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APPLICATIONS OF PULSED LASER INDUCED STRESS WAVES

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APPLICATIONS OF PULSED LASER INDUCED STRESS WAVES

ABSTRACT

Very short duration stress waves generated by rapid energy deposition from a Q-switched ruby laser were used both to evaluate material properties by the Reynolds method and as a signal source for flaw detection. Through a comparatively simple arrangement, dilatation and shear velocities were experimentally determined for ten materials and values were found to compare favorably with corresponding ultrasonic test measurements. Detection and location of holes drilled in aluminum plates were easily accomplished for hole sizes to 1/16-in. diam. An attempt to model the energy deposition stress wave phenomenon by finite elements gave reasonable low frequency information but did not provide the superposed high frequency stresses found in the experimental results.

INTRODUCTION

Since the advent of the pulsed laser in the early 1960's, a number of investigators have explored the various experimental situations in which stress waves are generated by very rapid energy deposition. The deposition of heat energy in a material results in an unbalanced stress state as the heated material wants to expand but is initially restrained by its own inertia. This stress gradient then begins to propagate through the material.

In the late 1960's Percival¹⁻³ reported on a rather extensive study of thermally generated stress waves in long, thin aluminum rods with an absorbing glass rod segment bonded to one end. He found excessive dispersion and explained the experimental results in terms of the higher modes of the Pochhammer-Chree solution as well as a one-dimensional solution to Love's modified wave equation. The latter showed excellent agreement with the low-frequency response of the rod but did not predict either high frequency stress signals or the arrival of stresses traveling at dilatational velocity, both of which were found in the experimental results. Percival later applied this study directly, using the Reynolds method, to evaluate elastic properties of 2024 aluminum at elevated temperatures.⁴

Our study further investigates the phenomenon of stress wave initiation by energy deposition. We repeated Percival's basic experiment with a higher frequency response oscilloscope (225 to 500 MHz) and with the more sensitive PZT crystal transducer. Then we extended the experiment to 1/2-in.-diam bars using the full energy output of a 1 to 2 J ruby laser. We devised a simple setup for elastic property measurements

using the Reynolds method and tested ten materials. The results were compared with those obtained on samples of the same specimen by the conventional ultrasonic technique using the transmitter-receiver approach.

We conducted similar experiments on thick plates using a 30-MHz ultrasonic receiver to record stress information induced by laser energy deposition on the plate. The possibility of using the laser induced stress wave for flaw detection was demonstrated by recording stress echos off holes drilled in the plate. This approach eliminates the need for coupling through water and provides a means of inducing a very short stress pulse into a body with an irregular shaped surface.

This report includes a summary of our effort to model the laser energy deposition phenomenon with a finite element approach. We modified an existing code, DTVIS2, to incorporate the energy deposition as an exponentially decaying temperature in the body at time zero.

PULSED RUBY LASER FACILITY

The pulsed ruby laser used in our experiments consists of a 6 in. long, 1/2-in.-diam ruby rod with a Brewster angle cut on each end. The lasing cavity is composed of a 99% reflective rear mirror, a 50% reflective output mirror and a Korad KQS2 Pockels Cell for Q switching.* The ruby rod is air cooled with chilled air and is optically pumped with a MKV, 5 kV capacitor bank. A 10 mW He-Ne laser is used in optical alignment. The laser energy range is 0.1 to 2.0 J/cm², with ~1.5 J/cm² the typical output. Figure 1 shows a typical output pulse recorded with a photodiode. The duration at half peak amplitude is ~35 nsec.

The Tektronix 7904 oscilloscope was used to record the response of the various stress transducers used in this study. This scope has a maximum frequency response of 500 MHz, using a 7A19 vertical amplifier with a 50-Ω input impedance. In addition, a dual trace 7A26 vertical amplifier can be used to provide a 1-MΩ input with a 225-MHz frequency response. We calibrated the oscilloscope by using the internal calibrator for the vertical amplifiers and a Tektronix time-mark generator for the horizontal sweep rate and delaying sweep. Figure 2 illustrates the pulsed ruby laser and its associated equipment as used in our study.

ENERGY DEPOSITION ON ALUMINUM ROD WITH AND WITHOUT ABSORBER

We chose a configuration similar to Percival's as a convenient starting point. A PZT transducer (1/8-in. diam × 0.008 in. thick, 10 MHz) was sandwiched between two

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Atomic Energy Commission to the exclusion of others that may be suitable.

Fig. 1. Typical photodiode output of ruby laser pulse (20 nsec/div).

Fig. 2. Schematic layout of pulsed laser system.

2.8-in. 6061-T6 aluminum rods and bonded in place with epoxy adhesive. A 1/8-in. diam $\times$ 0.5 in. didymium glass absorbing piece was bonded to the front end of the rod-transducer bar. Leads were attached to the aluminum rods on each side of the PZT crystal and connected to the Tektronix 7904 oscilloscope (using the 7A26 vertical amplifier) through $\sim$ 2 ft of RG-58 cable. Approximate stress levels, where indicated, were determined by a one-dimensional stress calibration using strain gages and a stress pulse induced by ball impact on the rod. The value of the piezoelectric constant for PZT was determined and used in subsequent transducers without direct calibration to a strain gage output.^{5,6} The laser induced stresses certainly are not one-dimensional, but we believe that the calibration leads to a rough approximation of the stress level present.

The composite bar configuration used is shown in Fig. 3. A beam-splitter placed in front of the bar provides light to a photodiode for externally triggering the scope at precisely the time of energy deposition. Oscilloscope traces of the transducer response are shown in Fig. 4 at sweep rates of 1 μ sec/div and 500 nsec/div. Our data agree very well with Percival's, once we note that our transducer polarity is reversed and that our PZT has greater sensitivity than Percival's quartz, producing greater signal strength. However, note that the impedance match of PZT with aluminum is not as good as with quartz.

The arrival of "bundles" of high frequency energy superposed on the low frequency signal is due to the arrival of stress traveling at the dilatational velocity and followed by succeeding orders of shear mode conversions. This was noted by Percival and is explained in detail by Reynolds.⁷ Trace B in Fig. 4 indicates that the arrival times of the first and second pulse can be quite accurately measured. With the Reynolds method these two arrival times can be used to determine dilatational and shear wave velocities and resulting elastic constants. See Ref. 4 for an application of this approach to mechanical properties at high temperatures.

When the absorbing glass piece is removed and the laser pulse is applied directly to the end of the aluminum rod, the transducer response is surprisingly similar to the previous case (see Fig. 5). However, the high frequency signals are much larger in proportion to the amplitude of the low frequency information.

Since the pulsed laser generates extremely high frequency signals, a high bandwidth instrument is necessary to record the signal accurately without significant attenuation and phase shift errors. By conducting the same experiment but recording the transducer output with a 7A19 vertical amplifier (50- Ω input), we found the trace to record the high frequency signal but filter out the low frequency information (see Fig. 6). We concluded that the transducer did not have sufficient power to drive the 50- Ω input amplifier at the low frequency. The high frequency signals appear identical in the two cases. A 10-M Ω probe used with the 7A26 amplifier produced no measurable difference from the 1-M Ω data.

Fig. 3. Composite bar arrangement (1/8-in. diam).

A. Sweep rate: 1 μ sec/div.

B. Sweep rate: 500 nsec/div.

Fig. 4. Transducer response to energy deposition in absorbing rod. Sweep delayed by 13 μ sec in each case.

Fig. 5. Bar response to energy deposition on aluminum end (10 μ sec delay). Input impedance is 1 M Ω .

Fig. 6. Transducer output for 50- Ω input impedance (10 μ sec delay).

ELASTIC CONSTANTS BY THE REYNOLDS METHOD

The elastic constants of a material can be easily characterized by using the conventional ultrasonic pulse technique. However, the elastic stress levels at which those measurements are taken are extremely low (strains on order of 10^{-12}), so there may arise some question as to the validity at the higher stress levels to which the material will actually be subjected. In addition, the ultrasonic technique is most suited to samples with large lateral dimensions compared to thickness and is not well adapted to long cylindrical specimens.

The basic approach of the ultrasonic technique is to induce a dilatational pulse in the sample with a thickness mode piezoelectric crystal transmitter (e.g., X-cut quartz), measure the dilatational velocity, V_D , induce a shear pulse with a shear mode piezoelectric crystal transmitter (e.g., ac-cut quartz), measure the shear velocity, V_S . The classical theory of isotropic elasticity shows that

$$V_S = \sqrt{\frac{\mu}{\rho}} \quad (1)$$

and

$$V_D = \sqrt{\frac{\lambda + 2\mu}{\rho}} = \sqrt{\frac{k + \frac{2}{3}\mu}{\rho}} = \sqrt{\frac{\mu}{\rho} \frac{4\mu - E}{3\mu - E}} = \sqrt{\frac{E}{\rho} \frac{1 - \nu}{(1 + \nu)(1 - 2\nu)}}, \quad (2)$$

where

- ρ —mass density of the sample
- μ —shear modulus
- E —Young's modulus
- k —bulk modulus
- ν —Poisson's ratio
- λ —Lame's constant.

As only two of the elastic constants are independent, the evaluation of V_D and V_S will lead to any of the five elastic constants desired.

Reynolds pointed out the possibility of evaluating V_D and V_S from just one experiment using specimens of cylindrical shape.⁷ This can be done by accounting for one mode conversion of a dilatational wave to a shear wave and back to a dilatational wave before striking the receiving transducer. These mode conversions arise from stress wave reflections at the cylindrical boundary of the rod. The slower traveling shear wave will result in a separation from the initial dilatational wave, provided the stress pulse is sufficiently short. Letting T be the transit time of a dilatational pulse through the rod and Δt the mode converted pulse separation from the dilatational pulse, it can be shown that

$$\Delta t = \frac{D}{V_S V_D} (V_D^2 - V_S^2)^{1/2} \quad (3)$$

and

$$V_D = \frac{L}{T}, \quad (4)$$

so the shear velocity can be found from the expression

$$V_S = \frac{D V_D}{D^2 + V_D^2 \Delta t^2}. \quad (5)$$

The sample length and diameter are given by L and D, respectively. By defining the velocity ratio r as

$$r \equiv \frac{V_D}{V_S}, \quad (6)$$

the five elastic constants are found from

$$\mu = \rho V_S^2 \quad (7)$$

$$\nu = \frac{1 - \frac{1}{2}r^2}{1 - r^2} \quad (8)$$

$$E = \rho V_S^2 \left(\frac{4 - 3r^2}{1 - r^2} \right) \quad (9)$$

$$k = \rho V_S^2 \left(r^2 - \frac{4}{3} \right) \quad (10)$$

$$\lambda = \rho V_S^2 (r^2 - 2). \quad (11)$$

Stress pulses induced by laser energy deposition appear to be ideally suited for use with the Reynolds method because of their relatively high amplitude and extremely short duration. By using the delayed sweep of the oscilloscope and calibrating it and the sweep rate with an accurate time-mark generator, we obtained precise measurements of T and Δt for the bare aluminum rod, as shown in Fig. 7.

Applying Eqs. (3)-(11) for the aluminum bar where D = 0.125 in. and L = 2.785 in. gives the following wave velocities and elastic constants:

$$V_D = 249,440 \text{ in./sec} \quad V_S = 123,223 \text{ in./sec}$$

$$E = 10.28 \times 10^6 \text{ psi}$$

$$\nu = 0.339$$

Fig. 7. Evaluation of T , Δt for elastic constant determination.

$$\begin{aligned}\mu &= 3.84 \times 10^6 \text{ psi} \\ k &= 10.62 \times 10^6 \text{ psi} \\ \lambda &= 8.06 \times 10^6 \text{ psi.}\end{aligned}$$

SYSTEM DESIGN FOR THE REYNOLDS METHOD APPLICATION

A 1/2-in.-diam 6061-T6 aluminum rod was fabricated with a sandwiched PZT 5-MHz transducer, as shown in Fig. 8. The rod was subjected to a laser pulse and the transducer output recorded on the scope. The backup bar permits a reflection-free recording time of $\sim 8 \mu\text{sec}$. The trace results are shown in Fig. 9. They indicate a definite ringdown of the transducer output at a frequency slightly above its 5-MHz natural frequency, which might be expected because of the increased effective stiffness caused by the bonding.⁶ The ringdown is the result of the large impedance mismatch between the aluminum and PZT and the very short wavelengths produced by the energy deposition. A quartz transducer would give a good impedance match, but its low sensitivity would give a low signal-to-noise ratio. Regardless of the transducer ringdown, the trace does clearly show the arrival of the dilatation pulse and two mode converted pulses. We also found that aperturing the pulse to the center 1/8-in. diam resulted in essentially the same waveform but at a greatly reduced amplitude.

The 1/2-in.-diam sample is convenient and it shows clear arrival and separation of the dilatational and mode converted pulses. However, because of the ringdown at the 5-MHz frequency, we selected an ultrasonic transducer that provides higher frequency response and eliminates the inconvenience of bonding and lead wire attachment required in the prior configurations. This 30-MHz transducer is similar to the sandwiched crystal except that the backup bar material is acoustically matched to the 3/8-in.-diam lithium-sulfate crystal used. It is a highly attenuating material that damps out stress waves entering it, resulting in little reflection to the transducer. The unit is self-contained in that the leads to the front and back side of the crystal are contained in the housing. We found the voltage output for this transducer to be positive for a compressive stress. The crystal is protected by a very thin (2 to 5 mil) lens of clear epoxy on the face of the unit. The transducer is held in a vertical position with the 1/2-in.-diam sample wrung to it with a small amount of vacuum grease. A mirror is positioned to deflect the horizontal laser beam onto the sample end as shown in Fig. 10.

As before, the scope is triggered with the photodiode output and the transducer signal recorded. A 7D11 digital delay amplifier was used in the Tektronix 7904 oscilloscope to provide very accurate delayed sweep timing (calibration to 2 to 5 nsec), with the amount of delay appearing as a digital readout in the upper right-center of the scope trace. Both the digital delay and sweep rate can be conveniently and accurately calibrated with a time-mark generator. However, we found that the stress pulse travel time through the vacuum grease and epoxy protective lens of the transducer had a

Fig. 8. Composite bar, 1/2-in. diam.

Fig. 9. Transducer response for 1/2-in.-diam bar (sweep delay 17.0 μ sec).

Fig. 10. Test configuration for the Reynolds method using energy deposition.

measurable influence for short specimens. The time of travel through these interface materials was evaluated by wringing a 0.001-in. aluminum mil stock piece to the transducer with the vacuum grease and recording the arrival time for the signal produced by the laser pulse in the usual manner. In addition, a greatly reduced energy pulse was applied directly to the crystal face through the transparent epoxy lens and the signal arrival noted. The results of these two experiments are shown in Fig. 11; they indicate a transit time through the grease-epoxy interface of ~200 nsec. There is a transit time of 4 nsec through the mil stock; we expect that the scope is triggered some time before the laser pulse intensity becomes large enough to cause a measurable stress level. Making these adjustments reduced the recorded time of dilatation arrival by 180 nsec.

For accurate measurement of the dilatation arrival time, T , and the first mode conversion delay time, Δt , it is desirable that the sample length be selected to allow arrival of these two pulses before any low frequency signal appears. If the low frequency information is assumed to travel at the rod wave velocity $V_o = \sqrt{E/\rho}$ or slower, the minimum specimen length L can be evaluated from the expression

$$\frac{L}{V_D} + \Delta t \leq \frac{L}{V_o}. \quad (12)$$

For a 1/2-in.-diam sample with approximate wave velocities of $V_D = 0.250$ in./ μ sec, $V_S = 0.125$ in./ μ sec, and $V_o = 0.200$ in./ μ sec, Eq. (3) gives $\Delta t \cong 3.5 \mu$ sec and the length is evaluated from Eq. (12) as $L \geq 3.5$ in.

ELASTIC CONSTANTS FOR TEN MATERIALS

The arrangement shown in Fig. 10 was used to evaluate elastic properties of ten 1/2-in.-diam samples of various lengths using laser energy deposition and the Reynolds method. A Fortran computer program (PROP) was written to calculate the wave velocities and five elastic constants in English and SI units. The listing is included in Appendix A with a sample output. The dilatational and shear wave velocities for the ten materials were also measured by the conventional ultrasonic method for comparison. These samples were 1/2 in. long and were taken from the same bar stock as the energy deposition samples. The trace data and resulting time of arrival, T (reduced by 180 nsec), and delay time, Δt , are shown in Fig. 12 for the ten materials. Table 1 gives a tabulation of the wave velocities and elastic constants E and ν found by this technique, along with the wave velocity information obtained from the conventional ultrasonic measurements. The density for each material was measured to four significant figures by the water immersion technique.

With the exception of brass, the ultrasonic and energy deposition velocity measurements agree very well, the majority of measurements being within 1%. The discrepancy in the brass velocity values of ~4% for V_D and 13% for V_S is probably due to the difficulty in obtaining good ultrasonic data for a specimen of 1/2-in. diam by 1/2 in.

a. Laser pulse applied directly to crystal face

b. Laser pulse applied to 0.001 in. aluminum

Fig. 11. Data for interface transit time correction.

6061 Aluminum
 $D = 0.4993$ in.
 $L = 4.499$ in.
 $T = 17.80 \mu\text{sec}$
 $\Delta t = 3.52 \mu\text{sec}$

1100 Aluminum
 $D = 0.5004$ in.
 $L = 2.997$ in.
 $T = 11.85 \mu\text{sec}$
 $\Delta t = 3.59 \mu\text{sec}$

1018 Steel
 $D = 0.4987$ in.
 $L = 4.495$ in.
 $T = 19.35 \mu\text{sec}$
 $\Delta t = 3.26 \mu\text{sec}$

304 SS
 $D = 0.4996$ in.
 $L = 4.494$ in.
 $T = 19.96 \mu\text{sec}$
 $\Delta t = 3.45 \mu\text{sec}$

Copper
 $D = 0.5016$ in.
 $L = 3.000$ in.
 $T = 16.05 \mu\text{sec}$
 $\Delta t = 4.98 \mu\text{sec}$

Brass
 $D = 0.5007$ in.
 $L = 4.498$ in.
 $T = 26.92 \mu\text{sec}$
 $\Delta t = 5.68 \mu\text{sec}$

Nickel
 $D = 0.4999$ in.
 $L = 2.998$ in.
 $T = 13.11 \mu\text{sec}$
 $\Delta t = 3.51 \mu\text{sec}$

Lucite
 $D = 0.5028$ in.
 $L = 1.996$ in.
 $T = 18.70 \mu\text{sec}$
 $\Delta t = 8.15 \mu\text{sec}$

Nylon
 $D = 0.5014$ in.
 $L = 1.998$ in.
 $T = 19.18 \mu\text{sec}$
 $\Delta t = 10.72 \mu\text{sec}$

Phenolic canvas
 $D = 0.5012$ in.
 $L = 1.999$ in.
 $T = 15.62 \mu\text{sec}$
 $\Delta t = 7.60 \mu\text{sec}$

Fig. 12. Trace data for time of arrival and delay time measurements.

Table 1. Wave velocities and elastic constants for ten materials.

Material	<u>Densities</u> g/cc	Ultrasonic data		Energy deposition data			ν
		V_D (in./ μ sec)	V_S (in./ μ sec)	V_D (in./ μ sec)	V_S (in./ μ sec)	E (10^6 psi)	
6061-T6 Aluminum	2.703	0.2510	0.1228	0.2528	0.1237	10.39	0.343
1100-F Aluminum	2.715	.2488	.1215	.2529	.1221	10.21	.348
1018 steel	7.846	.2314	.1280	.2323	.1278	30.76	.283
304 SS	7.873	.2228	.1208	.2252	.1218	28.26	.293
Copper, alloy 110	8.928	.1843	.0889	.1869	.0887	17.80	.355
Brass, alloy 360	8.493	.1746	.0898	.1671	.0780	13.15	.361
Nickel (Inco 200)	8.888	.2270	.1186	.2287	.1209	31.75	.306
Lucite	1.185	.1059	.0527	.1067	.0534	0.843	.333
Nylon 6	1.146	.1017	.0422	.1042	.0427	0.547	.399
Phenolic canvas	1.318	0.1108	0.0570	0.1280	0.0586	1.16	0.367

long. Although the shear velocity cannot be measured in the short specimen by energy deposition, the dilatational velocity can be easily determined. This measurement will give an indication of the repeatability of the energy deposition approach for different specimen lengths and might also indicate possible variations in material properties of the two samples. The trace data for the 1/2 in. long brass specimen are shown in Fig. 13.

Allowing for the 180-nsec correction, T is found to be 3.00 sec, resulting in $V_D = 0.1660$ in./ μ sec, which agrees closely with the corresponding value for the 4.5-in. specimen of 0.1671 in./ μ sec.

We anticipated the variations found in the nonmetal data because of the attenuation and dispersion occurring in the pulse shape as it propagates. In energy deposition tests the time measurements were made at the initial arrival of the pulse while the ultrasonic measurements were made at the peaks or 50% level. Some samples were blacked with a felt pen on the deposition surface to increase the pulse amplitudes, but this procedure had no effect on the time measurements. In addition, it was necessary to apply a piece of mil stock to the end of the Lucite to provide an absorbing layer.

ERROR ANALYSIS FOR THE REYNOLDS METHOD BY ENERGY DEPOSITION

The application of Reynolds method using laser energy deposition to generate the stress pulse requires accurate measurement of D , L , ρ , T , and Δt . The combined

Fig. 13. Dilatational velocity data for
1/2 in. long brass. $L = 0.4981$ in.

effect of the uncertainty in each individual measurement of the five quantities can be analyzed statistically to give an expected bound on the possible resulting error in the calculated elastic constants. Letting the uncertainties in the measurements be w_L , w_D , w_ρ , w_T , and $w_{\Delta t}$, then the uncertainty in the calculated Young's modulus, w_E , from all the w_i measurements, is

$$w_E = \sqrt{\left(\frac{\partial E}{\partial D} w_D\right)^2 + \left(\frac{\partial E}{\partial L} w_L\right)^2 + \left(\frac{\partial E}{\partial \rho} w_\rho\right)^2 + \left(\frac{\partial E}{\partial T} w_T\right)^2 + \left(\frac{\partial E}{\partial \Delta t} w_{\Delta t}\right)^2} \quad (13)$$

A similar expression can be written for Poisson's ratio. The following nominal values for an aluminum sample with estimates of the accuracy of each measurement will be used as a reference:

$$D = 0.500 \text{ in.} \pm 0.0005 \text{ in.}$$

$$L = 4.50 \text{ in.} \pm 0.005 \text{ in.}$$

$$\rho = 0.000253 \frac{\text{lb-sec}^2}{\text{in.}^4} \pm 0.000005 \frac{\text{lb-sec}^2}{\text{in.}^4}$$

$$T = 18.13 \text{ } \mu\text{sec} \pm 0.2 \text{ } \mu\text{sec}$$

$$\Delta t = 3.56 \text{ } \mu\text{sec} \pm 0.036 \text{ } \mu\text{sec}$$

Application of Eq. (13) and a like expression for Poisson's ratio gives the resulting uncertainties in the elastic constants of

$$w_E = 1.56\%$$

$$w_\nu = 1.42\%$$

These are certainly reasonable and could be reduced somewhat by tightening the limits on D , L , and ρ . The uncertainties on T and Δt of $\sim 1\%$ are about as good as can realistically be expected from oscilloscope measurements.

FLAW DETECTION WITH LASER INDUCED STRESS WAVES

Stress pulses were induced in 1 in. and 2 in. thick aluminum plates and monitored with the 30-MHz ultrasonic transducer attached to the back surface with vacuum grease. The transducer was aligned with the laser beam and positioned at least one plate thickness from the edge, as shown in Fig. 14. Two holes of 1/8-in. diam and 1/16-in. diam were drilled at the midthickness as shown. The oscilloscope was triggered with the photodiode and a delayed sweep used so that the first stress pulse

Fig. 14. Aluminum plate (1 in. thick) flaw detection arrangement.

arrival came near the beginning of the trace. We made successive tests with the transducer located at a no-flaw position, aligned with the 1/8-in.-diam hole, and aligned with the 1/16-in.-diam hole. The corresponding oscilloscope traces appear in Fig. 15.

The echo from the hole back to the front surface and return to the transducer on the back surface is clearly defined for both the 1/8-in.- and 1/16-in.-diam holes. Assuming a dilatation velocity of 0.250 in./ μ sec, the flaw location is calculated to be at 0.43 in. and 0.46 in. from the front surface for the 1/8-in.- and 1/16-in.-diam holes, respectively. The precise hole position at the transducer location was not measured, but these values are in very close agreement with the physical location of the front surface of the respective holes.

Similar experiments were conducted on a 2 in. thick aluminum plate with 1/4-in.-diam holes drilled parallel to the plate surface at various depths. For a hole located 0.54 in. from the front surface, the transducer was placed ~2 in. from the plate edge, aligned with the laser beam, and positioned relative to the hole as shown in Fig. 16.

Figure 17 contains the scope traces for the two positions. Position No. 1 clearly shows a first and second echo off the hole. The echo time of 3.5 μ sec in each case locates the hole front edge at ~0.44 in. from the front surface of the plate. An echo is just barely visible for Position No. 2 and comes at a time equivalent to 0.55 in., which seems reasonable with the transducer located farther from the hole. We think the signal appearing during the tenth centimeter of trace results from slight reflection from the transducer backing.

Holes were also drilled 0.94 in. and 1.53 in. from the front surface and tests conducted with the laser transducer setup aligned through the hole. The transducer response for these situations is shown in Fig. 18. Trace A shows the echo arriving at a time lag of 6.8 μ sec, correctly locating the hole front edge at ~0.85 in. from the front surface. The results of trace B do not clearly depict any flaw echos for the hole position near the back surface, although there appear to be low amplitude signals at ~4 and 12 μ sec after the initial pulse. These are the approximate times for echo arrival of the back and front sides of the hole, respectively.

NUMERICAL ANALYSIS OF ENERGY DEPOSITION ON A BAR

We tried to model the energy deposition on an absorbing 1/8-in.-diam aluminum rod using the finite element code DTVIS2. The code was modified slightly to incorporate an initial strain gradient from an exponentially decaying temperature suddenly applied at time zero. It is desirable to use a square mesh in wave propagation problems, so extremely fine axial zones are not possible in the long, thin rod without exceeding the limitations of the code. Also, the very rapid temperature decay in the didymium would indicate the need for close axial spacing. It would therefore appear very difficult to obtain an accurate finite element solution to the problem under consideration.

Fig. 15. Trace data for flaw location in 1 in. aluminum plate.

Fig. 16. Transducer location in 2-in. aluminum plate.

A. Position #1

B. Position #2

Fig. 17. Trace data for flaw location in 2-in. aluminum plate.

A. Hole position 0.94 in.

B. Hole position 1.53 in.

Fig. 18. Transducer data for holes at 0.94 in. and 1.53 in. from front surface of 2-in. aluminum plate.

If the code is applied to a simple pressure pulse of the form $A \sin^2 pt$, approximately equivalent to a ball impact, acting on the end of the rod, the solution for the axial stress is as shown in Fig. 19. For this relatively long duration pulse with only low order harmonics present, the solution shows the pulse traveling at the rod velocity (0.250 in./sec), without attenuation or dispersion, as would be expected.

The solution for the energy deposition problem using the same zone is shown in Fig. 20. This result for axial stress is very similar to Percival's solution for Love's modified wave equation and shows only the low frequency response found experimentally without any indication of the superposed higher frequency bursts of energy.

We reduced the zone dimensions to a 3×216 mesh, resulting in the axial stress output given in Fig. 21. Little significant change was found except for the appearance of numerical noise following the arrival of the low frequency signal. We tried additional mesh configurations and variations in the finite element parameters, but a solution depicting the dilatation arrival and higher frequency mode conversion information was not found.

SUMMARY AND CONCLUSIONS

This exploratory study has demonstrated that very short stress pulses of moderate amplitude can be easily induced in materials by direct laser energy deposition. Ultrasonic transducer data indicate a stress pulse duration of <100 nsec, equivalent to a pulse length of ~ 0.025 in. in aluminum. Such short stress pulses are not possible by mechanical means.

We obtained accurate measurement of the dilatation and shear wave velocities and calculated the elastic constants for ten materials using laser energy deposition and the Reynolds method. This technique is especially suited for long cylindrical specimens and provides a moderate stress level for testing. In contrast, data from conventional ultrasonic tests on cylindrical samples, especially for diameters <1 in., are difficult to interpret, and the stress level is several orders of magnitude smaller.

The use of the laser induced pulse for flaw detection appears promising. The deposition area could easily be expanded and a number of receivers used or the samples scanned for the location of flaw echoes from the laser induced stress pulse. This approach does not require water coupling of the transmitter receiver and the sample.

In future work techniques for coupling more of the laser energy into the sample are needed for possible studies in plasticity, strain rate effects, and fracture. The actual cause of laser induced stress waves is still not fully understood and the effect on the resulting stress pulse of the deposition depth, the type of material, and the noise occurring at time of deposition all need further study.

Transducer development is also needed to measure the actual induced stress pulse without ringdown, pulse attenuation, or phase lag while still providing sufficient monitoring time.

Fig. 19. DTVIS2 code solution to A $\sin^2$ pt pressure pulse of 10 μsec duration acting on end of a 1/8 in. $\times$ 5 in. long rod, 1 $\times$ 80 mesh. Element 40 is located 2.5 in. from the input end of the bar.

Fig. 20. DTVIS2 code solution to energy deposition, 1/8 in. $\times$ 4-1/2 in. long rod, 1 $\times$ 72 mesh.

Fig. 21. DTVIS2 code solution to energy deposition, 1/8 in. $\times$ 4-1/2 in. long rod, 3 $\times$ 216 mesh. Element 552 is located on the outer radius at 2.2 in. from the input end of the bar.

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APPENDIX A
 FORTRAN LISTING FOR ELASTIC CONSTANTS
 BY LASER ENERGY DEPOSITION

```

1      PROGRAM PROP (TAPE59)
2      CALL CHANGE (5H+PROP)
3      WRITE (59,50)
4      50 FORMAT (// *TYPE: *// MATRL DESCRIPTION    DIAMETER    LENGTH    D
ENSIT
5      1Y ARR TIME    DELTA T //
6      21H(.18X,2H)(.8X,2H)(.8X,2H)(.8X,2H)(.8X,1H) )
7      READ (59,100) MATL,DESCR,DIAM,TLEN,RHO,TIME,DELT
8      100 FORMAT (2A10,5F10.0)
9      WRITE (59,200)
10     200 FORMAT (/// *----- ELASTIC PROPERTIES BY PULSED LASER ENERG
Y DEP
11     10POSITION ----- *///)
12     WRITE (59,300) MATL,DESCR,DIAM,TLEN,RHO,TIME,DELT
13     300 FORMAT (* MATERIAL TESTED ----- * 2A10 //
14     1* MATERIAL DIAMETER, IN. ----- * F10.3 //
15     2* MATERIAL TEST LENGTH, IN. ----- * F10.3 //
16     3* MATERIAL MASS DENSITY, LB-SEC2/IN4 ---- * F10.7 //
17     4* DILATATION ARRIVAL TIME, MICROSEC ----- * F10.3 //
18     5* MODE CONV. DELAY TIME, MICROSEC ----- * F10.3 //
19     VELD = (TLEN/TIME)*1000000.
20     VELDS = VELD*.0254
21     VELS = DIAM*VELD/(SQRT(DIAM**2+VELD**2*DELT**2/1.E12))
22     VELSS = VELS*.0254
23     R = VELD/VELS
24     XMU = RHO*VELS**2
25     XMUS = XMU*6895.
26     XNU = (1. -R**2/2.)/(1.-R**2)
27     E = RHO*VELS**2*(4.-3.*R**2)/(1.-R**2)
28     ES = E*6895.
29     XK = RHO*VELS**2*(R**2-4./3.)
30     XKS = XK*6895.
31     XLAMB = RHO*VELS**2*(R**2-2.)
32     XLAMBS = XLAMB*6895.
33     EK = ES*1.E-8
34     XNUK = XNUS*1.E-8
35     XMUK = XMUS*1.E-8
36     XKK = XKS*1.E-8
37     XLAMBK = XLAMBS*1.E-8
38     VELR = SQRT(E/RHO)
39     VELRS = VELR*.0254
40     WRITE (59,400) VELD,VELDS,VELS,VELSS,R,R,VELR,VELRS
41     400 FORMAT (* DILATATION VELOCITY -- *F10.0* IN/SEC *F10.0* M/SE
C*//
42     1* SHEAR VELOCITY ----- *F10.0* IN/SEC *F10.0* M/SEC*//
43     2* VELOCITY RATIO ----- *F10.4* *F10.4 //
44     3* ROD VELOCITY ----- *F10.0* IN/SEC *F10.0* M/SEC*////////)
45     WRITE (59,500)
46     500 FORMAT (*          ENGLISH UNITS          SI UNITS
47     1 KILOBARS *///)
48     WRITE (59,600) E,ES,EK,XNU,XNU,XNU,XMU,XMUS,XMUK,XK,XKS,XKK,
49     1XLAMB,XLAMBS,XLAMBK
50     600 FORMAT (* YOUNGS MODULUS *E10.3* PSI *E10.3* PA *
F7.1*
51     1 KB*//
52     2* POISSONS RATIO *F10.3* *F10.3* * F7.3//
53     3* SHEAR MODULUS *E10.3* PSI *E10.3* PA * F7.1* KB
*//
54     4* BULK MODULUS *E10.3* PSI *E10.3* PA * F7.1* KB
*//
55     5* LAME LAMBDA *E10.3* PSI *E10.3* PA * F7.1* KB
*//)
56     CALL EXIT
57     END

```

SAMPLE OUTPUT OF PROP-

PROP / 1 1

TYPE:

MATRL DESCRIPTION	DIAMETER	LENGTH	DENSITY	ARR TIME	DELTA T
ALUM 6061-T6	.4993	4.499	.00025294	17.80	3.52

----- ELASTIC PROPERTIES BY PULSED LASER ENERGY DEPOSITION -----

MATERIAL TESTED -----	ALUM 6061-T6
MATERIAL DIAMETER, IN. -----	.499
MATERIAL TEST LENGTH, IN. -----	4.499
MATERIAL MASS DENSITY, LB-SEC2/IN4 ----	.0002529
DILATATION ARRIVAL TIME, MICROSEC -----	17.800
MODE CONV. DELAY TIME, MICROSEC -----	3.520

DILATATION VELOCITY --	252753 IN/SEC	6420 M/SEC
SHEAR VELOCITY -----	123698 IN/SEC	3142 M/SEC
VELOCITY RATIO -----	2.0433	2.0433
ROD VELOCITY -----	202693 IN/SEC	5148 M/SEC

	ENGLISH UNITS	SI UNITS	KILOBARS
YOUNGS MODULUS	1.039E+07 PSI	7.165E+10 PA	716.5 KB
POISSONS RATIO	.343	.343	.343
SHEAR MODULUS	3.870E+06 PSI	2.669E+10 PA	266.9 KB
BULK MODULUS	1.100E+07 PSI	7.583E+10 PA	758.3 KB
LAME LAMBDA	8.418E+06 PSI	5.804E+10 PA	580.4 KB

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