DYNAMIC FRACTURE OF GLASS MATERIALS UNDER SHOCKWAVES INDUCED BY PULSED LASER IRRADIATION AT VERY SHORT DURATIONS

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Abstract - The study of fracture induced by a laser-driven shockwave loading of solid targets leads to an unusual range of stress (hundreds of GPa) and pulse duration (a few ns). The present paper deals with the spallation of glass materials in this specific range. An analytical and numerical study reveals the influence of various parameters upon dynamic fracture, which is essentially characterized by the thickness of the spalled layer. Preliminary experimental results on glass targets irradiated by laser pulses are presented. The observed behaviour is very different from the one of ductile materials like aluminum or copper.

1.- Introduction

Fracture induced by strong shockwaves in solid materials has been a subject of considerable interest over the past several decades. In this field of investigation, the application of high-power pulsed lasers to generate high-pressure shocks differs from conventional techniques (explosives or plate-impacts), providing a wider range of stress (up to 200 GPa) and pulse duration (less than 1 ns). These specific characteristics of laser-driven shock loading lead to new experimental data. For instance, they are comparable to those produced by the impact of hypervelocity microparticles, so that pulsed lasers can offer a low-cost means of simulating such phenomena.

Dynamic fracture corresponds to planar separation of material parallel to the stress wave front. This wellknown phenomenon commonly called spallation is due to a dynamic tensile stress induced in the sample at the intersection of two rarefaction waves: one resulting from the reflection of the incident compression wave from the rear surface, the other coming from the front surface when the pressure loading on it falls off. In regard to their failure behaviour under tensile loading, solid materials are traditionally separated into two classes: ductile materials (aluminum, copper...) and brittle materials (glasses, ceramics...), even though some materials may sometimes exhibit either brittle or ductile behaviour. This distinction corresponds to important differences in the spall fracture process, involving different mechanisms: plastic growth of voids for the ductile type, and cleavage for the brittle type. Both mechanisms imply the nucleation, growth, and coalescence of microvoids in one case, or microcracks in the other. Spall fracture under conventional shock loading has been extensively studied in many ductile materials /1 to 3/ and brittle ones /4, 5/. The work concerning spalling under laser-driven shocks in ductile metals is more recent /6 to 9/. This paper presents a study of the brittle spall occurring in glass materials under shock loading generated by pulsed laser irradiation.

2.- Propagation of a laser-induced pressure pulse in glass materials

The response of a glass material to a dynamic stress wave differs noticeably from that of a classical metallic material (Al, Cu...). This specific behaviour, associated with a negative curvature of the Hugoniot curve in the low pressure range /5, 10/, is precised in the following study, describing the evolution of a pressure pulse propagating in a borosilicate glass target characterized by its Hugoniot curve /11/ (see figure 1).

The computer simulations were realized with a one-dimensional finite-difference hydrodynamic Lagrangian code [7]. This code was adapted to glass materials by the introduction of an artificial viscosity in order to improve numerical stability in the treatment of the rarefaction shockwaves. The densification of glass [12] has not been included in the model yet. The initial conditions reproducing laser irradiation are modeled in a Gaussian pressure pulse [7] of peak pressure P_m and duration at half maximum τ , applied on the front surface of a sample of unlimited thickness.

Fig. 1.- Hugoniot curve of a borosilicate glass

Three cases may occur, according to the position of the maximum pressure P_m on the Hugoniot curve:

- If P_m is less than 12 GPa, the compressive wave spreads when propagating in the target, whereas the rarefaction wave stiffens (see figure 2).
- If P_m is located between 12 and 30 GPa, the compressive wave separates into a stretching bundle, followed by a compressive shock corresponding to a classical curvature of the Hugoniot curve. The release wave marking the end of the initial loading gets deformed in a similar way: spreading then stiffening (see figure 3).
- If P_m exceeds 30 GPa, the Hugoniot curve presents a globally positive curvature, so that the initial profile develops a classical evolution: formation of a compressive shock followed by a spreading rarefaction bundle. Hydrodynamic attenuation causes a peak pressure decay, and consequently, the two preceding situations appear successively (see figure 4).

Fig. 2.- Propagation of a laser-induced pressure pulse, modeled in a Gaussian-shaped wave profile of amplitude 10 GPa and duration at half maximum 3 ns, in a glass target.

Fig. 3.- Propagation of a laser-induced pressure pulse, modeled in a Gaussian-shaped wave profile of amplitude 25 GPa and duration at half maximum 4 ns, in a glass target.

Fig. 4.- Propagation of a laser-induced pressure pulse, modeled in a Gaussian-shaped wave profile of amplitude 50 GPa and duration at half maximum 5 ns, in a glass target.

3.- Analytical study of spallation of a glass material under a laser-driven shock

The main parameters controlling spall fracture are the target thickness E_c , the induced peak pressure P_m , and the duration at half maximum τ . In order to determine the respective influences of these independent parameters upon the thickness of the spalled layer, a qualitative study based on the simplest spall model was carried out.

Spallation is modeled through a cutoff criterion, which assumes that instantaneous fracture occurs at a distance where the tensile stress reaches a critical value σ_R corresponding to the dynamic ultimate strength of the material. This approach does not take into account the time dependence for dynamic fracture, but such a simple formulation seems justified for glass materials, where brittle fracture is known to be a very abrupt event.

The propagation of a laser-induced pressure pulse in a glass sample leads to the development of a triangular-shaped wave profile (see figure 2). As this pressure wave reaches the free back surface, it reflects into a tensile wave and spallation occurs as soon as the corresponding stress exceeds the cutoff value σ_R . Thus, it is possible to study the effects of the different parameters (E_c , P_m , τ , σ_R) on the stress history in the sample, then on the spall thickness, and to compare these effects with those obtained in metallic materials (see figure 5).

4.- Experimental study of laser-induced spall failure in glass targets

Spall experiments similar to those realized in metallic materials [9] were performed in float glass targets of thicknesses ranging from 0.6 mm to 4 mm, using the L.U.L.I. neodymium-glass laser.

In order to prevent the laser beam from penetrating through the glass specimens, the irradiated surfaces of the samples were covered with a thin metallic coating constituting the ablation surface. The output laser energy at 1.06 μm wavelength was ranging from 30 J to 90 J. The corresponding irradiation resulted in the application of a Gaussian-shaped pressure pulse with a various peak pressure up to 80 GPa, and a full width at half maximum of 0.6 ns, 2.4 ns, or 30 ns.

Fig. 5.- Influences of the determining parameters on the spall thickness in glass materials:

(a): influence of E_c , (b): influence of P_m , (c): influence of τ , (d): influence of σ_R

The position of the spall plane in the target was evaluated by optical measurements on recovered samples by metallurgical cross sectioning and polishing (see figure 6). The experimental results obtained for a pulse duration of 2.4 ns are plotted on the diagram of figure 7, in a spall thickness - target thickness plane. It can be seen that the evolution of spall thickness versus target thickness corresponds to the predicted behaviour. The maximum induced pressure P_m seems to have a weak effect on the spall thickness, as it does in ductile materials. The rapid decrease of the shock amplitude resulting from the hydrodynamic attenuation leads to fairly close pressures near the rear face of thick targets, so it can account for this limited influence.

5.- Conclusion

The use of high-power lasers opens a new domain for the investigation of the mechanical behaviour of various solid materials in the context of shockwave research. Their interest as for the study of dynamic failure lies in the specific loading conditions (important stresses and very high strain rates) they induce, and in the possibility to recover and analyse damaged samples they offer.

Experimental and numerical work shows the effects of determining parameters (target thickness, peak induced pressure, laser pulse duration) on the thickness of the spalled layer in glass materials. Preliminary experimental results are in agreement with the predicted evolutions. The observed effects are very different from those obtained in ductile materials. This study will lead, like it did for ductile materials, to the determination of a computational model for dynamic fracture of very brittle materials under laser-induced shock loading.

Fig. 6.- Micrograph of a metallurgical cross section of a 1.6 mm-thick glass target, showing the effects of a laser-induced shock with a 68 GPa -peak pressure and a 0.6 ns-duration.

Fig. 7.- Experimental results on float glass targets irradiated by laser pulses of 2.4 ns-duration, for peak induced pressures ranging from 10 GPa to 70 GPa.

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