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FINAL REPORT

An Investigation of Irradiation Strengthening of B.C.C. Metals and
Their Alloys

To

DEPARTMENT OF ENERGY

BY

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FINAL REPORT

INVESTIGATION OF IRRADIATION STRENGTHENING

OF

BODY CENTERED CUBIC METALS AND THEIR ALLOYS

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R.J. Arsenault

Contract #DE-AS05-76ER03612

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The purpose of the proposed research was to determine how neutron damage affects the low temperature deformation mechanism or mechanisms in body centered cubic metals. The aims of this research can be stated more specifically as follows: *i.* the determination of the barrier to dislocation motion introduced by neutron irradiation damage, *ii.* determine the mechanism by which the dislocation overcomes this barrier. *iii.* determine the density of the neutron produced barriers which are overcome by thermally activated motion of the dislocation.

In order to accomplish these aims it was necessary to carry out investigations in a large number of areas. The following is a partial listing of these areas: *i.* the production of high-purity-single crystals of body centered cubic metals, *ii.* investigate techniques for introducing predetermined amounts of impurity interstitials into a large number of high-purity-single crystals, *iii.* develop a testing technique for handling neutron irradiated samples, *iv.* determine the effect of impurity interstitials on the yield stress of

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body centered cubic metals, v. determine the synergistic effects between neutron produced defects and impurity interstitials atoms, vi. determine the interaction between substitutional and interstitial solute additions in body centered cubic metals, vii. determine the effect of neutron produced defects on the binding energy between defects and substitutional-interstitial complexes, viii. develop a procedure for producing transmission electron microscopy foils of neutron irradiated body centered cubic metals and their alloys, ix. determine the nature of the neutron produced defects and to determine the nature of "channeling" in body centered cubic metals by transmission electron microscopy of neutron irradiated metals, x. develop a computer simulation program for the purpose for determining how "channeling" can be a thermally activated process, xi. develop a computer simulation program for the thermally activated motion of a dislocation through a random array of barriers (neutron irradiated produced defects), xii. determine the effect of hydrogen on the low temperature mechanical properties of body centered cubic metals, xiii. determine the effect of helium on the low temperature mechanical properties of body centered cubic metals.

In order to summarize what has been accomplished in all these areas would require many pages (it should be noted that progress report for each year of this contract was 200 to 400 pages in length). The summary comments will be restricted

to the main area of research i.e. irradiation damage,

which are as follows:

1) The intrinsic lattice is the rate-controlling barrier at low impurity interstitial concentrations.

2) The intrinsic lattice mechanism has two different modes, one operating at low stress and a second at higher stress.

3) The impurity interstitials appear to be part of the rate-controlling barrier at higher interstitial concentrations.

4) The magnitude of the effective stress of the irradiated samples is approximately independent of interstitial impurity concentration. The changes in the differences in effective stress between irradiated and non-irradiated samples are due to the effect of interstitial impurities on the effective stress of the non-irradiated samples and a scavenging mechanism.

5) The transmission electron microscopy results strongly indicate that the interstitial atoms act as nucleation sites for the observable defects. There is qualitative agreement between the increase in the change in the athermal component of the yield stress and the observable defect density. However, there is absolutely no changes in the differences in the effective stress between the irradiated and non-irradiated samples.

6) The results indicate that the defect barrier, which produces the change in temperature dependent portion of the yield stress, is small, i.e. a divancy, and density of these defects is large.

COMMENTS ON REMAINING AREAS WHERE RESEARCH
SHOULD BE UNDERTAKEN

An isothermal annealing investigation should be undertaken to determine whether the defect is a complex i.e. a divancy or not and to determine at which temperature this defect complex forms.

A field ion microscopy investigation to determine if the defect is as small and dense as the thermally activated strain rate analysis indicates.

An internal friction investigation of He^{+3} doped samples to determine the activation energy of diffusion of He^{+3} and to determine the tetragonal strength of the He^{+3} in the lattice.

List of Publications

Journal Articles

1. THE POSSIBILITY OF IRRADIATION DAMAGE AFFECTING THE RATE CONTROLLING MECHANISM OF SLIP IN B.C.C. METALS AND SOLID SOLUTIONS
Acta Met. 15, 1967, 1853
2. THERMALLY ACTIVATED DISLOCATION MOTION IN PERIODIC INTERNAL STRESS FIELD
R. J. Arsenault and J. C. M. Li
Phil. Mag. 16, 1967, 1307
3. COMMENTS ON THE RELATIONSHIP BETWEEN DISLOCATION VELOCITY MEASUREMENTS AND MACROSCOPIC DEFORMATION
Scripta Met. 3, 1969, 419
4. THE EFFECT OF NEUTRON IRRADIATION AND OXYGEN INTERSTITIALS ON THE DISLOCATION DYNAMICS IN VANADIUM
R. J. Arsenault and E. Pink
Met. Sci. Eng. 8, 1971, 141
5. THE PREPARATION AND SOME MECHANICAL PROPERTIES OF HIGH-PURITY VANADIUM
H. Beale and R. J. Arsenault
Met. Trans. 1, 1970, 3355.
6. A DYNAMIC DISLOCATION PILE-UP IN NEUTRON-IRRADIATED METALS
Phil. Mag. 24, 1970, 259
7. THE RELAXATION STRENGTH Δ PER ATOMIC PERCENT SOLUTE - a/o FOR OXYGEN IN VANADIUM
D. F. Hasson and R. J. Arsenault
Scripta Met. 5, 1971, 75,
8. UNUSUAL FRACTURE FEATURES OF OXIDIZED VANADIUM +1.31 AT.% TITANIUM ALLOYS
D. F. Hasson and R. J. Arsenault
Mat. Sci. Eng. 7, 1971, 215,
9. LOW TEMPERATURE DEFORMATION CHARACTERISTICS OF NEUTRON IRRADIATED VANADIUM-TITANIUM ALLOYS
E. Pink and R. J. Arsenault
Radiation Effects 10, 1971, 27
10. THE EFFECT OF NEUTRON IRRADIATION DAMAGE ON THE LOW TEMPERATURE DEFORMATION CHARACTERISTICS OF B.C.C. METALS AND ALLOYS
R.J. Arsenault, K. Kuo and Y. Huang
Proceedings of 1972 International Conference on the Mechanical Behavior of Materials 1, 18

11. THE EFFECT OF NEUTRON DAMAGE ON THE DISLOCATION DYNAMICS OF B.C.C. METALS AND SOLID SOLUTIONS AT LOW TEMPERATURES
R. J. Arsenault and E. Pink
Second International Conference in Strength of Metals and Alloys, 1970, 731
12. FURTHER COMMENTS ON THE ENTROPY OF THERMALLY ACTIVATED PLASTIC DEFORMATION AT LOW TEMPERATURES
Met. Trans. 3, 1972, 1014
13. THE NATURE OF DISLOCATION MOTION THROUGH A RANDOM ARRAY OF THERMALLY ACTIVATABLE OBSTACLES
T. Cadman and R. J. Arsenault
Scripta Met. 6, 1972, 593
14. SCAVENGING IN VANADIUM-TITANIUM ALLOYS
D. F. Hasson and R. J. Arsenault
J. of the Less Common Metals 27, 1972, 417
15. THE EFFECT OF OXYGEN ON THE DISLOCATION STRUCTURES IN VANADIUM
Y. Huang and R. J. Arsenault
Mat. Sci. and Eng. 12, 1973, 111
16. ROLE OF ENTROPY IN THERMALLY ACTIVATED DEFORMATION
Phil. Mag. 26, 1972, 1481,
17. THE EFFECT OF OXYGEN ON DISLOCATION CHANNELING IN NEUTRON IRRADIATED VANADIUM
Y. Huang and R. J. Arsenault
Rad. Effects 17, 1973, 3
18. SELECTION METHODS FOR THERMALLY ACTIVATED MOTION OF A DISLOCATION
R. J. Arsenault and T. W. Cadman
Scripta Met. 7, 1973, 631,
19. NEUTRON IRRADIATION SOFTENING AND THE EFFECT OF INTERSTITIALS ON STRENGTHENING
R. J. Arsenault and T. W. Cadman
Proc. of the International Conference of Defects and Defect Clusters in B.C.C. Metals and Their Alloys
ed. R. J. Arsenault
Nuclear Metallurgy Series, 18, 1973, 41
20. RADIATION EFFECTS ON THE YIELD STRESS AND DISLOCATION CHANNELING IN NEUTRON IRRADIATED MOLYBDENUM
D. F. Hasson, Y. Huang, E. Pink and R. J. Arsenault
Met. Trans. 5, 1974, 371
21. RADIATION ANNEAL HARDENING IN MOLYBDENUM
D. F. Hasson and R. J. Arsenault
Phys. Stat. Solidi 22, 1974, 39

22. DISCONTINUOUS TEMPERATURE-DEPENDENCE OF THE YIELD STRESS INDUCED IN VANADIUM BY DISSOLVED HYDROGEN RESULTING FROM CHEMICAL ETCHING
C. C. Chen and R. J. Arsenault
J. of the Inst. of Metals 101, 1973, 283
23. THE INTERSTITIAL CONCENTRATION DEPENDENCE OF HARDENING IN NEUTRON IRRADIATED VANADIUM
D. F. Hasson and R. J. Arsenault
Rad. Effects 21, 1974, 203
24. DISTRIBUTED GLIDE FORCE BETWEEN A NON-SPHERICAL DEFECT AND A DISLOCATION
R. J. Arsenault and R. deWit
Acta Met. 22, 1974, 819
25. DEFORMATION CHARACTERISTICS OF LOW TEMPERATURE NEUTRON-IRRADIATED VANADIUM
C. C. Chen and R. J. Arsenault
Scripta Met. 8, 1974, 1015
26. THE KINETICS OF A DISLOCATION SURMOUNTING TWO DIFFERENT STRENGTH BARRIERS
R. J. Arsenault and T. W. Cadman
Phys. Stat. Solidi 24, 1974, 299
27. THE THERMALLY ACTIVATED DISLOCATION MOTION IN NEUTRON IRRADIATED IRON-NICKEL ALLOYS
C. T. K. Kuo and R. J. Arsenault
Met. Trans. 6A, 1975, 207
28. LOW TEMPERATURE DEFORMATION CHARACTERISTICS OF GROUP VA METAL-HYDROGEN SINGLE CRYSTALS
C. C. Chen and R. J. Arsenault
Acta Met. 23, 1975, 255
29. EFFECT OF HYDROGEN ON THE LOW TEMPERATURE DEFORMATION PROPERTIES OF NEUTRON-IRRADIATED VANADIUM
C. C. Chen and R. J. Arsenault
Met. Trans. 7A, 1976, 55
30. MECHANICAL PROPERTIES OF SINGLE CRYSTAL V-Ti-O ALLOYS
H. Perelsztein, C. Yin and R. J. Arsenault
Met. Trans. 7A, 1976, 1027
31. MICROPLASTICITY IN VANADIUM SINGLE CRYSTALS
C. R. Crowe and R. J. Arsenault
Acta Met. 24, 1976, 925
32. THE EARLY STAGES OF FLOW IN MOLYBDENUM SINGLE CRYSTALS
C. R. Crowe and R. J. Arsenault
Met. Trans. 7A, 1976, 1275

33. A COMPARISON OF THE EFFECT OF NEUTRON IRRADIATION ON HIGH PURITY VANADIUM AND VANADIUM OXYGEN ALLOYS.
R. J. Arsenault and J. R. Bressers
Met. Trans., 8A, 1977, 925
34. LOW ENERGY NEUTRON IRRADIATION OF NIOBIUM
C. Yin and R. J. Arsenault
Proceeding of the Fourth International Conference
On the Strength of Metals and Alloys, 1976, vol. 2,
p. 789
35. DISLOCATION KINETICS
R. J. Arsenault and T. W. Cadman
Proceedings of the Conference on Computer
Simulation for Materials Applications, 1976, p. 658
36. DEFORMATION CHARACTERISTICS OF HIGH PURITY NEUTRON IRRADIATED VANADIUM
J. R. Bressers and R. J. Arsenault
Fundamental Aspects of Radiation Damage in Metals,
CONF-751006-P2, 1975, p. 1018
37. THERMALLY-ACTIVATED MOTION OF A GROUP OF DISLOCATIONS
R. J. Arsenault, and T. Cadman
Scripta Met. 12, 1978, p. 633.
38. MULTIPLE DISLOCATION MOTION
R. J. Arsenault and C. T. K. Kuo
Met. Trans., 9A, 1978, p. 459
39. FURTHER OBSERVATIONS OF ANOMALOUS SLIP IN NIOBIUM SINGLE CRYSTALS
R. E. Reed and R. J. Arsenault
Scripta Met. 10, 1976, 1003.
40. LOW TEMPERATURE NEUTRON IRRADIATION OF NIOBIUM
F. Vanoni and R. J. Arsenault
Scripta Met. 10, 1976, 1109.
41. THE EFFECT OF TRITIUM ON THE LOW TEMPERATURE YIELD STRESS OF NIOBIUM.
R. J. Burger, J. A. Donovan and R. J. Arsenault
Met. Trans., 8A, 1977, 2023.
42. THE EFFECT OF NEUTRON IRRADIATION DAMAGE ON NIOBIUM OXYGEN ALLOYS.
C. Yin and R. J. Arsenault,
Met. Trans. 9A, 1978, 1865.
43. THE EFFECT OF IMPURITY INTERSTITIALS ON THE LATTICE RESISTANCE TO DISLOCATION MOTION
R. J. Arsenault and T. W. Cadman
To be published in Met. Trans.

Book Chapters

1. Microplasticity of B.C.C. Metals and Solid Solutions
in Terms of the Double Kink Mechanism
R.J. Arsenault
Book Title: Microplasticity
Ed.: C. McMahon
Interscience, 1968, 91
2. An Investigation of Methods of Preparing High Purity
Vanadium
H. A. Beale and R. J. Arsenault
Fourth International Conference on Electron and Ion Beam
Science and Technology
Ed.: R. Bakish
Electrochemical Society, N.Y., 1971, 421
3. Low Temperature Strengthening of Group VA Metals Single
Crystals by Hydrogen
C. C. Chen and R. J. Arsenault
Book Title: Hydrogen in Metals
Ed.: I. M. Bernstein and A. W. Thompson
American Soc. for Metals, 1974, 393
4. Low Temperature Deformation of B.C.C. Metals and Their
Alloys
R. J. Arsenault
Book Title: Plastic Deformation of Materials
Ed.: R. J. Arsenault
Academic Press, 1975, 1

Invited Review Articles

1. Neutron Irradiation Strengthening in F.C.C. Single Crystals
T. J. Koppenaal and R. J. Arsenault
Metallurgical Reviews, 1971, 175
2. Dynamic Microplasticity of B.C.C. Metals and Solid
Solutions
R. J. Arsenault, C. R. Crowe, and R. D. Carnahan
Book Title: Pure Materials in Science and Technology,
1972, 345
3. Thermally Activated Dislocation Motion Through a Random
Array of Obstacles
R. J. Arsenault and T. Cadman
Dorn Memorial Conference Volume
ASM Publisher 1975, 102
4. The Effect of Post-Irradiation Annealing on the Strength
Properties of Proposed Reactor Materials
D. F. Hasson and R. J. Arsenault
The Indian and Eastern Engineer, 114, 1972, 45
5. Computer Simulation of Plastic Deformation
R. J. Arsenault, and T. W. Cadman
Reviews on the Deformation Behavior of Materials III, 1978, 5
Ed.: P. Feltham
Freund Publishing Company

INVITED SEMINARS

(At which DOE support was acknowledged).

1. International Nickel Company, 1969
2. Gordon Research Conference, Physical Metallurgy Section, "The Effects of Internal Stress on Low Temperature Creep of B.C.C. Metals", July, 1969
3. Max Planck Institute, Stuttgart, West Germany, 1970
4. Tokyo Institute of Technology, 1971
5. Dartmouth University, 1972
6. Memorial Symposium in honor of Professor John Dorn, 1972, "Thermally Activated Dislocation Motion Through a Random Array of Obstacles".
7. International Conference on Defects and Defect Clusters in B.C.C. Metals and Their Alloys, "Neutron Irradiation Softening and the Effect of Interstitials on Strengthening", with T. Cadman, 1973
8. MOL, Belgium, "Radiation Anneal Hardening in Molybdenum", Fall, 1974
9. University of Liverpool, "The Effect of Neutron Irradiations on the Deformation Characteristics of B.C.C. Metals," 1974
10. Euratom Lab., Petten N.H., Netherlands, "The Effect of Neutron Irradiations on the Deformation Characteristics of B.C.C. Metals," 1974
11. Max Planck Institute, Stuttgart, "The Effect of Neutron Irradiations on the Deformation Characteristics of B.C.C. Metals", 1974
12. Oxford University, "Computer Simulation of Dislocation Motion Through A Random Array of Thermally Activatable Obstacles," 1974
13. University of Gottingen, "Computer Simulation of Dislocation Motion Through A Random Array of Thermally Activatable Obstacles," 1974
14. Spring Meeting AIME 1975
Microplasticity in Vanadium Single Crystals
R. Crowe and R. J. Arsenault
15. Spring Meeting AIME 1975
Morphology of Neutron Produced Defects in Nb, V, Mo and Fe-Ni
C.A. Yin and R.J. Arsenault

16. Fourth International Conference on the Strength of Metals and Alloys, Nancy, France 1976
Low Energy Neutron Irradiation of Niobium
17. Dislocation Kinetics, Computer Simulation for Materials Applications (1976) R.J. Arsenault and T.W. Cadman
18. Technical University of Denmark. "Computer Simulation of Plastic Deformation" 1976
19. Center of Nuclear Studies Grenoble "Mechanical Properties of Irradiated Metals" 1976
20. University of Connecticut "Computer Simulation of Plastic Deformation", 1977
21. University of Kentucky "Computer Simulation of Plastic Deformation" 1978
22. Vanderbilt University "Computer Simulation of Plastic Deformation" 1978

PRESENTED LECTURES

(At which DOE support was acknowledged)

1. Annual Meeting AIME (1967)
Symposium on Radiation Effects in B.C.C. Metals. Possibility of Irradiation Damage Affecting the Rate-Control-ling Mechanism of Slip in B.C.C. Metals and Solid Solutions
J. of Metals 19, 1967, 79
2. Annual Meeting AIME (1969)
Low Temperature Deformation of Neutron-Irradiated Vanadium
R. J. Arsenault and E. Pink
3. Fall Meeting AIME (1970)
Determination of the Existence of the "Scavenging Effect" in Group V Solid Solutions
D. F. Hasson, E. Pink and R.J. Arsenault
4. Annual Meeting AIME (1970)
Low Temperature Deformation Characteristics of Neutron Irradiated Vanadium-Titanium Alloys
E. Pink and R. J. Arsenault
5. Third International Symposium of Pure Materials in Science and Technology (1970)
Dynamic Microplasticity of B.C.C. Metals and Solid Solutions
R. J. Arsenault, C. R. Crowe and R. D. Carnahan
6. Third International Symposium of Pure Materials in Science and Technology (1970)
High Purity Vanadium
H. Beale and R. J. Arsenault
7. Fourth International Conference on Electron and Ion Beam Science and Technology (1970)
An Investigation of Methods of Preparing High Purity Vanadium
H. Beale and R. J. Arsenault
8. Second International Conference on the Strength of Metals and Alloys (1970)
The Effect of Neutron Damage on the Dislocation Dynamics of B.C.C. Metals
R. J. Arsenault and E. Pink
9. Annual Meeting AIME (1971)
Low Temperature Deformation Characteristics of Neutron Irradiated Vanadium Titanium Alloys
R. J. Arsenault and E. Pink
10. International Conference on the Mechanical Behavior of Materials, Kyoto, Japan (1971)
The Effect of Neutron Irradiation Damage on the Low Temperature Deformation Characteristics of B.C.C. Metals and Alloys
R. J. Arsenault, K. Kuo and Y. Huang

11. Fall Meeting AIME (1971)
The Effect of Oxygen Content on the Dislocation Configurations in Vanadium
Y. Huang and R. J. Arsenault
12. Annual Meeting AIME (1972)
Effect of Post-Irradiation Annealing on the Strength of Vanadium-Interstitial Alloys
D. F. Hasson and R. J. Arsenault
13. Annual Meeting AIME (1972)
The Effect of Neutron Irradiation on the Low Temperature Deformation Characteristics of Molybdenum
D. F. Hasson and R. J. Arsenault
14. Annual Meeting AIME (1972)
The Effect of Oxygen Content on the Dislocation Channeling in Neutron Irradiated Vanadium
Y. Huang and R. J. Arsenault
15. Annual Meeting AIME (1973)
Hydrogen and Discontinuous Temperature Dependence of Yield Stress in Vanadium Single Crystals
C. C. Chen and R. J. Arsenault
16. Annual Meeting AIME (1973)
Radiation Anneal Hardening in Molybdenum
D. F. Hasson and R. J. Arsenault
17. Annual Meeting AIME (1973)
A Consideration of Computer Simulation Models for Dislocation Motion Through a Random Array of Obstacles
R. J. Arsenault
18. Fall Meeting AIME (1973)
Effect of Hydrogen on the Low Temperature Deformation Properties of Neutron Irradiated Vanadium
C. C. Chen and R. J. Arsenault
19. Hydrogen in Metals Conference, Seven Spring, PA (1973)
Low Temperature Strengthening of Group VA Metal Single Crystals by Hydrogen
C. C. Chen and R. J. Arsenault
20. Annual Meeting AIME (1974)
Deformation Characteristics of Low Temperature Neutron Irradiated Vanadium
C. C. Chen and R. J. Arsenault
21. Fall Meeting AIME (1974)
The Thermally Activated Dislocation Motion in the Neutron Irradiated Iron-Nickel Alloys
C. T. K. Kuo and R. J. Arsenault

22. Fall Meeting AIME (1974)
The Kinetics of a Dislocation Surmounting Two Different
Strength Barriers
R. J. Arsenault
23. Fall Meeting AIME (1974)
A Consideration of the Mobile Dislocation Density
R. J. Arsenault and H. Perelsztein
24. Spring Meeting AIME (1975)
Microplasticity in Vanadium Single Crystals
R. Crowe and R. J. Arsenault
25. Spring Meeting AIME (1975)
Morphology of Neutron Produced Defects in Nb, V, Mo, and
Fe-Ni
C. A. Yin and R. J. Arsenault
26. Fourth International Conference on the Strength of
Metals and Alloys, Nancy, France (1976)
Low Energy Neutron Irradiation of Niobium
C. Yin and R. J. Arsenault
27. Fall Meeting AIME, (1977)
Effect of Helium on the Low Temperature Deformation Charac-
teristics of Niobium
R. J. Arsenault and R. Burger

LIST OF STUDENTS

M.S. Candidates:

K. Kuo	-	Degree awarded 7/73
C. Serpan	-	Degree awarded 5/75
H. Perelsztein	-	Degree awarded 6/74
R. Burger	-	Degree awarded 8/77

Ph.D. Candidates:

D. Hasson	-	Degree awarded 8/70
H. Beale	-	Degree awarded 8/71
C.R. Crowe	-	Degree awarded 4/75

Post-doctoral fellows:

Dr. G. C. Das	-	1967-1968
Dr. E. Pink	-	1968-1970
Dr. P. Basu	-	1970-1971
Dr. C. Chen	-	1973-1975
Dr. C. Yin	-	1976-1977
Dr. Raghuraman	-	1976-1977