Final Report for ERDA

Contract No. E(11-1)-3153

ELASTIC AND PLASTIC

DEFORMATION OF SOLIDS

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Abstract

Special techniques were developed to study creep at high pressures. Results on activation volumes agreed with those for self-diffusion, confirming the work of John Dorn on the mechanism of creep. Activation volume for creep of aluminum was found to be 1.3Ω , a result later found in self-diffusion studies confirming an independent and simultaneous theoretical prediction. Study of the pressure dependence of creep showed unequivocally that mechanism changed near $0.5T_M$ where activation energy decreases.

Special techniques were developed for obtaining stress-strain curves at pressure and this was applied to study the pressure dependence of yield stress of potassium. It was found that the yield stress scaled with $G/(1-\nu)$ where G is the shear stress and ν is Poisson's ratio.

New techniques were developed for simultaneously measuring the sound velocity in several crystals at a given pressure using pulse interferometry. Elastic constants as a function of pressure were measured in several alkali halides, calcite, and several metals. In the case of sodium, the second derivatives were obtained. Later calculations by us showed these to be in excellent agreement with pseudopotential calculations.

A new length at pressure measuring system was developed which can measure fractional changes of length at pressures to 10^{-7} . This formed the basis for a new absolute pressure gauge which was used to redetermine the mercury freezing point at 0°C . This length measuring system has recently been used to obtain the pressure derivatives of the bulk modulus of NaCl and in particular, the second pressure derivative.

FINAL REPORT

The work on this contract began on Feb. 1, 1960 and continued until Jan. 31, 1976. It was a highly productive effort. The work can be divided into A. Plastic Deformation and B. Elastic Deformation. Only representative references will be given.

A. Plastic Deformation

1. Diffusion controlled creep

Techniques were developed to accurately measure the rate of creep at high pressure and the change of slope method (with changing pressure) was used to measure the activation energies. The results for Pb, In and Na were in excellent agreement with the activation volumes for self-diffusion, thus confirming John Dorm's results for activation energies.

[A. L. Ruoff and R. H. Cornish, "Electrical Leads for Pressure Vessels to 30 Kilobars", Rev. Sci. Instr., 32, 639 (1961);

A. L. Ruoff and B. M. Butcher, "The Effect of Hydrostatic Pressure on the High Temperature Steady-State Creep of Lead", J. Appl. Phys., 32, 2036 (1961);

A. L. Ruoff and R. H. Cornish and B. M. Butcher, "Techniques for Measuring Creep Strains at High Hydrostatic Pressures", ASME Publication #64-WA/PT-30 (1964);

A. L. Ruoff, B. M. Butcher, and H. Hutto, "Activation Volume and Energy for Self-Diffusion in Aluminum", J. Appl. Phys. Letters, 7, 35 (1965);

A. L. Ruoff and C. R. Kohler, "Pressure and Temperature Dependence of Creep in Potassium", J. Appl. Phys., 36, 2444 (1965); a) Third Order Elastic Const;

A. L. Ruoff, "Activation Volumes for Creep", in Physics of Solids at High Pressure, (Tucson Conf., April 1965), edited by C. T. Tomizuka, Academic Press, New York (1965);

A. L. Ruoff and C. R. Kohler, "Two Ranges of Creep Behavior in Potassium as a Function of Temperature and Pressure", J. Materials, 2, 20 (1967);

A. L. Ruoff and C. R. Kohler, "Creep in Potassium as a Function of Temperature and Pressure", J. of Materials, 2, 20 (1967);

A. L. Ruoff, G. Chevalier and P. G. McCormick, "Pressure Dependence of High Temperature Creep in Single Crystals of Indium", J. Appl. Phys., 38, 3697 (1967);

A. L. Ruoff and Paul G. McCormick, "Creep under High Pressures", Chapter in Mechanical Behavior at High Pressure, edited by David Pugh, Elsevier Publ. Company (1970);

A. L. Ruoff, K. L. Murty and M. Gold, "High Temperature Creep Mechanism in α -iron and Other Metals", J. Appl. Phys., 41, 4917 (1970).]

2. Activation volume for creep in aluminum

The value found was 1.3 atomic volumes whereas the known self-diffusion value for other fcc metals was less than one atomic volume. Simultaneously but unknown to each other. Theorists, using pseudopotential theory, predicted that for vacancy formation in aluminum the lattice relaxation around the vacant site should be expansion rather than contraction. Several years later, tracer diffusion in aluminum was studied elsewhere as a function of pressure and a value of 1.3 atomic volume was obtained.

[A. L. Ruoff, B. M. Butcher and H. Hutto, "Activation Volume and Energy for Self-Diffusion in Aluminum", J. Appl. Phys. Letters, 7, 35 (1965).]

3. Mechanism change

It was well known that at about $0.5T_m$ and at the usual laboratory creep rates, the activation energy decreased. It was not known whether this was sound by a change of mechanism or by a change in vacancy supersaturation. Experiments on a function of pressure readily clarified this issue (there was a mechanism change).

[A. L. Ruoff and P. G. McCormick, "Hydrostatic Pressure and the Mechanisms of Creep in Aluminum", J. Appl. Phys., 40, 4812 (1969);

A. L. Ruoff and P. G. McCormick, "Hydrostatic Pressure Dependence of Creep in Aluminum", Proceedings of Harwell Symposium 1968 on the Interactions Between Dislocations and Point Defects. H. M. Stationary Office (1968).]

4. Supersaturation

During the early 1960's, there was considerable debate concerning the vacancy supersaturation present during high temperature deformation; this was involved with the "enhanced diffusion debate". Both theoretical work and later experimental work helped show without question, that the vacancy

concentration (during plastic deformation at rates of 10^{-4} sec^{-1} at temperatures above $0.5 T_m$) was only slightly different from the equilibrium concentration values.

[A. L. Ruoff and R. W. Balluffi, "A Note on Enhanced Diffusion Effects During Plastic Deformation", J. Appl. Phys. Letters, 1, 59 (1962);

A. L. Ruoff and R. W. Balluffi, "Point Defect Models for Strain-Enhanced Diffusion in Metals", J. Appl. Phys., 34, 1634 (1963);

A. L. Ruoff and R. W. Balluffi, "Dislocation and Grain Boundary Shortcircuiting Models for Strain-Enhanced Diffusion in Metals", J. Appl. Phys., 34, 1848 (1963);
a) On Strain-Enhanced Diffusion in Metals;

A. L. Ruoff and R. W. Balluffi, "Interpretation of Recent Experiments of Diffusion in Metals During Plastic Deformation", J. Appl. Phys., 34, 2862 (1963);

A. L. Ruoff, "Diffusion During Deformation by Surface Intensity Methods", J. Appl. Physics, 36, 2207 (1965);

A. L. Ruoff, "Enhanced Diffusion During Plastic Deformation", J. Appl. Phys., 38, 3999 (1967);

A. L. Ruoff, "Vacancy Concentrations in Metals During High Temperature Deformation", Chapter in Point Defects and Their Interactions, edited by R. R. Hasiguti, Gordon and Breach (1968).]

5. Deceleration of creep in ionic solids by doping

We showed that high temperature creep in pure LiF was controlled by the motion of the F^- ion. Consequently we doped with Mg^{++} which depressed the F^- ion concentration. While this decreased the rate of creep by up to a factor of 16, the decrease was less rapid than expected from the law of mass action.

[A. L. Ruoff, "Mass Transfer Problems in Ionic Crystals with Charge Neutrality", J. Appl. Phys., 36, 2903 (1965);

A. L. Ruoff and C. V. S. H. Narayan Rao, "High Temperature Creep of Lithium Fluoride", J. Appl. Phys., 43, 1437 (1972);

A. L. Ruoff and C. V. S. H. Narayan Rao, "Impurity Effect on the High Temperature Creep of Lithium Fluoride", J. American Ceramic Society, 58, 503 (1975).]

6. Yield stress on a function of pressure

An extremely accurate method was developed for measuring stress-strain curves as a function of pressure. This was then used for potassium studies at liquid nitrogen temperature. It was found that the yield stress increased

42% at 5 kbars and scaled with the elastic modulus $G/(1-2)$. As a result of the combination of high accuracy and small modulus this is the most definitive result found on yield stress dependence on pressure in metals.

It was also shown that by the appropriate measurement of lattice spacings in a crystal in a high pressure cell, the yield stress could be measured.

[A. L. Ruoff, "Yield Stress Determination as a Function of Pressure at Very High Pressures", *Scripta Metallurgica*, 8, 1161 (1974);

A. L. Ruoff and Jaime O. Chua, "Pressure dependence of the Yield Stress of Potassium at low Homologous Temperature", *J. of Appl. Phys.*, 46, 4659 (1975).]

B. Elastic Deformation

1. Pressure Dependence of Elastic Constants

Techniques were developed for placing several crystals simultaneously in a high pressure apparatus for ultrasonic studies. The pressure dependence of the elastic constants of a large number of alkali halides as well as sodium and V_3Si were studied over a wide temperature range including the range of 4° to 30° K for V_3Si .

[A. L. Ruoff and P. J. Reddy, "Pressure Derivatives of Elastic Constants in Some Alkali Halides", in *Physics of Solids at High Pressures*, edited by C. T. Tomizuka and R. M. Emrick, Academic Press, New York (1965) p. 510; a) Prel. report Low Cycle Fatigue under Hydrostatic Pressure; b) Virial Coefficients Shock Ultrasonic Data AlCu;

A. L. Ruoff, K. M. Koliwad and P. B. Ghatge, "Pressure Derivatives of the Elastic Constants of NaBr and KF", *Phys. Status Solidi*, 21, 507 (1967);

A. L. Ruoff and D. P. Dandekar, "Temperature Dependence of the Elastic Constants of Calcite Between 160° and 300° K", *J. Appl. Phys.*, 39, 6004 (1968);

A. L. Ruoff and D. Dandekar, "Variation in the Elastic Constants of Calcite with Temperature", *J. Appl. Phys.*, 39, 3694 (1968); a) Elastic Constants of Sodium with Temperature;

A. L. Ruoff and P. S. Ho, "Pressure Dependence of the Elastic Constants for Aluminum from 77-300 K", *J. Appl. Phys.*, 40, 3151 (1969); a) Vacancy Migration and Spin Lattice Relaxation in NaF;

A. L. Ruoff, P. S. Ho and J. P. Poirier, "Pressure Dependence of the Elastic Constant of Silver from 77-300°K", *Phys. Status Solidi*, 35, 1017-25 (1969);

A. L. Ruoff, M. Ghafelehbashi and D. P. Dandekar, "Pressure and Temperature Dependence of the Elastic Constants of RbCl, RbBr and RbI", *J. Appl. Phys.*, 41, 452 (1970);

- A. L. Ruoff, M. Ghafeleboshi and K. M. Koliwoil, "Pressure Dependence of the Elastic Constants of NaCl at Low Temperatures", J. Appl. Phys., 41, 4010 (1970);
- A. L. Ruoff, Y. C. Chen and R. H. Martinson, "A Multiple Crystal Holder for Ultrasonic Measurements", Rev. of Sci. Inst., 43, 1712 (1972);
- A. L. Ruoff, L. S. Ching and J. Paul Day, "Pressure and Temperature Dependence of the Elastic Constants of LiBr and LiCl", J. Appl. Phys., 44, 1017 (1973);
- A. L. Ruoff and R. E. Larsen, "Pressure-Induced Elasticity Changes in V_3Si ", J. Appl. Phys., 44, 1021 (1973);
- A. L. Ruoff, J. Paul Day and Paul S. Ho, "A cw Interferometer for Elastic Constant Measurements", Rev. Sci. Inst., 44, 478 (1973);
- A. L. Ruoff and J. Paul Day, "The Pressure Dependence of the Elastic Moduli of a Tungsten Carbide Cermet", J. Appl. Phys., 44, 2447 (1973);
- A. L. Ruoff and J. Paul Day, "The Variation of Elastic Constants of Lithium with Temperature and Pressure", Physica Status Solidi, A25, 205 (1974);
- A. L. Ruoff and Kwang Yul Kim, (CERVIT) "Pressure and Temperature Dependence of the Elastic Moduli of a Low Expansion Lithium Aluminum Silicate Glass-Ceramic", Journal of American Society, 58, 352 (1975).]

2. B_0'' for sodium

Because sodium is relatively soft (small bulk modulus) it was possible with extreme care to measure the second pressure derivative of the elastic moduli and hence the second pressure derivative of the bulk modulus, B_0'' . It was shown that this quantity was -0.06. It should be noted that pseudopotential calculations were also carried out and that these correctly predicted this value of B_0'' .

[A. L. Ruoff and P. S. Ho, "Analysis of Ultrasonic Data and Experimental Equation of State for Sodium", J. Phys. Chem. Solids, 29, 2101 (1968);

A. L. Ruoff and R. H. Martinson, "Variation of the Elastic Constants of Sodium with Temperature and Pressure", Phys. Rev., 178, 902 (1969);

A. L. Ruoff and P. S. Ho, "A Quasi-Harmonic Calculation of Lattice Dynamics for Sodium", Phys. Stat. Sol., 23, 489 (1967);

A. L. Ruoff and P. S. Ho, "Lattice Dynamical Calculations for Alkali Metals", Phys. Rev., 169, 523 (1968);

A. L. Ruoff and K. J. Dunn, "First and Second Pressure Derivatives of the Bulk Modulus of Sodium", Phys. Rev. B, 10, 2271 (1974).]

3. Ultrasonic Studies of Liquids

Velocity of sound measurements were carried out in pure liquid metals and in alloys as a function of temperature; effects which might be described as ordering appeared to take place near the melting points.

[A. L. Ruoff and J. E. Hill, "Velocity of Sound Measurements in Liquid Metals", Rev. Sci. Instr., 36, 1465 (1965);

A. L. Ruoff and J. E. Hill, "Temperature Dependence of the Velocity of Sound in Some Liquid Metals and Eutectic Alloys", J. Chem. Phys., 43, 2150 (1965).]

4. Analysis of Shock Data

In our equation of state studies we compared our elastic constant studies with direct P-V data of Bridgman and others and with shock data. An important paper was written showing why the shock u_s vs. u_p curves were very close to being linear.

[A. L. Ruoff, "A Comparison of Virial Coefficients Obtained from Shock and Ultrasonic Data for Al and Cu", J. Phys. Chem. Solids, 28, 453 (1967);

A. L. Ruoff, "Linear Shock-Velocity-Particle-Velocity Relationship", J. Appl. Phys., 38, 4976 (1967).]

5. Absolute pressure measurements

In materials for which the linear compressibility coefficient is isotropic (cubic crystals as well as elastically isotropic solids), a single length versus pressure experiment suffices to yield P-V data. We showed that by combining direct length measurement with ultrasonic measurements absolute pressure could be made. We proceeded to construct the most accurate length at pressure devices possible and used this as an absolute pressure device to obtain the freezing point of mercury at 0°C; the result was 7571.2 bars. The most accurate free piston system measured this pressure to be 7571.0 bars. Except for the free piston system, this new absolute pressure invention is the only absolute pressure measuring system in existence.

[A. L. Ruoff, R. C. Lincoln and Y. C. Chen, "High Pressure Calibration with a New Absolute Pressure Gauge", Appl. Phys. Lett., 22, 310 (1973);

A. L. Ruoff and R. C. Lincoln, "Absolute Length Measurement at High-Pressure," Rev. Sci. Instrum., 44, 1239 (1973);

A. L. Ruoff, R. C. Lincoln and Y. C. Chen, "A New Method of Absolute High Pressure Determination", J. Phys. D: Appl. Phys., 6, 1295 (1973).]

6. Direct length studies

The system discussed in the previous paragraph has a sensitivity of measuring fractional length changes of less than 10^{-7} . We have used this system to study the equation of state of LiF and NaCl. We were in fact able to obtain reasonably accurate values of B_0 for NaCl from the length measurements, which is no small achievement.

[A. L. Ruoff and R. C. Lincoln, "Absolute Length Measurement at High Pressure", Rev. Sci. Instrum., 44, 1239 (1973);

A. L. Ruoff, R. C. Lincoln and Y. C. Chen, "A New Method of Absolute High Pressure Determination", J. Phys. D: Appl. Phys., 6, 1295 (1973);

A. L. Ruoff, K. Y. Kim and R. E. Terry, "Improved Technique for Shaping Long Fragile Alkali Halide Crystals", Rev. Sci. Instrum., 47, 636 (1976);

A. L. Ruoff, K. Y. Kim and L. C. Chhabildas, "Isothermal Equations of State for Lithium Fluoride", J. Appl. Phys., 47, 2862 (1976);

A. L. Ruoff, John Wanagel and Volker Arnold, "Pressure Transition of AlP to a Conductive Phase", J. Appl. Phys., 47, 2821 (1976).]

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