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UCID - 16617

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**EFFECTS OF ENHANCED LASER-INDUCED STRESS WAVES
IN THIN ALUMINUM SHEETS**

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November 6, 1974

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Prepared for U. S. Atomic Energy Commission under contract no. W-7405-Eng-48

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EFFECTS OF ENHANCED LASER-INDUCED STRESS WAVES IN THIN ALUMINUM SHEETS

ABSTRACT

Rear-surface spall, permanent deformation, and material failure are produced in thin sheets of aluminum using a Q-switched ruby laser and employing plasma-confinement techniques to enhance the amplitudes of laser-induced stress waves. A variety of aluminum thicknesses are tested both with and without plasma-confining tamping material on the target surface. Representative samples are examined by metallurgical sectioning and then photomicrographed to determine the effects of the high-amplitude, laser-induced stress waves.

INTRODUCTION

A number of experiments have been performed on the use of lasers to generate stress waves in both solids and liquids.¹⁻¹² The electromagnetic energy from a Q-switched laser can induce stress waves in many solid materials, the amplitude of the generated waves being dependent on the amount of energy the target material can absorb. The amount of energy available for absorption generally is a function of the laser system. The amount and form of energy absorbed depends on the method used to couple the energy to the target substance and on the physical properties of the material. This study examines the effects of enhanced, laser-induced stress waves in thin aluminum sheets.

A high-temperature, high-pressure plasma forms as a result of the interaction of the laser beam with the aluminum target. If allowed to expand freely, the plasma will expend most of its energy to the surrounding air where it will have little impact on the aluminum. The relatively small amount of heat energy absorbed by the aluminum will cause some surface melting, while the energy from the freely expanding pressure wave will have very little effect on the aluminum. If the plasma is confined, however, it increases energy absorption generating high-amplitude stress waves in the aluminum. These enhanced stress waves will cause significant damage in the aluminum.

EXPERIMENTAL PROCEDURE

A 2-J, Q-switched ruby laser was used as the energy source in this experiment. The system consisted of a Brewster-cut ruby rod 6 in. long and 1/2 in. in diameter. A

99% reflective rear mirror and a 50% output mirror were used as the oscillator cavity. A KD*P Pockels cell between the ruby rod and the rear mirror provided the Q-switching. The beam was monitored with a photodiode receiving a portion of the beam from a pellicle beam splitter. The ruby was optically pumped with two parallel, linear xenon flash tubes driven by a 12-kJ capacitor bank. Targets were mounted on a foam fixture with a relief hole behind the area of the target expected to be deformed. Since the main objective of the experiment was to produce as much damage as possible using 1.5 J of energy, experimental data consisted of the results of target examination by metallurgical sectioning. Targets were placed approximately perpendicular to the incoming laser beam. A thin lens with a 25-mm focal length was used to focus the beam to the desired spot size, nominally 0.06 cm in diameter. With this spot size and a 1.5-J, 35-ns laser pulse, typical input energy was 1.4×10^{10} W/cm², neglecting reflectance. The aluminum target could be moved along the focal length of the lens, thereby varying the power density of the beam. The experimental arrangement is shown in Fig.1.

Targets were irradiated both in a free-surface condition and with either a MgO crystal or a thin coat of epoxy on the front surface of the aluminum. While a variety of transparent materials could have been used to increase energy absorption, these materials (hereafter referred to as tampers) were selected because of their ease of application and proven ability to enhance energy absorption.⁹ The MgO tamper consisted of a single MgO crystal 1 cm square and 0.190 cm thick bonded to the aluminum target with either Eastman 910 or a fast cure epoxy. The thin coat of clear, fast-cure epoxy, used as a tamper, was simply spread evenly on the face of the aluminum and allowed to dry; typical thickness was 0.064 cm. Various thicknesses of aluminum were tested to compare the amounts and types of damage that could be produced using a constant input. Each target was irradiated only once and then examined visually for damage.

About 30 samples, ranging from 0.0025 to 0.152 cm thick were irradiated both with and without tampers. Six of these samples, chosen to show the effects of varying aluminum thickness and using or not using a tamper, were analyzed by metallurgical sectioning. Only samples 0.025, 0.076, and 0.152 cm thick were sectioned; the thinner aluminum samples (0.0025, 0.005, and 0.0127 cm thick) were felt to be too soft to section without destroying most of the results of laser damage. The thinner samples were type 1100 aluminum. The 0.025-cm-thick aluminum also was type 1100; the 0.076- and 0.152-cm-thick sheets were type 6061. Photomicrographs were taken of the sectioned samples at various magnifications to show the damage resulting from the laser-generated stress waves.

EXPERIMENTAL RESULTS

All irradiated samples exhibited some form of damage. The thinner aluminum (0.0025 to 0.0127 cm thick) showed surface melting and slight permanent deformation (shallow dimpling) in the free-surface condition. Figure 2 shows a 0.0127-cm-thick sample that was irradiated in the free-surface condition. The 500X magnification

Fig. 1. Experimental arrangement.

Magnification: 50X

Magnification: 500X

Fig. 2. Photomicrographs of irradiated 0.0127-cm-thick, type 1100 aluminum (free-surface condition).

shows melting to an average depth of 0.0005 cm. In addition, the lower magnification (50X) shows slight permanent deformation of the sample. Figure 3 shows a sectioned 0.025-cm-thick aluminum specimen also irradiated in the free-surface condition. Again, there is surface melting and pitting, but less permanent deformation. Figure 4 shows a sectioned 0.152-cm-thick aluminum specimen irradiated with an MgO tamper bonded to the input face. Here, there is surface melting and a much broader and deeper dimple than produced in the thinner, free-surface samples.

The most significant damage occurred in the 0.025-cm-thick, type 1100 aluminum. Damage was generally severe and permanent deformation, rupture, and rear-surface spall were readily detectable. Figure 5 shows a sectioned 0.025-cm-thick, 1100 aluminum specimen irradiated with a MgO tamper bonded to the input surface. Surface melting, gross permanent deformation, and rear-surface spall are evident. The spall plane averages 0.005 cm thick. This corresponds to a stress pulse 18 nsec wide with an amplitude high enough to exceed the yield stress of the 1100 aluminum. Figure 6 shows another 0.025-cm-thick 1100 aluminum sample irradiated with an MgO tamper bonded to the input surface. Here, there is observable front-surface melting and permanent deformation, but no apparent spall. Figure 7 also shows a 0.025-cm-thick, 1100 aluminum specimen irradiated in the same manner as the previous samples. In this case, there is observable front-surface melting, permanent deformation, rupture, and incipient rear-surface spall. The spall, however, is not as extensive as that shown in Fig. 5.

CONCLUSIONS

The causes of damage in the aluminum samples irradiated in this experiment can be described in terms of amplitudes and pulse widths of stress waves generated by the high-pressure, high-temperature plasma that forms due to the interaction of the laser beam with the aluminum. Following are descriptions of the mechanisms that we feel are responsible for the damage produced in the aluminum in the free- and tamped-surface cases.

Free-Surface Case

When the aluminum is free to expand, surface melting, blowoff, pitting, and minor permanent deformation result. Thermally generated stress waves expend their energy through front-surface "spallation" or blowoff, transmitting very low-amplitude stress waves through the sample. Pressure-generated stress waves in the aluminum are also extremely low in amplitude, since most of the energy from the expanding high-pressure plasma is lost to the surrounding air. In the extremely thin aluminum samples, however, pressure-generated stress waves were of sufficient amplitude to cause minor permanent deformation.

Magnification: 50X

Magnification: 100X

Fig. 3. Photomicrographs of irradiated 0.025-cm-thick, type 1100 aluminum (free-surface condition).

Magnification: 50X

Magnification: 100X

Fig. 4. Photomicrographs of irradiated 0.152-cm-thick, type 6061 aluminum (MgO tamped).

Not etched (25X)

Etched (25X)

Etched (250X)

Fig. 5. Photomicrographs of 0.025-cm-thick, type 1100 aluminum irradiated with MgO tamper bonded to surface (Sample A).

Not etched (25X)

Etched (25X)

Fig. 6. Photomicrographs of 0.025-cm-thick, type 1100 aluminum irradiated with MgO tamper bonded to surface (sample B).

Not etched (25X)

Etched (25X)

Fig. 7. Photomicrographs of 0.025-cm-thick, type 1100 aluminum irradiated with MgO tamper bonded to surface (sample C).

Tamped-Surface Case

When the aluminum sample has a tamper bonded to its input face, the ensuing plasma is confined. Because of its ability to confine the plasma, the tamper increases both thermally generated and pressure-generated stress waves. As a result, high-amplitude thermal and pressure stress waves are driven into the aluminum and into the tamper material. If the sample and the tamper were of the same material, identical damage would occur in both. The amount of energy delivered to a sample can be controlled by varying the strength of the tamper relative to the aluminum. This can be done by varying the thickness of the tamper or by using a material of known strength less or greater than the aluminum.

Thermal stress waves have much smaller pulse widths than pressure stress waves. The spall plane shown in Fig. 4 was produced by a thermal stress pulse approximately 18 ns wide. Moreover, this spall plane was produced before the following, longer-duration, pressure stress wave caused permanent deformation and rupture. This is evidenced by the fact that the spall plane was stretched, in a tensile manner, along the length of the plane. This does not occur during the formation of a rear-surface spall plane, but results from subsequent, permanent deformation of the sample.

These two modes of deformation were first observed by O'Keefe, *et al.*⁷ using a single-slit diffraction apparatus. While this method was not employed in this experiment, the rear-surface spall plane and its later deformation graphically point out the existence of the two modes of deformation. We attribute these early and late deformation modes to the thermally generated and pressure-generated stress pulses.

The Laser as a Materials Diagnostic Tool

The pulsed laser is a proven tool in the study of stress waves in materials.¹⁰ It is a highly repeatable energy source, and the extremely short stress pulses generated by laser energy can be used to study spall in many materials. Moreover, this experimental technique is straightforward and highly controllable. The elastic constants of materials can be determined accurately using laser pulses to generate stress waves in materials, and the potential of this technique for flaw detection is being explored. Further experimentation concerning spall and the response of materials to high strain and high-strain rate using laser-generated stress waves will lend even more recognition to the laser as an important materials diagnostic tool.

ACKNOWLEDGMENTS

The author wishes to acknowledge the support of R. G. Stone of the Mechanical Engineering Department (Research Engineering) and to thank D. E. Lord and C. A. Calder for their interest and help in these experiments.

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