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ENVIRONMENTAL REACTIONS AND THEIR EFFECTS ON MECHANICAL BEHAVIOR OF METALLIC MATERIALS

Technical Progress Report

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ABSTRACT

The results of research performed under DOE Contract No. DE-AC02-79ER10359.A000 are presented. In the past contract year, completed results have been obtained in each of three experimental project areas: (A) mechanical behavior of Nb-H and Nb-D alloys; (B) implantation softening of niobium; and (C) the crack path in hydrogen embrittlement of 4340 steel. The current results and near-future plans in each of these specific areas are reviewed.

We have shown, respectively, that: (A) hydrogen or deuterium softening in niobium is related to the ability of hydrides and deuterides to punch out glissile dislocations; (B) implanted surface layers of oxygen ions in niobium reduce the flow stress at low temperatures; and (C) the hydrogen-assisted crack path in 4340 steel can be identified at electron microscopy resolutions as intergranular, interlath or translath, depending upon the strength level.

CURRENT RESULTS

A. Mechanical Behavior of Nb-H and Nb-D Alloys (R. Fournier)

The microstructural analysis by transmission electron microscopy (TEM) has been investigated and completed during the past year. Previously we have shown that Nb-H single crystals exhibit a maximum in strength as a function of hydrogen concentration at 77°K in materials that are prestrained at 295°K as well as in unprestrained materials[1]. This behavior was initially attributed to the coherent-to-incoherent transition that hydrides undergo as hydrogen concentration is increased[2]. In this report we discuss the microstructural results obtained that have confirmed this interpretation.

In the last progress report, we presented slip trace analyses that illustrated a pronounced difference in slip line morphology in Nb-H alloys as a function of hydrogen concentration. Materials with close to the maximum strength, i.e. with less than ~300 ppma H and therefore coherent hydride precipitates, exhibited long fine straight traces with definite crystallographic slip on (011) and (121) planes. Materials with higher hydrogen concentrations and hence incoherent hydrides exhibited slip traces on only the primary (011) plane and were wavy and coarse. Additional results obtained in the past year on both Nb-H and Nb-D alloys confirmed these observations. The results for the low hydrogen alloys are consistent with the effects that alloying has on slip in Nb, where increasing friction stress can produce long crystallographic slip lines at low temperatures[3]. The coarse and wavy slip bands, with large slip steps that appear at high hydrogen concentrations, are consistent with massive non-screw dislocation generation by incoherent precipitates and the motion of these edge dislocations along with at least localized motion of the screw components.

The TEM results obtained over the past two years are consistent with the slip trace results and their interpretation. In the low hydrogen alloys, the dislocation substructures consist of screw dislocation segments aligned approximately equally along the primary $[1\bar{1}1]$ and secondary $[\bar{1}\bar{1}1]$ directions. There is also a large density of debris loops in the background and the occasional presence of dislocation tangles that are expected from extensive motion of screw dislocations. In the high hydrogen alloys, the dislocations are also in the screw orientation and are more prominantly aligned along the primary $[1\bar{1}1]$ direction. It is possible to identify incoherent hydride skeletons which create arrays of prismatic dislocation loops along the primary $[1\bar{1}1]$. The hydrides always appear to have abundant densities of emergent shear dislocations. There is a general lack of debris dislocations that would be expected from extensive motion of screw dislocations, but parallel groups of prismatic loops are frequently converted into a helix by interaction with screw dislocations formed in their vicinity(4). See Fig. 1.

The general conclusion from these results is that the strength maximum in Nb-H alloys as a function of hydrogen concentration does indeed result as a consequence of the coherent-to-incoherent hydride transition. In low hydrogen alloys, the principal contribution to the strength arises from the interaction between the stress fields of coherent hydrides and gliding dislocations. The resulting dislocation substructure is similar to that encountered in materials hardened by interstitials(5), i.e. as expected in a bcc metal with a high frictional stress. In high hydrogen alloys, the hydrides become incoherent by punching prismatic dislocation loops and creating interfacial shear dislocations(6). The material softens as a result of the increased mobile dislocation density that may be generated from the hydrides under an applied shear stress.

In the past year, we have completed our investigations of the dislocation substructures of the Nb-H alloys and have obtained data on hydride particle size and inter-particle spacing as a function of hydrogen concentration. We have also obtained similar results for Nb-D alloys. The data are being analyzed in terms of theories of hardening by coherent and incoherent precipitates [7].

B. Implantation Softening of Niobium (D. DeMiglio, J. Ratka)

Previous work in this program by Sethi [8] demonstrated that macroscopic gradients of oxygen in solid solution in niobium have large effects on the mechanical behavior of niobium at low temperatures $T \leq 0.15\%_m$, where T_m is the melting temperature. Gradients of oxygen were produced by diffusion oxide-coated specimens at a temperature of 1275°K for various lengths of time. Very steep gradients caused softening at low temperatures, while more diffuse gradients resulted in hardening, such that a maximum was observed in data giving the critical resolved shear stress as a function of gradient steepness.

The goal of this current project was to see if gradients of oxygen in solid solution in niobium produced by implantation of ^{16}O ions cause similar types of hardening and softening effects. ^{16}O ions were implanted by irradiation at room temperature in a Van der Graaf accelerator at the Sandia Laboratories at Albuquerque, N.M. High purity single crystals of the type prepared in our laboratories for many years were used. The initial project was done in collaboration with Drs. S.T. Picraux and D. Follstaedt at Sandia, who have extensive experience in characterizing implantation profiles in irradiated metals [9]. The first results are summarized in the following paragraph.

High purity single crystals of niobium ~2mm in diameter wth a [213] tensile orientation were ion-implanted with oxygen at an accelerating voltage of 50 keV for various times to produce oxygen fluences in the range 1×10^{15} - 1×10^{17} atoms/cm^2. The resulting near-surface oxygen profiles were approximately Gaussian with half-width ΔR_p ~31nm. The peak concentrations within the profiles correspponded to respective volume concentrations in the range ~0.2 - 20 at. % O. The crystals were tested in tension at 77°K and 296°K. In tests at 77°K, in the thermal hardening regime for niobium, ion-implantation reduced the flow stress substantially over the first five percent shear strain and caused a corresponding increase in ductility. The maximum softening effects occurred for a fluence of 1×10^{16} atoms/cm^2. Implantation caused no such softening in tests conducted at 295°K, which is in the athermal hardening regime for niobium. These results can be compared with previous ones on oxygen gradients produced by diffusion annealing of surface oxide films and with the large softening and hardening effects that surface films themselves have on the mechanical behavior of niobium[3,8]. Interstitial gradient softening in niobium appears to be a residual stress effect that is eventually eliminated after several percent plastic flow. Surface film softening, on the other hand, occurs mainly as a result of plastic constraint associated with the film-substrate composite.

The detailed presentation of these results is currently in preparation for the 1980 AIME Annual Meeting in Las Vegas at the Symposium on Surface Effects in Refractory Metals and Compounds.

C. The Crack Path in Hydrogen Embrittlement of 4340 Steel (D. DeMiglio)

The role that hydrogen plays in the fracture mode of high strength steels is complex. Hydrogen-assisted cracks can propagate intergranularly or transgranularly depending upon the strength (tempering) and residual impurity level[10-12]. We have investigated the potential of transmission electron microscopy (TEM) and in particular high voltage electron microscopy (HVEM) as a technique to develop a better understanding of metallurgical factors that control cracking by hydrogen in high strength steels. In the past year, a first project on examination of the hydrogen-assisted crack path in a commercial 4340 steel by TEM of specimens thinned from bulk materials has been completed. These results will be compared to ones obtained in later investigations involving in-situ deformation of the same material in the HVEM in a hydrogen atmosphere by use of an environmental cell.

The experimental procedure was essentially that described in previous reports. Briefly, notched-bar tensile specimens were prepared from 4340 steel which was austenitized at 870 C, oil quenched, and tempered at temperatures ~200°C (1550 MN/m^2 yield stress) to ~600°C (950 MN/m^2 yield stress). This produced materials that would crack primarily intergranularly and transgranularly, respectively, by static fatigue at room temperature(13,14). Specimens were cathodically charged in 4% H_2SO_4, cadmium-plated, baked at 150°C to obtain a homogeneous distribution of hydrogen(15), and finally were fractured under various static loads. The time to fracture was typically one hour. Thin foils were prepared from 0.25mm thick slices cut just beneath and parallel to the fracture surface. Discs 3mm in diameter were punched out and electrochemically back-thinned by a method similar to that used by Awatani et al.(16) Lacquer was applied to one side of the disc in order to reduce preferential etching along a crack path. The TEM observations were complemented by selective use of scanning electron microscopy (SEM) for verification of the primary crack path observed by other investigators(10).

Some of our TEM results were shown in previous contract reports. Others plus the SEM work will be included in publications that are now in preparation. The total results are summarized in Figs. 2 and 3, which show, respectively, the crack paths in relatively lower strength (400°C tempering) and in higher strength (200°C tempering) 4340 steels. In these figures, the primary crack paths at A and B were determined by SEM to be transgranular and intergranular, respectively. The secondary branching crack paths observed by TEM were predominantly translath in the lower strength steel and interlath, intercolony or intergranular in the higher strength material. Such results are being analyzed in terms of the relative densities and interaction energies of possible microstructural traps for hydrogen[17].

Initial work has also begun in the preparation of in-situ tensile specimens for a side entry deformation stage of the Hitachi HU-650B high voltage electron microscope at CWRU. Full-scale effort on this project will begin during the proposed contract year in cooperation with Professor Gerhard Welsch, who is supervising all CWRU HVEM projects involving in-situ tensile deformations.

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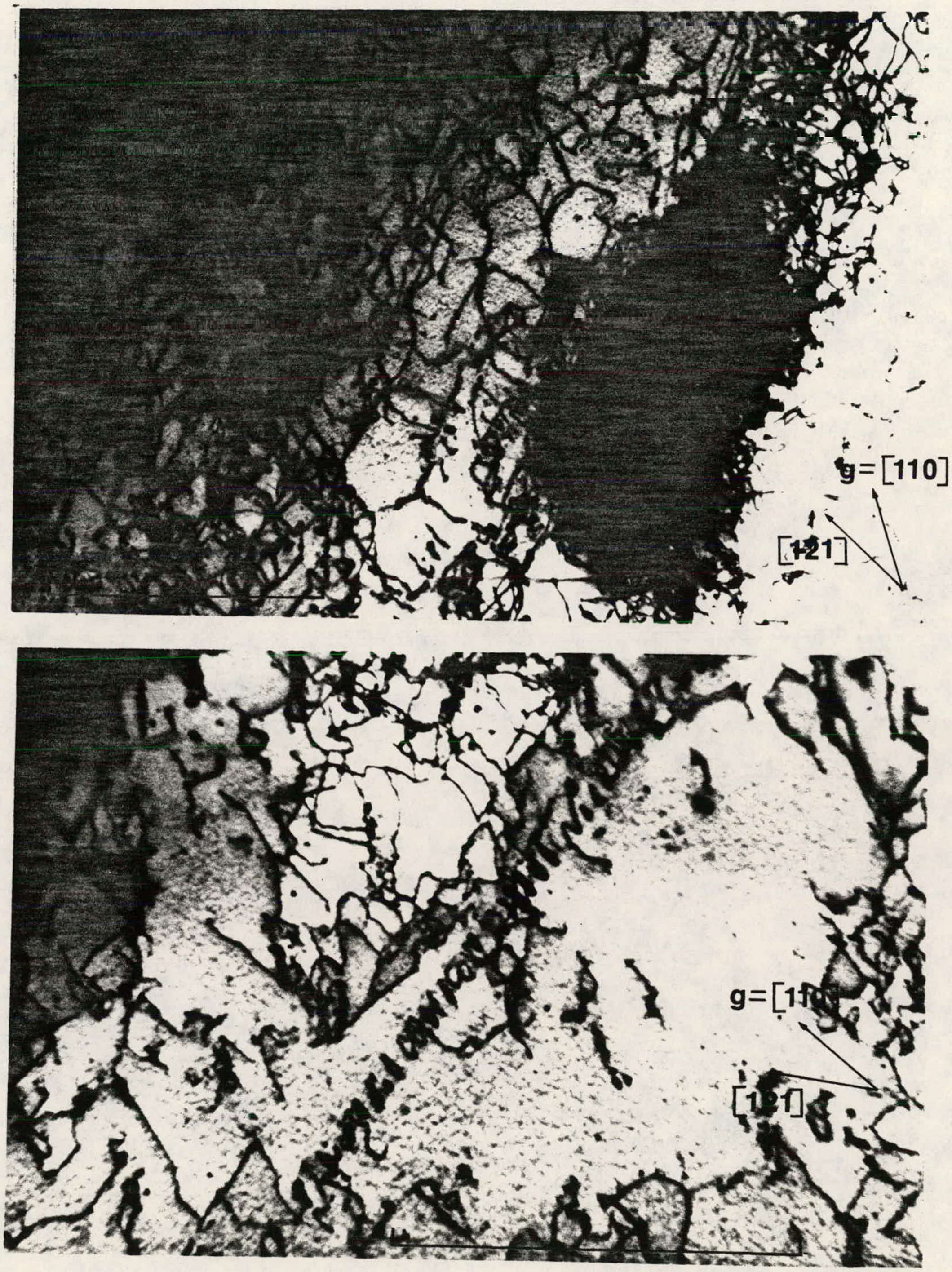

Fig. 1. Examples of (121) sections of thin foils obtained from Nb-2000 ppma H alloys deformed ~5% at 77°K. Magnification markers indicate 1μm. Upper figure shows a skelton of a dissolved incoherent hydride precipitate that has punched out small sessile prismatic interstitial loops and a dense tangled array of glissile edge-type dislocations. Lower figure shows a long array of prismatic loops that emanate from the hydride. Note the partial formation of small helices by some of the loops.

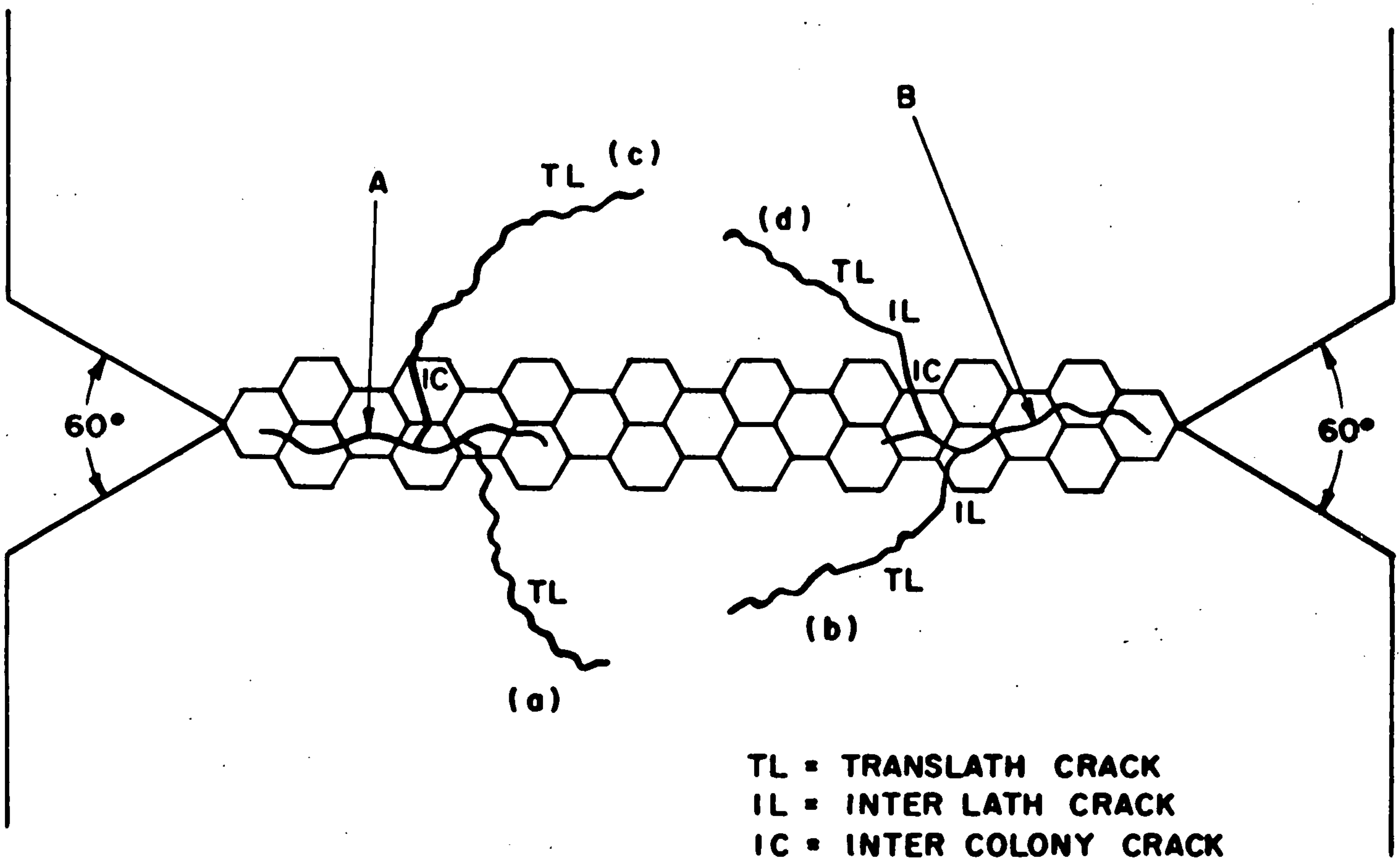

Fig. 2 Schematic diagram of hydrogen assisted primary and secondary cracking in a sharp-notched 4340 steel tempered at 400°C. Primary transgranular cracks are shown at A and B. Secondary crack paths (a) - (d) are translath at ~1 mm from the plane of the notch but can be some combination of intercolony, interlath or translath cracking near the plane of the notch.

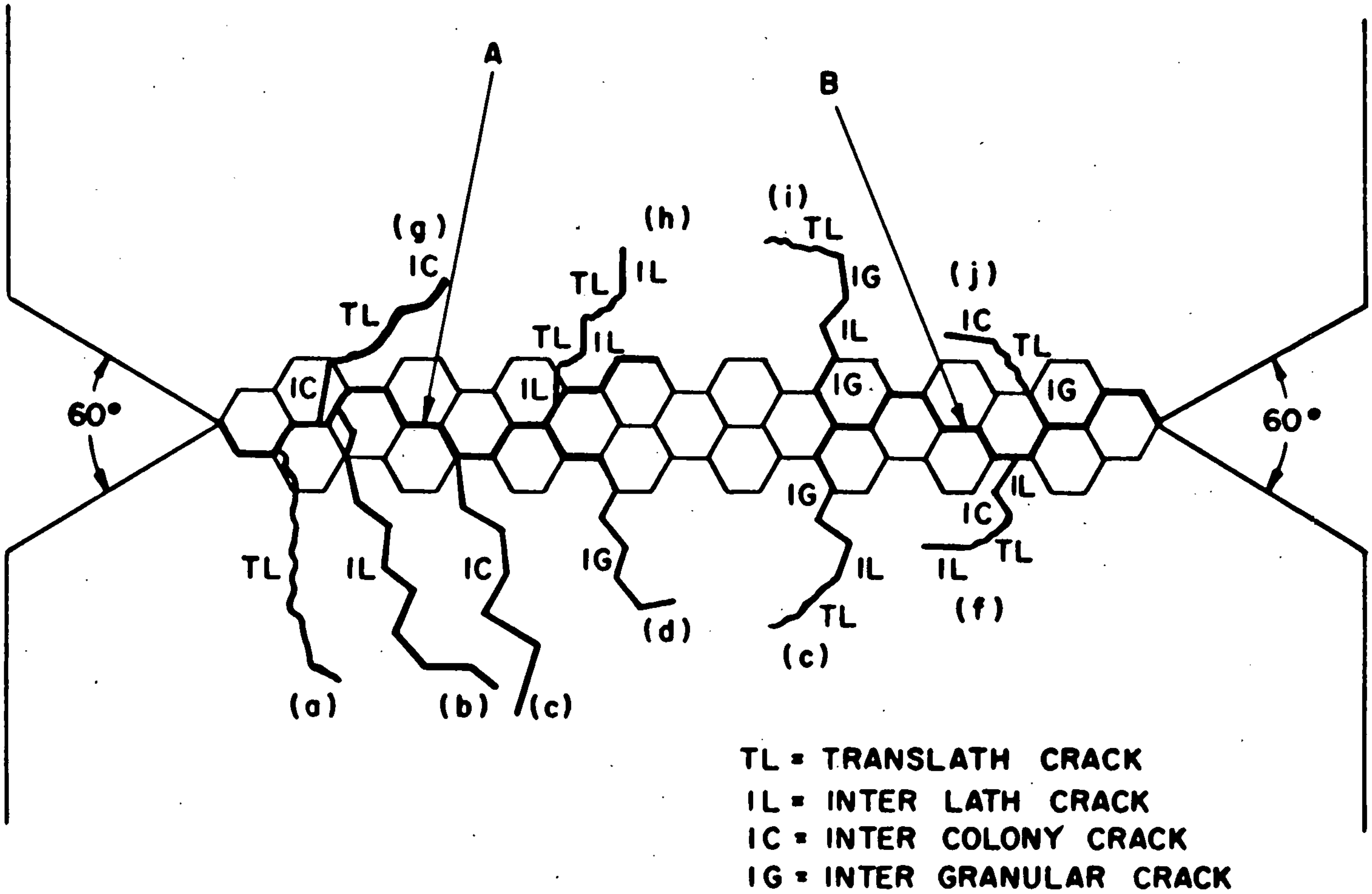

Fig. 3 Schematic diagram of hydrogen assisted primary and secondary cracking in a sharp-notched 4340 steel in the as-quenched and 200°C tempered conditions. Primary intergranular cracks are shown at A and B. Cracks (a) - (d) are the basic secondary fracture modes that are used in various combinations in cracks (e) - (j).

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A SUMMARY OF REPORTS SUBMITTED TO

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C00-1676-2	R. Gibala, Comments on the Cold-Work Peak in Alpha Iron, October 31, 1967.
C00-1676-3	R. Gibala and C.A. Wert, Interstitial Alloys of BCC Metals, October 31, 1967.
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33. V.K. Sethi and R. Gibala, "The Strength-Differential Effect in Surface Oxide Softening of Niobium Single Crystals", Scripta Met. 11, 635 (1977)

34. R. Gibala, "Hydrogen Defect Interactions in Iron-Base Alloys", Stress Corrosion Cracking and Hydrogen Embrittlement of Iron-Base Alloys, R.W. Staehle, J. Hochmann, R.D. McCright and J.E. Slater, eds., NACE, Houston, pp. 244-268 (1977)

35. V.K. Sethi and R. Gibala, "Anisotropy of Surface Oxide Softening in Niobium Single Crystals", Phil. Mag. 37, 419 (1978).

36. J. Talia, L. Fernandez, V.K. Sethi and R. Gibala, "Surface Oxide Softening of Body Centered Cubic Refractory Metals", Proc. Fifth Int. Conf. on Strength of Metals and Alloys," Vol. 1, p. 821 (1979).

37. F. Povolo and R. Gibala, "Dislocation Damping in Niobium" Proc. Fifth Inter-American Conf. on Materials Technology, Vol. 2, p. 677 (1979).

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ORAL PRESENTATIONS

1. R. Gibala, "Internal Friction of BCC Metals", Purdue University, April 1968.
2. K.V. Ravi and R. Gibala, "The Strength of Niobium-Oxygen Solid Solutions", AIME Meeting, Pittsburgh, May 1969.
3. M.G. Ulitchny and R. Gibala, "Internal Friction and Strain Aging of Austenite", AIME Meeting, Philadelphia, October 1969.
4. K.V. Ravi and R. Gibala, "Thermally Activated Deformation of Niobium and Niobium Base Interstitial Solid Solutions", AIME Meeting, Philadelphia, October 1969.
5. R. Gibala, "Strength and Structure of Solid Solutions", Cornell University, February 1970.
6. K.V. Ravi and R. Gibala, "The Effects of Aging on the Mechanical Behavior of Niobium-Oxygen Solid Solutions", AIME Meeting, Los Vegas, May 1970.
7. R. Gibala, "Strength and Structure of Solid Solutions", Argonne National Laboratory, August 1970.
8. K.V. Ravi and R. Gibala, "The Strength Differential Effect in Niobium-Oxygen Solid Solutions", Second International Conference on the Strength of Metals and Alloys, Pacific Grove, California, August 1970.
9. F. Povolo and R. Gibala, "Low Temperature Dislocation Damping in BCC Metals", AIME Meeting, Cleveland, Ohio, October 1970.
10. R. Gibala, "Interstitial Solid Solutions", Case Western Reserve University, February, 1971.
11. R. Gibala, "The Effect of Solute and Point Defect Interactions on Mechanical Properties," AIME Meeting, Atlanta, May 1971.
12. K.V. Ravi and R. Gibala, "The Influence of Interstitials on the Dislocation Velocity Exponent in Niobium-Oxygen Solid Solutions", AIME Meeting, Atlanta, May 1971.
13. M.G. Ulitchny, A.A. Sagues and R. Gibala, "Alloy Softening in Niobium- and Tantalum-base Solid Solutions", Discussion Meeting on Defects in Refractory Metals, Mol, Belgium, September 1971.
14. R. Gibala, "Alloy Softening in Body-Centered Cubic Materials", Cleveland Section, AIME Meeting, October 1971.

15. T.E. Mitchell and R. Gibala, "Solution Softening in BCC Metals: The Importance of Solute Interactions", AIME Meeting, Detroit, October 1971.

16. A.K. Vasudevan and R. Gibala, "Alloy Softening in Nb-Mo-O Single Crystals", AIME Meeting, Detroit, October 1971.

17. M.G. Ulitchny and R. Gibala, "Mechanical Behavior of Niobium-base Interstitial Solid Solutions", AIME Meeting, Detroit, October 1971.

18. C.J. Klems, R.E. Miner, F.A. Hultgren and R. Gibala, "Internal Friction in Twinned Fe-Ni-C Martensites", AIME Meeting, Detroit, October 1971.

19. R. Gibala, "Point Defects in Refractory Metals", Case Western Reserve University, October 1971.

20. M.G. Ulitchny and R. Gibala, "Internal Friction and Strain Aging Behavior of Ferrous Austenites", AIME Meeting, Boston, May 1972.

21. M.G. Ulitchny and R. Gibala, "Thermally Activated Deformation Behavior of Nb-O-N Single Crystals", AIME Meeting, Boston, May 1972.

22. R.E. Miner, F. Hultgren and R. Gibala, "An Analysis of the Cold-Work Internal Friction Peak in Iron", AIME Meeting, Boston, May 1972.

23. M.G. Ulitchny and R. Gibala, "Solute Interactions Involving Hydrogen and Their Influence on the Mechanical Behavior of Niobium Single Crystals", International Congress on Hydrogen in Metals, Paris, France, May 1972.

24. R. Gibala,"The Strength Differential Effect in Niobium-Oxygen Solid Solutions", ONR Workshop on the Strength Differential Effect in Metals and Polymers, Boston, June 1972.

25. R. Gibala, "The Strength and Structure of Solid Solutions", General Electric Research and Development Laboratory, Schenectady, N.Y., November 1972.

26. R. Gibala, "The Strength and Structure of Solid Solutions", University of Illinois, Urbana, November 1972.

27. A.K. Vasudevan and R. Gibala, "Alloy Softening in Nb-Mo-O and Nb-Mo-N Solid Solutions", AIME Meeting, Philadelphis, May, 1973.

28. A.A. Sagues and R. Gibala, "Substitutional-Interstitial Solute Interactions in Ta-Re-N and Ta-Re-O Solid Solutions", AIME Meeting, Philadelphia, May, 1973.

29. R. Gibala, "Hydrogen-Defect Interactions in Iron-Base Alloys", International Conference on Stress Corrosion Cracking and Hydrogen Embrittlement of Iron Base Alloys, Unieux-Firminy, France, June, 1973.

30. M. G. Ulitchny, A.K. Vasudevan and R. Gibala, "Solution Hardening and Softening in Nb-Base Solid Solutions", Third International Conference on the Strength of Metals and Alloys, Cambridge, England, August, 1973.

31. A.A. Sagues and R. Gibala, "Crystallographic Orientation Dependence of Interstitial Anelasticity in Ta-Re-N and Ta-Re-O Alloys", Fifth International Conference on Internal Friction and Ultrasonic Attenuation in Crystalline Solids, Aachen, Germany, August, 1973.

32. G.J. Klems, R.E. Miner, F.A. Hultgren and R. Gibala, "Internal Friction in Ferrous Martensites", Fifth International Conference on Internal Friction and Ultrasonic Attenuation in Crystalline Solids, Aachen, Germany, August, 1973.

33. M.G. Ulitchny and R. Gibala, "Mechanical Properties of Nb Single Crystals Containing H and H+O", International Conference on "Hydrogen in Metals: Effects on Properties, Selection and Design", Seven Springs, Champion, Pa., September, 1973.

34. A.K. Vasudevan and R. Gibala, "Adoucissement par Alliage du Niobium par Addition de Molybden et Oxygene", Colloque Plasticité, Toulouse, France, March, 1974.

35. R. Gibala, "Dislocation Relaxation in BCC Metals", Max-Planck Institut fur Metallforschung, Stuttgart, Germany, April, 1974.

36. R. Gibala, "Internal Friction in Ferrous Alloys", Université de Paris, Colloque Internationale, Paris, France, April, 1974.

37. R. Gibala, "Relaxation de Dislocation dans Metaux Cubiques Centres", Laboratoire de Mechanique et Physique des Materiaux, Université de Poitiers, Poitiers, France, April, 1974.

38. R. Gibala, "Interactions Hydrogene-Defaut dans Metaux", Centre d'Etudes Nucléaires de Grenoble, Grenoble, France, April, 1974.

39. R. Gibala, "Relaxation de Dislocation dans Metaux Cubiques Centres", Ecole Polytechnique Federale de Lausanne, Lausanne, Switzerland, July, 1974.

40. R. Gibala, "Interstitials in BCC Metals", General Electric Company, Lamp Division, Cleveland, Ohio, October, 1974.

41. R. Gibala, "Effects of Interstitials on Mechanical Behavior of BCC Metals", Rice University, Houston, Texas, December, 1974.

42. R. Gibala, "Anelastic and Magnetic Relaxation in Ni-Co Alloys", Case Western Reserve University, February, 1975.

43. R. Gibala, "Internal Friction of Ferrous Martensites", Conference on Martensite Transformations, M.I.T., Cambridge, Mass., April, 1975.

44. R. Gibala, M. Wuttig, W. Kunz and P. Moser, "Anelastic and Magnetic Relaxation in Face-Centered Cubic Ni-Co-C Alloys", AIME National Spring Meeting, Toronto, Canada, May, 1975.

45. R.P. Krupitzer and R. Gibala, "Effects of Preferred Orientation on Snoek Phenomena in Commercial Steels", AIME National Spring Meeting, Toronto, Canada, May, 1975.

46. V.K. Sethi, and R. Gibala, "Low Temperature Mechanical Behavior of Oxide-Coated Single Crystals of Niobium", AIME National Spring Meeting, Toronto, Canada, May, 1975.

47. A.A. Sagues, M.G. Ulitchny and R. Gibala, "Hydrogen Strengthening in Niobium and Niobium Base Alloys", International Conference on Effects of Hydrogen on Behavior of Materials, Jackson Hole, Wyoming, September, 1975.

48. V.K. Sethi and R. Gibala, "Effect of Oxide Coatings on the Mechanical Properties of Niobium Single Crystals Deformed at Low Temperatures", NATO Advanced Study Institute on Surface Effects in Crystal Plasticity, Hohegeiss, W. Germany, September, 1975.

49. V.K. Sethi and R. Gibala, "Low Temperature Mechanical Behavior of Oxide-Coated Single Crystals of Niobium and Tantalum", ASM/AIME Materials Science Symposium, Cincinnati, Ohio, November, 1975.

50. V.K. Sethi and R. Gibala, "The Effect of Anodic Oxide Coatings on the Mechanical Behavior of Niobium and Tantalum Single Crystals", International Conference on Metallurgical Coatings, San Francisco, California, April, 1976.

51. V.K. Sethi and R. Gibala, "The Effect of Oxygen Distribution on the Low Temperature Mechanical Behavior of Niobium Single Crystals", Second International Conference on Mechanical Behavior of Materials, Boston, Mass., August, 1976.

52. V.K. Sethi and R. Gibala, "Surface Oxide Softening in Single Crystals of Niobium and Tantalum", Fourth International Conference on Strength of Metals and Alloys, Nancy, France, August, 1976.

53. R. Gibala, "Effects of Interstitial Distributions on Mechanical Behavior of BCC Refractory Metals", AIME Fall Meeting, Niagra Falls, N.Y., September, 1976.

54. T.E. Mitchell, V.K. Sethi and R. Gibala, "Interstitial Solution Hardening in BCC Refractory Metals", AIME Fall Meeting, Niagra Falls, N.Y., September, 1976.

55. R. Gibala, "Effects of Interstitial Distributions on Mechanical Behavior of BCC Metals", General Motors Corporation, Warren, Michigan, January 1977.

56. V.K. Sethi and R. Gibala, "An Analysis of Surface Oxide Softening in Niobium Single Crystals", AIME Annual Meeting, Atlanta, Ga., March 1977.

57. R. Gibala, "Hydrogen-Defect Interactions in Metals", Polish Academy of Sciences, Commemorative Symposium on Contributions of Michal Smialowski, Hydrogen Embrittlement and Corrosion of Metals, Warsaw Poland, May 1977.

58. R. Gibala, "Surface Film Softening in BCC Metals", Max-Planck-Institut fur Eisenforschung, Dusseldorf, West Germany, May 1977.

59. R. Gibala "Effects of Interstitial Distributions on Mechanical Behavior of BCC Metals", Institut fur Festkorperforschung der Kernforschungsanlage, Julich, May 1977.

60. R. Gibala, "Effect of Interstitial Distributions on Mechanical Behavior of BCC Metals", Universitat Gottingen, Institut fur Physik, Gottingen, West Germany, May 1977.

61. R. Gibala, "Recent Experiments and Interpretations on Hydrogen-Defect Interactions in Metals", Max-Planck Institut fur Metallforschung, Stuttgart, West Germany, May 1977.

62. R. Gibala, "Effect of Purity, Prestrain and Cooling Rate on Hydrogen Strengthening in Niobium Single Crystals", Second International Congress on Hydrogen in Metals, Paris, France, June 1977.

63. R. Gibala, "Plasticite des Metaux Cubiques Centres a Basse Temperature" Centre d'Etudes Nuclearies de Grenoble, Grenoble, France, June 1977.

64. R. Gibala, "Effect of Interstitial Distributions on Mechanical Behavior of BCC Alloys", Michigan Technological University, Houghton, Michigan, August, 1977.

65. V.K. Sethi and R. Gibala, "Anisotropy of Surface Oxide Softening of Niobium Single Crystals", AIME Fall Meeting, Chicago, Illinois, October, 1977.

66. V.K. Sethi, I. Rusakova and R. Gibala, "Dislocation Substructures in Surface Oxide Softened Niobium", AIME Annual Meeting, Denver, Colorado, March, 1978.

67. V.K. Sethi, J.E. Talia, L. Fernandez and R. Gibala, "Surface Oxide Softening in BCC Refractory Metals", AIME Fall Meeting, St. Louis, Missouri, October, 1978.

68. J. Talia, L. Fernandez, V.K. Sethi and R. Gibala, "Surface Oxide Softening of Body Centered Cubic Refractory Metals", Fifth Int. Conf. on Strength of Metals and Alloys, Aachen, W. Germany, August, 1979 (poster paper).

69. D. DeMiglio, D. Follstaedt and R. Gibala, "The Effect of Implanted Oxygen on the Mechanical Properties of Niobium Single Crystals", AIME Annual Meeting, Las Vegas, Nevada, February, 1980.

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THESES

1. M.G. Ulitchny (M.S. , 1969), "Internal Friction and Strain Aging of Austenite".

2. K.V. Ravi (Ph.D., 1969), "The Strength of Niobium-Oxygen Solid Solutions".

3. G.J. Klems (Ph.D., 1971), "Internal Friction of Ferrous Martensites."

4. M.G. Ulitchny (Ph.D., 1972), "Mechanical Behavior of Interstitial Solid Solutions of Niobium".

5. A.A. Sagues (Ph.D., 1972), "Substitutional-Interstitial Solute Atom Interactions in Ta-Re-N and Ta-Re-O Solid Solutions".

6. J.A. Slane (M.S., 1973), "Carbon-Vacancy Interactions in Austenites".

7. R.P. Krupitzer (M.S., 1973), "Effects of Preferred Orientation on Snoek Phenomena in Commercial Steels".

8. A.K. Vasudevan (Ph.D., 1974), "Solution Softening in Niobium Base Substitutional Alloy Single Crystals".

9. V.K. Sethi (Ph.D., 1976), "Effects of Solute Gradients and Oxide Films on the Mechanical Behavior of Niobium and Tantalum".

10. R. Fournier (M.S., 1977), "Mechanical Behavior of Niobium-Hydrogen Single Crystals".

11. D.S. DeMiglio (M.S., 1979), "Observations of the Hydrogen-Assisted Crack Path in 4340 Steel by Transmission Electron Microscopy".

EFFORT DISTRIBUTION OF THE PRINCIPAL INVESTIGATOR

During the contract period February 1, 1979 to January 31, 1980, Professor Ronald Gibala, principal investigator for Contract No. DE-AC02-79ER10359.A000, has allotted his time as follows:

1. February 1, 1979 - May 31, 1979.

30% of these four months was spent on Contract research. 30% of this time was charged to the Contract.

2. June 1, 1979 - August 31, 1979.

65% of this two month period during the summer session was spent on Contract research, and 65% of the time was charged to the contract.

3. September 1, 1979 - January 31, 1980.

30% of these five months of the academic year was spent on Contract research. The full 30% was financed by the Contract.