

Laser Induced Thin Film Spallation

Junlan Wang, Nancy R. Sottos, Richard L. Weaver

Department of Theoretical and Applied Mechanics
University of Illinois at Urbana-Champaign
Urbana, IL 61801, USA

ABSTRACT : We report studies of the generation of elastic waves by a pulsed laser and the associated spalling of the thin surface films by the corresponding high stresses. Numerical and analytic results from a thermo-elastic model for the stress generation are presented. Qualitative observations of spallation as a function of substrate thickness, film thickness, laser energy, and various parameters governing the source are made. Surface displacement due to the stress wave is measured by optical interferometry and used to infer the stresses on the film interface. The work is conducted with a view towards testing of thin film adhesion under a variety of mixed mode dynamic loading conditions.

1 INTRODUCTION

Thin films are crucial components in a wide range of multilayer microelectronic and optical devices. They are also desirable candidates for micro-actuators in MEMs due to their high energy densities and strain capabilities. The size scales and dissimilar nature of the constituents present great challenges in regard to thermomechanical integrity and reliability (Evans and Hutchinson, 1995). Large residual stresses are induced in films during fabrication, which then have a significant impact on mechanical properties and performance. Under appropriate conditions the residual stress can cause the film to decohere, crack, or buckle away from the substrate. A particular challenge is the design and implementation of test procedures that measure thin film interface properties.

Several practical techniques for the measurement of thin film adhesion have been described in the literature, of which the most common are the scratch, peel, pull and blister tests. The first quantitative use of the scratch test was reported by Heavens (1950) and Weaver (1975). Later, this method was used to calculate adhesion energies by Langier (1984) and Hull *et al.* (1987). In the scratch test, a conical diamond indenter is driven into a film sample until a load drop occurs, indicating delamination. The scratch test is simple but the data are difficult to interpret (Hull *et al.* 1987). In the peel test, first used by Strong (1935), an adhesive tape is applied directly to the film. A force is applied to the tape and used to peel off the film from the substrate. This test is only suitable for

films in which the adhesion to the substrate is weaker than to the tape. For cases where the adhesion is considerably higher, the pull test (Jacobsen, 1976; Hull *et. al.*, 1987) is often used. In a pull test, a stud is attached to the film using a strong adhesive. The perpendicular force required to remove the stud is measured and then divided by the area of removed film to calculate the adhesive strength. A major limitation of pull test is that the maximum measurable strength cannot exceed the maximum bonding strength of available adhesives. Another technique is the blister test, in which a film layer is deposited on a rigid flat substrate with a center perforation. A pressurizing fluid is injected through the perforation creating a blister and causing a progressive debonding of the film/substrate interface at a critical pressure (Gent and Lewandowski 1987; Chu *et. al.*, 1992). During all these tests, scratch, peel, pull and blister, the interface is subjected to very high stress levels and consequent inhomogeneous deformations. Large amounts of plastic deformation can result (especially in the peel test) and dominate the behavior during the test (Thouless, 1994). The stress fields are difficult to analyze and the resulting adhesion measurements tend to be qualitative and comparative.

A novel laser spallation technique was first introduced by Vossen (1978) which loaded the film using stress waves produced by short laser pulses as developed by Ready (1965), Anderholm (1970), Peercy (1970), Lang (1974) and Fox (1974). This technique involved impinging a high-energy laser pulse (pulse width of nanosecond duration) from a Q-switched laser (1064 μm wavelength) onto a thin absorbing layer confined between a plate and the back surface of the substrate. Upon absorbing the laser energy, the sudden expansion of the confined layer generated a compressive stress wave directed towards the front surface of the substrate. Yang (1974) used an x-cut quartz crystal to measure the stress at the front surface of the substrate.

Gupta and co-workers (1992) adopted Yang's idea to measure the adhesion of a thin film deposited on the front surface of the substrate. The reflection of the compressive wave packet from the surface of the testing film generated a tensile pulse which led to the spallation of the front film. Like Yang (1974), the stress impinging the interface was measured using a micro-electronic device with x-cut piezoelectric crystal. In more recent publications (Gupta and Yuan, 1993; Yuan and Gupta, 1993; Gupta and Pronin, 1993; Gupta, Yuan and Pronin, 1994), a laser Doppler interferometer was introduced to measure the free surface displacement and velocities interferometrically which were then related to interface stress (Gupta, *et. al.*, 1992). This technique was used to measure the tensile strength of a wide variety of metal/ceramic interfaces (Gupta and Yuan, 1993) and ceramic/ceramic interfaces (Gupta, Yuan and Pronin, 1994). The film thickness was typically of 0.3-3 μm .

In all of the experiments reported in literature, only normal pressure pulses were applied to the films. Consequently, the interfaces were subjected only to tensile (mode I) loading. In most commercial applications, however, thin film interfaces fail under mixed mode conditions (Evans and Hutchinson, 1995). Design of experiments to measure the interface debonding over a range of mode mixity relevant to practical problems is a significant challenge. The ultimate goal of this project is to investigate the feasibility of using a laser pulse induced shear wave to obtain a range of mixed mode failure of thin film interfaces.

Although the tensile (mode I) spallation technique has been reported extensively by Gupta and co-workers (Gupta, 1992; Gupta and Yuan, 1993; Yuan and Gupta, 1993; Gupta and Pronin, 1993; Gupta, Yuan and Pronin, 1994), it was judged necessary here to systematically investigate the effects of film thickness, substrate thickness, and laser fluence before extending this experiment for the case of shear wave loading. Here we report on a series of spallation experiments for Al thin films on both (100) Si and fused quartz substrates of varying thickness. The results reveal important design parameters for the shear wave experiment. Furthermore, a rigorous theoretical analysis of the stress wave generation was also carried out. Calculations provide meaningful insight into the nature of the wave propagation in the samples. These results will help us to determine the material, dimension and setup configuration for our shear wave experiment in the future.

2 THERMO-ELASTIC CALCULATIONS

Fig.1 is the schematic of the laser spallation experiment. The thin film sample consists of from left to right: confining plate (C), thin energy absorbing layer (A), substrate (S) and the testing film (F).

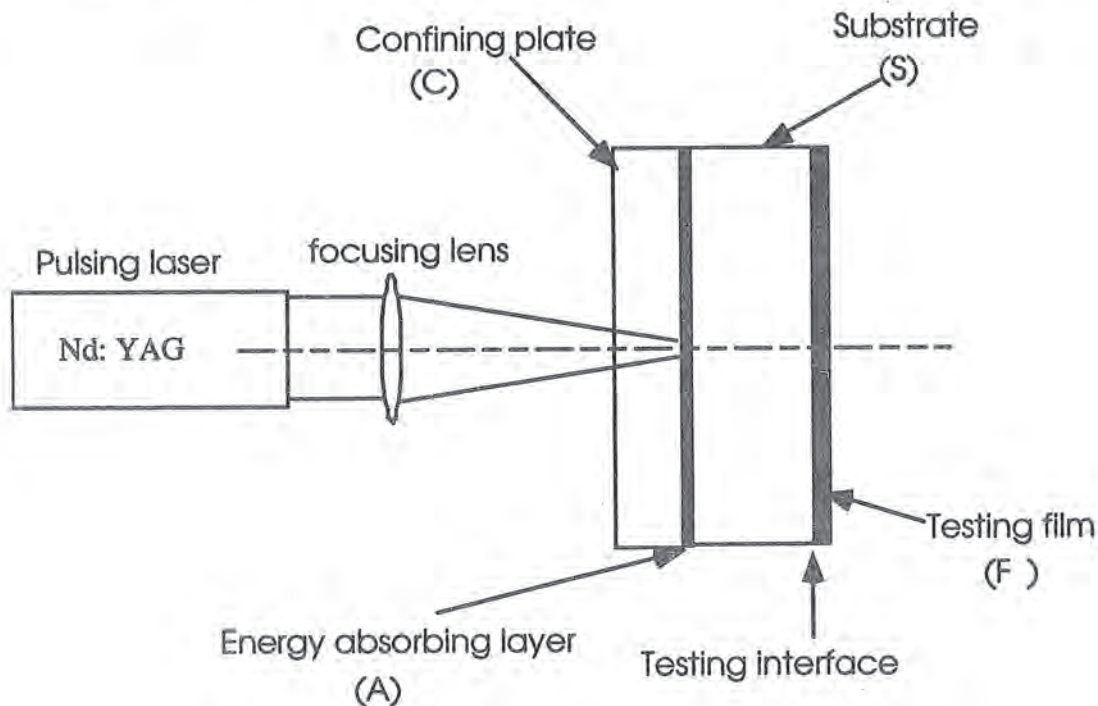


Fig. 1 Schematic of laser spallation technique:
absorbing layer and testing film are typically between 0.3-3 μm .

In our experiment, an infra-red, Nd:YAG pulse ($\lambda=1064\mu\text{m}$) with a variable energy content between 1 and 100mJ, and a rise time of order 5 nanoseconds is incident on a metallic absorbing layer sandwiched between the confining plate and substrate. The energy-absorbing layer is chosen to be much thicker (typically $\sim 0.5\mu\text{m}$) than the critical

penetration depth (10's nm) of laser light at this wavelength. Under this consideration, we assume that the total laser energy is deposited at the interface of the confining plate and the energy-absorbing layer. A longitudinal stress wave of rise time comparable to that of the laser pulse is emitted from the metallic layer. The wave that propagates towards the film/substrate interface is then reflected back from the free film surface into a tensile wave which then loads the testing interface in tension.

2.1 Mathematical Statement of the Problem

The essential mechanics behind the generation of the compressive stress wave following the deposition of the thermal energy at an interface is implicit in the texts of Achenbach (1984) and Graff (1991). It was also described by Gupta *et al* (1992) and is summarized below:

The one-dimensional heat transfer equation in all relevant media is expressed as

$$\left(\frac{\partial T}{\partial t} \right)_i = D_i \frac{\partial^2 T_i}{\partial x^2} \quad (1)$$

where subscript i refers to C , A , S (the front testing film F is too far to be affected by the thermal effect) and D is the thermal diffusivity of the medium and defined as $k / \rho C$, where k is the thermal conductivity, ρ is the density and C is the specific heat. The boundary conditions at the interface of confining plate and absorbing layer are given by

$$q(t) = \begin{cases} \left(k \frac{\partial T}{\partial x} \right)_C - \left(k \frac{\partial T}{\partial x} \right)_A & \text{for } t < \Delta t_l \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

where Δt_l is the duration of the YAG laser pulse, $q(t)$ is the absorbed laser fluence. The associated one-dimensional elastic wave equation is

$$(\lambda + 2\mu)_i \frac{\partial^2 u_i}{\partial x^2} = \rho_i \frac{\partial^2 u_i}{\partial t^2} + (3\lambda + 2\mu)_i \alpha_i \frac{\partial T_i}{\partial x} \quad (3)$$

where λ and μ are Lamé moduli, u is longitudinal displacement, ρ is density and α is the coefficient of thermal expansion of the medium. The stress is calculated from the displacement and temperature gradients,

$$\sigma_i = (\lambda + 2\mu)_i \frac{\partial u_i}{\partial x} + (3\lambda + 2\mu)_i \alpha_i T_i \quad (4)$$

where σ is stress. At distances far from the thermal deposition, the latter term vanishes.

2.2 Analytical Solution

Equations (1)-(4) were solved by Gupta *et. al.* (1992) using one dimensional finite element analysis. With a closer observation, one may find that these equations can be solved analytically. The result is a closed form expression for the stress pulse and displacement propagating away from the deposition zone. Consider a system consisting of two juxtaposed isotropic thermo-elastic half spaces. The more complicated case of a thin film between two half spaces may be treated by a similar procedure. The anisotropic case is a trivial generalization since the governing equations will essentially take the same form with different coefficients(Gupta, 1989).

Consider two half spaces of two different materials perfectly bonded at $x=0$. A laser fluence is deposited at the interface.

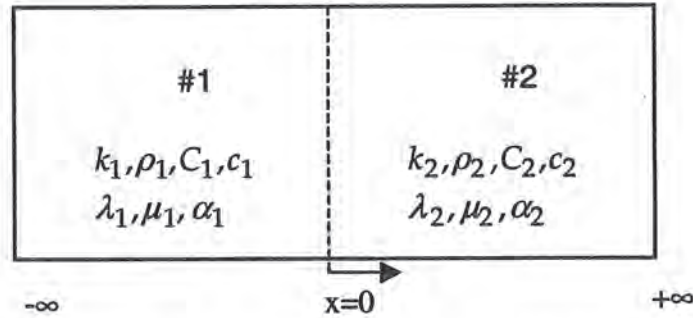


Fig. 2 Schematic of two half spaces of different materials.

The heat transfer problem is given by equation (1) with boundary conditions

$$\begin{cases} T_1 = T_2 \\ q(t) = k_1 \left(\frac{\partial T_1}{\partial x} \right)_{x=0^-} - k_2 \left(\frac{\partial T_2}{\partial x} \right)_{x=0^+} = \phi \delta(t) \end{cases} \quad \text{at } x = 0 \quad (5)$$

The solution is obtained using Laplace transformation (See Appendix A) as

$$\begin{cases} T_1(x,t) = \frac{\phi}{\sqrt{k_1 \rho_1 C_1} + \sqrt{k_2 \rho_2 C_2}} \cdot \frac{e^{-\frac{x^2}{4D_1 t}}}{\sqrt{\pi}} \cdot H(t) \\ T_2(x,t) = \frac{\phi}{\sqrt{k_1 \rho_1 C_1} + \sqrt{k_2 \rho_2 C_2}} \cdot \frac{e^{-\frac{x^2}{4D_2 t}}}{\sqrt{\pi}} \cdot H(t) \end{cases} \quad (6)$$

The associated one dimensional elastic wave problem is given by equation (3) with boundary conditions

$$\begin{cases} u_1 = u_2 \\ (\lambda + 2\mu)_1 \frac{\partial u_1}{\partial x} + (3\lambda + 2\mu)_1 \alpha_1 \Delta T_1 = (\lambda + 2\mu)_2 \frac{\partial u_2}{\partial x} + (3\lambda + 2\mu)_2 \alpha_2 \Delta T_2 \end{cases} \quad \text{at } x = 0 \quad (7)$$

Equation (7) is essentially the continuity condition of displacement and stress at the interface. Since both the displacement and coefficient in the above equations are changing at the interface, we choose to treat an equivalent problem with two variables, material velocity and stress, as follows

$$\begin{cases} \rho_i \frac{\partial v}{\partial t} = \frac{\partial \sigma}{\partial x} \\ \frac{\partial \sigma}{\partial t} = (\lambda + 2\mu)_i \frac{\partial v}{\partial x} - \alpha_i (3\lambda + 2\mu)_i \frac{\partial T}{\partial t} \end{cases} \quad (8)$$

where $i=1$ when $x < 0$, $i=2$ when $x > 0$. And boundary conditions at $x=0$ are

$$\begin{cases} v|_{x=0^-} = v|_{x=0^+} \\ \sigma|_{x=0^-} = \sigma|_{x=0^+} \end{cases} \quad (9)$$

As the symbolic derivation is long and tedious (See Appendix A), we only give the final result

$$\begin{aligned} \sigma(x, t) = & A \cdot H\left(t - \frac{x}{c_2}\right) \int_0^{t - \frac{x}{c_2}} \left\{ 1 - \frac{[x - c_2(t - t_s)]^2}{2D_1 t_s} \cdot \frac{c_1^2}{c_2^2} \right\} \cdot \frac{e^{-\frac{[x - c_2(t - t_s)]^2}{4D_1 t_s}}}{t_s^{3/2}} dt_s \\ & + B \cdot \left(\int_{\max\left\{0, t - \frac{x}{t_2}\right\}}^t \left\{ 1 - \frac{[x - c_2(t - t_s)]^2}{2D_2 t_s} \right\} \cdot \frac{e^{-\frac{[x - c_2(t - t_s)]^2}{4D_2 t_s}}}{t_s^{3/2}} dt_s \right. \\ & \left. + C \cdot H\left(t - \frac{x}{c_2}\right) \cdot \int_0^{t - \frac{x}{c_2}} \left\{ 1 - \frac{[x - c_2(t - t_s)]^2}{2D_2 t_s} \cdot \frac{c_1^2}{c_2^2} \right\} \cdot \frac{e^{-\frac{[x - c_2(t - t_s)]^2}{4D_2 t_s}}}{t_s^{3/2}} dt_s \right) \end{aligned} \quad (10)$$

where

$$A = \frac{\phi\alpha_1(3\lambda + 2\mu)_1}{2\sqrt{\pi}(\sqrt{k_1\rho_1C_1} + \sqrt{k_2\rho_2C_2})} \cdot \frac{\rho_2c_2}{\rho_1c_1 + \rho_2c_2},$$

$$B = \frac{\phi\alpha_2(3\lambda + 2\mu)_2}{4\sqrt{\pi}(\sqrt{k_1\rho_1C_1} + \sqrt{k_2\rho_2C_2})},$$

$$C = \frac{\rho_1c_1 - \rho_2c_2}{\rho_1c_1 + \rho_2c_2}$$

Making the change of variables, $x = c_2t + z$, $t_s = \xi$, and $z' = zc_2/D_2$, $\xi' = \xi c_2^2/D_2$, we obtain the nondimensionalized stress

$$\begin{aligned} \sigma(z') = & A \cdot \frac{c_2}{\sqrt{D_2}} \cdot H(-z') \int_0^{-z'} \left\{ 1 - \frac{(z' + \xi')^2}{2\xi'} \cdot \frac{D_2c_1^2}{D_1c_2^2} \right\} \cdot \frac{e^{-\frac{(z' + \xi')^2}{4\xi'} \cdot \frac{D_2c_1^2}{D_1c_2^2}}}{\xi'^{3/2}} d\xi' \\ & + B \cdot \frac{c_2}{\sqrt{D_2}} \cdot \left(\int_{\max\{0, -z'\}}^t \left\{ 1 - \frac{(z' + \xi')^2}{2\xi'} \right\} \cdot \frac{e^{-\frac{(z' + \xi')^2}{4\xi'}}}{\xi'^{3/2}} d\xi' \right. \\ & \left. + C \cdot H(-z') \cdot \int_0^{-z'} \left\{ 1 - \frac{(z' + \xi')^2}{2\xi'} \right\} \cdot \frac{e^{-\frac{(z' + \xi')^2}{4\xi'}}}{\xi'^{3/2}} d\xi' \right) \end{aligned} \quad (11)$$

And the nondimensionalized displacement is

$$\begin{aligned} u(z') = & 2A \cdot \frac{\sqrt{D_2}}{\rho_2c_2^2} \cdot H(-z') \int_0^{-z'} \frac{e^{-\frac{(z' + \xi')^2}{4\xi'} \cdot \frac{D_2c_1^2}{D_1c_2^2}}}{\xi'^{1/2}} d\xi' \\ & + 2B \cdot \frac{\sqrt{D_2}}{\rho_2c_2^2} \cdot \left(\int_{\max\{0, -z'\}}^t \frac{e^{-\frac{(z' + \xi')^2}{4\xi'}}}{\xi'^{1/2}} d\xi' + C \cdot H(-z') \cdot \int_0^{-z'} \frac{e^{-\frac{(z' + \xi')^2}{4\xi'}}}{\xi'^{3/2}} d\xi' \right) \end{aligned} \quad (12).$$

The integrals in equations (11) and (12) can be evaluated numerically.

2.3 Asymptotic Solution

The asymptotic solution for slow illumination is also derived. It is justified by recognizing that $\Delta t_l \gg c^2/D$. A detailed derivation of this solution is provided in Appendix B. It turns out that the asymptotic solution for displacement is essentially a Heavy side function and the stress is essentially a delta function,

$$\begin{cases} u(t) = A_1 H(t - \frac{x}{c_2}) \\ \sigma(t) = -\rho_2 c_2 A_1 \delta(t - \frac{x}{c_2}) \end{cases} \quad (13)$$

where

$$A_1 = \frac{1}{\rho_1 c_1 + \rho_2 c_2} \cdot \frac{1}{\sqrt{k_1 \rho_1 C_1} + \sqrt{k_2 \rho_2 C_2}} \cdot \left[\frac{(3\lambda + 2\mu)_1 \alpha_1 \sqrt{D_1}}{c_1} + \frac{(3\lambda + 2\mu)_2 \alpha_2 \sqrt{D_2}}{c_2} \cdot \frac{\rho_1 c_1}{\rho_2 c_2} \right].$$

2.4 Solution due to Practical Energy Deposition

In the above derivations, we assumed that a laser energy of the form $q(t) = \phi \delta(t)$ is deposited at the interface of the confining plate and absorbing layer. However, the actual laser pulse is not a perfect Delta function. As shown in Fig. 3, the actual laser pulse of energy 100mJ is deposited within a period of 6-8ns that can be fitted to a Gaussian distribution,

$$q(t) = q_{\max} \exp\left(-\frac{t^2}{s^2}\right) \quad (14)$$

where $q_{\max} = 18.9 \text{ mJ/ns}$, $s = 2.9 \text{ ns}$.

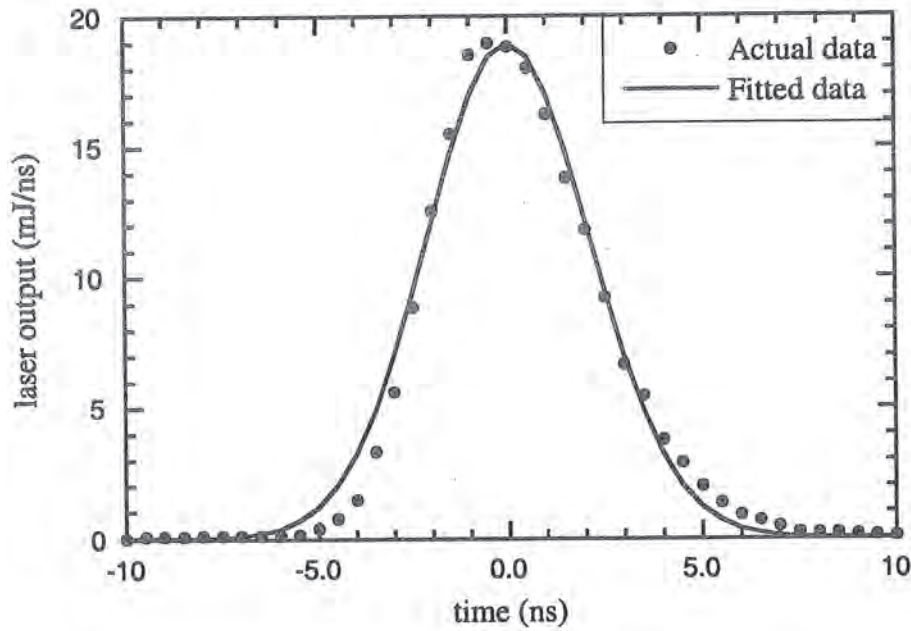


Fig. 3 Nd:YAG laser pulse provided by NewWave Laser.

The actual late time response in the detector is the convolution of the real energy distribution and the previous asymptotic solution, i.e.,

$$u^{actual} = u^{asymptotic}(t) \otimes q(t) \quad (15)$$

$$\sigma^{actual} = -\rho c \frac{\partial u^{actual}}{\partial t} \quad (16)$$

For small testing film thickness h , the stress at the interface is given by

$$\sigma_{interface} = -2\rho_{film}h \frac{\partial^2 u^{actual}}{\partial t^2} \quad (*) \quad (17)$$

Values of displacement, stress in the substrate and the stress at interface were predicted for the case of glass/Aluminum sample and plotted in Figs. 4, 5 and 6, respectively. Relevant material properties are given in Table 1.

^(*)The stress acting on the interface can be much less than the stress of eqn (16) because the nearby free surface releases some of the stress. The relation can be calculated using elastic wave transmission and reflection coefficients. Here we make a simpler calculation, valid for small h , that the stress is ph times by the acceleration of the free surface. We also recognize that the displacement at the free surface is twice that of the wave in the substrate.

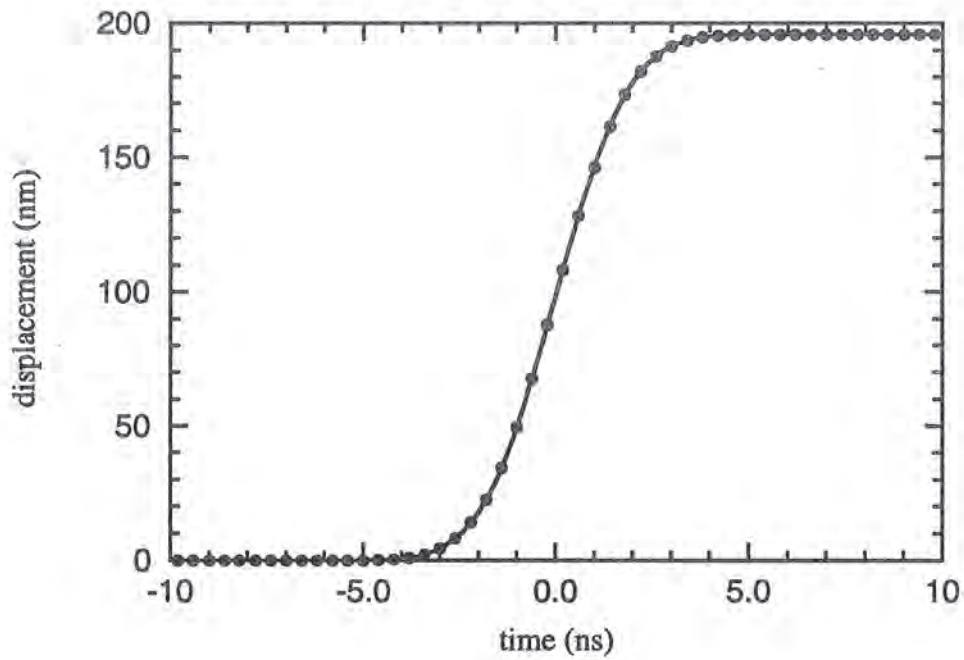


Fig. 4 Predicted displacement in the aluminum portion of the glass/Al sample far from the interface .

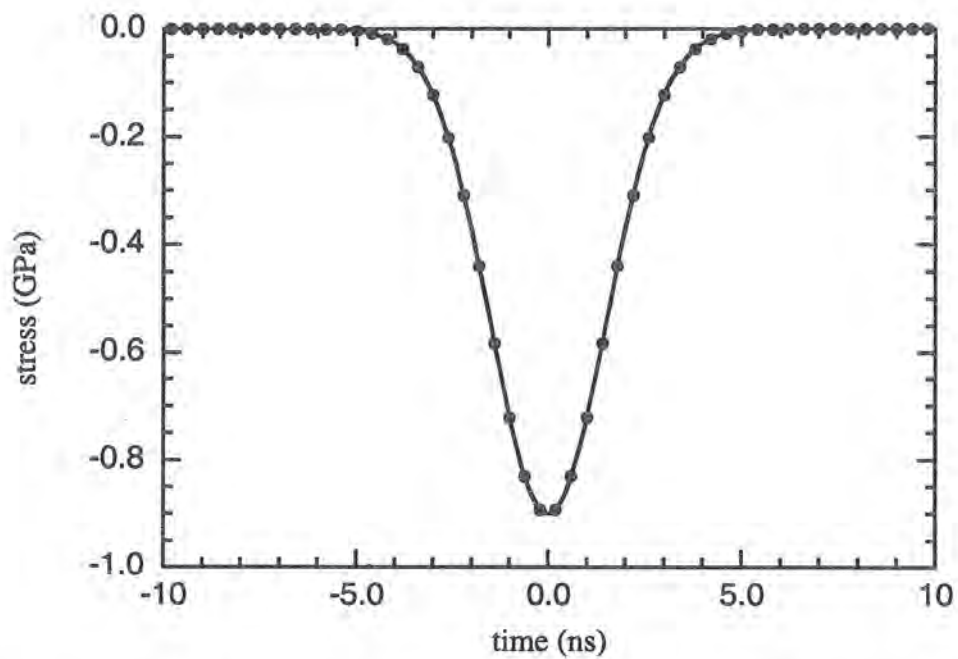


Fig. 5 Predicted stress in aluminum portion of the glass/Al sample far from the interface.

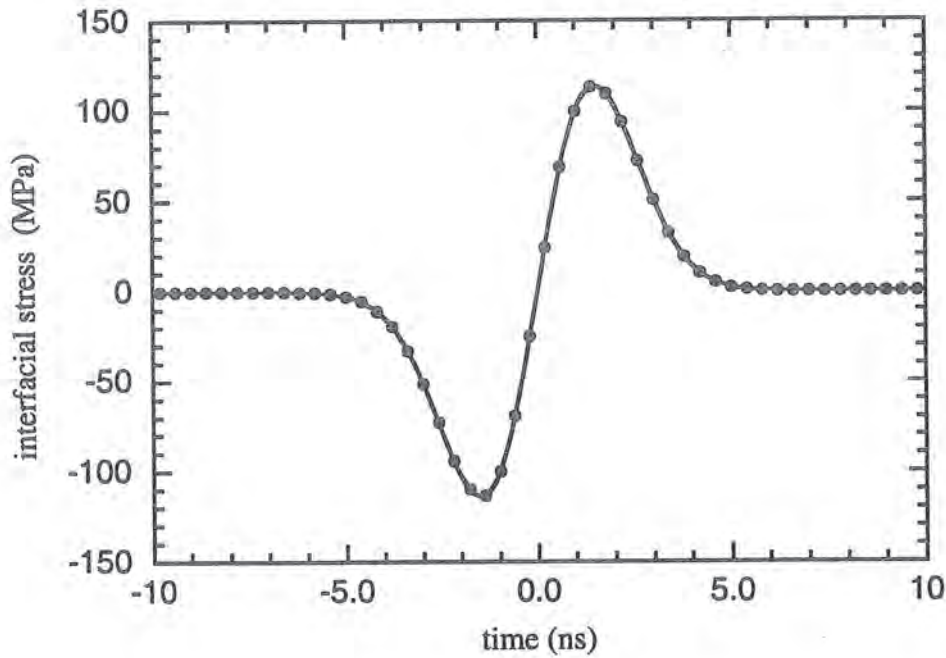


Fig. 6 Predicted stress at the interface of a 1 μ m thick Al film.

The maximum displacement is around 195nm, the maximum compressive stress is about 0.85GPa and the maximum stress at the interface of a 1 μ m thick aluminum film is about 120MPa. The width of the stress pulse is determined by the width of the laser pulse.

Table 1. Properties of glass, Al, fused quartz and Silicon

Material	Glass	Aluminum	Fused quartz	Silicon
ρ (g/cm ³)	2.5	2.71	1.8	2.3
C (J/kg.k)	750	896	1130	729
k (J/ms.k)	1.4	204	1.7	138
λ (GPa)	23.3	58.5	84.3	62.0
μ (GPa)	29.6	26.0	21.1	41.0
c (m/s)	5377.7	6385.5	8380.0	7910.0
α (k ⁻¹)	5×10^{-6}	8.4×10^{-6}	4×10^{-7}	7.6×10^{-6}

2.5 Discussion

The above calculation is based on the one-dimensional thermo-elastic deposition. The real source mechanism could be much more complicated than thermo-elastic, for example, it could involve melting or ablation. The actual laser beam size is finite, and the geometry is more complicated than considered here. These simplified calculations may only be considered as a lower bound on predicting the expected magnitudes of displacement and stress. In order to find the real magnitudes, it is necessary to measure then as done in section 4.

3 LASER SPALLATION EXPERIMENT

3.1 Experimental Procedure

As discussed in section 2, a pulsed Nd:YAG ($\lambda=1064\mu\text{m}$) laser with nominal beam diameter of 3.5mm is used to launch a compressive stress wave in the sample substrate (Fig. 1). In order to increase the laser fluence, the laser beam is focused into a 2mm diameter spot at the energy-absorbing layer. The laser energy is slowly ramped up until a longitudinal wave is generated with an amplitude high enough to fail the film/substrate interface. Laser Doppler interferometric measurements of out-of-plane displacement are made at the surface of the testing film (F). From displacement measurements at the free surface, the stress history at interface is inferred using standard wave mechanics (e.g. Miklowitz, 1978) and the maximum stress acting on the interface is calculated.

A detailed schematic of the Michaelson interferometer is shown in Fig.7. A single, linearly polarized light beam of wavelength $\lambda_0=514.5\text{nm}$ from an Argon laser is incident upon a beam splitting cube (BS). One beam is focused to a sharp point (less than 0.1mm) on the testing film using an objective lens, while the second beam is directed towards a stationary mirror (M2). The two beams are recombined in the beam splitter and then imaged onto the active area of photodiode detector. The signal from the detector is acquired using a digitizing oscilloscope.

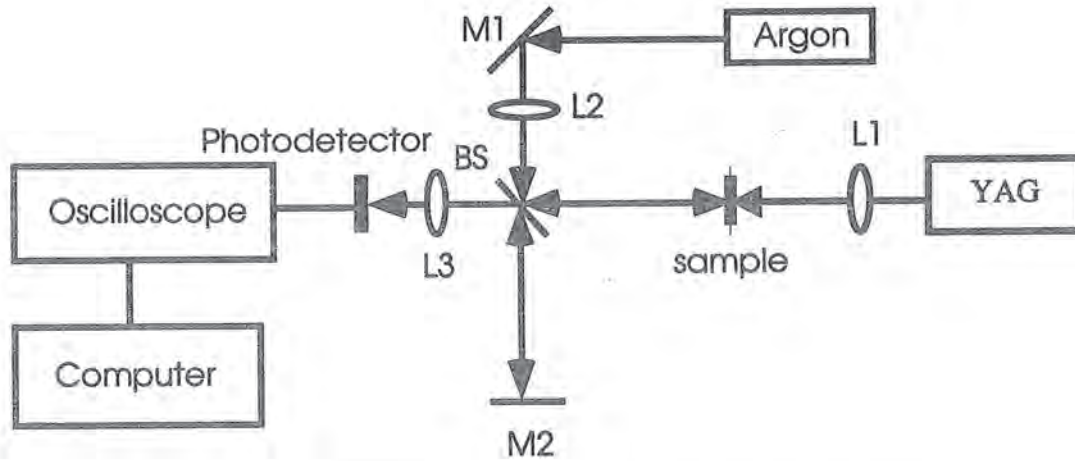


Fig. 7 Schematic of Mode I spallation experiment and interferometric displacement measurement.

Because the stress pulse in the experiment has a rise time of less than a few nanoseconds, detection of sub-nanosecond displacement fringes is challenging. The fringe frequency of Argon laser is 3.88 GHz per mm/sec ($\lambda_0=514.5\text{nm}$). The laser methods widely used for detection of low amplitude ultrasonic waves for nondestructive evaluation are generally limited to signals with frequency content below 40MHz (Wagner, 1990). Much faster signals (well beyond 40 MHz), however, have been successfully measured in plate impact research (e.g. Zhou and Clifton, 1997; Raiser et al., 1994), shock wave studies (e.g. Barker and Hollenbach, 1970) and previous spallation experiments (Gupta et al., 1993) where the elastic wave amplitudes are much greater and the demands for sensitivity are lower. An ultra-high speed photodetector was selected with a rise time less than 300psec. A high resolution LeCroy oscilloscope which has a cut off frequency of 1 GHz and sample rate of 8G Sample/sec is used to record the interferometric fringes with a resolution of 0.125ns.

3.2 Measuring Principles

Any movement of the sample surface causes a change in the signal frequency due to the Doppler effect. The Doppler frequency deviation for laser light of wavelength λ_0 reflected normally from a moving surface with velocity $V(t)$ is given by the Doppler shift equation as,

$$v(T) = \frac{2V(t)}{\lambda_0} \quad (18)$$

At the stabilization point with maximum sensitivity (the so-called $\pi/2$ point), the light intensity on the photodiode detector is related to the fringe count, $n(t)$, as

$$I(t) = \frac{(I_{\max} + I_{\min})}{2} + \frac{(I_{\max} - I_{\min})}{2} \sin(2\pi n(t) + \phi) \quad (19)$$

where $I_{\max}$ and $I_{\min}$ are the maximum and minimum intensities of the interference fringes and ϕ is the phase angle. The surface displacement is obtained in terms of the fringe count by integrating Eq.18 (Barker and Hollenbach, 1970):

$$u(t) = \frac{\lambda_0 n(t)}{2} \quad (20)$$

The fringe count is determined from the output of the photodiode detector (Eq.19) and the displacement is calculated using Eq.20. One complete fringe shift corresponds to a displacement of $\lambda_0/2$ (257nm). The resolution of this type of inteferometer is limited by the noise arising from fluctuations in the laser intensity and fluctuations in the environment (i.e., temperature). In our test, both of these two effects are minimized. Once the free surface displacement is obtained from the interferometric measurements, the compressive stress propagating from absorbing layer toward the substrate is calculated using simple 1-D wave mechanics,

$$\sigma = -\frac{1}{2}(\rho c)_{\text{substrate}} \frac{\partial u}{\partial t} \quad (21)$$

The associated tensile stress that strikes the film/substrate interface is given by

$$\sigma_{\text{interface}} = -\rho_{\text{film}} h \frac{\partial^2 u}{\partial t^2} \quad (22)$$

This u is approximately twice the u^{actual} of section 2 of the stress pulse in the substrate, because of the free surface reflection.

3.3 Sample Fabrication

The thin film sample used for the spallation experiments is shown schematically in Fig. 8. For these preliminary experiments, an Al film was used for both the absorbing layer and the testing film. The Al was deposited on either a fused quartz or Si substrate. For all the samples, waterglass was chosen as the confining material based on the work of previous researchers and on an extensive test comparison in our own lab between water, glass and waterglass.

In preliminary experiments, water was squirted onto the back surface of the sample. The interferometric signal induced by the laser was enhanced slightly by the water, but it evaporated too quickly and was difficult to get consistently. Next, an ordinary glass slide was glued onto the backside of the sample. A large increase in the interferometric signal was obtained, but the thickness of glue layer was difficult to control. If the glue layer was too thick, the signal decreased significantly. In order to get a thin layer of glue, the

substrate had to be very flat. Finally, a waterglass layer was applied to the back surface. The waterglass was easy to apply and gave consistently high interferometric signal.

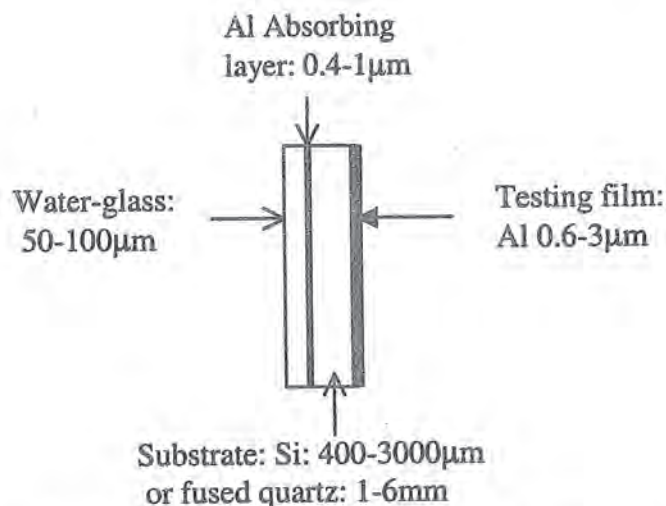


Fig. 8 Schematic of thin film sample for spallation experiment.

For samples with a fused quartz (FQ) substrate, an aluminum film was vapor deposited onto both sides of a fused quartz disc of thickness 1531 μm , 3063 μm and 6125 μm . The vacuum rate of the evaporator was controlled between $2-5 \times 10^{-6}$ Torr and the deposition rate was held between 10–15 $\text{\AA}/\text{sec}$. The final thickness of the Al was approximately 0.4–1.0 μm for the absorbing layer and 1.0–1.5 μm for the testing film. A thin layer of waterglass with thickness of 50–100 μm was then painted onto the back of the absorbing Al layer.

For samples with a (100) single side polished Si substrate, aluminum films were plasma sputtered onto both the rough side and polished side of the wafer using the ATC2000 sputtering system in the MRL at UIUC. The main chamber pressure was held at $4-8 \times 10^{-7}$ Torr and the sputtering rate was typically 1.5–2.0 $\text{\AA}/\text{sec}$. The Al layer on the rough side of the Si substrate was used as an absorbing layer, while the Al film on the polished surface served as the film for testing. The absorbing layer was approximately 1 μm thick and the front testing film was 0.4–3 μm thick. After deposition of the film, a thin layer of waterglass was painted onto the back of the absorbing Al layer as confining material as shown in Fig. 8.

3.4 Qualitative Damage Observations

The thin film samples described in Section 3.3 were tested using the experimental apparatus in Fig. 7. Prior to making any quantitative displacement measurements, a series of qualitative experiments were carried out to assess the influence of YAG laser power, thickness of the testing film, and thickness of substrate, on spallation and damage of the front film.

3.4.1 Spallation patterns

Two typical spallation patterns were observed at the front surface of Al films deposited on Si (Fig. 9). In the first pattern only the testing film was spalled off, leaving the underneath substrate intact (Fig.9a). In the second type of pattern the testing film was spalled off, leaving behind a crater in the substrate (Fig.9b). The height distribution along the dashed line in each figure was measured using a Sloan Dektak³ST stylus surface profilometer. The corresponding height profiles are plotted in Figs. 9c and 9d. The profilometer trace clearly shows the extensive damage to the substrate in Fig. 9d. Since the purpose of this experiment is to test the adhesion between film and substrate, damage pattern in Fig. 9b is not desired.

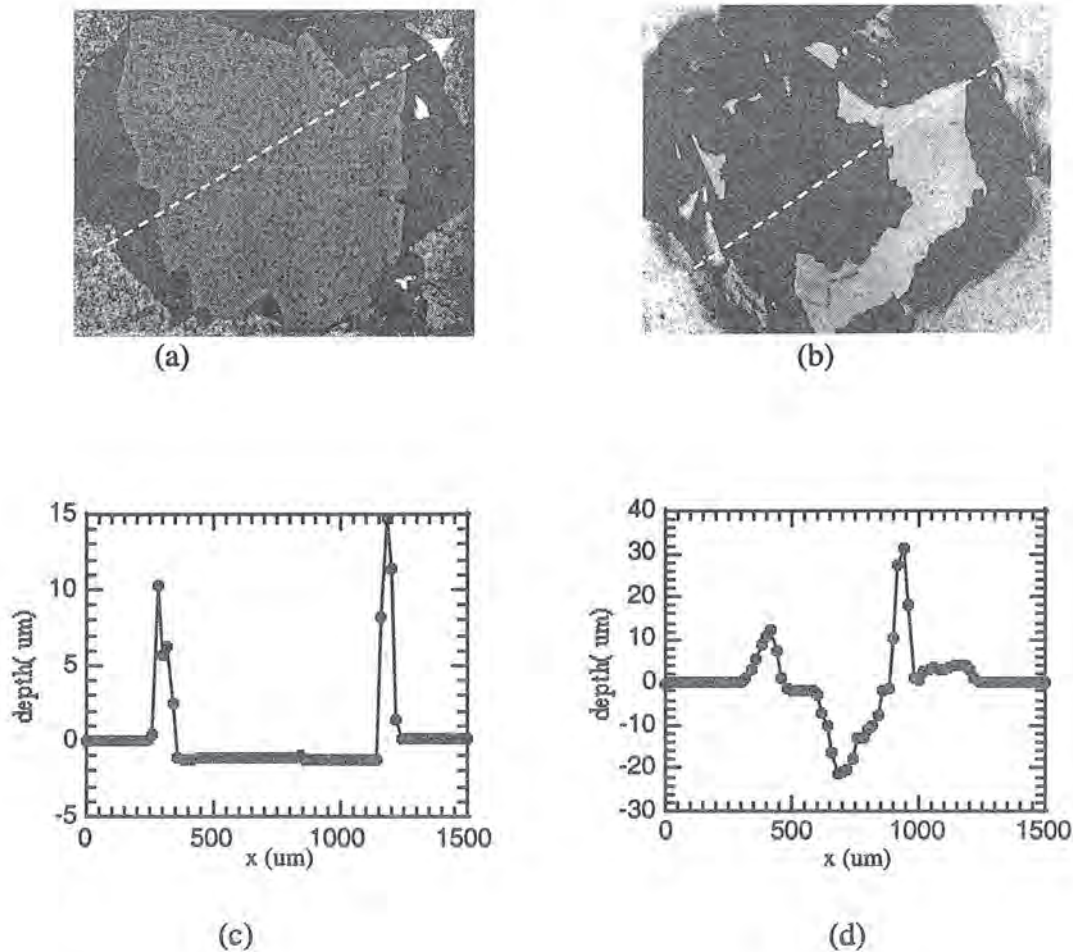


Fig. 9 Damage pattern at the testing film: (a) no substrate damage, only film spallation, (b) substrate damage plus film spallation, (c) height profile corresponding to (a), (d) height profile corresponding to (b).

To further investigate the damage to the substrate, samples with no testing film were fabricated. Two distinct damage patterns were observed on the bare substrate (Fig. 10). In the first pattern, a crater formed in the substrate while in the second a donut like damage

zone was observed. From the associated height profiles, the crater depth generated at full laser power was between 80-120microns. Also the height profile in Fig. 10d associated with the donut like damage shows that the central area of the donut region was elevated from the original substrate height which may indicate a deep crack under that region. While these two damage patterns are very typical for Si substrate, they are not desired in the laser spallation experiments. The severe damage in substrate may cause the film to come off before the interface actually fails.

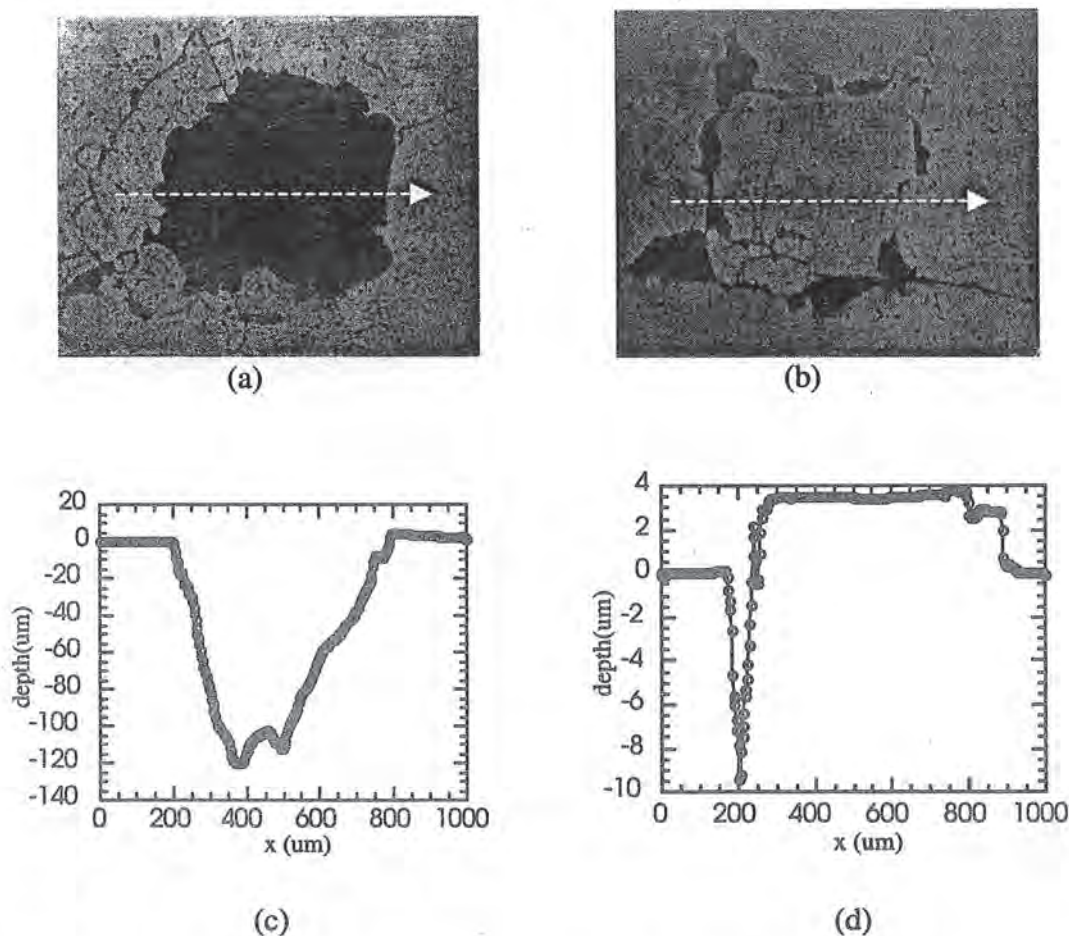


Fig. 10 Damage patterns on substrate without front film: (a) crater shaped damage, (b) donut shaped damage, (c) height profile corresponding to (a), (d) height profile corresponding to (b).

3.4.2 Influence of laser power

The effect of laser power was studied on a sample with testing film thickness of 1.5 μ m, Si substrate thickness of 700 μ m and absorbing layer thickness of 1.0 μ m. The YAG laser power was slowly ramped up from 30% to 90% on different spots. The development of damage patterns in the testing film are shown in Fig. 11.

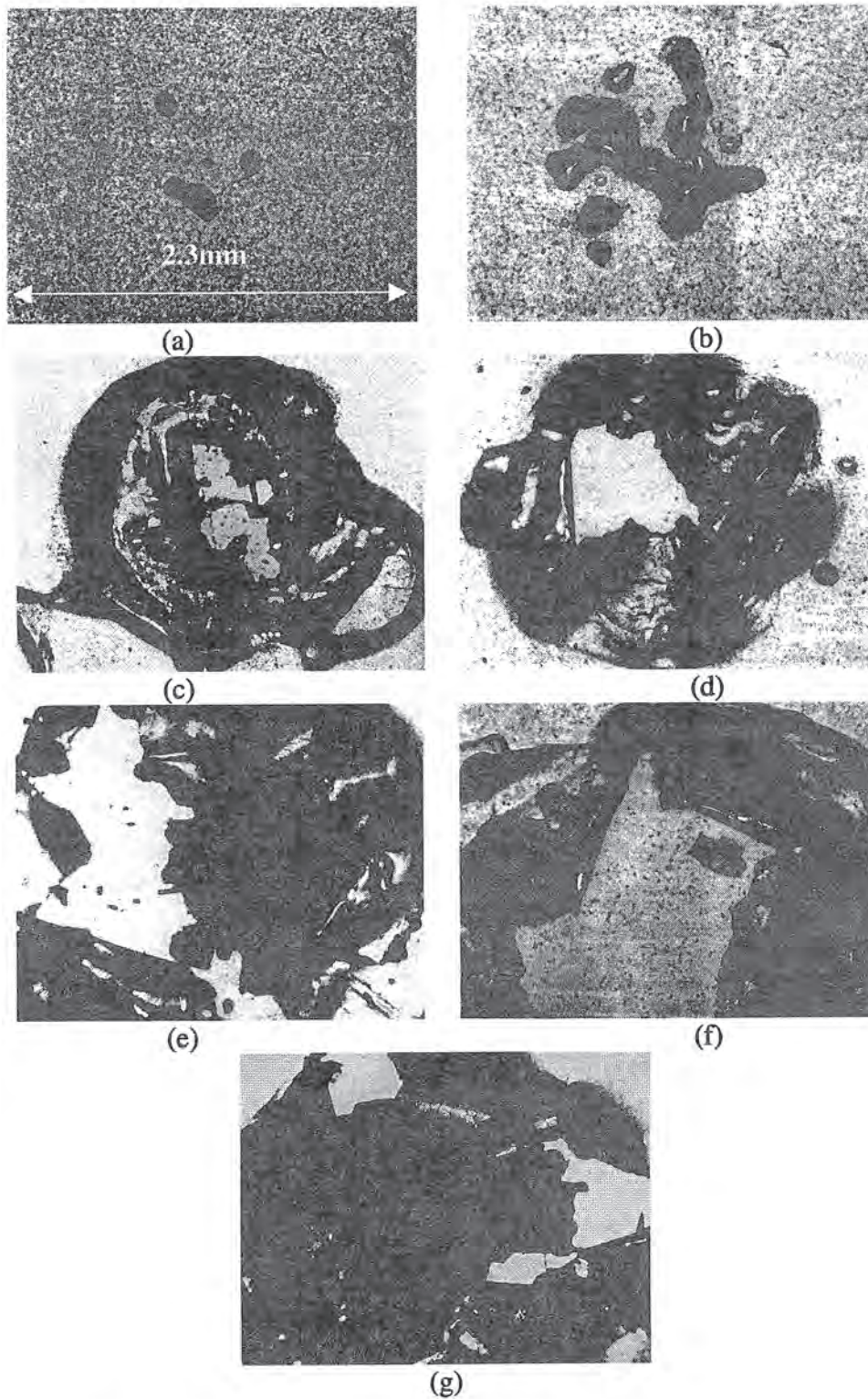


Fig. 11 Damage development as YAG laser power increases:
(a) 30%, (b) 40%, (c) 50%, (d) 60%, (e) 70%, (f) 80%, (g) 90%.

As the laser power increases, the amount of damage to the film also increases. The damage pattern shows that below 70% of laser energy, most damage occurs in the testing film while above 70%, damage occurs for both substrate and testing film. This suggests that in the case of strong adhesion where high laser energy is preferred in order to get the desired spallation, Si is not a good substrate material.

3.4.3 Effect of testing film and substrate thickness

The effect of testing film thickness was first investigated for samples with a constant Si substrate thickness of $400\mu\text{m}$, absorbing aluminum layer of $0.6\mu\text{m}$ and similar waterglass thickness. Three different testing film thicknesses, $0.4\mu\text{m}$, $1.4\mu\text{m}$ and $2.0\mu\text{m}$ were studied. Spallation was observed at the testing film for all three samples (Fig. 12). The extent of the damage strongly depends on the film thickness. The spallation patterns of the film in Fig. 12 indicate that with the same substrate thickness, same absorbing layer, and same YAG laser power, the extent of damage is larger for thicker films. This is consistent with expectations from Eq. 22, i.e., thicker film (larger h) has larger interface stress.

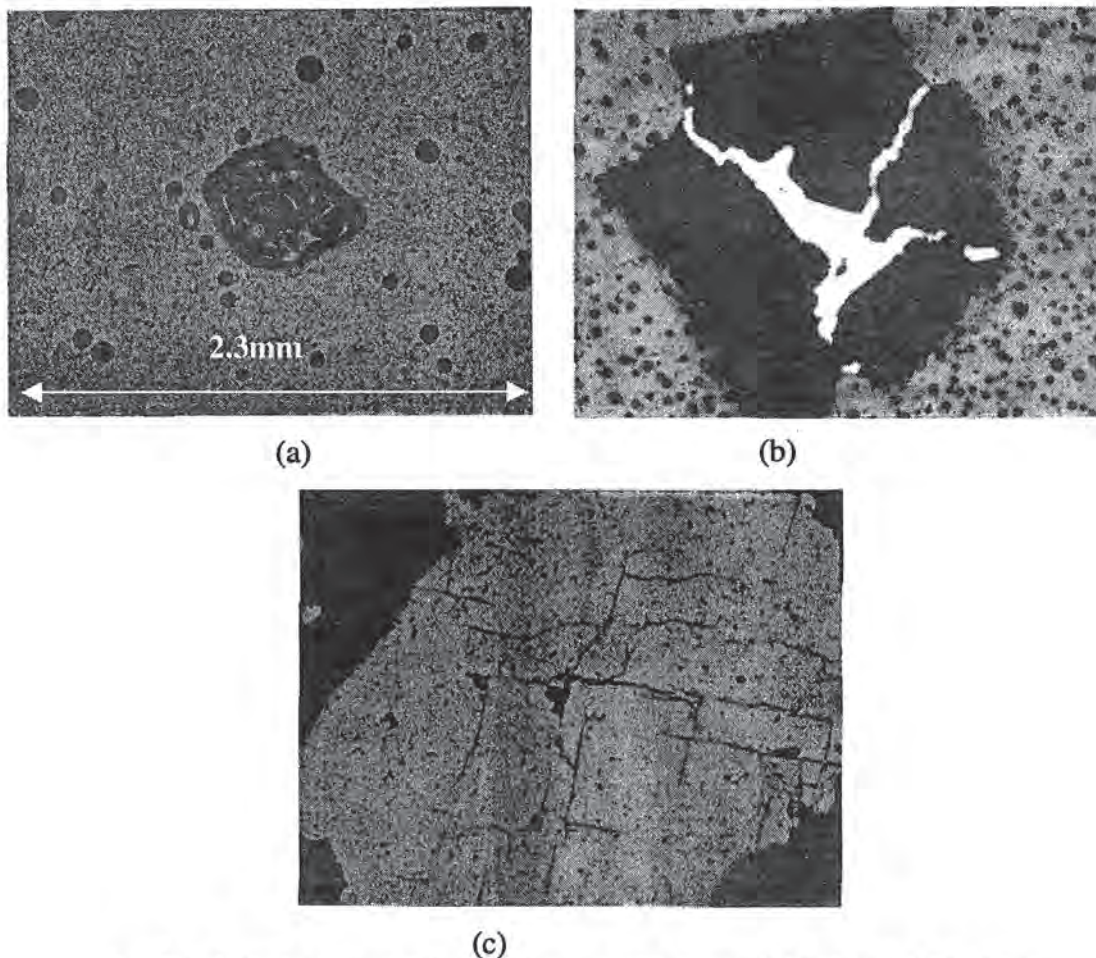


Fig. 12 Effect of front film thickness: (a) $0.4\mu\text{m}$; (b) $1.4\mu\text{m}$; (c) $2.0\mu\text{m}$.
(substrate thickness: $400\mu\text{m}$; absorbing layer thickness: $0.6\mu\text{m}$).

Samples were then fabricated using Si wafers of thickness 400 μ m, 500 μ m, 700 μ m, 3000 μ m as the substrate while keeping the absorbing layer thickness at 1 μ m. Several different front film thicknesses, 0.6 μ m, 1.0 μ m, 1.5 μ m, 3.0 μ m, were studied sequentially for each of the different substrate thicknesses. The results are summarized in Table 2. At full YAG power, spallation always occurred for the thinnest 0.6 μ m film on the 400 μ m and 500 μ m substrates. No spallation was observed for the 0.6 μ m film on the 700 μ m and 3000 μ m substrate. For the thicker 1.0 μ m film, spallation occurred for all of the 400 and 500 μ m substrate samples, for only a few samples with 700 μ m substrate, and for no samples of 3000 μ m substrate. After increasing the film thickness to 1.5 μ m, spallation was observed for all 400, 500, and 700 μ m substrate samples but not for the 3000 μ m substrate. Finally, for a film thickness of 3.0 μ m, some spallation appeared on the 3000 μ m sample.

Table 2 Effect of substrate thickness

film thickness	substrate thickness			
	400 μ m	500 μ m	700 μ m	3000 μ m
0.6 μ m	Yes	Yes	No	No
1.0 μ m	Yes	Yes	Yes	No
1.5 μ m	Yes	Yes	Yes	No
3.0 μ m				Yes

Note: Yes means some spallation is observed; No means no spallation at all.

For the thinnest substrate (400 μ m), most of the spallation patterns are similar to that in Fig. 9a, in which only the testing film fails and no damage occurs in the substrate. As the substrate thickness increases, more spallation patterns appear like those in Fig. 9b. In this case, not only the testing film spalls off, but also the substrate is left with a crater. When the testing film and absorbing layer thickness are identical, more film damage occurs for a thinner substrate.

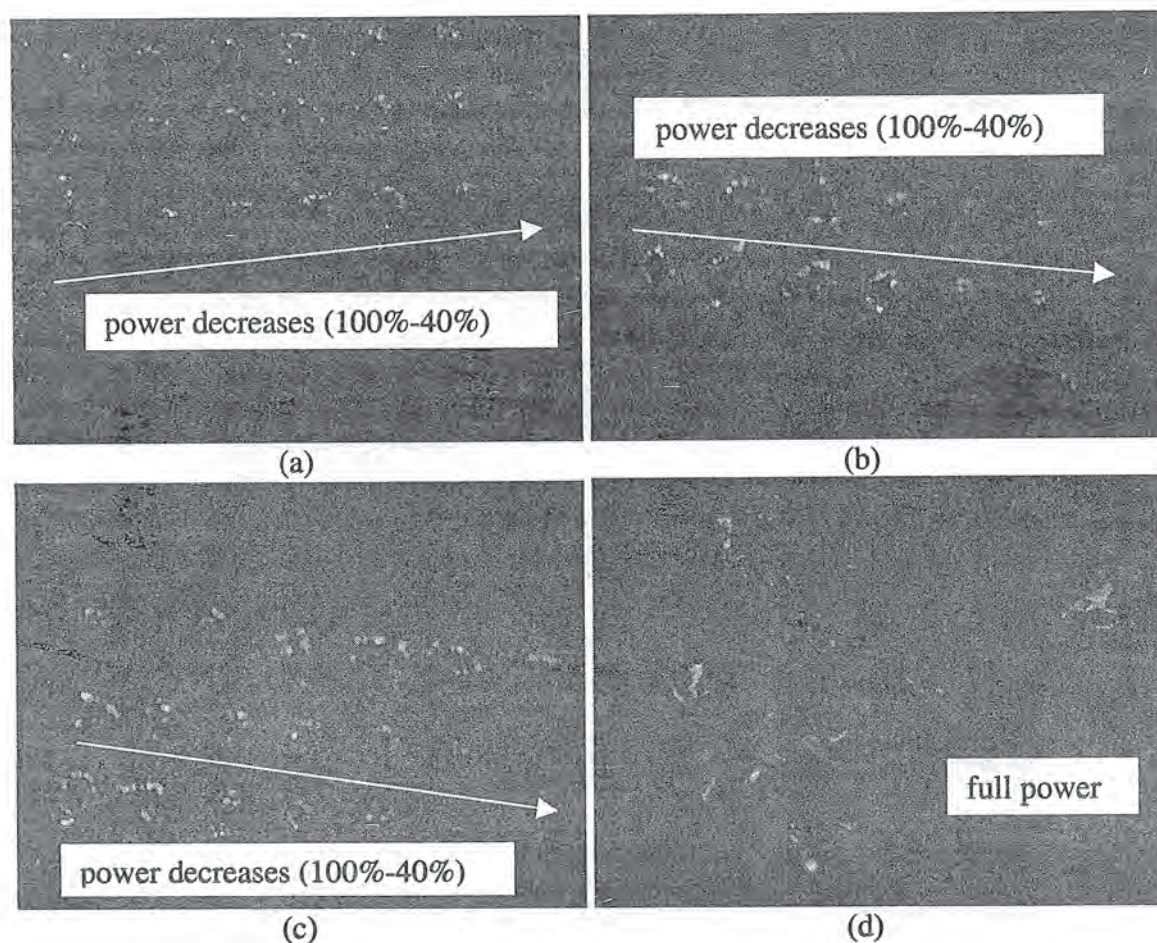


Fig. 13 Effect of substrate thickness: (a) 400 μ m substrate; (b) 500 μ m substrate; (c) 700 μ m substrate; (d) 3000 μ m substrate. (a)-(c) has same film thickness, 1.5 μ m; (d) has a thicker film, 3.0 μ m. (Diameter of the largest spot is about 2mm).

Three different thicknesses of the fused quartz substrate samples, 1531 μ m, 3063 μ m and 6125 μ m, were also investigated. For an Al testing film thickness of 1.0 μ m, film spallation was observed only for the 1531 μ m fused quartz substrate at laser power levels at about 40%. Typical damage patterns are shown in Fig. 14 for increasing laser energy. For the 3063 μ m fused quartz substrate, some testing film damage was observed at power levels above 60% but the film didn't actually spall off (Fig. 15). No damage was observed in the testing film deposited on the 6125 μ m substrate, even at full power.

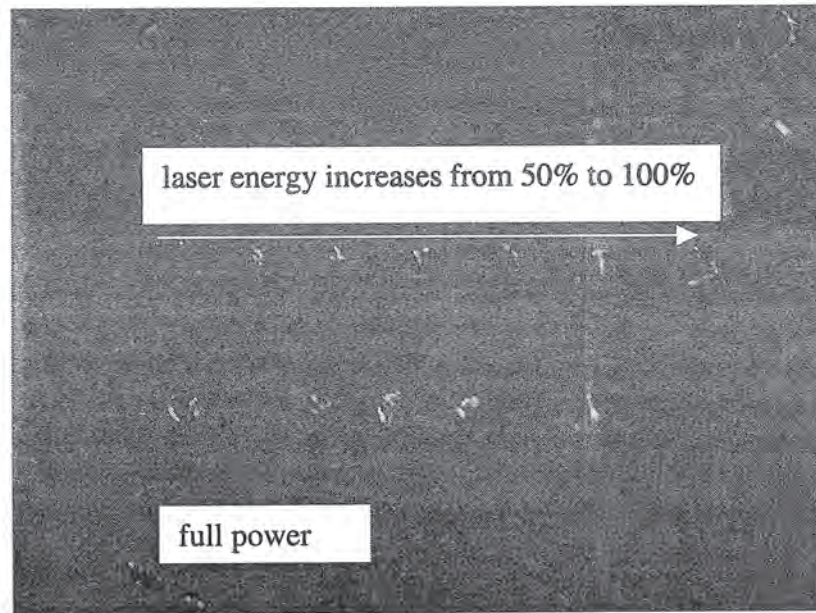


Fig. 14 Damage at testing film on 1531 μ m fused quartz disc. The diameter of the largest spot is about 2mm. YAG beam was focused to 2mm spot.

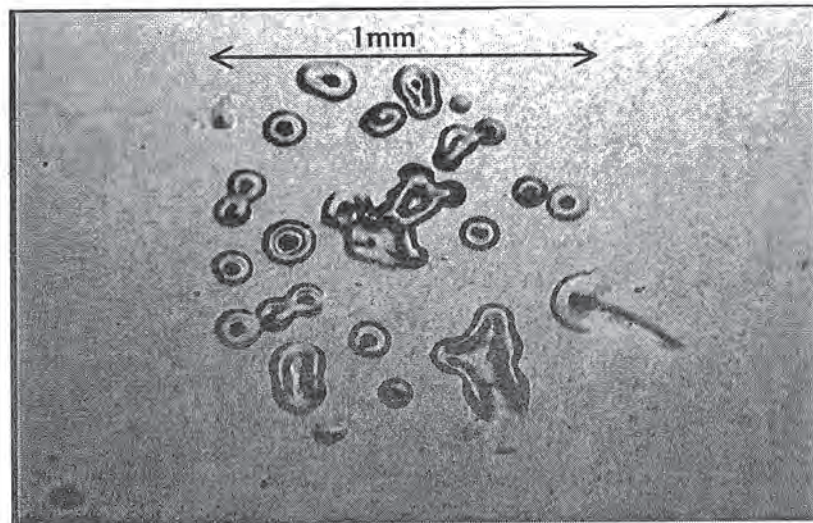


Fig. 15 Damage at testing film on 6125 μ m fused quartz disc for 1 laser spot at full laser power. For this test, YAG beam was focused to 1mm.

3.4.4 Discussion

For both fused quartz and Si substrate samples, the higher the YAG laser power, the greater amount of damage to the film. The thicker the testing film and the thinner the substrate, the more the damage. The effect of substrate thickness indicates that there may be strong stress attenuation with respect to substrate thickness. The qualitative damage observations also show that at some spots, there is a large amount of substrate damage in the Si substrate samples at high laser power which is due to Si substrate cleavage. Since

the ultimate goal of this project is to test the adhesion between the film and substrate, substrate cleavage is not desired for this purpose. In the fused quartz substrate samples, however, no substrate damage was observed which suggest that fused quartz may be a better substrate material for laser spallation testing.

3.5 Quantitative Interferometric Measurements

Quantitative measurements of the displacement, substrate stress and interface stress were obtained using a Michelson interferometer as shown in Fig. 7. A typical interferometric signal measured for an Al front film on Si substrate sample is shown in Fig. 16a. Using Eqs. 19 and 20, the displacement profile of the film free surface (Fig. 16b) is determined from the fringe data (Fig. 16a). As discussed in Section 3.2, the compressive substrate stress (Fig. 16c) and the stress at the testing film interface after reflecting from the free surface (Fig. 16d) are calculated from Eqs. 21 and 22, respectively.

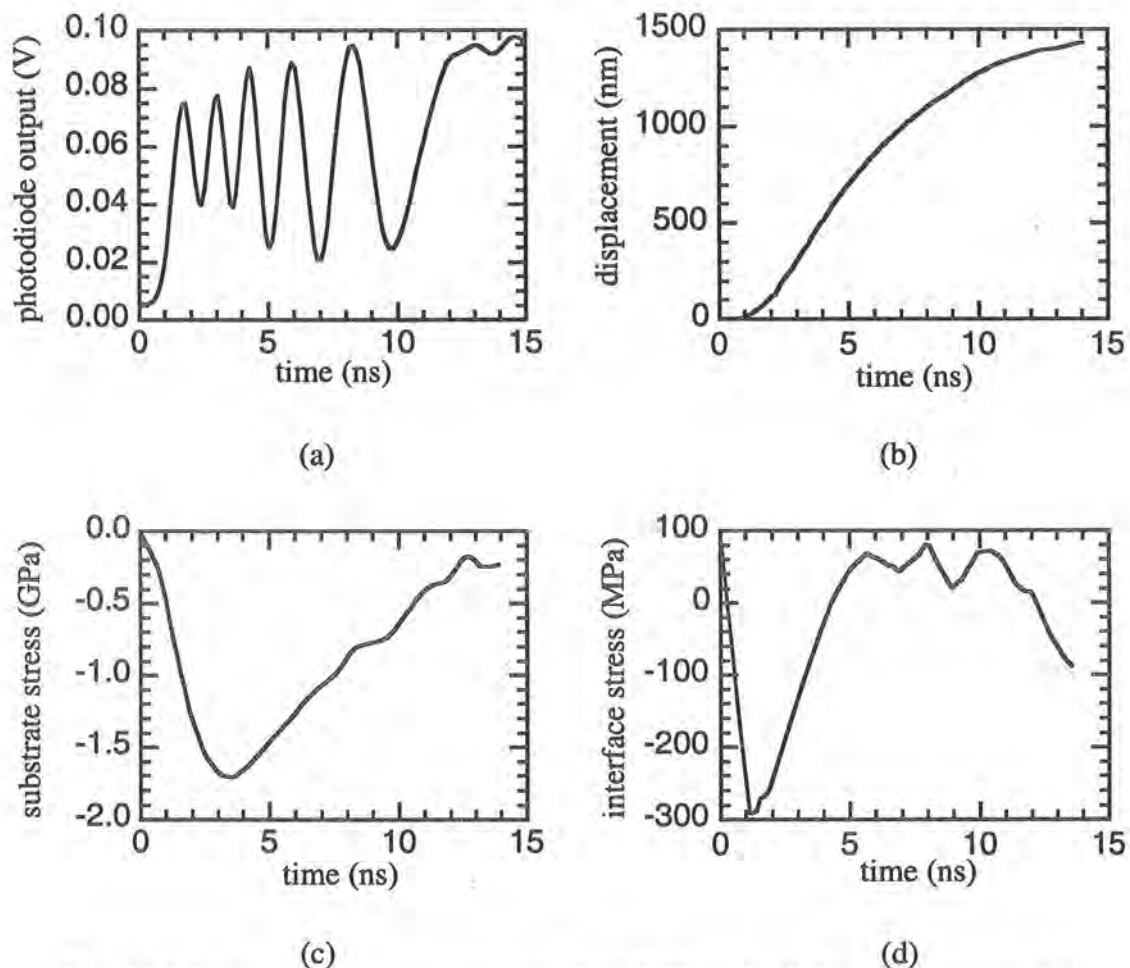


Fig. 16 A typical data processing cycle for a 600 μ m thick Si substrate sample:
 (a) interferometric fringe pattern; (b) displacement profile; (c) substrate stress profile;
 (d) interface stress profile.

Within 15ns, 5 fringes developed which correspond to a maximum displacement of 1400nm. A maximum compressive substrate stress of 1.7GPa was achieved at 3.5ns and the maximum tensile interface stress of 60MPa occurred at 5.6ns. The long fall time of the substrate stress in Fig. 16c corresponds to only modest tensile loading of the testing film interface.

A typical fringe pattern for an Al testing film on a fused quartz substrate sample is plotted in Fig. 17a. In contrast to the data for a Si substrate (Fig. 16a), the fringe data for the fused quartz have a very sharp turning point (indicated by the arrow). The corresponding displacement profile is plotted in Fig. 17b. At the turning point, the velocity goes to zero and the displacement starts to decrease. The substrate stress profile in Fig. 17c provides evidence that a shock is developed just before the turning point. The maximum interface stress (Fig. 17d) is achieved right at the turning point and is much greater than it was for the Si substrate. The occurrence of the shock that is responsible for the fast fall time is consistent with the known nonlinear elastic properties of fused quartz (Barker and Hollenbach, 1970).

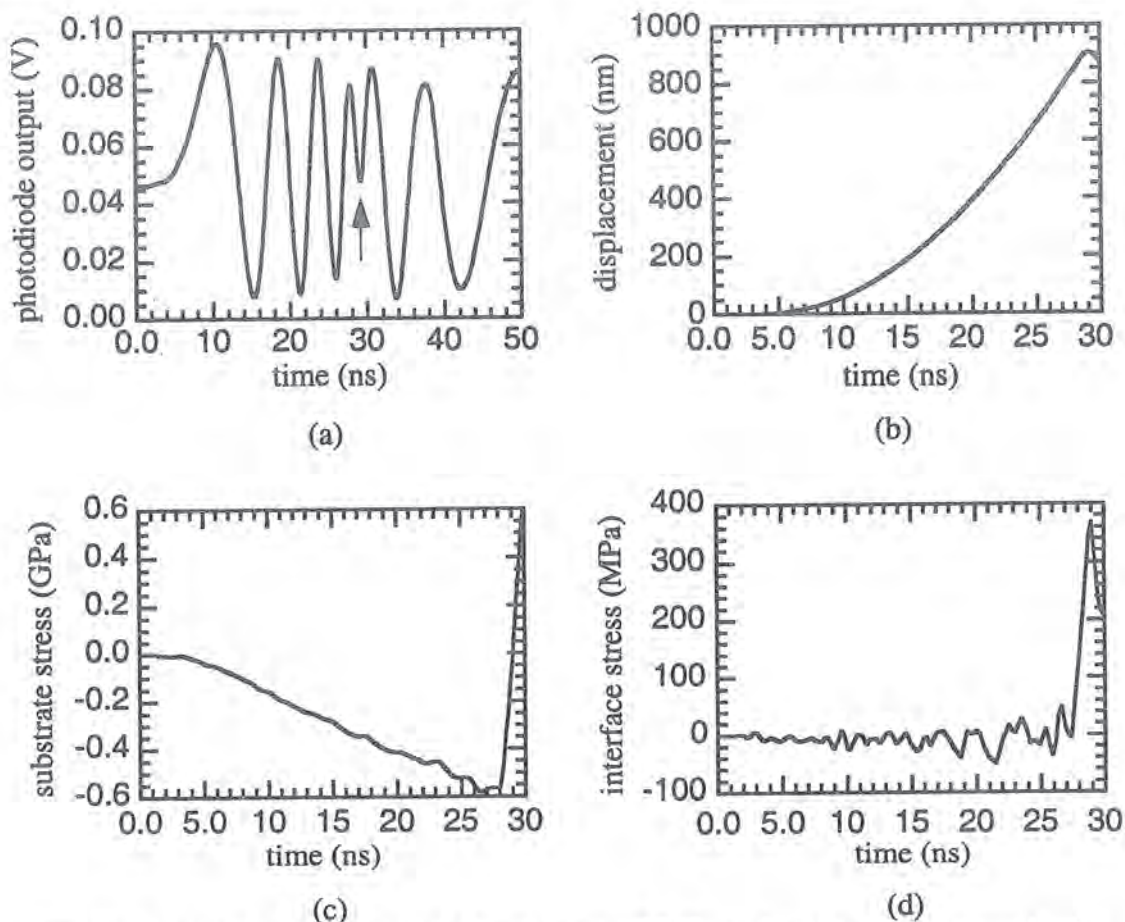


Fig.17 Typical data profile for a fused quartz (3063 μ m thick) substrate sample: (a) interferometric fringe pattern, arrow points to turning point; (b) displacement profile; (c) substrate stress profile; (d) interface stress profile.

Using these data acquisition and processing procedures, a large number of tests were performed on both Si substrate samples and fused quartz substrate samples. Again, the effects of laser power, substrate thickness, and film thickness were investigated.

3.5.1 Effect of laser power

The effect of laser power were studied on a sample with a testing film thickness of $1.1\mu\text{m}$, fused quartz substrate thickness of $3063\mu\text{m}$ and absorbing layer thickness of $0.4\mu\text{m}$. The YAG power was ramped up from 40% to 100% on different spots. Fig. 18 shows the development of stress with increasing laser power.

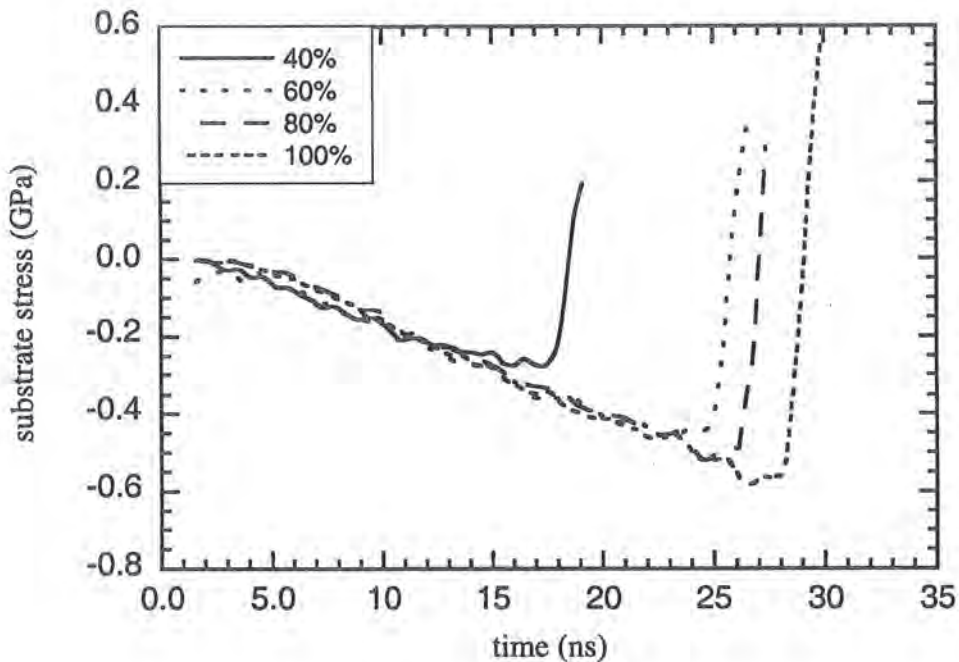


Fig. 18 Effect of laser power on fused quartz ($3063\mu\text{m}$) substrate sample: front Al film thickness: $1.1\mu\text{m}$, absorbing layer thickness: $0.4\mu\text{m}$.

As laser energy increases, the maximum compressive substrate stress also increases. At 40% laser power, the maximum substrate stress of 0.28GPa is achieved in a rise time of 18ns, while for 100% laser power a maximum substrate stress of 0.6GPa is obtained in 28.5ns. The higher maximum stress always occurs at later times and is approximately proportional to the laser power.

The corresponding tensile interface stress can be estimated from Fig. 18 as described previously. The maximum interface stress are 200MPa, 100MPa, 350MPa and 400MPa for 40%, 60%, 80% and 100% laser power respectively. Overall, the maximum interface stress increases with increasing laser power.

The effect of laser power was also studied on a $600\mu\text{m}$ thick Si wafer with a $1.1\mu\text{m}$ thick testing film and $0.4\mu\text{m}$ absorbing layer. As YAG laser power increased from 40% to

100%, the maximum compressive substrate stress increased from 0.7 to 2.3 GPa and was achieved at 3.2ns and 4.0ns respectively. The corresponding maximum tensile interface stress also increased from 60MPa to 100MPa.

Although the maximum substrate stress and maximum interface stress increase as laser power increases for both fused quartz and Si substrate samples, the data is quite different for the two kinds of samples. In the data for Si substrate samples, the maximum substrate stress and interface stress were achieved in a very short time, usually within 5ns. The higher stress level occurs at only slightly later time. But for the fused quartz substrate samples, the rise time of the maximum substrate stress and interface stress was very late (from 15 to 30ns). These differences are probably due to the development of the shock in the fused quartz substrate as discussed by Baker and Hollenbach. Also, the shock is responsible for the much greater interface stress in fused quartz samples than that in Si substrate.

3.5.2 Effect of testing film thickness

The effect of testing film thickness was studied for 3063 μ m thick fused quartz substrate samples. Three film thicknesses, 1.1 μ m, 1.45 μ m and 1.90 μ m were tested at full laser power. The absorbing layer thicknesses varied between 04 μ m and 0.54 μ m for these samples. Previous experiments by Yang (1974) indicated that small variations in absorbing layer thickness have little effect on the generated stress. The results for these tests are summarized in Table 2. Both the maximum substrate stress and maximum interface stress increased with increasing testing film thickness.

Table 2. Effect of front film thickness on $\sigma_{\text{substrate}}^{\text{max}}$ and $\sigma_{\text{interface}}^{\text{max}}$

Film thickness	1.1 μ m	1.45 μ m	1.9 μ m
$\sigma_{\text{substrate}}^{\text{max}}$ (GPa)	0.6	0.7	0.8
$\sigma_{\text{interface}}^{\text{max}}$ (MPa)	400	600	1000

3.5.3 Effect of substrate thickness

The influence of substrate thickness was investigated for both fused quartz and Si substrate samples with a 1.1 μ m thick front film and 0.4 μ m thick absorbing layer. The resulting maximum substrate stress and maximum interface stress values are summarized in Table 3 for three thicknesses of fused quartz (1531 μ m, 3063 μ m and 6125 μ m) and in Table 4 for three thicknesses of Si (400 μ m, 600 μ m and 3000 μ m). For both types of samples, the maximum substrate stress and maximum interface stress decrease significantly with increasing substrate thickness. The maximum substrate stress decreases more rapidly than the maximum interface stress.

Table 3. Effect of substrate thickness on Si substrate samples

Substrate thickness	400 μm	600 μm	3000 μm
$\sigma_{\text{substrate}}^{\text{max}}$ (GPa)	1.7	1.4	0.55
$\sigma_{\text{interface}}^{\text{max}}$ (MPa)	100	90	75

Table 4. Effect of substrate thickness on fused quartz samples

Substrate thickness	1531 μm	3063 μm	6125 μm
$\sigma_{\text{substrate}}^{\text{max}}$ (GPa)	1.2	0.5	0.3
$\sigma_{\text{interface}}^{\text{max}}$ (MPa)	370	350	50

The attenuation in maximum substrate stress and maximum interface stress is due to the finite size of the YAG source. The greater the distance from the source, the greater the attenuation. The effect of the substrate thickness can be estimated analytically by considering a circular region of diameter D as shown in Fig. 19.

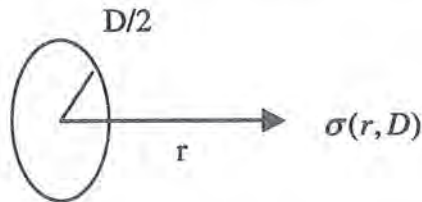


Fig. 19 Stress generated by a finite sized pancake YAG source.

The stress signal picked up at distance r from the source can be approximated by an integral of a Gaussian distribution over the entire source region, i.e.,

$$\sigma(r, D) = \frac{A}{D^2} \int_0^{2\pi} \int_0^{D/2} \frac{1}{\sqrt{r^2 + x^2}} \exp\left(-\frac{\left(t - \sqrt{r^2 + x^2} / c\right)^2}{T^2}\right) x dx d\theta \quad (24)$$

The stress at the testing film interface is proportional to the time derivative of (24)

$$\sigma_{interface}(r,D) = \frac{B}{D^2} \int_0^{2\pi} \int_0^{D/2} \frac{t - \sqrt{r^2 + x^2}/c}{\sqrt{r^2 + x^2}} \exp\left(-\frac{\left(t - \sqrt{r^2 + x^2}/c\right)^2}{T^2}\right) x dx d\theta \quad (25)$$

where A and B are material constants and $T=2.9\text{ns}$. The relative maximum stress in substrate and maximum stress at the interface were evaluated numerically for difference source size D at different distance r and plotted in Fig. 20 and 21.

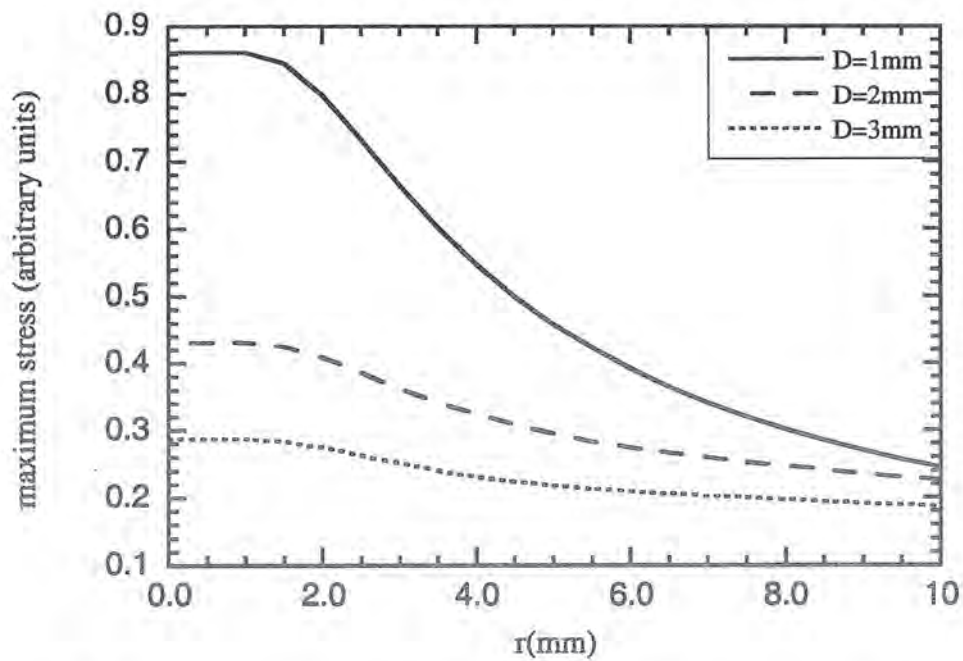


Fig. 20 Attenuation of maximum stress w.r.t. distance and source diameter

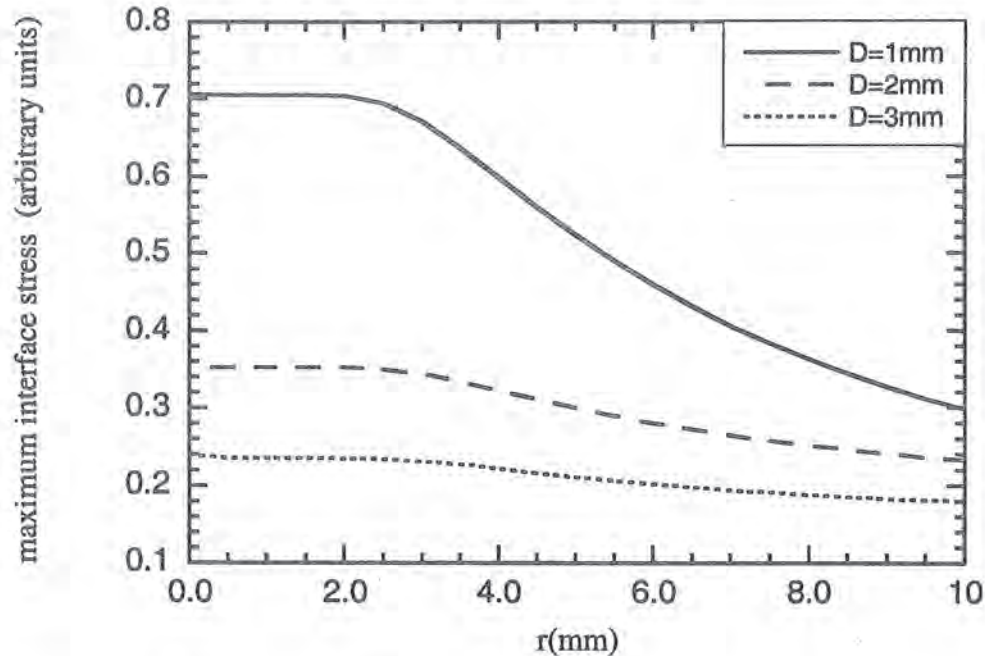


Fig. 21 Attenuation of maximum stress at interface w.r.t. distance and source diameter.

The larger the source size, the lower the maximum substrate stress and maximum interface stress attenuate. For the same source diameter, greater attenuation occurs at longer distances. The diameter of the YAG spot in the current experiment is about 1mm. Based on the $D=1\text{mm}$ curves in Fig. 20 and 21, the maximum substrate stress begins to attenuate after about 1mm and the maximum interface stress begins to attenuate after 2mm. The maximum substrate stress attenuates faster than the maximum interface stress, which is consistent with the effect of substrate thickness reported in Table 3 and 4.

3.5.4 Discussion

For both fused quartz and Si substrate samples, the maximum stress in the substrate and the maximum stress at the interface increase with increasing YAG laser power. For testing film thickness in the range of $1.1\mu\text{m}$ and $1.9\mu\text{m}$, the maximum substrate stress and maximum interface stress on fused quartz substrate were enhanced with increasing film thickness. Thicker films have higher interface stress. For both types of samples, the maximum substrate stress and maximum interface stress decrease with increasing substrate thickness due to the finite diameter of the YAG source and geometric attenuation. Analytical estimates show that stress level could be enhanced by either increasing the YAG spot size or reducing the substrate thickness. In practical experiments, several factors including YAG spot size, film thickness and substrate thickness, must be coordinated. Although a larger YAG laser spot can make the stress level more constant with respect to substrate thickness, it may not be able to produce high enough fluence to fail the film. Thicker films lead to higher interface stress. However, the surface reflectance of the film decreases with increasing film thickness causing poor

interferometric signal. For a particular substrate thickness and laser energy level, there should be an optimal coordination between these factors

The quantitative measurements also reveal significant difference between the data for fused quartz substrate and Si substrate samples. This difference is presumably due to the existence of a decompression shock in the fused quartz substrate.

4 CONCLUSIONS

Analytical predictions of displacement, substrate stress and interface stress provided meaningful insight into the mechanics of the laser spallation experiment. Qualitative observations of damage revealed both substrate and film failure in Si substrate samples but only film failure in fused quartz substrate samples. Quantitative interferometric measurements confirmed differences in the stress development for the two kinds of samples. In fused quartz substrates, the compressive pulse evolved into a weak shock. The existence of a shock created a large stress at the film interface, promoting failure. We anticipate this shock mechanism will be highly beneficial in the extension to the shear mode test. In addition, fused quartz is a better material for spallation test in the sense that no substrate damage will occur before the film spallation. For both types of substrates, the maximum substrate stress and maximum interface stress increased with increasing laser fluence, testing film thickness and decreasing substrate thickness.

APPENDIX A

Analytical Solution

To solve equation (1) with boundary condition (5), we use Laplace transformation to obtain a partial differential equation in the Laplace domain,

$$\tilde{T}(x, s) = \frac{s}{D_i} \tilde{T}_i \quad (\text{A1})$$

with boundary conditions

$$\begin{cases} \tilde{T}_1(0, s) = \tilde{T}_2(0, s) \\ k_1 \tilde{T}_1' \big|_{x=0^-} - k_2 \tilde{T}_2' \big|_{x=0^+} = \phi \end{cases} \quad (\text{A2})$$

and

$$\begin{cases} \tilde{T}_1(x, s) \rightarrow 0 & \text{as } x \rightarrow -\infty \\ \tilde{T}_2(x, s) \rightarrow 0 & \text{as } x \rightarrow +\infty \end{cases} \quad (\text{A3})$$

The solution of above equations is

$$\begin{cases} \tilde{T}_1(x,s) = \frac{\phi}{\sqrt{k_1\rho_1C_1} + \sqrt{k_2\rho_2C_2}} \cdot \frac{1}{s} \cdot e^{\sqrt{\frac{s}{D_1}}x} \\ \tilde{T}_2(x,s) = \frac{\phi}{\sqrt{k_1\rho_1C_1} + \sqrt{k_2\rho_2C_2}} \cdot \frac{1}{s} \cdot e^{-\sqrt{\frac{s}{D_2}}x} \end{cases} \quad (A4)$$

Using inverse Laplace transformation , we obtain the solution to the initial problem.

In order to solve equation (8), we solve for the Green 's function when x is large and positive. The thermal source can be located in material 1 or 2.

For the case where the thermal source is in material 2, the PDE to solve for the Green's function is given by

$$\begin{cases} \rho \frac{\partial g_v}{\partial t} = \frac{\partial g_\sigma}{\partial x} \\ \frac{\partial g_\sigma}{\partial t} = (\lambda + 2\mu) \frac{\partial g_v}{\partial x} - \delta(x - x_s, t - t_s) \end{cases} \quad \text{where } x_s > 0 \quad (A5)$$

where

$$\begin{cases} v(x,t) = g_v \otimes (3\lambda + 2\mu)\alpha \frac{\partial T}{\partial x} \\ \sigma(x,t) = g_\sigma \otimes (3\lambda + 2\mu)\alpha \frac{\partial T}{\partial x} \end{cases} \quad (A6)$$

Equation (A5) is equivalent to

$$\begin{cases} \rho_i \frac{\partial g_v}{\partial t} = \frac{\partial g_\sigma}{\partial x} \\ \frac{\partial g_\sigma}{\partial t} = (\lambda + 2\mu)_i \frac{\partial g_v}{\partial x} \end{cases} \quad (A7)$$

with boundary conditions

$$\begin{cases} g_v|_{x=0^-} = g_v|_{x=0^+} \\ g_v|_{x=x_s^-} = \frac{1}{(\lambda + 2\mu)_2} \delta(t - t_s) \\ g_\sigma|_{x=0^-} = g_\sigma|_{x=0^+} \\ g_\sigma|_{x=x_s^-} = g_\sigma|_{x=x_s^+} \end{cases} \quad (\text{A8})$$

Using Laplace transformation, Eqs. (A7) and (A8) become

$$\begin{cases} \rho_i s \tilde{g}_v = \frac{\partial \tilde{g}_\sigma}{\partial x} \\ s \tilde{g}_\sigma = (\lambda + 2\mu)_i \frac{\partial \tilde{g}_v}{\partial x} \end{cases} \quad (\text{A9})$$

with boundary conditions

$$\begin{cases} \tilde{g}_v|_{x=0^-} = \tilde{g}_v|_{x=0^+} \\ \tilde{g}_v|_{x=x_s^-} = \frac{1}{(\lambda + 2\mu)_2} e^{-st_s} \\ \tilde{g}_\sigma|_{x=0^-} = \tilde{g}_\sigma|_{x=0^+} \\ \tilde{g}_\sigma|_{x=x_s^-} = \tilde{g}_\sigma|_{x=x_s^+} \end{cases} \quad (\text{A10})$$

the solution in the Laplace domain is found to be

$$\begin{cases} \tilde{g}_v(x, s) = \frac{1}{2\rho_2 c_2^2} \left[e^{-s(t_s + \frac{x-x_s}{c_2})} + \frac{\rho_1 c_1 - \rho_2 c_2}{\rho_1 c_1 + \rho_2 c_2} \cdot e^{-s(t_s + \frac{x+x_s}{c_2})} \right] \\ \tilde{g}_\sigma(x, s) = -\frac{1}{2c_2} \left[e^{-s(t_s + \frac{x-x_s}{c_2})} + \frac{\rho_1 c_1 - \rho_2 c_2}{\rho_1 c_1 + \rho_2 c_2} \cdot e^{-s(t_s + \frac{x+x_s}{c_2})} \right] \end{cases} \quad (\text{A11})$$

By inverse Laplace transformation, we obtain the Green's when $x > x_s > 0$ as

$$\begin{cases} g_v(x, x_s, t-t_s) = \frac{1}{2\rho_2 c_2^2} \left[\delta\left(t-t_s - \frac{x-x_s}{c_2}\right) + \frac{\rho_1 c_1 - \rho_2 c_2}{\rho_1 c_1 + \rho_2 c_2} \cdot \delta\left(t-t_s - \frac{x+x_s}{c_2}\right) \right] \\ g_\sigma(x, x_s, t-t_s) = -\frac{1}{2c_2} \left[\delta\left(t-t_s - \frac{x-x_s}{c_2}\right) + \frac{\rho_1 c_1 - \rho_2 c_2}{\rho_1 c_1 + \rho_2 c_2} \cdot \delta\left(t-t_s - \frac{x+x_s}{c_2}\right) \right] \end{cases} \quad (A12)$$

which is a sum of a direct pulse and a reflection off the interface.

For the case when the thermal source is located in material 1, solution follows as before. when $x \gg 0$ and $x_s < 0$, the Green's function are given by

$$\begin{cases} g_v(x, x_s, t-t_s) = \frac{1}{c_1} \cdot \frac{1}{\rho_1 c_1 + \rho_2 c_2} \cdot \delta\left(t-t_s - \frac{x}{c_2} + \frac{x_s}{c_1}\right) \\ g_\sigma(x, x_s, t-t_s) = -\frac{1}{c_1} \cdot \frac{\rho_2 c_2}{\rho_1 c_1 + \rho_2 c_2} \cdot \delta\left(t-t_s - \frac{x}{c_2} + \frac{x_s}{c_1}\right) \end{cases} \quad (A13)$$

which consists of a single pulse that has been transmitted through the interface.

The solution to the one-dimensional wave equation (16) is then obtained using

$$\sigma(x, t) = \int_{-\infty}^{+\infty} \int_0^t g_\sigma(x, x_s; t-t_s) \cdot (3\lambda + 2\mu) \cdot \frac{\partial T(x_s, t_s)}{\partial t_s} \cdot dx_s dt_s \quad (A14)$$

To find the displacement field, we integrate Equ. (A14) by parts to obtain

$$\sigma(x, t) = \frac{\partial}{\partial t} \int_{-\infty}^{+\infty} \int_0^t (3\lambda + 2\mu) \alpha \cdot g_\sigma(x, x_s; t-t_s) \cdot T(x_s, t_s) dx_s dt_s \quad (A15)$$

Because

$$\sigma(x, t) = \rho_2 c_2 \frac{\partial u(x, t)}{\partial t} \quad (A16)$$

For $x > 0$, we can write

$$u(x, t) = -\frac{1}{\rho_2 c_2} \int_{-\infty}^{+\infty} \int_0^t (3\lambda + 2\mu) \alpha \cdot g_\sigma(x, x_s; t-t_s) \cdot T(x_s, t_s) dx_s dt_s \quad (A17)$$

APPENDIX B

Asymptotic Solution

We start from the heat transfer equation (1) with boundary conditions

$$\begin{cases} T(x=0^-) = T(x=0^+) \\ \left(k \frac{\partial T}{\partial x} \right)_{x=0^-} - \left(k \frac{\partial T}{\partial x} \right)_{x=0^+} = \delta(t) \end{cases} \quad (B1)$$

Use Fourier transform w.r.t. time, from (1) and (B1), we get

$$\hat{T}(x, w) = \frac{1}{\sqrt{k_1 \rho_1 C_1} + \sqrt{k_2 \rho_2 C_2}} \begin{cases} \frac{1}{\sqrt{iw}} e^{\sqrt{\frac{iw}{D_1}} x} & \text{for } x \leq 0 \\ \frac{1}{\sqrt{iw}} e^{-\sqrt{\frac{iw}{D_2}} x} & \text{for } x \geq 0 \end{cases} \quad (B2)$$

Still using single Fourier transform w.r.t. time, from the wave equation (8) together with continuity conditions of stress and velocity at the interface, we get

$$\hat{\sigma}_{,xx} + \frac{w^2}{c^2} \hat{\sigma} + \frac{(3\lambda + 2\mu)\alpha w^2}{c^2} \hat{T} = 0 \quad (B3)$$

the coefficients in (B3) take different values of material #1 and #2 respectively for $x < 0$ and $x > 0$.

Substitute (B2) into (B3) and after a long and tedious derivation, we get

$$\sigma(w) = B(w) e^{-i \frac{w}{c_2} x} - \frac{(3\lambda + 2\mu)_2 \alpha_2}{\sqrt{k\rho C} + \sqrt{k\rho C}} \cdot \frac{\sqrt{iw}}{iw - \frac{c_2^2}{D_2}} \cdot e^{-\sqrt{\frac{iw}{D_2}} x} \quad \text{for } x \geq 0 \quad (B4)$$

where

$$B(w) = \frac{\rho_2 c_2}{\rho_1 c_1 + \rho_2 c_2} \cdot \frac{1}{\sqrt{k_1 \rho_1 C_1} + \sqrt{k_2 \rho_2 C_2}} \left\{ \left[\frac{(3\lambda + 2\mu)_1 \alpha_1 \sqrt{D_1}}{iw \frac{D_1}{c_1} - c_1} + \frac{(3\lambda + 2\mu)_2 \alpha_2 \sqrt{D_2}}{iw \frac{D_2}{c_2} - c_2} \cdot \frac{\rho_1 c_1}{\rho_2 c_2} \right] \right. \\ \left. + \left[- (3\lambda + 2\mu)_1 \alpha_1 \sqrt{D_1} \cdot \frac{\sqrt{iw}}{iw D_1 - c_1^2} + (3\lambda + 2\mu)_2 \alpha_2 \sqrt{D_2} \cdot \frac{\sqrt{iw}}{iw D_2 - c_2^2} \right] \right\}$$

We only need the solution in the right half space, because our signal will be picked up at $x > 0$.

Since

$$\sigma = -\rho_2 c_2 \frac{\partial u}{\partial t} \quad (B5)$$

we get $u = -\frac{1}{\rho_2 c_2} \cdot \frac{\hat{\sigma}}{iw}$, after substituting $\hat{\sigma}$ in and take the limit as $w \rightarrow 0$, we get

$$\hat{u}(x, w) = A_1 \frac{e^{-\frac{iw}{c_2}x}}{iw} + A_2 \frac{e^{-\frac{iw}{c_2}x}}{\sqrt{iw}} + A_3 \frac{e^{-\sqrt{\frac{iw}{D_2}}x}}{\sqrt{iw}} \quad (B6)$$

where

$$\begin{cases} A_1 = \frac{1}{\rho_1 c_1 + \rho_2 c_2} \cdot \frac{1}{\sqrt{k_1 \rho_1 C_1} + \sqrt{k_2 \rho_2 C_2}} \cdot \left[\frac{(3\lambda + 2\mu)_1 \alpha_1 \sqrt{D_1}}{c_1} + \frac{(3\lambda + 2\mu)_2 \alpha_2 \sqrt{D_2}}{c_2} \cdot \frac{\rho_1 c_1}{\rho_2 c_2} \right] \\ A_2 = \frac{1}{\rho_1 c_1 + \rho_2 c_2} \cdot \frac{1}{\sqrt{k_1 \rho_1 C_1} + \sqrt{k_2 \rho_2 C_2}} \cdot \left[-\frac{(3\lambda + 2\mu)_1 \alpha_1 \sqrt{D_1}}{c_1^2} + \frac{(3\lambda + 2\mu)_2 \alpha_2 \sqrt{D_2}}{c_2^2} \right] \\ A_3 = -\frac{(3\lambda + 2\mu)_2}{\sqrt{k_1 \rho_1 C_1} + \sqrt{k_2 \rho_2 C_2}} \cdot \frac{D_2}{\rho_2 c_2^3} \end{cases}$$

In (B6), only the first term counts for the late time response, for which if we take the inverse Fourier transform, we get the asymptotic solution of displacement. Substitute it back into (B5), we get the asymptotic solution of stress.

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