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"DYNAMIC RESPONSE OF A THIN DISK
SUBJECTED TO A THERMAL PULSE"

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DYNAMIC RESPONSE OF A THIN DISK SUBJECTED TO A THERMAL PULSE*

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ABSTRACT

The dynamic response of a thin steel disk to a transient thermal pulse induced by a pulsed neodymium-glass laser was studied experimentally and compared with numerical results from a finite element code. The experiment was designed to provide data for use in code development work for erosion/corrosion studies.

INTRODUCTION

Material degradation due to erosion/corrosion processes occurring at very high temperatures and pressures (up to thousands of degrees K and hundreds of MPa) is a serious problem encountered in various applications of combustion. The metal and nonmetal surfaces containing the combustion in such applications as rocket nozzles, internal combustion engines, gas turbine combustors, and flow metering orifices degrade by material blow-off, fissuring, and other related mechanisms. The rate and degree of erosion and corrosion occurring is directly dependent on the combined effects of the heating and cooling rates, temperature peak, gases and particulates present, peak pressures, and the cycles of combustion to which the surface has been subjected. Due to the complexity and severe environment in which the erosion/corrosion phenomena occur, little experimental data are available for use in numerical code development work.

To provide data for modeling the fundamental mechanisms of erosion/corrosion, an approach using high energy pulsed laser deposition on various samples at differing levels of energy and in different atmospheres and pressures was considered. This relatively inexpensive method of testing can produce many of the relevant phenomena present by subjecting the sample to laser deposition through a transparent window of a pressure vessel container. The environment and pressure of the vessel can be easily changed and monitored

to give desired test conditions. These tests would induce highly transient temperatures with possible melting and vaporization as well as the corresponding thermal stresses and chemical reactions at the specimen surface.

The purpose of this segment of the study was to evaluate a thin metal disk sample subjected to laser energy deposition as a suitable specimen geometry for providing usable data for the development of erosion/corrosion models to be used in numerical analysis.^{1,2} The transient temperature, strain, and stress were measured using conventional transducers and the corresponding specimen surface degradation was studied. The transient response results were then compared with the predictions of a finite element code (DTVIS2) where the specimen was subjected to a transient energy flux input.

LASER-MATERIAL INTERACTION

Laser energy deposition will produce a thermal compressive stress on the deposition side of the disk sample. That is, the sudden heating causes the metal surface to want to expand but it is confined by surrounding unheated metal. At high laser pulse energies, specimen melt, vaporization, and momentum transfer due to the resulting blow-off are known to occur.^{3,4}

In particular, earlier work has shown that compressive stress waves are induced in the sample when subjected to a Q-pulsed laser deposition with a pulse duration of about 30 nsec. Response to a much longer normal mode pulse (about 600 μ sec) has not been as thoroughly studied but it would be expected to be more quasi-static in nature. Certainly, considerably more energy is available in the normal pulse mode of operation.

The surface degradation due to laser deposition will depend on the flux intensity, absorptivity of the surface, and the specimen environment. A range of flux intensities can be achieved by focusing or expanding the laser beam and by changing the laser beam energy. Successive depositions can be easily accomplished using repeated pulsing of the laser. As would be expected, increasing the pulse energy and the number of depositions will result in a corresponding increase in specimen surface damage. The laser-induced transient heating undertaken on various samples at suitable pressures and gaseous environments should provide meaningful data for computer model development.

TRANSIENT HEATING OF A THIN DISK

When one side of a thin disk specimen is suddenly heated, the induced compressive thermal stress causes an outward cupping of the disk. The

opposite cooler side, curved inward, is correspondingly subjected to an initial compressive strain. As heat flows through the disk thickness and radially, a tensile thermal strain will result throughout. A strain gage mounted on the back side of the disk specimen will, therefore, respond to the suddenly increasing compressive strain which peaks at the end of the laser pulse. The gage output will then be decreasingly compressive and gradually go tensile as thermal equilibrium is established.

Whereas relatively slow surface heating would be expected to result in a quasi-static type response, the very rapid heating from a Q-pulsed laser configuration could excite vibrations in the disk corresponding to its fundamental natural frequency. A freely supported, circular disk will vibrate with a fundamental natural frequency in Hz given by⁵

$$f = \frac{1.45}{a^2} \sqrt{\frac{D}{\rho h}} \quad \text{Eq. (1)}$$

where a = sample radius

D = flexural rigidity, $Eh^3/12(1-\nu^2)$

h = sample thickness

ρ = mass density

and E , ν are Young's modulus and Poisson's ratio.

When vibratory modes are excited by the laser heating, a strain gage mounted at the center of the rear face will detect the gross compressive strain level with a superposed oscillating strain having a frequency equal to that given by Eq. 1.

The transient response of the disk sample will also be affected by the speed of heat transmission through the sample. This is determined by the magnitude of the diffusivity of the sample material given by the relation

$$\alpha = \frac{k}{\rho c} \quad \text{Eq. (2)}$$

where k = the conductivity

and c = the specific heat.

The time at which the back surface temperature has reached one-half the peak temperature amplitude can be shown to be

$$t_{1/2} = \frac{0.138 h^2}{\alpha} \quad \text{Eq. (3)}$$

A thermocouple attached at the back center of the specimen will give the temperature-time data from which $t_{1/2}$ can be measured and the value of determined.

EXPERIMENTAL ARRANGEMENT

Specimens for testing were fabricated from 4340 steel alloy and were 19 mm in diameter by 1.6 mm thick. Both surfaces were finished to a 600 grit. A neodymium-glass laser capable of a 10-15 Joule pulse in the Q-switched mode (30 nsec) and up to a 100 Joule pulse in the normal mode (600 μ sec) was used. The 19 mm beam was directed through a glass beam-splitter sending a small portion of the output to a photodiode to provide a trigger pulse for the recording oscilloscope. The main beam then passed through a converging lens, an aperture, and was deposited on the specimen. The specimen had either a thermocouple, strain gage, or stress transducer mounted on its rear face and the corresponding output was fed into an oscilloscope. A schematic diagram of the test facility is shown in Fig. 1 with the sample located at the extreme left.

SAMPLE PROPERTIES

Samples for all tests were fabricated from 4340 alloy steel in the form of disks 19 mm in diameter by 1.6 mm thick. Table properties for the samples were taken to be:

$$E = 200 \text{ GPa}$$

$$\nu = 0.285$$

$$\rho = 7840 \text{ kg/m}^3$$

$$k = 41.8 \frac{\text{W}}{\text{m}\cdot\text{K}}$$

$$c = 502 \frac{\text{J}}{\text{kg}\cdot\text{K}}$$

For these values, Equations 1-3 give the fundamental frequency for a freely supported plate and the half-time back surface thermal response to be,

$$f = 38,600 \text{ Hz}$$

$$\text{and } t_{1/2} = 33 \text{ msec.}$$

TEST PROCEDURE

The 4340 steel disk samples were prepared for testing by attaching an intrinsically mounted thermocouple (type E, chromel-constantan), a 1.6 mm gage length semiconductor strain gage, or an ultrasonic transducer wrung on the rear surface using vacuum grease. The transient signals from the transducers were recorded on an oscilloscope simultaneously with the photodiode output of the laser pulse (used as a timing fiducial). The prepared sample was then carefully aligned with the high energy laser beam path using a helium-neon alignment laser. A focusing lens and aperture were used to give the desired intensity and spot size. (See Figure 2).

Tests were conducted by subjecting the sample to either a normal mode pulse of up to 100 Joules and 600 μ sec duration or a Q-pulse of up to 15 Joules and 30 nsec duration. The sample was found to absorb only 20%-50% of the laser energy, the balance being reflected or blocked by the plume developed. Figure 3 shows a time integrated photograph of a normal mode deposition and illustrates the plume developed during the pulse. The sample was held in place by the three nylon supports shown. The laser beam does not appear in the photograph as the film is not sensitive to the 1.06 μ m wavelength of the neodymium glass laser.

Tests were numerically modeled using a finite element code (DTVIS2) capable of dynamic response calculations with a specified thermal flux input. The 48 element grid layout is shown in Fig. 4 with deposition indicated over the central area of the sample. The flux-time variation given in Fig. 4 is for a normal mode pulse.

RESULTS AND DISCUSSION

Table I gives typical data from selected experimental and computational runs.

TABLE I

Selected Experimental (EXP) and Computational (COMP) Results

<u>Run</u>	<u>Energy,J</u>	<u>Deposition Area</u>	<u>Rear $\Delta T,K$</u>	<u>$t_{1/2,ms}$</u>	<u>Rad Strain</u>	<u>Vib Freq</u>
EXP1	80	Full Face	21	33	-280 $\mu\epsilon$	-----
EXP2	80	Center 6.3 mm	103	34	-460 $\mu\epsilon$	-----
EXP3	80	Center 6.3 mm	---	---	-----	38000 Hz
EXP4	40	Center 6.3 mm	79	33	-370 $\mu\epsilon$	-----
EXP5	9 (Q)	Full Face	---	---	-----	38500 Hz
COMP1	40	Full Face	22	36	-195 $\mu\epsilon$	-----
COMP2	40	Center 6.3 mm	168	34	-----	-----

Of particular note from the table is the excellent agreement between analysis, experiment and numerical results for the half-time temperature rise on the back face of the sample (about 33 msec). The rear surface temperature rise for a 40 Joule computational run (22K) was about the same as found experimentally for an 80 Joule input pulse (21K). This would indicate about 50% of the total energy was coupled into the specimen -- the balance being lost through reflection, vaporization, and blowoff. For these same deposition energies, the finite element run predicted a considerably larger back face temperature rise. This was due to extensive surface vaporization not accounted for in the numerical theory. The two runs showing induced vibration were also in close agreement with the analytical calculation of fundamental plate frequency of 38,600 Hz. The vibration was excited by a normal mode, 80 Joule pulse in one run and by a Q-pulse mode, 9 Joule pulse in another run.

Rear surface thermocouple temperature measurements for normal mode deposition showed rapid temperature rise to a peak temperature occurring at about 80 msec. Subsequent decay to room temperature due to thermal equilibrium and heat transfer from the sample occurred by 2-3 seconds after pulse time. As would be expected, much higher peak temperature was reached for the focused beam. Temperature history is shown in Fig. 5 and compared to predictions of the finite element code. Quite good agreement is indicated with the $t_{1/2}$ values essentially the same. Successive shots on the same disk typically showed progressive increases in the peak temperature due to increased absorptivity. For example, tests at 80 Joules focused to a 6.3 mm diameter gave a 40 K temperature rise on the first shot and a 93 K rise on the tenth shot. This is due to oxidation of the deposition area as later testing (not reported here) in an inert or evacuated environment showed little change in absorptivity and the corresponding peak temperature rise between the first and tenth shot.

Strain histories were recorded for both 600 μ sec and 30 nsec pulses. The response to the focused normal mode pulse showed an immediate compressive strain which peaked shortly after the end of the laser pulse (about 1 msec) and then decayed to zero strain as temperature equilibrium was reached. However, in all cases the gage output returned compressive rather than going tensile as expected from the final thermoelastic tensile strain. This result was apparently due to thermal effects on the semiconductor strain gage as the higher temperatures reached the back face. The computer code predicted the expected strain history with initial compressive strain followed by decay and *a subsequent tensile strain. The deformed shape history for the disk subjected*

to a central flux with energy of 40 Joules and duration of 600 μ sec is shown in Fig. 6. The series of disk profiles show a maximum cupping shape at 600 μ sec with the disk nearly flat again by two seconds.

Although plate vibrations were not readily evident for normal mode tests, appropriate signal amplification and low frequency filtering produced a superposed high frequency signal of about 38,000 Hz - the fundamental natural frequency of the plate. Similar testing in the Q-switched mode excited strong vibration at the fundamental frequency. This is illustrated in Fig. 7 at two sweep rates with the expanded rates given at the beginning (A) and at 540 μ sec after deposition (B). Fig. 7A shows a superposed higher mode of vibration present. This higher mode has damped out by the time of the Fig. 7B trace.

Three types of piezoelectric stress gages were mounted to the back face of the sample by wringing them on, using vacuum grease. The configuration was then subjected to a 40 Joule, 600 μ sec pulse (see Fig. 8) and the output recorded. Although ultrasonic transducers in general do not give a true history of the actual transient stress, all three transducers used indicated a compressive stress state generated during the laser pulse duration. The trace data for a one-inch diameter, five MHz commercial transducer is shown in Fig. 9.

CONCLUSIONS

The general dynamic behavior of a thin disk subjected to a laser energy deposition pulse can be described in terms of its thermal and mechanical response. The thermal response can be accurately predicted using an analytical half-time temperature relation or a finite element thermoelastic code. Strain gage response is valid until heat transmission through the sample thickness affects the gage output. Laser deposition can excite the fundamental mode of plate vibration - especially when subjected to a Q-switched pulse. With the dynamic response of the thin disk reasonably well understood, this sample configuration should be a suitable form for erosion/corrosion testing using laser energy disposition.

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Fig. 1. Schematic diagram for pulsed laser deposition experiments.

Fig. 2. Time-integrated photo showing plume.

Fig. 3. Specimen configuration for laser deposition experiments.

Fig. 4. Finite element mesh showing normal mode thermal flux.

Fig. 5. Back surface temperature history comparing experimental measurements with finite element prediction.

Fig. 6. Magnified deformed shape histories predicted by finite element code.

Fig. 7. Disk back-surface strain response to Q-switched laser deposition on full face of specimen.

Fig. 8. Stress gage test configuration.

Fig. 9. Signal from piezoelectric ultrasonic stress gage resulting from normal mode laser deposition.