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Laser simulation of hypervelocity impacts in space

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Abstract

A high irradiance, short-duration pulsed laser can simulate hypervelocity micrometeroid and debris impacts both on inactive substrates and on surface-active impact detectors. The similarity between impact events in space and laser impacts is evidenced by crater morphology and consecutive failure stages as a result of hydrodynamic flow in the shocked area for aluminum, gold and alumina (ceramics), and by discharge initiation on metal-oxide-silicon (MOS) capacitor impact detectors. The similarity between conditions was based on the assumptions that (1) the laser induced surface ablation pressure is equal to that created by a hypevelocity impactor, (2) the impact time and impactor diameter are equal to the laser pulse time and spot diameter, and (3) the laser and impactor induced impulses are equal. Using this information, the threshold impactor energy required to discharge the MOS detectors was obtained and compared to that derived from hypervelocity iron particle impact experiments. The feasibility of using the pulsed laser for post-integration instrument and subsystem performance check is shown. The velocity of 1.7 km/sec and laser spot diameter of 10 microns was the threshold sensitivity for MOS detectors.

1. Introduction

When interplanetary dust and orbital debris particles strike a detector or a target at hypervelocity speeds, the target will sustain damage proportional to the energy of the impactor. For lower energies, damage is limited to small craters caused by vaporization of surface material. At increasing energies internal fracture damage will occur, with spallation at the back surface. At even higher energies the targets will be perforated. These micro particles or cosmic dust may damage critical surfaces such as optical surfaces, windows, coatings, etc.

Short pulse time, high irradiance laser induced shock waves are used to assess the dynamic failure behavior of materials under extreme conditions such as those prevailing in hypervelocity impact events in space. Strong laser induced shock waves in the kbar-Mbar range, can produce the same crater morphology and fracture damage as hypervelocity impactors with the same energies.
MOS sensors that had flown on the Long Duration Exposure Facility (LDEF) for 6 years in low earth orbit were subjected to pulsed laser irradiation with two objectives in mind. First, the laser was used to generate chemically pure blank impact-induced discharge sites that were subsequently analyzed by secondary ion mass spectroscopy (SIMS). These blanks helped to confirm the identification of micron sized sodium-potassium hypervelocity impact sites on the MOS detectors that have been tentatively linked to leaking coolant from Russian nuclear reactors in storage orbits at 100 km altitude[1]
The second objective was to determine the threshold energy level for detector discharge initiated by the laser pulse and compare the result to hypervelocity impact calibration experiments on the MOS detectors using iron particles in a Van der Graff accelerated at two million volts. This required application of a theory for the analogy between pulsed laser irradiation and hypervelocity microparticle impact.

2. Laser induced shock waves

Absorption of laser radiation by a target material takes place within a very thin surface layer. The rapid temperature increase and the high temperature gradient (10^7 eV/cm) induce ablation of material to plasma. The plasma expansion drives a strong shock wave into the material. The shock wave is supported by the expanding plasma as the laser pulse operates. Even before the end of the laser pulse, ablation at the surface drops and a continuous sequence of rarefaction waves propagate into the material, attenuating the shock. This shock wave is approximately triangular in shape. When the shock reaches the back surface of the target, or a different acoustic impedance interface in a multilayer structure such as the MOS detector, a tensile stress wave of increasing negative amplitude is reflected. When this tensile stress becomes larger (more negative) than the dynamic tensile strength of the target, spall or perforation occurs[3-6].
The ablation induced shock wave pressure P is directly related to laser pulse intensity, I, scaling approximately as $Pa \sim I^{0.7}$. More precise values can be obtained experimentally. The pressures obtained are in the kbar-Mbar range for our experiments.

The strain rate $\dot{\varepsilon}$ can be obtained also from experiment:

$$\dot{\varepsilon} = \frac{-\dot{\rho}}{\rho} = -\frac{1}{\rho}\frac{\partial \rho}{\partial X}C$$

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where $\partial\rho/_{\partial x}$ is the density gradient at the time and position just before spall occurs, and C is the speed of sound in the target material. The strain rates calculated from experiments are in the range of $(1\text{-}4)\times10^7$/sec.

3. Laser simulation of hypervelocity impacts in space

In terms of duration and energy transfer, there is very close correspondence between pulsed laser-induced impact and the impact produced by a hypervelocity microparticle. Laser simulation of microparticle impacts is based on the following assumptions:
a) The average laser-induced surface ablation pressure is equal to the shock pressure generated by the hypervelocity impactor.
b) The impactor has a diameter equal to the laser spot diameter.
c) The laser-induced impulse is equal to the impactor momentum and the loading time of the target material is equal to the laser pulse duration.
The achievable pressures in the kbar-Mbar range and the variable laser spot diameter can extend the particle impact to a wide range of conditions.

3.1 Theory for the simulation of hypervelocity impacts in space

Regarding the phenomena of impact duration and energy transfer, there is a close analogy between the irradiation of a surface by a short pulsed laser (of the order of the few ns) and the impact upon this surface by a hypervelocity microparticle. In both cases the impact is transferred to the target material through shock waves which are in general one dimensional (1D). In our experiments the laser spot diameter was of the order of 10 μm and the target (detector front layers of aluminum and silica is 1.1 μm thick, therefore the 1D approximation that we are going to use is appropriate. For impact particles with a diameter larger than 2.2 μm the impact is 1D to a good approximation, and therefore the analogy between laser irradiance and microparticle impact seems to hold assuming that two conditions are satisfied:
(i) The impact duration (t_i) of the microparticle is of the order of the laser pulse width (τ_L).

$$\tau_L \sim t_i \approx \frac{2R}{V_o} \qquad (1)$$

where 2R is the microparticle diameter or the impactor length and V_o its initial impact velocity. This equation should be satisfied only as an order of magnitude. The main requirement for the analogy to hold is:
(ii) The induced shock wave pressure should be equal in both cases; the laser irradiance and the microparticle impact. The laser induced pressure is given to a good approximation by [7,8]:

$$P(GPa) = 600\left(\frac{I_L}{10^{14} W / cm^2}\right)^{2/3} \left(\frac{1\mu m}{\lambda_L}\right)^{2/3} \quad (2)$$

where I_L and λ_L are the laser irradiance and wavelength respectively. The microparticle pressure produced by a particle with initial impact velocity V_o is given by the following calculation (1D) and nomenclature:

ρ_{op}=Micro particle (projectile) density before shock.
ρ_{lp} = Micro particle density after shock.
P_{lp} = Shock pressure in projectile.
P_{op} = 0, initial pressure in the projectile.
U_{pp} = Particle (i.e. flow) velocity of shocked projectile.
U_{sp} = Shock velocity in the projectile.
ρ_{ot} = Target density before shock.
ρ_{lt} = Target density after shock.
P_{lt} = Shock pressure in the target.
P_{ot} = 0, initial pressure in the target.
U_{pt} = Particle velocity of shocked target.
U_{st} = Shock velocity in the target.
EOS = Equation of State.
The continuity equations yield:

$$_{lt} = P_{lp} \equiv P \quad (3)$$

$$V_o = U_{pp} + U_{pt} \equiv U_{pp} + U \quad (4)$$

The conservation equations (mass and momentum) are:

$$\rho_{op} U_{sp} = \rho_{1p} (U_{sp} - U_{pp}) \quad (5)$$

$$\rho_{op} U_{sp}^2 = P_{1p} + \rho_{1p} (U_{sp} - U_{pp})^2 \quad (6)$$

$$\rho_{ot} U_{st} = \rho_{1t} (U_{st} - U_{pt}) \quad (7)$$

$$\rho_{ot} U_{st}^2 = P_{1t} + \rho_{1t} (U_{st} - U_{pt})^2 \quad (8)$$

In order to solve Eqs. (3) - (8) the equations of state (EOS) of the target and the projectile are needed[9,10].
For the target material the EOS of aluminum was taken:

$$U_{st}\,(km/s) = 5.4 + 1.34\, U_{pt} \quad (9)$$

where U_{pt} and U_{st} are given in units of km/s. For the projectile two different cases were considered:
For iron, with a density 7.8 g/cm^3

$$U_{sp}\,(km/s) = 2.05 + 3.80\, U_{pp} \quad (10)$$

and porous "iron" with a density of 4.1 g/cm^3 and an EOS[10].

$$U_{sp}\,(km/s) = 7.4 + 1.25\, U_{pp} \quad (11)$$

This kind of "iron" is found in the mantle of the earth and it may be conceivable that some micrometeorites have a similar composition.

Equations (3) - (10) [or (11) instead of (10)] are 8 algebraic equations with 8 unknowns with a unique solution. (Note: the equations are nonlinear). Eqs. (5) and (6) yield a Hugoniot (shock wave) pressure in the projectile:

$$P_{1p} = \rho_{op} U_{sp} U_{pp} \quad (12)$$

while Eqs (7) and (8) yield the Hugoniot pressure in the target:

$$P_{1t} = \rho_{ot} U_{st} U_{pt} \quad (13)$$

Using Eqs. (3), (4), (12) and (13) and the appropriate EOS, the following equation is obtained:

$$\rho_{op} [A + B(V_o - U)] (V_o - U) = \rho_{ot} (5.4 \cdot 10^5 + 1.34U)U \quad (14)$$

where A and B are the coefficients of the EOS according to the projectile, i.e., A = 2.05 x 10^5 and B = 3.80 for iron [Eq. (10)]. A = 7.40 x 10^5. B = 1.25 for the porous "iron" (Eq. 11). Eq. (14)is given in cgs units. If the flow velocity in the shocked target is denoted by U (see Eq. 4), then a quadratic equation in U (see Eq. 14) is obtained with a solution of U as a function of the initial projectile velocity V_o:

$$U = f_1 (V_o) \quad (15)$$

The shock pressure is given by

$$P = \rho_{ot} (5.4 \cdot 10^5 + 1.34U) U \quad (16)$$

where the pressure in (16) is in cgs units. Eq. (15) is of the form

$$P = f_2 (U) = f_2 (f_1 (V_o)) \quad (17)$$

P is calculated for the laser impact, see Eq. (2) and Eq. (17) is solved for V_o. The microparticle velocity calculations from laser experiments are given in Table 1.

4. Experimental Method

The laser used in the experiments was an oscillator-amplifier Nd:YAG, Q switched laser at 1.06 micron wavelength. The pulse width at half maximum is 7 nsec. The diameter of the laser spot is ~10 ± 2.5 microns. The maximum laser intensity used for detector calibration was 10^{13}W/cm^2. The detector was mounted inside the vacuum chamber and connected to a Tektronics TDS 540 digital oscilloscope for signal monitoring.

The metal-oxide-silicone (MOS) capacitor discharge sensors are fabricated by starting with a 250 μm thick, boron-doped single-crystal silicon wafer. Single crystal silicon dioxide is then thermally grown on the surface of the wafers to a thickness of 1.0 μm under very highly controlled conditions. This results in a very clean interface with a thickness of only a few atomic layers. The 0.1 μm thick aluminum surface, which serves as the top electrode, is deposited by physical vapor deposition.

A 60 V dc potential across the (MOS sensor) activates it. An impacting microparticle breaks down the insulator layer and causes an electrical discharge. This discharge vaporizes a small area of the top aluminum layer and self-terminates. The detector then recharges and is ready for the next impact. The damage to MOS detectors was recorded with electrical signals of the discharge and scanning electron microscopy for crater morphology.

5. Experimental results

Intensive research has been conducted on metals, composites, ceramics and multilayer adhesive bonds to study the stages of failure under hypervelocity impact conditions using laser induced shock waves[3-6]. Two impact geometries were used: one-dimensional (1-D) shock waves where the laser spot diameter is at least three times greater than sample thickness; and spherical shock waves, where the laser spot diameter is very small simulating small particle hypervelocity impact in space. A few examples of impact morphologies from these experiments are given below.

Figures 1 and 2 show the front and back crater lips of a thin punctured aluminum foil. The perfectly circular hole indicated that the laser beam was well aligned. Re-solidified aluminum droplets cant be seen splashed around the rim of the front side of the crater. The back side shows petalling of the torn foil. These features are typical of hypervelocity impact morphology. Figures 3 and 4 show the smooth crater wall of a shallow surface laser impact and the cross section of the same damage with intensive spall at the back surface in gold foil. Figure 5 shows the cross-section through an impacted ceramic (alumina) target. The damaged area of the shock wave's passage became visible due to selective dye absorption. The above information was applied to calibrate the damage parameter required to activate the MOS detectors.

Fig. 1 - Front of a penetrated aluminum foil with splashed molten material around the hole.

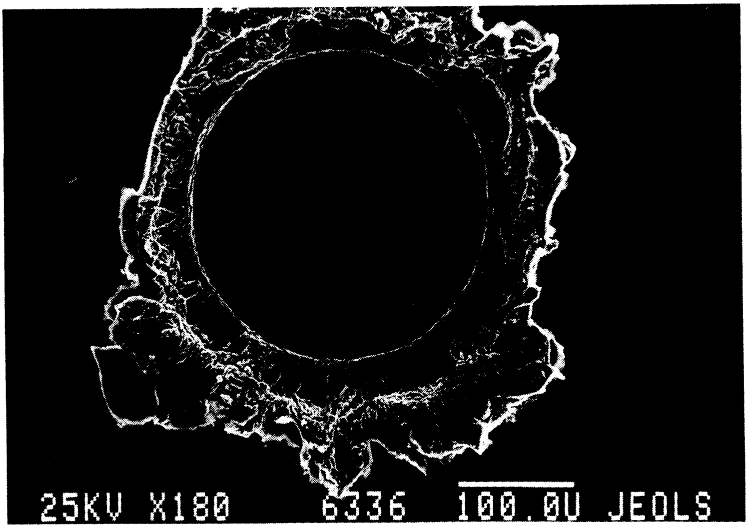

Fig. 2 - Back surface of a penetrated aluminum foil with petalling around the hole.

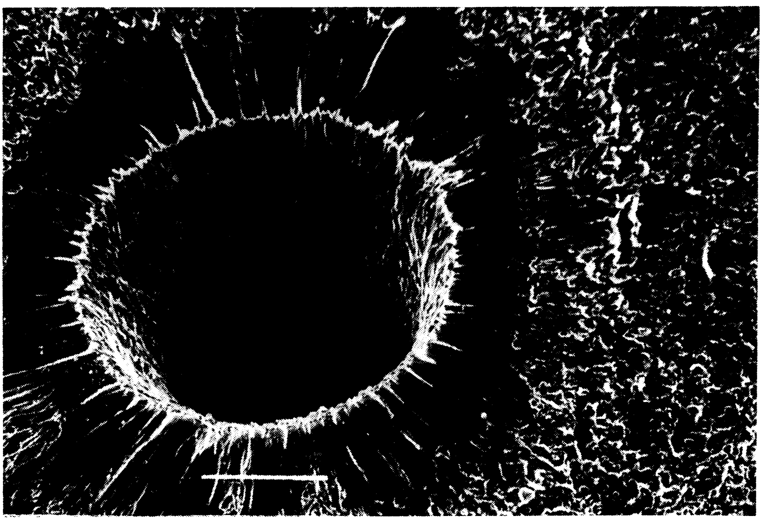

Fig. 3 - Smooth crater wall of a shallow surface damage in a gold foil.

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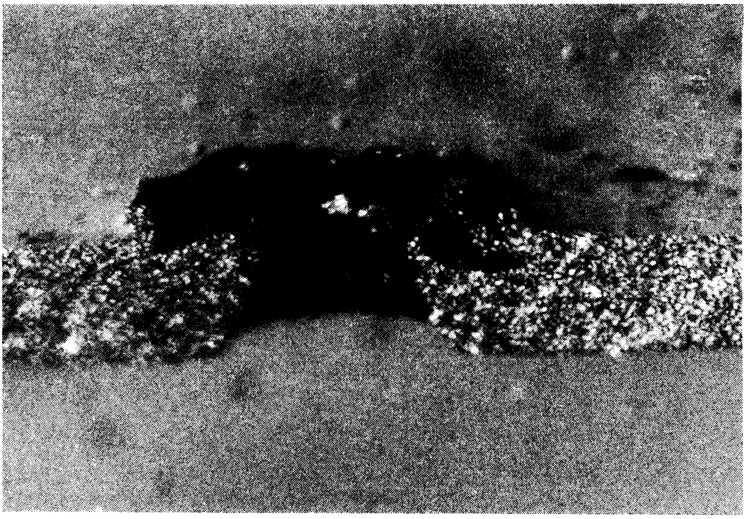

Fig. 4 - Cross section through the damage depicted in Fig. 3, showing intensive spall at the back surface.

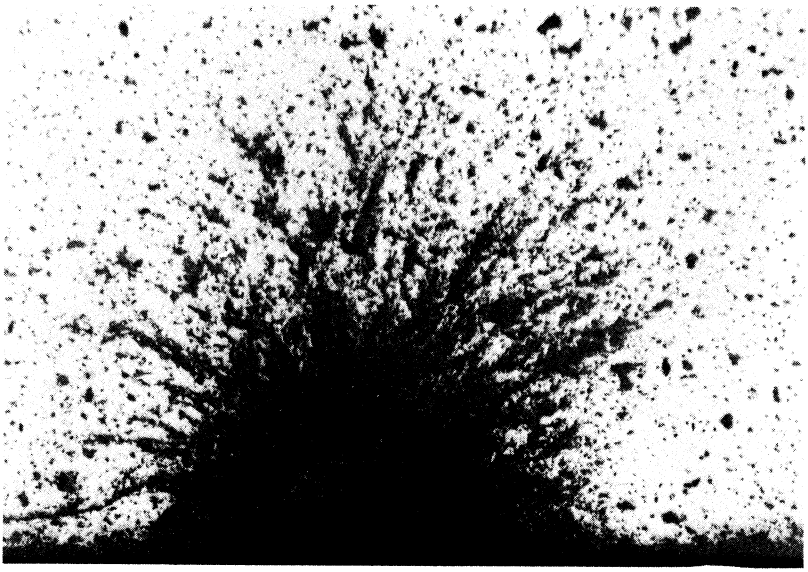

Fig. 5 - Cross section through an impacted ceramic sample. The damaged area is visible due to dye absorption.

The threshold conditions for MOS detector activation were recorded when no pulse was detected, corresponding to the laser intensity of $(4\text{-}12) \times 10^{11}$ W/cm^2 used in our calculations. The solutions to the equations described in the theory are summarized in Table 1.

Table 1. Microparticle velocity calculations from laser experiments

Laser Energy (mJ)	Laser Intensity (W/cm^2)	Ablation Pressure (Gpa)	Initial Microparticle velocity for iron (km/s)	Initial Microparticle velocity for porous iron (km/s)
290	3.7E+13	348	24.5	27.8
78	9.9E+12	145	10.3	15.5
35	4.4E+12	87	7	10.5
9.4	1.2E+12	35	3.2	5.6
3.5	4.4E+11	18	1.7	3.5
0.9	1.2E+11	7.5	0.7	1.8

5.1 Comparison with accelerator experiments

Kassel and Wortman[2] evaluated over 1000 hypervelocity impacts of Van der Graaf accelerated iron particles in the 0.5-5.0 micron size range at velocities of 2-20 km/s. They derived a relationship describing the MOS sensor's detection threshold with respect to iron impactor diameter (D) in microns, velocity (V) in km/s, and incident angle (B), and the total thickness (T) in microns of the detectors dielectric and top aluminum electrode layers.

$S = (D)\,(V)\,\cos B^{1.5}\,(T)^{-0.875} - 1.814$

S>0; discharge signal

S<0; no signal

In the current study, B = 0° and T = 1.1μ, and the equation reduces to:

$S = (D)\,(V)\,(0.920) - 1.814$ or $D(\mu m)\,V(km/s) \geq 2$

Using our threshold value obtained with pulsed laser activation: 1.7 km/s, we obtain $D \geq 1.2/f\lambda = 2.4\ \mu m$ where f=2 and $\lambda = 1\ \mu m$. Due to dispersion of the beam, $D \geq 2.4$ microns. The laser produced crater on the MOS detector showed a 10 μm impact diameter. Therfore the laser spot diameter is $10 > D > 2.4$ microns.

Conclusions

Short pulsed laser induced shock waves is a very suitable method for studying material response at hypervelocity conditions such as those prevailing in space during meteoroid or debris impact. One dimensional or spherical impact conditions can be simulated by changing the impact diameter (laser spot diameter) vis-a-vis target thickness. The theory of hypervelocity impact was based on the assumptions that the laser induced ablation pressure is equal to the

shock pressure generated by hypervelocity impactor; its diameter is equal to the laser spot diameter, and the loading times are equal.
From the threshold laser energy conditions, it was estimated that an iron microparticle with a diameter of ~ 10 μm and a velocity of 1.7 km/sec will activate the MOS impact sensor.

References

1. P. Oliver and C. Simon: "Origins of micro particles encountered by the LDEF", Space 96, submitted.
2. P. C. Kassel and J. J. Wortman: "Metal-oxide-silicon capacitor detectors for measuring micro meteoroid and space debris flux", in press, J. of Spacecraft and Rockets.
3. I. Gilath, S. Eliezer, T. Bar-Noy, R. Englman and Z. Jaeger: "Material response at hypervelocity impact conditions using laser induced shock waves", Int. J. Impact Eng., 1993, 14, 279-289.
4. I. Gilath, S. Eliezer and Y. Gazit: "Fracture modes in alumina at hypervelocity impact conditions", J. Mater. Sci., 1991, 2023-2125, 26.
5. I. Gilath, S. Eliezer and T. Bar-Noy: "Hemispherical shockwave decay in laser matter interaction", Laser and Particle Beams, 1993, 11, 221-225.
6. S. Eliezer, I. Gilath and T. Bar-Noy: "Laser induced spall in metals: Experiment and simulation", J. Appl. Phys., 1990, 67, 715-724.
7. V. E. Fortov, V. V. Kostin and S. Eliezer, J. Appl. Phys., 1991, 70, 4524.
8. C. R. Phipps et al., J. Appl. Phys., 1988, 64, 1083.
9. S. Eliezer, A. Chatak and H. Hora, An Introduction to Equations of State: Theory and Applications, (Cambridge University Press, Cambridge, 1986).
10. R. G. McQueen, High Pressure Equations of State: Theory and Applications, Eds. S. Eliezer and R. A. Ricci (North Holland, Amsterdam, 1991) p. 208.