27
2-1-77
25 cap to NTIS

UCID- 17258

Lawrence Livermore Laboratory

LASER-GENERATED STRESS PULSES FOR MATERIAL-RESPONSE STUDIES

David S. Wood*

William W. Wilcox

September 7, 1976

MASTER

*California Institute of Technology, Pasadena, California.

This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the laboratory.

Prepared for U.S. Energy Research & Development Administration under contract No. W-7405-Eng-48.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

CONTENTS

Abstract	1
Introduction	1
Experimental Method	2
Experimental Equipment	3
Results	7
Discussion	7
Conclusions	21
References	23

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

LASER-GENERATED STRESS PULSES FOR MATERIAL-RESPONSE STUDIES

ABSTRACT

Experimental techniques for the generation of stress pulses of submicrosecond duration, in the form of uniaxial strain waves, were developed by absorbing the radiation from a Q-switched laser in thin films of liquids and solids resting on hard steel substrates. The experiments employed pulses of radiation at a wavelength of $1.06 \mu\text{m}$, with a duration of about 30 ns at half maximum power and fluences from 8 to 13 J/cm^2 . The stress waves produced in the steel substrates were measured by means of x-cut quartz piezoelectric gages.

The typical stress pulse consisted of a rapid rise to a peak value followed by a slower delay over a period of about one-quarter microsecond. The maximum stress generated with a liquid absorber was 3.4 kbar when a solution of cupric chloride in water was irradiated with a fluence of 8 J/cm^2 . A peak stress of 15 kbar was obtained with a $1\text{-}\mu\text{m}$ -thick layer of aluminum under glass and a fluence of 8 J/cm^2 .

INTRODUCTION

Stress pulses of submicrosecond duration are useful for studies of material properties such as elastic constants and plastic deformation at high rates. The rate of plastic strain in crystalline solids is directly related to the crystal defects known as dislocations through the relation

$$\dot{\gamma}_p = b\rho v,$$

where $\dot{\gamma}_p$ is the plastic shear strain rate on a given slip system, b is the slip vector of the dislocations, ρ is the total length of moving dislocation line per unit volume, and v is the dislocation velocity. Thus, knowledge of the influence of applied stress, temperature, and other variables upon dislocation velocity is of fundamental importance for a basic understanding of the response of crystalline materials to loading at high rates.

First-order theory¹ indicates that dislocations cannot move faster than the speed of elastic shear waves, typically $3 \times 10^3 \text{ m/s}$. More detailed theoretical models² indicate, however, that dislocation velocities may not be restricted in this way. Experimental measurements of dislocation velocities have, so far, not exceeded about 10^2 m/s .³ Thus the behavior of dislocations at velocities of the order of elastic shear waves is still unresolved, in spite of the fact that it is of basic importance in understanding the response of materials to very rapidly applied loads of high intensity, such as high-speed impact and explosive loading.

The velocities of individual dislocations are determined experimentally by subjecting them to stress pulses of known amplitude and duration and observing their initial and final positions.⁴ The distance which a dislocation moves in such experiments cannot, as a practical matter, exceed about 1 mm; otherwise, it passes out of the crystal and disappears or becomes entangled with other dislocations. Thus, if dislocation velocities near the speed of elastic shear waves are to be measured, the duration of the applied stress must be of the order of $1/3 \mu\text{s}$ or less.

The objective of the investigation reported herein is to develop an experimental technique for generating stress pulses of submicrosecond duration and several kilobars amplitude which would be employed to measure high dislocation velocities. Such stress pulses may also be useful in other material studies, including the measurement of elastic constants under unusual environmental conditions.

EXPERIMENTAL METHOD

Several investigators⁵⁻¹² have demonstrated that short-duration stress pulses may be produced when the energy in a Q-switched laser pulse is absorbed on the surface or in the interior of a solid. This is the basic method employed in the present investigation.

A "square" pulse — that is, a constant stress for the desired period of time — would be the most convenient type of stress pulse for dislocation-velocity studies because the dislocation motion observed in a given test would then be associated with a single value of stress. When the stress varies significantly during a given experiment, a more complex analysis of the data is required to determine the dislocation-velocity-vs-stress relationship.

Theoretically, a close approximation to a square pulse can be obtained by the following scheme: A layer of liquid of uniform thickness is placed on the surface of the test specimen, and the laser pulse energy is absorbed in the liquid. If the coefficient of absorption, μ , of the laser radiation in the liquid is adjusted, by the use of suitable soluble dyes or other absorbing additions, so that $\mu h = 1/2$, where h is the thickness of the liquid, and if the specimen surface reflects the laser radiation which reaches it, then it can be shown that the absorbed energy is nearly uniformly distributed throughout the depth of the liquid. Then, if the duration of the laser pulse is small compared to the time for a sound wave to traverse the liquid thickness, the liquid will

be uniformly heated at constant volume, and a pressure that is nearly constant throughout the liquid thickness will result. This pressure will then act upon the surface of the test specimen until rarefaction waves from the free surface of the liquid reach the test specimen.

This basic concept was implemented experimentally with several liquid-plus-absorber combinations, as follows:

1. Isoamyl alcohol containing various concentrations of colloidal graphite particles obtained by dilution of Acheson Colloids' Alkadag ("Dag").
2. A saturated solution of copper sulfate in water.
3. 1,2-dichloroethane containing Eastman Dye A9740 (Eastman Improved Formula A9740 liquid Q-switch for 1.06 μm).

4. Solutions of several concentrations of cupric chloride in water.

Stress pulses were also produced by absorbing the laser energy in very thin layers of aluminum and colloidal graphite "contained" under a layer of clear glass in the manner described by Anderholm.⁷ Finally, stress pulses were obtained with Wilson-Weld shade 4 didymium glass.

EXPERIMENTAL EQUIPMENT

The laser pulses were obtained from a Holobeam Model 6082 Nd:glass laser. This consists of an oscillator, Q-switched by a Pockels cell, a single amplifier stage, and the associated power supply and control equipment. The output beam is 19 mm (3/4 in.) in diameter, with a maximum pulse energy of 15 J of radiation at a wavelength of 1.06 μm .

Most of our experiments were performed at a laser output of 7-1/2 J. The laser beam was reduced to 10 mm in diameter by a suitable lens, in order to match the diameter of the test specimen and energy absorber, and was redirected from a horizontal to a vertical path by a suitable mirror.

The time history of the laser intensity was measured by means of a photodiode. A plain glass sheet at 45° to the laser beam axis redirected about 10% of the beam to the photodiode, and the signal was recorded on a Tektronix type 7904 oscilloscope.

The laser beam irradiated an absorbing layer on top of an assembly of test specimen, momentum trap, and quartz gage designed for later use in dislocation-velocity studies. A schematic diagram of this arrangement is shown in Fig. 1. For the present experiments a dummy specimen of 17-4PH stainless steel, heat treated to condition H900 (45 Rc hardness), was employed. The momentum trap

Fig. 1. Schematic diagram of absorbing layer, test specimen, momentum trap, and quartz gage.

is of the same material. The quartz gage is of the type described by Jones, Neilson, and Benedick.¹³ It is connected to the input of a 7904 oscilloscope through the circuitry shown and provides the means for measuring the stress pulse.

The matching surfaces of the test specimen, momentum trap, and quartz gage were flat to one wavelength of visible light. A very small amount of methylene diiodide (CH_2I_2), a liquid of relatively high acoustic impedance, was employed to fill any residual voids at these interfaces. These provisions permitted transmission of the stress wave with negligible distortion. Some of the experiments were performed with the energy absorber resting directly on the quartz gage. Some experiments employed larger quartz gages, 3.2 mm (1/8 in.) thick and 25 mm (1 in.) in diameter. In all cases the geometry of the arrangement was such that edge-effect waves from the periphery of the irradiated area did not affect the measurements.

The electrical output of the quartz gages was related to stress amplitude at the upper surface of the quartz by the calibration factor determined by Jones, Neilson, and Benedick,¹³ together with the known thickness of the gages and area of the measuring electrode. When the steel specimen and momentum trap were employed, the stress in the specimen and momentum trap was related to that in the quartz by the well-known acoustic mismatch relations. Further, the zero of the time base of the quartz gage output was shifted by the known wave-transit time through the specimen and momentum trap. Thus all stress-vs-time relations shown in the section on results represent stress-vs-time relations at the base of the energy-absorbing layer, with zero time corresponding to the beginning of the laser pulse.

Figure 2 is a photograph of those portions of the test fixture immediately adjacent to the test specimen and quartz gage. The quartz gage and momentum trap are held in position by light spring pressure exerted upward on the bottom of the quartz gage by the cylinder of Styrofoam at the left in the photograph. Figure 3 is a magnified photograph of the bottom surface of a quartz gage. This shows two narrow rings within which the gold plating has been removed from the gage to form two isolated electrodes. The circular central electrode provides the gage output signal. The potential of the surrounding annular electrode is the same as that of the central electrode at all times and thus serves to reduce electrical edge effects at the periphery of the central electrode.

Fig. 2. Test fixture parts.

Fig. 3. Quartz gage.

Figure 4 shows the assembled lower portion of the test fixture, which includes provisions for leveling and alignment relative to the laser beam. Figure 5 shows the test fixture mounted in front of the beam-converging lens and the laser. The upper portion of the test fixture shown in this photograph contains the 45° mirror and optical-alignment provisions.

RESULTS

The more significant stress pulses obtained are shown in Figs. 6 through 15. Each figure shows both the laser intensity and the stress plotted on a common time base. The zero of the time base is the instant at which the laser pulse began. The stress is plotted at the time it occurred at the lower surface of the energy-absorbing layer, as explained above. The stress-vs-time record is terminated at the end of the appropriate recording time for the quartz gage employed in that test. The laser fluence and the nature of the energy absorber are noted for each figure.

The point marked t_1 on the time axes in Figs. 6 through 12 and 15 is the time at which an acoustic wave originating at the top surface of the energy absorber at the beginning of the laser pulse would arrive at the lower surface of the energy absorber. In Figs. 13 and 14, the time interval denoted by $2t_1$ and beginning when the stress pulse begins is the time for an acoustic wave to travel upward from the thin confined absorber to the upper (free) surface of the glass confining layer, be reflected as an unloading wave, and return downward to the absorber.

DISCUSSION

The stress pulse produced by a fluence of 8 J/cm^2 incident on a 0.25-mm-thick absorbing layer of 2.5% Dag in isoamyl alcohol, given in Fig. 6, shows that the stress did not develop significantly until after the time t_1 . This shows that the radiation was absorbed almost entirely at the top surface of the liquid layer, rather than uniformly through the depth. After the peak stress of about 0.7 kbar is reached, the stress decreases relatively slowly. Thus it appears that a relatively small fraction of the liquid, at its upper surface, was heated to a relatively high temperature and vaporized, while the remainder of the liquid only transmitted the stress without participating in its production.

Fig. 4. Test fixture.

Fig. 5. Experimental apparatus.

Fig. 6. Stress pulse. Laser fluence: 8 J/cm^2 . Energy absorber: 2.5% Dag in isoamyl alcohol, 0.25 mm thick.

Fig. 7. Stress pulse. Laser fluence: 8.9 J/cm^2 . Energy absorber: 10% Dag in isoamyl alcohol, 0.1 mm thick.

Fig. 8. Stress pulse. Laser fluence: 12.8 J/cm^2 . Energy absorber: 10% Dag in isoamyl alcohol, 0.1 mm thick.

Fig. 9. Stress pulse. Laser fluence: 8 J/cm^2 . Energy absorber: 14 g CuSO₄ in 100 cc H₂O, 0.4 mm thick.

Fig. 10. Stress pulse. Laser fluence: 8 J/cm^2 . Energy absorber: Eastman Improved Formula A9740 Dye Solution, 0.25 mm thick.

Fig. 11. Stress pulse. Laser fluence: 8 J/cm^2 . Energy absorber: 35 g CuCl_2 in 100 cc H_2O , 0.3 mm thick.

Fig. 12. Stress pulse. Laser fluence: 8 J/cm^2 . Energy absorber: 70 g CuCl_2 in 100 cc H_2O , 0.2 mm thick.

Fig. 13. Stress pulse. Laser fluence: 8 J/cm^2 . Energy absorber: 10% Dag in isoamyl alcohol under 0.14 mm glass.

Fig. 14. Stress pulse. Laser fluence: 8 J/cm^2 . Energy absorber: $1 \text{ }\mu\text{m}$ aluminum under 0.14 mm glass.

Fig. 15. Stress pulse. Laser fluence: 8 J/cm^2 . Energy absorber: Willson-Weld shade 4 didymium glass, 1.17 mm thick.

Figure 7 shows that when the concentration of colloidal graphite particles in the liquid absorber is increased by a factor of 4, the behavior is essentially the same. The fact that the stress pulse began earlier in this experiment is a consequence of the fact that the liquid layer was thinner, so the propagation time through it was shorter.

Figure 8 shows that when the total energy of the laser pulse is increased by about 50% (from 8.9 J/cm^2 to 12.8 J/cm^2), a higher peak stress is produced, namely 1.2 kbar, but the behavior is otherwise very similar.

In view of the above results with a colloidal suspension of graphite in isoamyl alcohol as the energy-absorbing medium, we decided to investigate the behavior of true solutions. Figure 9 shows the stress pulse obtained when a 0.4-mm-thick layer of a saturated solution of 14 g of copper sulfate in 100 cc of water was irradiated by 8 J/cm^2 of laser energy. This shows that the stress rises to its maximum value of about 1.3 kbar well before the time t_1 . Following the initial peak, the stress decays to about 0.7 kbar, which is sustained until the end of the recording time of the quartz gage.

If all the laser energy had been absorbed within the liquid and uniformly distributed in depth, the temperature rise would be about

$$\Delta T = \frac{\Phi}{h\rho C_p} = 48^\circ\text{C},$$

where Φ is the fluence of the laser pulse, h the thickness of the liquid, ρ the density of the liquid, and C_p the specific heat (of water).

Since the duration of the laser pulse is much smaller than the time, t_1 , for a sound wave to traverse the depth of the liquid, this heating occurs at a constant volume, and the pressure would increase to

$$p = \frac{\alpha\Delta T}{\beta} = 0.43 \text{ kbar},$$

where $\alpha = 4 \times 10^{-4}/^\circ\text{C}$ is the average volume coefficient of thermal expansion of water over the temperature interval $20\text{--}68^\circ\text{C}$, and $\beta = 0.045 \text{ kbar}^{-1}$ is the compressibility of water.

The fact that the measured stress is significantly greater than the pressure due to uniform heating of the water indicates that some other physical mechanism is involved in the production of this stress pulse. Probably a major fraction of the laser energy in this experiment was actually absorbed by heating and

vaporization of the surface of the stainless steel specimen. Two observations point toward this conclusion. First, the surface of the steel showed visual evidence of laser damage. Second, the stress pulse shape is consistent with this interpretation. The initial peak in the stress occurs after sufficient laser energy has been absorbed in a thin surface layer of the steel to vaporize that layer. The stress results because the density of this vapor is still quite high. The stress then produces an upward-propagating wave in the overlying water, which accelerates the water upward. Thus the metal vapor begins to expand and the pressure decreases. The observed stress pulse may have arisen from a combination of vaporization of the metal surface and heating of the liquid.

Other liquid solutions were investigated with a view to finding a solution which would absorb more of the laser energy than the saturated copper sulfate solution. Figure 10 shows that Eastman Improved Formula A9740 Dye Solution (intended for use as a Q-switching dye solution with Nd:glass lasers) produces a stress pulse quite similar to that obtained with the copper sulfate solution.

Figures 11 and 12 show that solutions of cupric chloride in water behave similarly to the colloidal graphite suspensions in isoamyl alcohol. The stress does not rise significantly until after the acoustic travel time t_1 , indicating energy absorption at the upper surface of the liquid rather than throughout the depth. The more concentrated CuCl_2 solution, Fig. 12, gives a stress pulse which rises more rapidly to a higher peak (3.4 kbar) and decays somewhat more quickly thereafter. This is consistent with the view that the higher concentration of CuCl_2 absorbs the laser energy within a thinner layer of liquid, thus raising it to higher temperatures and pressures.

The nature of the stress pulses produced when the energy-absorbing medium is "confined" under a layer of inert transparent material (glass) is illustrated by the results shown in Figs. 13 and 14. Fig. 13 shows that, when a thin layer of the 10% Dag/isoamyl-alcohol suspension is confined under glass, a much higher peak stress (3.4 kbar) is obtained than without "confinement" for the same energy input (0.8 kbar in Fig. 7).

Figure 14 shows that a 1- μm film of aluminum "confined" under glass produces a much higher peak stress (15 kbar) than the confined Dag suspension (note the different stress scale of Fig. 14). The stress pulse from the aluminum is, however, much shorter in duration. This stress pulse is similar to that observed by Anderholm⁷ in a similar experiment. The differences in

detail are that 1) Anderholm observed a peak stress of 34 kbar for a laser fluence of about 23 J/cm^2 as compared with our peak stress of 15 kbar for a fluence of about 8 J/cm^2 , and 2) Anderholm employed a laser pulse of about 12 ns width at half maximum compared with about 30 ns for our laser pulse.

The main features of the stress pulse shown in Fig. 14 are consistent with the following approximate physical concepts. First the aluminum film absorbs the laser radiation until it is vaporized, at which time the pressure rises very rapidly to the observed peak. This may be seen quantitatively as follows: The total energy required to heat aluminum to its boiling point and to vaporize it is $3.66 \times 10^5 \text{ J/mole}$. A $1\text{-}\mu\text{m}$ -thick layer of aluminum of normal solid density contains $10^{-5} \text{ mole/cm}^2$; thus the fluence required to vaporize the aluminum film in our experiment is 3.66 J/cm^2 . Thus the energy required for complete vaporization of the film is equal to about one half of the energy provided by the laser pulse. The other half of the laser pulse energy may have been reflected by the aluminum, rather than absorbed.

The peak pressure observed is consistent with the crude concept that the aluminum vapor at its boiling point, 2740°K , and at a specific volume equal to that of the solid, $10 \text{ cm}^3/\text{mole}$, behaves like a perfect gas. The pressure according to this theory is 23 kbar, compared with the observed 15 kbar.

The decay phase of the stress pulse of Fig. 14 may be understood on the basis of the model which considers the aluminum to be an expanding monatomic perfect gas contained between solids of known acoustic impedance. If p is the pressure at an arbitrary time t during the expansion, the velocities of the two solid surfaces (glass and quartz in this case) are

$$v_1 = \frac{p}{z_1} \text{ and } v_2 = \frac{p}{z_2},$$

where z_1 and z_2 are the acoustic impedances of the solids. The rate of change of the thickness x of the gas film is therefore

$$\frac{dx}{dt} = p \left(\frac{1}{z_1} + \frac{1}{z_2} \right).$$

Assuming that the gas is expanding adiabatically, we have

$$px^\gamma = p_0 x_0^\gamma,$$

where $\gamma = 5/3$ for the monatomic gas, and p_0 and x_0 are the initial values of the pressure and film thickness.

Solving this for x and substituting in the previous relation gives

$$\frac{dp}{p^{2+1/\gamma}} = - \frac{\gamma \left(\frac{1}{z_1} + \frac{1}{z_2} \right)}{x_0 p_0^{1/\gamma}} dt,$$

which integrates to

$$\frac{1}{p^{1+1/\gamma}} = \frac{(\gamma + 1) \left(\frac{1}{z_1} + \frac{1}{z_2} \right)}{x_0 p_0^{1/\gamma}} t + C.$$

The integration constant is chosen so that $p = p_0$ at $t = 0$ (that is, $t = 0$ at the peak of the stress pulse), with the result

$$\frac{p}{p_0} = \frac{1}{\left[1 + (\gamma + 1) \left(\frac{1}{z_1} + \frac{1}{z_2} \right) \frac{p_0}{x_0} t \right]^{\gamma/\gamma+1}}.$$

The values of the constants appropriate for the present experiment are:

$$p_0 = 15 \times 10^3 \text{ bars}$$

$$x_0 = 10^{-4} \text{ cm}$$

$$z_1 = 1.45 \frac{\text{bar-s}}{\text{cm}} \text{ (glass)}$$

$$z_2 = 1.52 \frac{\text{bar-s}}{\text{cm}} \text{ (x-cut quartz),}$$

so that the pressure-time decay curve is given by

$$\frac{p}{p_0} = \frac{1}{(1 + 0.54t)^{5/8}}$$

where t is measured in nanoseconds.

This model therefore predicts, for example, that the stress decays from the observed peak of 15 kbar to 6 kbar in about 6.6 ns. The observed stress pulse required roughly 15 ns for this stress decay. Thus the model gives the correct order of magnitude of the observed stress-decay time. Closer agreement is not to be expected for such a crude model.

Figure 14 shows that near the time $2t_1 = 48$ ns, which is required for a stress wave to propagate from the aluminum to the free surface of the glass and return to the aluminum, there appears to be a perturbation of the stress decay curve. This is to be expected, since the velocity of the glass adjacent to

the aluminum changes in response to the reflected wave. The above theoretical expression for the pressure-vs-time relation in the aluminum is not applicable after this time.

The relatively slow increase in stress following the minimum stress point in Fig. 14 was also observed by Anderholm. It may be associated with the relatively slow diffusion of heat from the vaporized aluminum into the adjacent solids.

Figure 15 shows the stress pulse obtained when a fluence of 12.5 J/cm^2 was incident on a 1.17-mm-thick layer of Willson-Weld shade 4 didyium glass resting on a hard steel substrate. The peak stress is about 4.65 kbar. At the end of the recording time of the quartz gage, the stress is 1.25 kbar. The peak stress occurs well before the wave transit time through the glass, t_1 . It was also noted that the surface of the hard steel substrate had suffered significant laser damage. These observations indicate that a major portion of the laser fluence was absorbed by vaporization of the surface of the steel substrate. On the other hand, the fact that the stress decays relatively more slowly than in Fig. 14 and remains at a relatively higher level at the end of the quartz-gage recording time suggests that a significant amount of the laser energy may have been absorbed in the glass.

CONCLUSIONS

A stress pulse, in the form of a uniaxial strain wave with an amplitude ranging from a fraction of a kilobar to 15 kbar and a duration of a fraction of a microsecond, may be generated using a pulse of laser radiation of $1.06 \mu\text{m}$ wave length having a fluence of about 8 J/cm^2 and a duration of about 30 ns at half maximum power. This is accomplished by absorbing the laser radiation in a thin layer of liquid or solid placed on the surface of a solid in which the stress pulse propagates as an elastic wave.

The shape of a typical stress pulse consists of a rapid rise to the peak stress followed by a slower, roughly exponential, decay.

Liquid absorbing layers consisting of colloidal suspensions of graphite or solutions of simple salts absorb the laser radiation very near the entrance surface, rather than throughout the thickness of the liquid. For this reason they do not produce "square" stress pulses.

An absorber consisting of a 1- μ m-thick layer of aluminum under a glass cover plate gave the maximum stress observed (15 kbar). The amplitude and shape of this stress pulse are shown to be in approximate agreement with a simple physical model in which the vaporized aluminum is assumed to behave like a perfect gas.

An absorber consisting of Willson-Weld shade-4 Didymium glass, 1.17 mm thick, appeared to absorb some of the laser energy, but the major portion of the energy was probably absorbed by vaporization of the surface of the hard steel substrate. It may be that an absorber consisting of a glass having a larger coefficient of absorption at the laser wavelength, together with a coating on the lower surface which reflects rather than absorbs, would produce an approximately "square" stress pulse.

REFERENCES

1. F.C. Frank, *Proc. Phys. Soc. London A* 62, 131 (1949).
2. F.R.N. Nabarro, *Theory of Crystal Dislocations* (Oxford University Press, 1967), p. 482.
3. K.M. Jassky and T. Vreeland, Jr., *Phil. Mag.* 21, 1147 (1970).
4. D.P. Pope and T. Vreeland, *Phil. Mag.* 20, 1163 (1969).
5. C.M. Percival, *J. Appl. Phys.* 38, 5313 (1967).
6. J.C. Bushnell and D.J. McCloskey, *J. Appl. Phys.* 39, 5541 (1968).
7. N.C. Anderholm, *Appl. Phys. Letters* 16, 113 (1970).
8. J.D. O'Keefe and C.H. Skeen, *Appl. Phys. Letters* 21, 464 (1972).
9. J.D. O'Keefe, C.H. Skeen, and C.M. York, *J. Appl. Phys.* 44, 4622 (1973).
10. M.P. Felix, Ph.D. Dissertation, University of California, San Diego (1973).
11. C.A. Calder and W.W. Wilcox, Lawrence Livermore Laboratory, Report UCID-16353 (1973).
12. B.P. Fairand, A.H. Clauer, R.G. Jung, and B.A. Wilcox, *Appl. Phys. Letters* 25, 431 (1974).
13. O.E. Jones, F.W. Neilson, and W.B. Benedick, *J. Appl. Phys.* 33, 3224 (1962).

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research & Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights.

NOTICE

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. Energy Research & Development Administration to the exclusion of others that may be suitable.

Printed in the United States of America

Available from

National Technical Information Service

U.S. Department of Commerce

5285 Port Royal Road

Springfield, VA 22161

Price: Printed Copy \$; Microfiche \$3.00

Page Range	Domestic Price	Page Range	Domestic Price
001-025	\$ 3.50	326-350	10.00
026-050	4.00	351-375	10.50
051-075	4.50	376-400	10.75
076-100	5.00	401-425	11.00
101-125	5.50	426-450	11.75
126-150	6.00	451-475	12.00
151-175	6.75	476-500	12.50
176-200	7.50	501-525	12.75
201-225	7.75	526-550	13.00
226-250	8.00	551-575	13.50
251-275	9.00	576-600	13.75
276-300	9.25	601-up	*
301-325	9.75		

*Add \$2.50 for each additional 100 page increment from 601 to 1,000 pages; add \$4.50 for each additional 100 page increment over 1,000 pages.

Technical Information Department

LAWRENCE LIVERMORE LABORATORY

University of California | Livermore, California | 94550