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Annual Summary Report No. 10
(Period Ending July 1972)

A STUDY OF DISLOCATION MOBILITY AND DENSITY
IN METALLIC CRYSTALS

Prepared Under Project Agreement No. 3,
Master Contract No. AT(04-3)-767

for the
San Francisco Operations Office
U.S. Atomic Energy Commission

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DATE 11/30/72

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October 26 1972

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INTRODUCTION

This report presents the current status of the research on dislocation mobility and density in metallic crystals under Project Agreement No. 3, Master Contract No. AT(04-3)-767, and gives a summary of the work accomplished since the last reporting period (July 1971). The research has as its objective a first principle understanding of dislocation origin and behavior. The experimental phase of this work is directed toward measurements of the response of isolated dislocations or groups of dislocations to stresses applied under controlled conditions. The dislocations are observed by X-ray topography, transmission electron microscopy and etch pit methods.

The theoretical phase of this work applies solid state theories to predict the strength of the interactions between moving dislocations and lattice phonons, electrons, and crystal defects.

The following are descriptions of investigations begun in a previous contract period and continued during this reporting period.

INVESTIGATIONS

1) Mobility of Dislocations in Copper at 4.2°K

Edge dislocation mobility experiments in copper at 4.2°K were completed during this contract year. These experimental results confirmed the trend, previously observed, of decreasing interaction between a moving dislocation and the crystal lattice as

a function of decreasing temperature. The temperature-dependence of the interaction was in qualitative agreement with theoretical predictions concerning the influence of thermal phonons on dislocation motion.

Although the damping force acting on a moving edge dislocation decreased monotonically with decreasing temperature, the actual magnitude of this force measured at 4.2°K was significantly greater than that which can be attributed to conduction electrons alone. The strength of this force was in good agreement with indirect experiments conducted elsewhere in lead and aluminum. It is concluded that some phonon dissipation mechanism, not thought to be important at low temperature, was responsible for a large measure of the energy dissipation. This mechanism may derive from the influence of the discrete nature of the crystal lattice.

2) Mobility of Dislocations in Normal and Superconducting Lead

The first successful mobility experiments in superconducting lead were completed during this contract year, using an experimental technique similar to that employed with copper.

The lengths of dislocation slip bands were measured by optical techniques. In the superconducting state in lead, preliminary results indicate that dislocation mobility is somewhat greater than in copper at the same temperature. This result is in good quantitative agreement with the indirect experiments performed in lead, but stands in marked contrast to other direct measurements made elsewhere.

We have attempted to observe dislocation slip bands with the aid of Berg-Barrett X-ray topography. Berg-Barrett topography will

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allow us to label the Burgers' vector of the dislocations in the slip bands and provide more positive identification of displaced dislocations. However, resolution of the dislocation structure has been hampered by the poor quality of the test crystals used. We have successfully grown a second lead crystal of much greater perfection than the one from which the present specimens were machined, and have begun to prepare test specimens of better quality.

4) Dislocation Studies in Body-Centered Cubic Metals

The immediate objective of this study is to determine the velocity-stress relationship for both screw and edge oriented dislocations in Mo. Two phenomenon unique to B. C. C. crystals have been attributed to screw dislocation behavior: the irreversibility of the flow stress (different values for tension and compression), and the breakdown of Schmid's law. Confirmation of this must await direct measurement of screw dislocation behavior, and such measurements will provide a quantitative understanding of these important phenomena in B. C. C. crystals.

Studies of means to selectively introduce isolated dislocations near (110) and (112) surfaces of Mo, Nb, and Fe have continued using line focused laser pulses and mechanical loading of the surfaces. While some success on (110) surfaces on Mo was achieved with laser pulses, point loads with a conical indenter were more effective for producing isolated slip bands. In August of 1972, Dr. Sylvanus Lau will join our staff as Bechtel Instructor, and will contribute his research efforts to this study. The immediate objective of the study is to determine the optimum crystal orientation and stress

system for mobility measurements of both edge and screw oriented dislocations. Mobility measurements will then be made over a wide range of test temperatures.

5) Energy Measurements of Screw Dislocations

The objective of this study is to make direct measurements of the line energy of dislocations. The line energy must be known to predict dislocation behavior such as the vibratory motion of a line segment, the character of extended dislocation nodes used to estimate stacking fault energies, and the equilibrium configuration of a bowed-out line.

A single dislocation between two pinning points, a so-called Frank-Read source, bows out under an applied shear stress. There is a critical stress just sufficient to bow the dislocation to an unstable configuration. When this critical stress is exceeded, the dislocation loop grows without limit. The critical stress is a function of the energy per unit length of the dislocation, the magnitude of the Burgers vector, and the initial dislocation length. The total energy per unit length is determined from experiments in which the critical stress is measured for dislocations on known Burgers vector and length. The energy per unit length calculated from anisotropic elasticity theory cannot give the total energy because the theory cannot be applied to the highstrain region in the dislocation core. The theory may be applied to give the energy outside the core if the dislocation depth below the surface is known. Initial measurements of this depth show it is on the order of a few microns for the dislocations in our experiments. Attempts to make measurements of the actual depth of the dislocations have resulted in a new technique for Berg-

Barrett topography (CALT-767-P3-25), and we are continuing to apply this and other techniques to study the depth of dislocations introduced by controlled scratching of crystal surfaces. These depth measurements will permit us to make a more accurate determination of the strain energy in the dislocation core than that given in CALT-767-P3-17.

6) Dislocation Mobility on Second Order Pyramidal Planes in Zinc

The objective of this study is to obtain stress-velocity-temperature relationships for edge and screw oriented dislocations on the $\{11\bar{2}2\} \langle 11\bar{2}3 \rangle$ slip system of zinc. Previous measurements indicate a transition from a non-linear stress-velocity relationship to a linear one at stresses above 50 Mdyne/cm^2 at room temperature. A Peierls mechanism is thought to control the low stress behavior, and the velocity is thought to be governed by phonon interactions in the linear region at high stresses. This system is ideal for testing theories of dislocation-phonon interaction in anisotropic crystals since zinc is highly anisotropic, and the dislocation-phonon interaction for basal dislocations has been determined. The theory for isotropic F.C.C. crystals (CALT-767-P3-9) may be extended to dislocations in anisotropic H.C.P. crystals to predict the drag on both basal and second order pyramidal dislocations in screw and edge orientations.

It has been confirmed that in the high stress region at room temperature, edge dislocation velocities exceed screw velocities by about a factor of two. This surprising result has been found before

using etching techniques to reveal the length of slip bands produced by a single, rectangular stress pulse, and more reliable X-ray topographic examination of the slip bands has been used in the most recent experiments. The X-ray examination has the distinct advantage of being insensitive to slight misorientations of the crystal surface from a (0001) or (10 $\bar{1}$ 0) plane. We will now apply the improved techniques to measure the temperature dependence of the stress-dislocation velocity relationship

7) Neutron Irradiation Damage in Zinc

The objective of this investigation is to obtain the first direct measurements of the strength of dislocation-defect interactions. Knowledge of these interactions will contribute to a fundamental understanding of irradiation hardening in crystals.

A quantitative study of interactions between basal dislocations and irradiation induced defects is being made. Five crystals prepared in our laboratory were irradiated at the Argonne National Laboratory. Dr. T.H. Blewitt is working with us on this experiment. Initial doses were 6.8, 18, and 78×10^{16} neutrons/cm² with an average neutron energy of 0.8 MEV and a temperature between 4.2°K and 5°K. The activity of the crystals after irradiation was approximately 150mr/hr. The techniques for handling the radioactive specimens throughout our testing sequence have been worked out and approved by the Radiation Safety Committee at the California Institute of Technology. The test program on the five crystals is to begin in August, 1972. Six additional crystals have been prepared and delivered to Argonne. These crystals will be irradiated at dose levels which will be determined after the initial test results on the first set of crystals have been analyzed.

8) Structure Analysis of Defects

A perturbation theory of high energy electron diffraction, utilizing a modified Bloch wave expansion, has been developed for use in the analysis of diffraction contrast images from imperfect crystals. To compute these new Bloch waves one must solve a linear hyperbolic system in n unknowns. Scattering among the Bloch waves is controlled by the matrix elements of the perturbing potential, and various approximations to these scatterings can be made. We have also developed numerical schemes for solving these equations.

CONTRACT EFFORT, PERSONNEL, AND PUBLICATIONS

Total expenditures have been nearly equal to those contemplated in the budget. The following staff members and graduate students have contributed to the research during this reporting period:

Prof. T. Vreeland, Jr.	Mr. J. Wayne Miller
Prof. R. E. Villagrana	Mr. Richard F. Boyce
Dr. Kenneth M. Jassby	Mr. Lawrence K. Tu
Alvin Illig, Technician	Mr. Gregory Hamill
Henri Arnal, Technician	

In addition, four undergraduates have worked part time as student assistants. Profs. T. Vreeland, Jr., and R. E. Villagrana have devoted approximately 50 percent of their total effort to this contract and 20 percent of each of their salaries is charged to the contract. Dr. K. M. Jassby has devoted 100 percent of his efforts to the contract since March 6, 1972, and will continue to do so for the remainder of this contract year. Dr. Sylvanus Lau will join our staff in August, 1972, and will devote his research efforts to the contract with no charge made to the contract.

The following publications were issued during the period July 31, 1971 to July 31, 1972:

CALT-767-P3-20 "A Study of Dislocation Mobility and Density in Metallic Crystals," by T. Vreeland, Jr. and R. E. Villagrana, July 1971.

CALT-767-P3-21 "Dislocation Mobility in Pure Copper at 4.2°K," by K. M. Jassby and T. Vreeland, Jr., October 1971.

CALT-767-P3-22 "A Perturbation Treatment of High Energy Electron Diffraction from Imperfect Crystals," by Alan L. Lewis and R. E. Villagrana, February 1972.

CALT-767-P3-23 "Damping of Dislocation Motion by Conduction Electrons in Metals," by K.M. Jassby and M. Shull, March 1972.

CALT-767-P3-24 "The Dynamics of Individual Dislocations," by T. Vreeland, Jr., April 1972.

CALT-767-P3-25 "A Technique for Berg-Barrett Stereo Topography," by Lawrence K. Tu and T. Vreeland, Jr., August 1972.

CALT-767-P3-26 "Computer Enhancement of High Resolution Electron Micrographs Containing Weak Periodic Information" by H.M. Horgen, R.E. Villagrana and D.M. Maher, August 1972.

The following reports appeared in the literature during this period:

CALT-767-P3-15 "On the Measurement of Dislocation Damping Forces at High Dislocation Velocity," by K.M. Jassby and T. Vreeland, Jr. *Acta Metallurgica* 20, (April 1972) 611-615.

CALT-767-P3-16 "Dislocation Mobility in Copper and Zinc at 44°K," by K.M. Jassby and T. Vreeland, Jr., *Scripta Metallurgica* 5, (November 1971) 1007-1012.

CALT-767-P3-18 "Basal Dislocation Interactions with a Forest of Non-basal Dislocations in Zinc," by Norio Nagata and T. Vreeland, Jr., *Philosophical Magazine* 5, No. 5, (May 1972) 1137.

CALT-767-P3-19 "The Observation of Slip Bands in Molybdenum Single Crystals by X-ray Diffraction," by R.F. Boyce and T. Vreeland, Jr., *Materials Science and Engineering* 9, No. 1 (1972) 56.

LECTURES AND INVITATIONS

Professor Vreeland delivered an invited lecture to members of the Materials Science Division of the Argonne National Laboratory on January 6, 1972. He has been invited to give a Keynote Address at the Ninth International Congress of Crystallography on September 4, 1972 at Kyoto, Japan in the session on Plastic Deformation and the Dynamical Behavior of Dislocations. Professor Vreeland will give an invited lecture on experimental methods for the measurement of dislocation drag at a conference on Metallurgical Effects at High Strain Rates sponsored by Sandia Laboratories and the AIME, in February 1973 at Albuquerque, New Mexico.

Professor R. E. Villagrana presented invited lectures at 1971 ASM-AIME Materials Engineering Congress at Detroit, Michigan, and the Naval Weapons Center, China Lake, California.