabbing at very high strain rates, such as that generated in laser-driven shock wave experiments, has not been done. So the main purpose of this work is to analyse the spallation in this unusual range of stress and strain rates (0.2 - 2 Mbar and more than  $10^7 \text{s}^{-1}$ ). This experimental and numerical study permits one to obtain new data and to validate spallation simulation models in this case of very short loading conditions.

### 2 - FRACTURE CRITERIA AND NUMERICAL SIMULATION

A number of different descriptions are available in computer codes to model failure of metals and to reproduce the experimental results obtained under widely varying conditions. The simplest model,

and one of the earliest, is the pressure cutoff. When the hydrostatic pressure (or mean stress) reaches a critical value in tension, failure is assumed to occur instantaneously and the pressure is not allowed to grow beyond this user-specified limit. In reality, material failure does not occur instantaneously, but rather a finite time is required for crack initiation. So, the models use the concept of cumulative damage as a basis to describe the time dependent dynamic fracture /5,6/. Cumulative damage models have the advantage of being more realistic : failure depends on a critical level of stress acting over a finite time. This property has been verified by flyer-plate impact experiments in which the duration of the applied stress is easily controlled. In the present work, the time-dependent fracture model, proposed by Tuler et al. /5/, was used. This criterion introduces three adjustable parameters which can be determined experimentally.

The numerical simulations were obtained using a one-dimensional finite-difference computer program, called SHYLAC, for solving the hydrodynamic equations in Lagrangian form. An elastic-plastic behaviour of material is included in the code. In the elastic region, a linear elastic evolution of solid ( Hooke solid) is assumed with a shear modulus  $\mu$  and the limit between elastic and plastic behaviour is given by the Von Mises criterion, related to the static yield strength  $Y_0$ . The hydrodynamic pressure equation of state is described by the Gruneisen equation of state, referring to the Hugoniot curve described by the linear relation between the shock velocity  $D$  and the particle velocity  $u$  :  $D=C_0+Su$ . This code was modified to include the calculation of the spallation process corresponding to the cumulative damage model. For each mesh point (or cell) and at each time step  $\Delta t$ , the sum  $\{[(Y_s - Y)^\lambda \Delta t]\}$  is calculated and the fracture is indicated by the program when any one of the sums exceeded a constant  $K$  :

$$\sum_t [(Y_s - Y)^\lambda \Delta t] \geq K \quad \text{when } Y \leq Y_s \leq 0$$

Tensile stresses are taken as negative in wave propagation calculations. The stress  $Y_s$  is some stress below which fracture would not occur, even at very long time durations; for example, it might be assigned the static stress for fracture. All the parameters ( $\mu, Y_0, C_0, S, Y_s, \lambda, K, \dots$ ) necessary for the calculations were obtained from experimental data /5,6,7/ and are presented for aluminum in the table 1.

The process of laser-matter interaction was not included in the code. So, the initial conditions are taken as the applied pressure generated by laser-driven ablation, generally modeled by a gaussian pulse reproducing the laser pulse shape with the same width at half maximum  $\tau$ , the maximum induced pressure  $P_m$  being related to the incident laser intensity.

Table 1 - Properties of aluminum used in simulations.

Property	Symbol	Value	Units
Initial density	$r_0$	2785	Kg cm <sup>-3</sup>
Gruneisen coefficient	$\gamma_0$	2	-
Equation of state, Hugoniot	$C_0$	5386	Km s <sup>-1</sup>
( $D=C_0+Su$ )	$S$	1.339	-
Static yield strength	$Y_0$	$3 \cdot 10^8$	Pa
Shear modulus	$\mu$	$2.65 \cdot 10^8$	Pa
Fracture stress	$Y_s$	$10^9$	Pa
Tuler-Butcher coefficients	$\lambda$	2.02	-
	$K$	$3.8 \cdot 10^{11}$	-

Using the code SHYLAC, the evolution of the spall thickness was investigated in function of the target thickness for applied pressure pulses with three different durations of 0.5 ns, 2 ns and 20 ns and maximum pressures of 0.5 Mbar and 1 Mbar, corresponding to possible laser-experiments conditions. The results of these numerical studies of spallation process under the action of a laser-driven shock wave are shown in the figures 1, 2 and 3.

In the first case (0.5 ns and 2 ns pulse durations, figures 1 and 2 respectively), The increasing function of spall thickness versus target thickness is due to the decrease of the shock amplitude during its propagation in the target. The lower the pressure reaching the back face of the target, the longer the integration time of spallation calculation to reach the fracture limit and therefore the thicker the spall. The main feature of laser-driven shock wave is the short duration of pressure pulse induced in the target. This short time leads to an extremely rapid shock decay by hydrodynamic attenuation, and, consequently, samples used in such experiments will not exceed a few 100  $\mu\text{m}$ . The shock pressure decreasing mechanism leads to a spallation threshold corresponding to a too weak pressure at the rear face of a thick target : 250  $\mu\text{m}$  for a maximum induced pressure of 0.5 Mbar in 0.5 ns pulse duration, 750  $\mu\text{m}$  for a maximum induced pressure of 0.5 Mbar and 900  $\mu\text{m}$  for 1 Mbar in 2 ns pulse duration.

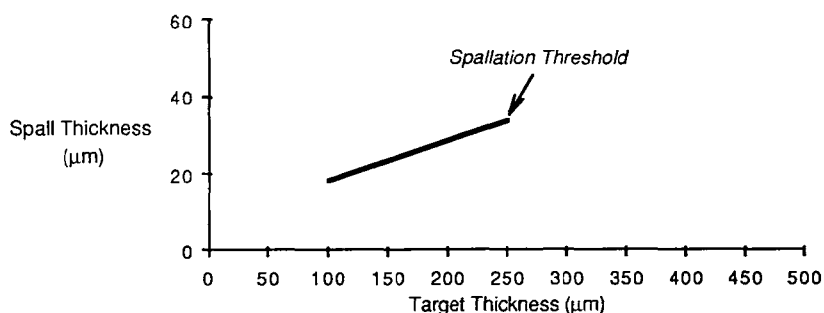


Fig. 1 - Numerical simulations of the evolution of the spall thickness in function of the target thickness for a gaussian-shaped applied pressure profile with a duration at half maximum of 0.5 ns and a peak pressure of 0.5 Mbar.

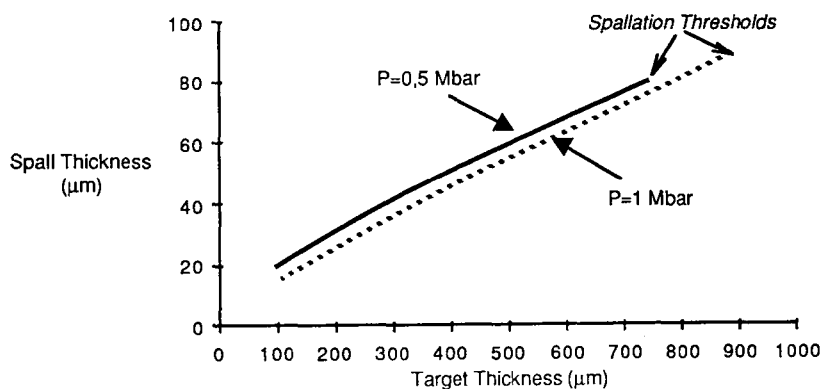


Fig. 2 - Numerical simulations of the evolution of the spall thickness in function of the target thickness for a gaussian-shaped applied pressure profile with a duration at half maximum of 2 ns and peak pressures of 0.5 Mbar and 1 Mbar.

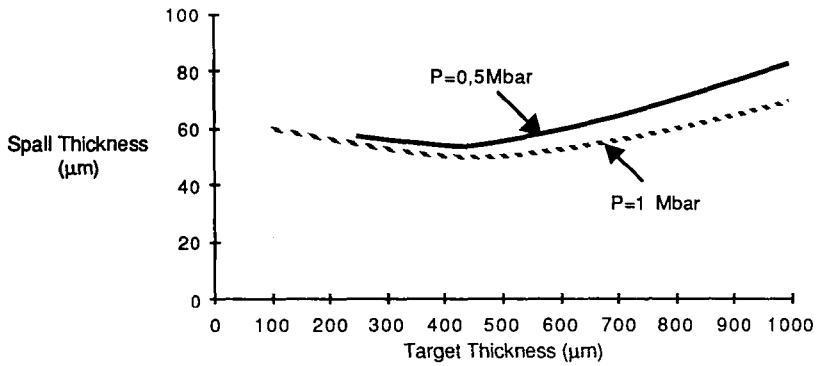


Fig. 3 - Numerical simulations of the evolution of the spall thickness in function of the target thickness for a gaussian-shaped applied pressure profile with a duration at half maximum of 20 ns and peak pressures of 0.5 Mbar and 1 Mbar.

In the second case (20 ns pulse duration, figure 3), the spall thickness evolution in function of target thickness is quite similar to the first case if the target thickness is more than 500  $\mu\text{m}$  for both checked maximum induced pressures. For thinner targets, the pulse duration is long enough to avoid the decay of the shock amplitude and therefore the spall thickness is roughly independent of the target thickness.

### 3 - EXPERIMENTAL STUDY

The experiments were performed with the use of the University of British Columbia neodymium-glass laser, doubled in frequency. The available output laser energy at 0.53  $\mu\text{m}$  wavelength was 7 J in 2 ns full width at half maximum (FWHM) pulses. The laser beam was focused onto the target front surface with a 300 mm lens in a 600  $\mu\text{m}$  diameter spot, measured by the "burn-paper" technique. The average incident intensity was about  $10^{12}$   $\text{W}/\text{cm}^2$ , corresponding to a peak pressure of about 0.5 Mbar [8]. We used in these experiments pure aluminum foils of various thicknesses : from 100  $\mu\text{m}$  to 1 mm.

The damage was evaluated by optical measurements on recovered samples by metallurgical cross-sectioning and polishing. The spall thicknesses were measured with an accuracy of 10  $\mu\text{m}$ .

Table 2 - Spallation experiment results for aluminum targets irradiated by 2 ns laser pulses at  $10^{12}$   $\text{W}/\text{cm}^2$  incident intensity.

target thickness ( $\mu\text{m}$ )	spall thickness ( $\mu\text{m}$ )	comments
100	14	severe spall damage, crater
"	15	" "
240	40	visible spall damage, complete separation
"	43	" "
"	44	" "
434	53	visible spall damage, incipient separation
"	56	visible spall damage, complete separation
"	58	" "
1000	--	no visible spallation and no swelling

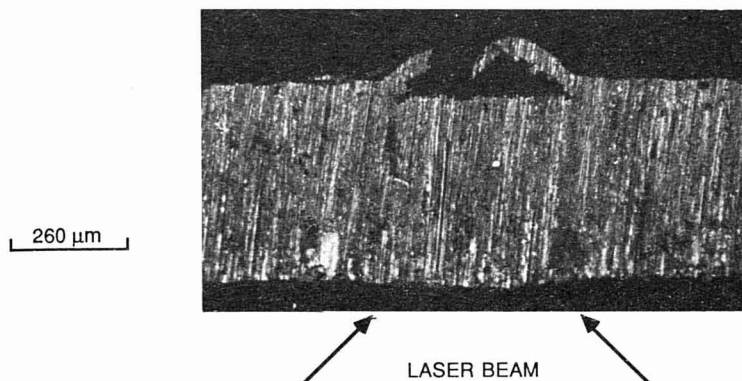


Fig. 4 - Cross-sectional view of a 434  $\mu\text{m}$ -thick aluminum target irradiated by 2 ns laser pulse at  $10^{12}\text{W}/\text{cm}^2$  incident intensity. The spall thickness is about 56  $\mu\text{m}$ .

The results for different target thicknesses are reported in the table 2. The figure 4 shows an example of a typical picture of the cross-sectional view of 434  $\mu\text{m}$ -thick aluminum target. It can be clearly seen that the spallation area corresponds approximately to the focal spot area and the fracture plane is parallel to the irradiated surface, indicating the planar shock wave propagation through the target. On each side of the spall zone, some pieces of spall not-completely separated from the target are observed.

The comparison of these results with the corresponding simulation is shown in figure 5. The solid line represents the simulation results obtained from SHYLAC code with the initial conditions :  $P_m=0.5$  Mbar and  $\tau=2$  ns. The dots represent the experimental data. So the numerical model successfully describes the principal features of our spall experiments in aluminum without any changes in spallation criterion coefficients.

For these initial conditions (0.5 Mbar, 2 ns), the target thickness limit , numerically determined, is 750  $\mu\text{m}$  (see figure 2). Experimentally, we checked that, for a target thickness of 1 mm, spallation does not occur and no swelling is visible.

#### 4 - CONCLUSION

The cumulative-damage criterion for simulating the spallation process, included in an hydrodynamic elasto-plastic code (SHYLAC), seems to reproduce quite well the general behavior of the main characteristics of spalling. The simulations work well in reproducing spall thickness and spall stress evolution as a function of initial conditions (maximum pressure, pulse duration and target thickness) in the case of a gaussian shape pressure profile applied on the front face of the target.

Moreover, the simulations of the evolution of spall thickness versus target thickness are quite consistent with the experimental data obtained in the conditions 2 ns laser pulses at  $10^{12}\text{W}/\text{cm}^2$  incident intensity, corresponding to 0.5 Mbar peak pressure.

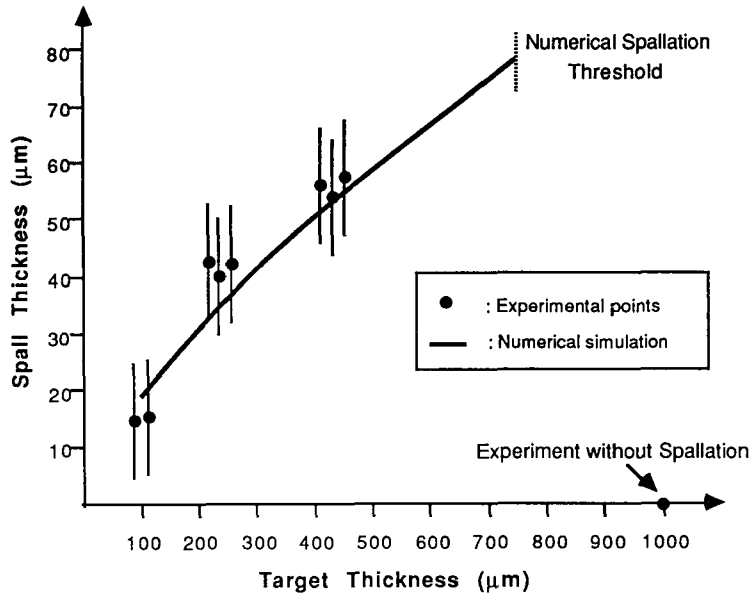


Fig. 5 - Evolution of spall thickness versus aluminum target thickness. Comparison of experiments (2 ns laser pulse at  $10^{12}$  W/cm<sup>2</sup> incident intensity) and simulations (2 ns gaussian-shaped pressure pulse with 0.5 Mbar maximum pressure).

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