MASTER

EFFECT OF POINT DEFECTS ON MECHANICAL PROPERTIES OF METALS

Technical Progress Report
for Period January 1, 1978 - November 30, 1978.

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TECHNICAL PROGRESS REPORT FOR THE PERIOD
FROM JANUARY 1, 1978 to NOVEMBER 30, 1978

ABSTRACT

There are three sections in this technical progress report. The first section, consisting of three subsections, discusses the deformation behavior of niobium single crystals below 77° K. The second section reports the effect of electron irradiation on the deformation behavior of niobium single crystals. The third section describes the surface film softening phenomenon in Ni-plated iron single crystals. Reports resulting from these investigations during the period from January 1, 1978 to November 30, 1978, are listed at the end of this report as COO-1367-86 to COO-1367-96.

1. Deformation of Niobium Single Crystals Below 77° K

(a) Introduction

The UHV purified niobium single crystals have been examined extensively on two tensile axis orientations: The crystals oriented for the ideal (110) slip (the tensile axis being in the center of the standard triangle) are designated as C specimens (or C orientation) and the crystals oriented for the hard (112) slip are called H specimens (or H orientation). The examination of at least two orientations is crucial in the understanding of the low temperature deformation of niobium and probably other b.c.c. metals, as clearly revealed in this report. The nearly exclusive usage of niobium single crystal specimens near the C orientation may have resulted in a biased picture of solid solution effects on the low temperature deformation. This point is discussed briefly in section 2 and in detail in COO-1367-92, which is attached to this report.

(b) Deformation at 4.2, 10, 30, and 50° K

In the last technical progress report, COO-1367-85, a preliminary study of the deformation behavior of niobium single crystals at 77° K was reported. Although the more important deformation temperature for irradiation studies is in the lower range, the 77° K results were important; they established that the deformation behavior of thin sheet single crystals is comparable to that of rod single crystals, with which nearly all the previous studies had been carried out at 77° K.

During the past eleven months the deformation behavior was investigated at temperatures of 4.2, 10, 30, and 50° K. The tensile axis orientation dependence of the stress-strain curves observed at 77° K was confirmed at all the temperatures investigated. We believe that this orientation dependence of the stress-strain relation is an important feature of the low temperature deformation of b.c.c. metals. This dependence must be carefully examined with the operating slip systems. In the present investigation, the operating slip systems were determined by the surface observation and the determination of tensile axis rotation by the x-ray diffraction technique.

(c) Flow stress-temperature relation

The flow stress-temperature relation in the temperature range from 4.2 to 77° K was established. The small fluctuation in this relation from specimen to specimen was found to be caused by the variation in temperature* ($\sim 50^\circ$ K) during the UHV purification. This fluctuation was due to the fluctuation in the athermal component of the flow stress. The thermal component was not affected by the temperature variation, suggesting that the residual dislocation density or the subgrain size is primarily contributing to the variation in the flow

* This variation existed among the specimens in the same purification run. As the specimens were heated by the direct current, the variation in the cross-sectional area caused the temperature variation.

stress. The residual interstitial concentration must be similar among all the specimens tested. Because of the small specimen size used, the purification process should be readily completed; the high ductility of the C specimens observed at 4.2° K corroborates this contention.

(d) Surface morphology

The deformation of the C specimens took place nearly exclusively by the anomalous slip. On the other hand, the H specimens deformed exclusively by the primary slip. Thus, the deformation mechanisms are entirely different in these two specimens; the interpretation of the solute and irradiation effects must be interpreted accordingly.

Although the H specimens deformed with a significant yield drop, no evidence of twinning was observed at any of the temperatures investigated. It is suggested that the sudden multiplication of primary dislocations is responsible for the yield drop. The subsequent decrease in the apparent flow stress is believed to be caused by severe local deformation coupled with low work-hardening. Although no significant uniform elongation was attained in the H specimens, the necked region shows a high degree of ductility by a reduction of cross-section area reaching $1/6 \sim 1/10$.

(e) Prestraining effect

In the C specimens, the prestraining at room temperature enhanced the microstrain region, although the remaining part of the stress-strain curve was unaffected. This prestraining also caused the fragmentation of anomalous slip lines, indicating that the dislocations introduced at room temperature restrict the long-distance propagation of anomalous dislocations. In the H specimens, the room temperature prestraining also enhanced the microstrain region. The complete suppression of the yield drop took place after a prestraining of 2%. No significant change in slip line morphology was observed.

2. Effects of Electron Irradiation

(a) Introduction

It is known that electron irradiation at a temperature below Stage I recovery produces a significant softening effect in pure iron, especially in the hard (112) slip oriented crystals. A softening effect was also reported in iron doped with carbon or nitrogen. These results are taken as evidence for the intrinsic softening mechanism and also imply that the low temperature strength of iron observed in the specimens represents that of pure iron. On the other hand, extensive studies reported for doped niobium indicate that no solute dopant produces the intrinsic softening effect. As any alloying or doping experiment involves handling the specimen at elevated temperatures, the diffusional processes can produce complications in the solute distribution which cannot be determined without ambiguity. The introduction of self-interstitials by electron irradiation at a temperature below the migration temperature is much cleaner in this respect. This series of experiments was carried out to study electron irradiation effects in niobium, the missing link in information. It is shown, in this section, that the seemingly contradictory experimental results in iron and niobium can be rationalized if one considers that niobium single crystals deform in different slip systems, depending on the tensile axis orientation. The electron irradiation experiments demonstrated that both softening and hardening effects occur depending on the operating slip system which was determined by the surface observation and the tensile axis rotation. The dislocation mechanisms for the operation of the different slip systems explain the observed softening or hardening effect.

(b) Irradiation effects in 15° and 30° K experiments

Electron irradiation and the subsequent tensile tests were carried out at both 15°* and 30° K, since the previous investigations on the recovery of electron

* Irradiation at or below 15° K and tensile test at 10° K.

irradiation in niobium are not decisive on whether the long range migration of interstitials takes place above or below 30° K.

A large hardening effect^{*} was produced by electron irradiation in the C specimens. This tensile axis orientation has been used exclusively in most of the experiments with niobium single crystals including the series of experiments in doped niobium. Thus, the electron irradiation hardening observed is consistent with the doping experiments. On the other hand, electron irradiation caused a significant softening effect^{*} in the H specimens. As reported earlier (C00-1367-58 and C00-1367-63), the most significant irradiation softening was observed in iron single crystals of similar tensile axis orientation. The deformation of the H specimens took place exclusively on the primary slip system, while the C specimens deformed exclusively by the anomalous slip. Since iron single crystals deform by the primary slip system in both H and C orientations, the irradiation softening and the solution softening are suggested to be characteristic of the primary slip. A mechanism for such softening phenomena has been proposed.[†] On the other hand, the irradiation hardening and the solution hardening must be characteristic of the anomalous slip. The dislocation mechanism for the anomalous slip is thought to be the co-planar motion of the primary and conjugate screw dislocations. The two sets of screw dislocations form a grid on the anomalous slip plane. The details of the interaction between the anomalous dislocations and the interstitials, and the resulting hardening, are discussed in C00-1367-94 and -96. A calculation[‡] was carried out to examine the hardening effect due to the interaction between kinks and interstitials. The results indicated that a significant hardening was expected from such an interaction.

* The stress-strain curves demonstrating these hardening and softening effects are given in C00-1367-94.

† C00-1367-46

‡ See C00-1367-96 for details.

(c) Dosage dependence of hardening

The dosage dependence of the electron irradiation hardening was examined in the C specimens after 15° K irradiation. The flow stress increase due to irradiation was proportional to the square root of the dosage, suggesting a hardening caused by dispersed point defects. A similar dosage dependence has been observed in f.c.c. metals in which the hardening mechanism by dispersed point defects has been accepted.

(d) Recovery of irradiation hardening

Only a small recovery of radiation hardening was observed at and below 30° K in the C specimens. Although the resistivity recovery reported for this temperature range does not show significant recovery peaks, a gradual recovery of a moderate magnitude exists. The present results indicate that rearrangement of interstitial atoms might be taking place in this temperature range. A large recovery stage was found to be near room temperature. An annealing at 30° K did not change the characteristic features of the observed electron irradiation hardening.

3. Surface Film Softening in Nickel-Plated Iron Single Crystals

The mechanical behavior of Ni-plated iron single crystals has been characterized and reported in the previous Technical Progress Reports. The fine structure of slip steps formed on the iron substrate underneath the cracks in the nickel film was studied carefully to determine the size and morphology of the dislocation sources. Then the fine structure observed was compared with the dislocation structure examined by a TEM and an HVEM. A clear correlation was established between the fine surface structure and the dislocation structure. The dislocation sources for the primary slip were a few to several thousand angstroms and were connected by slips on other slip planes. These slips were

due to cross-slipping of primary screw dislocations. A calculation based on the dislocation pile-up model was carried out to determine the backstress due to screw dislocations using the observed source lengths. The calculations clearly indicated that the back stress builds up very quickly with several dislocations. For the observed slip steps to occur there must be annihilation of these pile-up screw dislocations. A mechanism for this annihilation was worked out. The details of the calculation and the proposed model have been described in the attached report C00-1367-95. Two manuscripts on the mechanism and calculation are currently being prepared for publication.

Reports resulting from the present research project:

- (1) - (85) COO-1367-1 through COO-1367-85. These reports have been included in previous Technical Progress Reports.
- (86) "Examination of Low Temperature Deformation Mechanisms in Niobium by Electron Irradiation", abstract of talk presented at Fall Meeting of TMS-AIME, St. Louis, October 1978. COO-1367-86.
- (87) "Calculations on Surface Film Softening Mechanism", abstract of talk presented at Fall Meeting of TMS-AIME, St. Louis, October 1978. COO-1367-87.
- (88) "Surface and Dislocation Structures in Surface Film Softened Iron Single Crystals", abstract of talk presented at Fall Meeting of TMS-AIME, St. Louis, October 1978. COO-1367-88.
- (89) "Effects of Orientation and Prestraining on Low Temperature Deformation of Niobium Single Crystals", abstract of talk to be presented at Annual Meeting of TMS-AIME, New Orleans, March 1979. COO-1367-89.
- (90) "Electron Irradiation Effects on Low Temperature Deformation of Niobium Single Crystals", abstract of talk to be presented at Annual Meeting of TMS-AIME, New Orleans, March 1979. COO-1367-90.
- (91) "A Mechanism of Surface Film Softening", abstract of talk to be presented at Annual Meeting of TMS-AIME, New Orleans, March 1979. COO-1367-91.
- (92) "Surface Film Softening of Ni-Plated Iron Single Crystals", abstract of talk to be presented at 5th International Conference on Strength of Metals and Alloys, Aachen, Germany, August 1979. COO-1367-92.
- (93) "Rationalization of Softening and Hardening Effects by Interstitial Atoms in B.C.C. Metals", abstract of talk to be presented at 5th International Conference on Strength of Metals and Alloys, Aachen, Germany, August 1979. COO-1367-93.
- (94) "Effect of Electron Irradiation on the Low Temperature Deformation of Niobium", submitted to Scripta Metallurgica, November 1978. COO-1367-94.
- (95) "Surface Film Softening in Ni-Plated Iron Single Crystals", Doctorate Dissertation by S. Kobayashi, Northwestern University, August 1978. COO-1367-95.
- (96) "Effect of Electron Irradiation on the Strength of Niobium Single Crystals", Doctorate Dissertation by J. Nagakawa, Northwestern University, June 1979. COO-1367-96.
- (97) "Technical Progress Report for the Period from January 1, 1978 to November 30, 1978", submitted to the U. S. Department of Energy for renewal of Contract EY-76-S-02-1367.A002. COO-1367-97.

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Review of Research Highlights Resulting from the Present Project since 1965

This research project was initiated in April 1965 under the sponsorship of the U. S. Atomic Energy Commission. All the reports resulting from the project are summarized at the end of this Technical Progress Report. We believe that the project has been very successful in terms of a number of new discoveries and also in terms of the recognition these works have received. One of the reports was selected as the best paper of the year by A.S.M. in 1967, and the principal investigator and his co-worker* received the Henry Marion Howe Medals. The principal investigator was chosen as the recipient of the Koseki-Sho (Achievement award) in Metal Physics by the Japan Institute of Metals in 1972 for a series of his works on point defects. This recognition came primarily from journal publications and presentations at international meetings which resulted from the present project.

This project evolved around the point defects effect. We shall review briefly the major accomplishments and their significance as follows.

(i) Electron Irradiation Hardening

in f.c.c. and h.c.p. Metals and Alloys (3,9,10,15,17,11,19) **

This research project was the first to report on the effect of electron irradiation below the interstitial migration temperature. The irradiation produced a very significant hardening in aluminum. Since the concentration of interstitials can be accurately controlled and their distribution is ideally random, the resistance of a single interstitial to dislocation has been determined with the least ambiguity. The results

* Professor Kanji Ono of UCLA, who was a former graduate student of the principal investigator.

** The references are cited by the numbers given in the list of reports at the end of this section.

enabled us to examine critically the accuracy of calculations on dislocation-point defects (or solutes) interaction and yield stress.

The method was applied to determine the concentration dependence of the yield stress and activation volume (strain rate dependence of flow stress) in various metals (over the concentration range of two orders of magnitude). The results obtained were used to examine the basic assumptions used in solid solution theories.

The electron irradiation hardening technique was also applied to examine the work-hardening behavior of aluminum single crystals.⁽¹⁰⁾ Here the technique has a unique capability; that is, it is possible to "alloy" a specimen with self-interstitials at any stage of work-hardening without changing the dislocation structure. Another important point which should be brought out is that the electron irradiation hardening is the consequence of $10^{-7} \sim 10^{-5}$ interstitials.* Therefore there is no change in the nature of dislocation width due to a change in stacking fault energy. Although the details of this investigation are deleted from this report, it suffices to state that the work-hardening coefficient can be reduced to nearly zero by a few ppm of interstitials even at the middle of the stage II work-hardening.

(ii) Effect of Annealing on Electron Irradiation Hardening and Electron Irradiation Hardening above Interstitial Migration Temperature^(1,2,4,7,8)

The recovery of electron and (other particular) irradiation has been investigated very extensively by resistivity in aluminum and in various other metals and alloys. Our results have uniquely supplemented some of these works. In addition, most other works in the electron irradiation effect on strength were carried out at temperatures where the long range

* The vacancy part of Frenkel pairs contributes little to the strength in the concentration range under investigation.

migration of interstitials took place. Our annealing study and the results discussed in (i) are essential in interpreting these other results.

(iii) Theoretical Calculations^(15,17,23,29,34)

Various calculations have been carried out in conjunction with the experiments discussed above. We would like to mention two of these here. A generalized formulation of dislocation-point defect interaction was carried out to analyze critically the experimental results on electron irradiation. The formulation allows a dislocation to be any type (screw, edge, or various degree of mixture) with any width. Limiting cases of this formulation are the edge dislocation-spherical defect interaction^{*} and the screw dislocation-tetragonal defect interaction.^{**} The calculation clearly indicated that commonly accepted concepts based on simpler calculations were wrong. For example, it is a wrong belief that a screw dislocation does not interact with a spherical defect (strain field).^{**} A screw dislocation with the narrowest width (aluminum) should have a strong interaction with a spherical defect. The identification of a tetragonal obstacle from the force-distance curve (or yield stress-temperature relation) is also completely erroneous. Another calculation using the continuous dislocation distribution was able to define the cut-off distance theoretical. Although the magnitude of the cut-off determines the magnitude of the interaction, a value is often chosen rather arbitrarily. Our work eliminated this arbitrariness.

^{*} N. F. Mott and F. R. N. Nabarro, Proc. phys. Soc. Lond. 52, 86 (1940).

^{**} R. L. Fleischer, Acta Met. 10, 835 (1962).

(iv) Effects of Quenched-in Vacancies

When one analyzes the effects of irradiation, the presence of vacancies must be taken into account along with interstitials. Although the interaction of dispersed single vacancies with a dislocation was expected to be considerably smaller than that of dispersed single interstitials, no attempt had been made to demonstrate this point. An experiment in the project examined the relative strength of vacancies and interstitials by comparing the yield stress immediately after quenching (dispersed vacancies) with that after low temperature electron irradiation (dispersed vacancies plus interstitials in the equal numbers).⁽³⁵⁾ It was concluded that the strengthening coefficient⁽¹⁷⁾ of interstitials is at least an order of magnitude greater than that of vacancies.

Another work that needs to be mentioned here is the analysis of plastic deformation of quench-hardened aluminum single crystals.⁽²¹⁾ The heterogeneous nature of plastic deformation (slip band formation) was examined quantitatively and a method was proposed to determine the parameters representing the slip localization and to relate them to the macroscopic deformation. The slip localization has been ignored by most researchers; however, it is the outstanding characteristic of plastic deformation in solids as the fact that slip lines are observable on the surface symbolizes the heterogeneous nature of the deformation. We believe this subject will become an important area of investigation in the future, particularly in conjunction with crack initiation.

(v) Electron Irradiation Softening^(36,51,58,63)

The irradiation effect is generally considered to harden metals. We demonstrated, for the first time, that electron irradiation softens pure iron single crystals at low temperatures. Since our first report, several works

by other investigators have reported the irradiation softening effect by electron and neutron irradiations in iron at low temperatures and the irradiation softening is now a well-recognized phenomenon.

We characterized the electron irradiation softening phenomenon thoroughly by determining the dosage dependence, the temperature and strain rate, the tensile axis orientation dependence, and the recovery behavior. This experimental characterization was important in determining the softening mechanism and the low temperature deformation mechanism in b.c.c. metals.

(vi) Mechanism of Electron Irradiation Softening

We proposed the screw dislocation-interstitial interaction model to rationalize the observed softening and carried out calculations using this model to predict the temperature, strain rate, and dosage dependence of the yield stress.⁽⁴⁶⁾ The results of these calculations are in excellent agreement with the experimental results. Furthermore, the model clearly indicates that the irradiation softening is a kind of solid solution softening in which dispersed interstitials promote the motion of screw dislocations by assisting the double kink formation.

This type of solid solution softening mechanism is called "intrinsic" as opposed to an extrinsic mechanism in which a solute element causes a softening effect by neutralizing other solute elements which cause a hardening effect. We proved conclusively that the softening is caused by an intrinsic mechanism in iron at least in the case of electron irradiation softening. Among a number of results substantiating this conclusion, the following points are important:

- 1) The irradiation softening occurs without warming the specimen to the temperature where interstitials can diffuse.

- 2) The softening effect disappears as soon as the specimen is warmed to this temperature.
- 3) The softening is most prominent in the purest iron specimen tested.*
- 4) A strong tensile-axis orientation dependence exists in this softening.
- 5) In the same specimen, a hardening effect due to irradiation was observed in the microstrain range where edge dislocations move, while the softening effect was observed in the macrostrain region where screw dislocations must move.

Although the case against the intrinsic mechanism has been made in other metals such as Nb and Ta, it is generally accepted that the intrinsic softening occurs in iron by self-interstitials. There is also evidence of intrinsic softening by solute interstitials reported by us⁽⁶⁰⁾ and by other workers.**

(vii) Electron Irradiation Effect in Niobium

As reported in the Technical Progress Report for 1977-78, we have an answer to why dispersed interstitials of a low concentration produce both a softening effect and a hardening effect in otherwise pure b.c.c. specimens at low temperature. Although the work is still in progress, we believe the crystallography of the operating slip system must be examined carefully along with the deformation behavior and dislocation structure. If we are right in this belief, the work so far carried out should be recognized as the path-finder in understanding the low temperature deformation mechanism of b.c.c. metals.

* This single crystal was grown from the Battelle-AISI ultrapure iron which was zirconium hydride treated.

** The most recent report is Acta Met. 26, 1179 (1978).

(viii) Surface Film Softening(65,74,77,81)

This is a new phenomenon discovered by us in Ni-plated Fe single crystals and by Professor Gibala and his coworkers in oxide-coated Nb single crystals. The two groups complemented each other and the phenomenon is very well characterized. The mechanism of the softening has also been given. We believe this softening mechanism provides a possibility of improving the ductility of b.c.c. metals at low temperature.

Reports resulting from Contract AT(11-1)1367 beginning 1965.

M. Meshii, Principal Investigator

- (1) "On the Interruption Yield Point of Irradiated Aluminum Single Crystals", Acta Metallurgica 13, 140 (1965) C00-1367-1.
- (2) "Recovery of Electron Irradiated Aluminum", The Proceedings of the International Conference on Lattice Defects in Quenched Metals, Academic Press (1965) C00-1367-2.
- (3) "Point Defect Hardening of Aluminum--I. Yield Stress Increase Due to Electron Irradiation at 23°K", Acta Metallurgica 13, (1965) 1123, C00-1367-3.
- (4) "Effect of Annealing on Mechanical Properties of Electron-Irradiated Aluminum Single Crystals at 23°K", Applied Physics Letters 7 (1965) 191, C00-1367-4.
- (5) "Electron Irradiation Hardening of Aluminum at 23°K", B.A.P.S. 10 (1965) 690, C00-1367-5.
- (6) "Recovery of Electron Irradiation Hardening", B.A.P.S. 10 (1965) 690, C00-1367-6.
- (7) "Point Defect Hardening and Its Recovery", Journal of Metals 17 (1965) 1026, C00-1367-7.
- (8) "Electron Irradiation Hardening", Lattice Defects and Their Interactions, R. R. Hashiguchi, ed. (1967) Gordon and Breach, p. 747, C00-1367-8.
- (9) "Electron Irradiation Hardening and the Interstitial Dislocation Interaction in Aluminum", The Nature of Small Clusters (1966), H.M.S.O., London, England, p. 539, C00-1367-9.
- (10) "Work Hardening Behavior of Irradiated Aluminum" The Proceedings of Work Hardening Symposium, AIME Fall Meeting (1966), Gordon and Breach, In Press, C00-1367-10.
- (11) "Strengthening Due to Point Defects", New Insight Into Strengthening, Metal Science Forum, National Metal Congress, A.S.M. (1966) C00-1367-11.
- (12) "Electron Irradiation Hardening of Copper", Abstract of Talk to be presented at annual meeting of AIME, Los Angeles, February, 1967, C00-1367-12.
- (13) "Effect of Electron Irradiation on Mechanical Properties of Al-Zn Alloy Single Crystals", Abstract of talk ^{to be} presented at annual meeting of AIME, Los Angeles, February 1967, C00-1367-13.
- (14) "Technical Progress Report for the Period from January 1, 1966, to December 31, 1966", submitted to A. E. C. as a part of the proposal to the U. S. Atomic Energy Commission for Renewal of Contract AT(11-1)1367, C00-1367-14.

- (15) "Point Defect Hardening of Aluminum--II. Analysis of Electron Irradiation Experiments at 23°K", Trans. ASM 60 (1967) 426, C00-1367-15.
- (16) "Effect of Electron Irradiation on Plasticity of Metallic Single Crystals", Proceedings of International Conference on Solid State Physics Research with Accelerators, (1967) Brookhaven, C00-1367-16.
- (17) "Electron Irradiation Strengthening in Metals and Alloys", Proceedings of the International Conference on the Strength of Metals and Alloys, Tokyo, Japan (1968) 193, C00-1367-17.
- (18) "Electron Irradiation Hardening of Aluminum-1 at.% Zn Single Crystals", Applied Physics Letters 11 (1967) 282, C00-1367-18.
- (19) "Yield Stress Increase in Electron Irradiated Copper", Philosophical Magazine 17 (1967) 235, C00-1367-19.
- (20) "Technical Progress Report for the Period from January 1, 1967, to December 31, 1967", submitted to A.E.C. as a part of the proposal to the U. S. Atomic Energy Commission for renewal of Contract AT(11-1)1367, C00-1367-20.
- (21) "Plastic Deformation of Quench-Hardened Aluminum Single Crystals", Acta Metallurgica, 17 (1969) 167. C00-1367-21.
- (22) "Interaction of Glide Dislocations with Interstitials and Lattice Vacancies", The Proceedings of Symposium on The Interactions between Dislocations and Point Defects (1968) H.M.S.O., In Press, C00-1367-22.
- (23) "An Elasticity Calculation of the Interaction between a Misfit Defect and an Extended Dislocation in a FCC Metal", C00-1367-23.
- (24) "The Effect of Stacking Fault Energy on the Yield Stress of FCC Metal", Abstract of Talk presented at Fall Meeting of AIME, Detroit, October, 1968, C00-1367-24.
- (25) "Interaction of Glide Dislocation with Quenched-in Vacancies in Gold", Abstract of Talk presented at Fall Meeting of AIME, Detroit, October, 1968, C00-1367-25.
- (26) "Technical Progress Report for the Period from January 1, 1968, to December 31, 1968", submitted to A.E.C. as a part of the proposal to the U. S. Atomic Energy Commission for renewal of Contract AT(11-1)1367, C00-1367-26.
- (27) "Nature of Interaction between Dislocations and Electron-Induced Defects", Abstract of Talk Presented at Spring Meeting of AIME, Pittsburgh, May 1969, Journal of Metals, 21 (1969) No. 3 p. 64A, C00-1367-27
- (28) "Effect of Annealing on Deformation Parameters of Electron Irradiated Al-1 At.% Zn", Abstract of Talk Presented at Spring Meeting of AIME, Pittsburgh, May 1969, Journal of Metals, 21 (1969) No. 3, p. 64A, C00-1367-28.

- (29) "An Elasticity Calculation of the Interaction between a Misfit Defect and an Extended Dislocation in FCC Metals", Acta Metallurgica 17 (1969) 1253, COO-1367-29. (Revised version of COO-1367-23)
- (30) "Electron Irradiation Hardening and Its Recovery in Aluminum- 1 At.% Zinc", submitted to Physica Status Solidi, COO-1367-30.
- (31) "An Evaluation of a Dislocation-Imperfection Interaction Using a Continuously-Distributed Dislocation Model", Abstract of Talk Presented at Fall Meeting of AIME, Philadelphia, October 1969, COO-1367-31.
- (32) "Electron Irradiation and Plastic Deformation of Iron Single Crystals", Abstract of Talk to be Presented at Spring Meeting of AIME, Las Vegas, May 1970, COO-1367-32.
- (33) "Technical Progress Report for the Period from January 1, 1969, to December 31, 1969", submitted to A.E.C. as a part of the proposal to the U. S. Atomic Energy Commission for renewal of Contract AT(11-1) 1367, COO-1367-33.
- (34) "Evaluation of Interactions between a Dislocation and Imperfections Using a Continuously Distributed Dislocation Model", Journal of the Physical Society of Japan, 29 (1970) 579, COO-1367-34.
- (35) "Initial Hardening in Quenched Gold", Physica Status Solidi 40 (1970) 725, COO-1367-35.
- (36) "Effect of Electron Irradiation on the Strength of Iron Single Crystals", to be published in The Proceedings of the Second International Conference on the Strength of Metals and Alloys, Asilomar, Calif., September 1970, COO-1367-36.
- (37) "Electron Irradiation Strengthening of Magnesium Single Crystals at 4.2°K", Abstract of Talk Presented at Fall Meeting of AIME, Cleveland, October, 1970, COO-1367-37.
- (38) "Plastic Deformation of Purified Iron Single Crystals at Low Temperatures and the Effect of Electron Irradiation", Abstract of Talk to be Presented at the Spring Meeting of AIME, Atlanta, May, 1971, COO-1367-38.
- (39) "Dislocation Motion in a Combined Peierls and Misfit Strain Field", Abstract of Talk to be Presented at the Spring Meeting of AIME, Atlanta, May 1971, COO-1367-39.
- (40) "Technical Progress Report for the Period from January 1, 1970, to December 31, 1970", submitted to A.E.C. as a part of the proposal to the U. S. Atomic Energy Commission for renewal of Contract AT(11-1)1367, COO-1367-40.
- (41) "Plastic Deformation of Iron Single Crystals in Microstrain Region and the Effect of Electron Irradiation", Abstract of Talk presented at the Fall meeting of AIME, Detroit, October, 1971, COO-1367-41.

- (42) "Dislocation Velocity Measurements in Electron Irradiated Copper", Abstract of Talk to be presented at the Spring meeting of AIME, Boston, May, 1972, COO-1367-42.
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