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AN EXPERIMENT TO PRODUCE AND MEASURE HIGH  
DISLOCATION VELOCITIES USING A LASER PULSE LOADING  
TECHNIQUE

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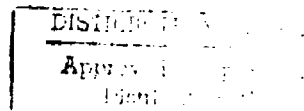
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AN EXPERIMENT TO PRODUCE AND MEASURE  
HIGH DISLOCATION VELOCITIES USING A  
LASER PULSE LOADING TECHNIQUE

by

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ABSTRACT

A method for the generation of a single short duration stress pulse in a solid is described. A giant laser pulse of 10 to 20 nanosecond duration is used to heat a layer of liquid on top of the solid. The heating occurs at constant volume, producing a pressure which is relieved by a wave propagating through the liquid layer. A 0.2 microsecond pulse is produced when a 0.25 mm layer of ethyl alcohol is used.

I. INTRODUCTION

The understanding and prediction of the deformation behavior of crystalline solids subjected to high intensity impulsive loading depends upon a knowledge of the behavior of dislocations moving at high velocity through the crystal lattice. The velocities of individual dislocations have been measured in single crystals of aluminum (1), (2), copper (3), (4), (5), and (6) and zinc (7) as a function of applied stress and temperature during recent years in the W. M. Keck Laboratory of Materials Science at the California Institute of Technology. The maximum dislocation velocity

attained in these experiments was approximately  $10^4$  in./sec. This is about one order of magnitude less than the speed of elastic shear waves. The results show that the dislocation velocity is linearly proportional to the applied stress and that the velocity decreases with increasing temperature at a given stress.

The behavior of dislocations is expected to change when their velocity approaches the speed of elastic shear waves more closely. The theory of dislocations based upon the approximations of a linearly elastic continuum predicts that the total energy of a dislocation tends toward infinity as the dislocation velocity approaches the speed of shear waves (8), (9) and (10). This indicates that the linear increase of velocity with stress cannot continue up to the speed of shear waves, and that the speed of shear waves is an upper limit for dislocation velocity. On the other hand, atomistic dislocation models have been proposed (11), in which the dislocation energy remains finite at the shear wave speed, so that it may be possible to have supersonic dislocations.

New experimental data regarding dislocations moving at velocities of the order of the speed of elastic shear waves is needed to resolve this and related issues. In order to obtain such data, a new technique of load application is required in which a controlled state of stress is applied to single crystals for a time of the order of one microsecond or less. This short duration of loading is needed so that a dislocation, moving at or near sound speed, will only move a distance of the order of one millimeter or less. This will insure that it remains within the crystal. Thus the velocity may be determined by observing the positions before and after a stress

application of known duration. Further, such a small distance of motion is needed to prevent significant interactions between different dislocations during the period of motion.

## 2. LASER PULSE LOADING

We propose to produce such controlled short duration stress pulses by means of giant laser pulses. The test crystal will be in the form of a flat plate about 0.5 mm thick and 1 cm diameter. A layer of liquid, such as ethyl alcohol about 0.25 mm thick, will be placed on top of the test crystal. This liquid layer will be irradiated at normal incidence by a giant laser pulse of 10 to 20 nanoseconds duration so as to heat the liquid in a time short compared to the time for a sound wave to propagate through the thickness of the liquid. Thus, the liquid will be heated at constant volume and hence a pressure will be developed in it, thus applying the desired loading to the test crystal. The duration of loading is the time required for the pressure unloading wave to propagate from the free surface of the liquid to the specimen surface. A 0.25 mm thick layer of ethyl alcohol gives a loading time of about 0.2 microsecond, for example.

The amount of energy required in the laser pulse depends upon the stress needed to move the dislocations at high velocity, the duration of the stress and the thermodynamic properties of the liquid energy absorbing layer. The stress required may be estimated by extrapolation of results obtained previously at lower dislocation velocities. For example, a pressure of 4 kilobars applied to the surface of a [111] oriented copper crystal at 200°K should accelerate the dislocations to a velocity of about  $10^5$  cm/sec

The heat which must be added to ethyl alcohol, at constant volume, in order to increase the pressure to the desired value was estimated in the following manner: first, Bridgman's (12) measurements of volume as a function of temperature and pressure were extrapolated, by least squares curve fitting, from his experimental temperature range of +20°C to +80°C to the range -100°C to +400°C. (His pressure range was from one atmosphere to 12 kilobar, so no extrapolation on the pressure scale was required.) From these results, it was found that, if the alcohol was initially at -78.5°C and one atmosphere pressure, an increase of temperature to about 236°C would be required to raise the pressure to 4 kb, at constant volume.

Second, the heat required to raise the temperature from -78.5°C to +236°C, at constant volume was estimated.

We have

$$dQ = c_v dT$$

where  $c_v$  is the specific heat at constant volume. Specific heat measurements have been made only at constant pressure, however. Thus the known relation

$$c_v = c_p + T \frac{\left(\frac{\partial V}{\partial T}\right)^2}{\frac{\partial V}{\partial P}}$$

must be employed where  $c_p$  is the specific heat at constant pressure,  $V$  is the volume, and  $T$  is the absolute temperature. Further, the specific heat at constant pressure has been measured only at atmospheric pressure. Thus the known relation

$$\frac{\partial c_p}{\partial P} = -\Gamma \frac{\partial^2 V}{\partial T^2}$$

must be employed to obtain

$$c_p(P, T) = c_p(P_0, T) - T \int_{P_0}^P \frac{\partial^2 V}{\partial T^2} dP$$



where  $c_p(P_0, T)$  is the constant pressure specific heat as a function of temperature at atmospheric pressure,  $P_0$ . The constant pressure specific heat at atmospheric pressure was determined as a function of temperature in the form

$$c_p(P_0, T) = A + B T + C T^2 + D T^3,$$

where the constants A, B, C, and D were determined by a least squares fit to the data Tyrer (13) obtained over the temperature range 0°C to 50°C. The value of the integral

$$-T \int_{P_0}^P \frac{\partial^2 V}{\partial T^2} dP$$

was obtained by numerical integration of the extrapolated Bridgman, P, V, T data. Thus  $c_p(P, T)$  was obtained. The quantity

$$T \frac{\left(\frac{\partial V}{\partial T}\right)^2}{\frac{\partial V}{\partial P}}$$

was also obtained as a function of P and T from the extrapolated Bridgman data. Thus  $c_v(P, T)$  was obtained. Finally, the heat added at constant volume was obtained from

$$\Delta Q = \int_{T_0}^T c_v dT$$

where the integration is along a line of constant volume, from the initial to the final temperature.

If the initial conditions are  $T_0 = -78.5^\circ\text{C}$  (195°K),  $P_0 = 1$  atmosphere, it is estimated, by the above method, that about 800 Joules/cm<sup>3</sup> must be added to the alcohol to raise the pressure to 4 kb. Thus the energy which must be absorbed by a layer of alcohol 1 cm. in diameter and 0.25 mm. thick is about 16 Joules.

The fraction of the energy of the incident laser pulse which can be absorbed in the liquid is limited by the need to have the energy reasonably uniformly distributed within the thickness of the liquid layer so that the pressure will be reasonably uniform through the thickness. If the test specimen is provided with a coating which reflects the laser radiation, the energy absorbed per unit depth in the liquid is

$$\frac{dQ}{dx} = 2\mu I_0 e^{-\mu \ell} \cosh \mu (\ell - x) \quad ,$$

where  $I_0$  is the intensity of the incident laser beam,  $\mu$  is the absorption coefficient,  $\ell$  the total thickness of the liquid and  $x$  the position within the liquid, measured from the surface at which the radiation enters. The ratio of the maximum to the minimum values of  $\frac{dQ}{dx}$  is  $\cosh (\mu \ell)$ . If we adjust  $\mu$ , by using suitable dyes, such that  $\mu \ell = 0.5$ , then the ratio of maximum to minimum energy absorption per unit depth is 1.13, i. e., a total variation of 13%, which is reasonable. The total fraction of the laser energy absorbed is then

$$1 - e^{-2\mu \ell} = 1 - \frac{1}{e} = 0.63 \quad .$$

Thus, under these conditions, the estimated laser pulse energy required to produce a pressure of 4 kb is

$$\frac{16}{0.63} = 25 \text{ Joules.}$$

A similar estimate based upon the thermodynamic data of Sage and Lacey (14) indicates that about 40 Joules would be required if n-pentane was employed as the liquid rather than ethyl alcohol. The order of magnitude equality of these estimates indicates that a number of different organic liquids would probably give results of the same order, thus permitting some flexibility

in the choice of liquid depending upon other factors such as freezing point (for experiments at different temperatures), solubility for suitable dyes, etc.

### 3. THE TEST ASSEMBLY

The test crystal will be backed up by an acoustically matched momentum trapping plate (steel in the case of (111) oriented copper crystals). A reflected wave from the downstream surface of this plate will cause it to separate from the test crystal such that all the momentum associated with the initial pressure pulse is trapped in it. The test crystal and momentum trap geometry must be capable of trapping the radial waves induced by the pressure pulse so that they do not reflect back into the crystal. Thus the test crystal will be subjected to a single stress vs. time pulse which is the same at all positions through the thickness of the crystal. Furthermore, the test crystal will have no residual velocity. This will facilitate recovery of the test crystal without application of spurious stresses which might produce unknown additional movements of the dislocations. The amplitude and shape of the pressure vs. time pulse applied to the test crystal will be measured by means of a quartz crystal gage of the type developed by Jones, Neilson and Benedick (15). The quartz gage will be located on the downstream face of the momentum trapping plate, and its output signal will be recorded by means of a suitable cathode ray oscilloscope and camera.

The test crystal, momentum trap and quartz gage will be mounted in a suitable holder within a temperature control enclosure. The entire assembly will be relatively small so that it can easily be transported to a high power

laser installation capable of supplying the necessary single pulse energy.

The positions of dislocations within the test crystals before and after pulse loading will be determined by means of X-ray topographic and/or etch pit techniques presently employed in this laboratory, so that their velocities may be determined.

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