REPORT

of

ARPA MATERIALS RESEARCH COUNCIL

and

MATERIALS SUMMER PROJECT (1968)

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Advanced Research Projects Agency

Department of Chemical and Metallurgical Engineering

Introduction

This report describes the purpose, formation and method of operation of an activity which has been formed as the ARPA Materials Research Council, and the output of its first Summer Materials Project. The motivation for establishing this activity stemmed, on the one hand, from a genuine concern and interest on the part of a group of university scientists to helpfully relate, personally and professionally, with the needs and aims of the DOD, and on the other hand, from the desire of the Materials Science Office in ARPA to achieve effective coupling relationships - not merely at a policy or advisory level, but at problem solving as well.

We set out to bring together a group of the foremost scientists and engineers in the fields of materials and materials science on a continuing consultative and working arrangement. The group was to be briefed on the current state of a particular problem area and to be challenged collectively to develop solutions or to develop a consensus for suitable approaches to the possible solutions of these problems.

We believed that above all other considerations it was essential to have only the most able and qualified individuals in the country as participants, otherwise we could not bring any unique capability or resource to the complex problems of the DOD. Moreover, we felt that a group of this caliber (somewhat similar to JASON, but with background in Materials Science) did not exist, and was needed. We achieved this aim to a remarkable degree in our first summer project, and believe that the membership is probably the most able and versatile working group in Materials Science ever assembled for this purpose.

The purpose of the Council was not to concentrate the efforts of the group on present, high priority, and highly focused materials problems. This type of problem is apt to be currently in the hands of highly competent people, be part of a larger systems problem, and probably be highly classified. While the Council can and has been used to look at such problems, its real value lies in using it for its longer and broader vision. One would expect this group to recognize future critical needs and to work on these, rather than immediate problems.

Since the personnel of the Council is largely drawn from the academic community, their exposure to longer range problems will have a valuable effect on the direction and choice of problems they, their students, and their colleagues will undertake in these communities. The interdisciplinary nature of the group insures a broad approach to the problem areas and encourages such cooperative linkages at their own institutions.

The historical origins of the project go back to 1966 when several individuals interested in materials and materials sciences; physicists, chemists and engineers, together with Dr. Robb Thomson in the Materials Sciences Office of ARPA, examined the idea of bringing together not two or three experts in each field for a few days, but rather to bring together 20-30 of the Country's outstanding people in the materials field and for an extended period each year, to challenge them as we have indicated. Thus, the concept of a concentrated Summer Project took shape, and became the principal component of the program we developed.

A Steering Committee consisting of seven individuals, later expanded to nine, was constituted to perform the following functions:

a) Work with ARPA in selecting the problem areas for study by the group.

b) Select the participating scientists and engineers who would work on the project.

c) Evaluate and monitor the project.

d) Participate in establishing a management format and assist its Project Director in reporting its activity.

The constitution of the Steering Committee was as follows:

Professor James A. Krumhansl
Secretary, Steering Committee

Department of Physics
Clark Hall of Science
Cornell University
Ithaca, New York 14850

Professor Michael B. Bever
Department of Metallurgy
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Professor Herbert S. Gutowsky
Department of Chemistry
University of Illinois
Urbana, Illinois 61801

Professor Walter Kohn
Department of Physics
University of California,
San Diego
La Jolla, California 92037

Professor William Prager
Department of Mechanical Engineering
University of California,
San Diego
La Jolla, California 92037

Professor J. Robert Schrieffer
Department of Physics
University of Pennsylvania
Philadelphia, Pennsylvania 19104

Professor William A. Tiller
Department of Materials Science
Stanford Unviersity
Stanford, California 94305

A contract was initiated between ARPA and the University of Michigan to carry out the management of the Council affairs and Professor M. J. Sinnott, Prof. Chemical and Metallurgical Engineering, became Project Director. Under this contract the following functions were performed by the University:

a) Working with the Steering Committee to insure coordination of plans.

b) Provide a central, responsive contact point and clearing house for all matters concerning the Council.

c) Negotiate consulting agreements with the project participants.

d) Arrange and contract for all the facility and facility support items to carry out the objectives of the Council

e) Publish reports generated by the Council.

The contract was for the period February 14, 1968 to February 14, 1969.

The Steering Committee also chose the participants who were to take part in the Summer Conference. They were as follows:

Dr. Philip W. Anderson
Bell Telephone Laboratories
Murray Hill, New Jersey

Professor Bernard Budiansky
Harvard University
Division of Engineering and
Applied Science
Cambridge, Massachusetts 02138

Professor Morris Cohen
Massachusetts Institute of Technology
Department of Metallurgy
Cambridge, Massachusetts 02139

Professor Pol E. Duwez
California Institute of Technology
Department of Mechanical Engineering
Pasadena, California 91109

Professor Willis H. Flygare
University of Illinois
Noyes Chemical Laboratory
Urbana, Illinois 61801

Professor John J. Gilman
Department of Mining, Metallurgy and
Petroleum Engineering
University of Illinois
Urbana, Illinois 61801

Professor John P. Hirth
Department of Metallurgical Engineering
Ohio State University
Columbus, Ohio 43210

Professor Erastus H. Lee
Stanford University
Department of Applied Mechanics
Stanford, California 94305

Professor John L. Margrave
Rice University
Department of Chemistry
Houston, Texas 77001

Professor Bernd T. Matthias
University of California, San Diego
Department of Physics
La Jolla, California 92037

Professor Elliott W. Montroll
University of Rochester
Department of Physics & Astronomy
Rochester, New York

Professor Frank A. McClintock
Massachusetts Institute of Technology
Department of Mechanical Engineering
Cambridge, Massachusetts 02139

Professor Howard Reiss
University of California at Los Angeles
Department of Chemistry
Los Angeles, California

Professor Charles P. Slichter
University of Illinois
Department of Physics
Urbana, Illinois 61801

Professor Michael Tinkham
Harvard University
Department of Physics
Cambridge, Massachusetts 02138

Dr. George H. Vineyard
Brookhaven National Laboratory
Upton, Long Island, New York

Preliminary Screening

In March, the Steering Committee met in Washington for a series of briefing sessions with various people from DOD to screen areas where materials problems were believed to be critical. Dr. Thomson of ARPA contacted various agencies of DOD soliciting interests of the various groups.

Briefings were given in the following areas:

1. Re-entry physics and chemistry
2. Trees (DASA)
3. EM transmission and absorption

4. Fire quenching
5. Corrosion and oxidation resistance
6. Composites
7. Properties of matter under extreme conditions
8. Rapid excavation and drilling (U.S. Bureau of Mines)
9. Non-destructive testing

In May a meeting of the Steering Committee and the participants was held in Washington for more detailed briefings in the areas that had been chosen from the group originally examined in March.

One of the areas covered in depth was that of Material problems encountered in re-entry vehicles. Presentations were made in the areas of R-V Nose Tip and Heat Shield Design by A. Fields of SAMSO, D. L. Schmidt of AFML, D. Erickson of AFML, and T. Nicholas, M. L. Minges of AFML. Dr. A. Lovelace of AFML assisted by H. S. Schwartz, N. Pagano and W. Stuhrke of AFML made a detailed presentation of the Advanced Structural Composites Materials area indicating the potentials, progress and problem areas in this field.

Major J. McGee of DASA assisted by Taslitt and Kenyon of NOL, R. H. Stahl of Systems Science and Software, and VanLint and Flanagan of Gulf-General Atomics gave a survey of problems in electronic systems and components under rapidly changing environmental conditions; we heard about studies of the stability of electronic and magnetic states.

Dr. T. Howard of the U.S. Bureau of Mines assisted by

M. Deul, E. Flint, J. McWilliams, J. Paone, and S. Tandanand, all of the Bureau of Mines, gave detailed briefings in the area of high-speed tunnelling problems; rock mechanics, penetration techniques, drilling methods, sensing methods, etc.

On the completion of this May briefing program, a general discussion by the Steering Committee and the participants showed that the topics of major interest to the group were:

Composite Materials

Shock Propagation in Materials

Constitutive Relations for Materials at high temperatures and high pressures

Underground Sensing

This two-day meeting then served to focus the efforts of the group for the first Summer Project into the areas indicated.

The Summer Conference

In order to supply expert information to the participants at the Summer Conference, during May and June the ARPA Materials Science Office made arrangements for consultants, both in DOD and from DOD contractors, to be available during various stages of the conference to assist the participants.

In the Composite Materials area the following individuals came as consultants: Dr. Roger Bacon and Dr. R. Didchenko, Union Carbide Corporation; Dr. Paul W. Dimiduk, AFML (MAYT), Wright-Patterson AFB; Dr. Raymond Foye, North American Rockwell; Dr. Merrill L. Minges, AFML (MAAS), Wright-Patterson AFB; Dr. Erwin Rudy, Aerojet General Corporation; Dr. M. J. Salkind, United Aircraft Research Laboratory; Mr. Herbert S. Schwartz, AFML (MAN), Wright-Patterson AFB; Lt. William F. Stuhrke, U.S. Air Force, AFML (MAMS), Wright-Patterson AFB; and Dr. W. H. Sutton, General Electric Company.

In the tunnelling area the following consultants were used: Mr. Carl Roach, Mines System Engineering, Defense Federal Center, and Professor H. Gene Simmons, Department of Geology and Geophysics, Massachusetts Institute of Technology.

In the area of shock and constitutive relations, the following individuals were available: Dr. William L. Bade, AVCO Corporation Missiles System; Dr. Harvey M. Berkowitz, Douglas MSSD; Dr. Lawrence R. Bidwell, AFML (MAMS), Wright-Patterson AFB; Dr. Barry M. Butcher, Sandia Corporation; Dr. John W. Taylor, Los Alamos Scientific Laboratories; Capt. John T. Viola, AFWL (WLRP), Kirtland Air Force Base; Dr. Mark Wilkins, Lawrence Radiation Laboratory.

For information on environmental effects on electronic materials, the following people were used as consultants: Dr. Henry S. Belson and Mr. Van L. Kenyon of the U.S. Naval Ordnance Laboratory.

A briefing session on Materials problems in the Deep Sea Submergence Program (DSSP) of the U.S. Navy was given by the following individuals: Mr. Lincoln D. Cathers of DSSP; Dr. William S. Pellini and Dr. Irvin Wolock of the Naval Research Laboratory.

The Summer Conference was held in Centerville, Massachusetts. A school was leased and equipped to handle the group. This area was chosen for its remoteness in the sense that the surroundings were quiet and conducive to concentrated study. On the other hand, the proximity of the M.I.T. and Harvard Libraries, with whom arrangements were made for library service, made access to these facilities relatively easy. A computer terminal from Project MAC at M.I.T. and one to the Dartmouth Computer Center was available for the use of the participants. Secretarial and stenographic assistance was available and the necessary security arrangements were made.

Conference Operation

After an initial short orientation period the group split into two subgroups. One was concerned with the general area of composite materials while the other worked in the area of shock and constitutive relations, the larger groups then broke into smaller subgroups to deal with the various subsets of problems in these general areas.

Presentations by the consultants to the various groups helped to focus the participants' attention on the problem areas, brought them up to date on solutions that had been tried and in general enabled the group to arrive at the current state of the art and the science in the problem areas. Individuals then worked independently on the various segments of the problem areas and then reconvened as groups and subgroups to arrive at a consensus and issue preliminary position papers. In this fashion the participants eventually were able to distill their efforts into the form of finished reports, partially finished reports and technical memoranda. Much of this material will become available externally as either research reports for general distribution, or research reports for restricted distribution. The technical memoranda are internal working papers, but their content may occasionally have value in follow-up discussions between participants and interested DOD parties; in the case of such an interest, the Council member involved in the problem may be contacted through the Project Director, Professor Sinnott, to make appropriate arrangements. Personal follow-up activities are an important derivative of the summer work and will be discussed below.

Technical Summary of the Summer Project

The work of the Council is now summarized by listing the titles and authors of reports and memoranda, then by a brief discussion of some of the main contributions.

Research Reports for General Distribution

Wave Propagation through Dispersive Media
J. R. Schrieffer, W. H. Flygare, C. P. Slichter

Underground Sensing
Michael Tinkham

Wave Front Analysis in Composite Materials
E. H. Lee, T. C. T. Ting

Plastic Failure of Fiber-Reinforced Materials
W. Prager

A Simple Composite Problem
J. P. Hirth, J. A. Krumhansl, E. H. Lee

A Survey of Non-Mechanical Applications of Composites
M. B. Bever, P. E. Duwez, W. A. Tiller

Scanning Electron Micrographs of Spall Fracture
J. Joyce, J. T. Viola, F. A. McClintock

A General Scheme for the Characterization of Composite Materials
M. B. Bever

Segregation of Solutes in Stressed Solids
H. Reiss

Research Reports for Restricted Distribution

Atomic Models of Shock Fronts in Solids
J. J. Gilman & G. H. Vineyard

Sonar Search for Faults Ahead of Tunnelling Operations
Walter Kohn, Elliott Montroll

Worthwhile Problems in the Theory of Mechanical Properties of Composite Materials
B. Budiansky, W. Prager

Non-Local Stress Analysis in Composites
F. A. McClintock

Problems in the Mechanics and Fracture of Composites
F. A. McClintock

Graphite Thermodynamics
J. L. Margrave

Preparation of Oriented Graphite Filaments
H. S. Gutowsky

Current Status of Composite Fibers
P. E. Duwez, J. A. Krumhansl, M. J. Sinnott

X-ray Absorption and Wave Propagation through Dispersive Media (CLASSIFIED)
W. H. Flygare, W. Kohn, J. R. Schrieffer, C. P. Slichter

Technical Memoranda

Fracture of Composites - Need for Comprehensive Test Program
A. S. Tetelman, F. A. McClintock

Strengthening of Metal Fibers for Composites
Morris Cohen

An Atomistic Picture of Composite Interfaces
W. A. Tiller

Degradation of Composite Interfaces
W. A. Tiller, J. P. Hirth

Retarding Spall in Composites
F. A. McClintock

Proposed Analysis of Dynamic Hole Growth to Fracture
F. A. McClintock, J. T. Viola, M. Wilkins

On the Strength-Differential Effect in Steel
J. P. Hirth, M. Cohen

Properties of Cured Epoxy Resins
J. L. Margrave

Interactions of Graphite and Metal Fibers with Epoxy Resins and Carbon as Matrix Materials
J. L. Margrave

Considerations on Ultimate Strength of Anisotropic Materials at the Molecular Level: Polymer Fibers
P. W. Anderson

On the Potentiality of ZrB_{12} as a Fiber Material for Composites
M. Cohen

Ideas From A Journal
F. A. McClintock

Some Materials Problems within North American Rockwell Corporation
H. Reiss

Energy Relaxation of Magnetic Electrons in Metallic Ferromagnets (CLASSIFIED)
J. R. Schrieffer

Internal Memo (CLASSIFIED)
W. H. Flygare, R. Thomson

A Note on Non-Uniform Ablation (CLASSIFIED)
J. P. Hirth

Abstracts of the papers for general and restricted distribution will be found in the Appendix of this report.

Shock   There are hardly any topics that have received as thorough and as sophisticated an analysis as those of shock generation, its propagation, and its effects in and on solid materials, both homogeneous and heterogeneous. We were well aware of this and regarded our efforts as exploratory in nature and designed to familiarize the participants with the current state of the art and science. As our studies proceeded, the extent of this prior study became apparent and classification became a limitation on our access to critical recent work. To remedy this, steps have been taken to visit several installations to follow up on this recent work, then to carry on the studies into next year.

Because of the experience and interests of the group, there were problems in the shock area that could be treated: shocks and related phenomena on an atomic scale; wave propagation in composite media; energy deposition in materials; and graphite thermodynamics as related to high temperature stability.

The work of Gilman and Vineyard covered the atomic modeling of shock. Systems were developed to show shock behavior which involves plastic deformation by dislocation generation and motion, and they indicate a need for machine calculations to carry this work to a further stage of development. They also cited a need for and the advantages of miniaturization of shock-wave experiments. For some shock data it is believed that such laboratory experimental techniques could supplant large scale field tests.

The work of Margrave on the thermochemistry of graphite led to the conclusions that the prediction of carbon vaporization can not be made accurately without the following information: the role of negative ions; the enthalpy of the solid phase to 4000°K; sublimination kinetics and the role of oxygen, hydrogen, water, etc., on these kinetics. An extensive bibliography was prepared.

Several members made exploratory model calculations on shock propagation through dispersive and composite media (Schrieffer, Flygare, Slichter, Lee, Kohn), and consideration of how these results may be applied to predict and control material behavior will continue, and will be part of the summer 1969 study.

Composites The interest and support of AFML and other DOD groups in the field of composites has produced a tremendous amount of engineering information on these materials. Excellent briefings of the current state of the art were given by various DOD contractors who have been and are active in this field. Good engineering progress is being made with presently available materials for a few specific applications. We feel however that there are several areas where we would suggest that further effort be made and steps were taken into these areas by the participants.

The entire field of surfaces and interfaces, their chemistry, physics and engineering properties, must be put on a firmer theoretical base. The work of Tiller, Hirth, Tetelman, McClintock, Margrave, Prager, Gutowsky, Krumhansl, Duwez and Sinnott all emphasize this need. From a mechanics standpoint the elastic behavior of composites can be said to be understood but the plastic behavior is not as well known and their fracture mechanisms are in a rather primitive state of development.

While several fibers have been developed it appeared to the participants that the greatest potential lay in the continued development of graphite continuous fibers. Here it appeared to us that most of the work was in engineering development and that more emphasis should be given to studies on the precursor materials and to the discrepany between the theoretical and achieved strengths of these materials. While currently this material is used with epoxies and there is some possibilities for improvement in these materials (Margrave), ultimately one would envision the use of these materials at much higher temperatures and one then encounters the interface problems between graphite and metal or ceramic matrices.

The emphasis on mechanical properties of composites has tended to overshadow other potential uses of these materials. The report of Bever, Duwez and Tiller emphasizes a large potential field of uses of these materials which has not yet been exploited.

While the emphasis on fibers has been concentrated on such materials as graphite, Al_2O_3, SiC, B, etc., the report by Cohen on the strengthening of iron wires points up the possibility of the use of less costly materials to attain the same high strength properties. In a similar vein the controlled solidification of eutectics and near eutectic melts to produce composites (Salkind and associates at United Aircraft) appeared to have immediate applicability, particularly in the high temperature materials area.

As in the other problem areas that were examined by the participants, our immediate contributions could only be of limited and probably of no great immediate value but the longer range view does show that there are difficult and important future problem areas on which we should be working now; particularly the surface and interface problems.

Tunnelling Rapid and efficient underground tunnelling has received considerable recent discussion both for civilian and defense applications. The Bureau of Mines have been particularly active in this subject, and presented our group with a series of briefings. From the principal aspects - digging (cutting), propulsion, disposal of excavated material, control and direction - it became clear the matter of searching for faults ahead of tunnelling operations, in order to control and direct, was presently a critical problem to which limited attention had been given. We therefore directed attention to the question of underground fault finding, on the scale appropriate to tunnelling.

First, the physical characteristics of faults and surrounding earth were translated into electrical, mechanical, magnetic (essentially magnetostatic) and electromagnetic specifications; then a wide variety of experimental techniques were appraised for sensitivity and selectivity (report by Tinkham). It was concluded that electromagnetic induction techniques, and sonic techniques offer the greatest promise for short and long range sensing, respectively. A perspective analysis was prepared by Montroll and Kohn, and the problems of sound propagation, array design, multiple use of prepared holes for fault sensing and other missions were appraised. Mr. Carl Roach, Bureau of Mines and Professor H. Gene Simmons, Massachusetts Institute of Technology, were significantly useful to us as consultants.

These studies led to ideas for experiments and tests, so a meeting was set up at the Department of Mines System Engineering, U.S. Bureau of Mines, Denver, on November 13, 14, 1968. Attending were Kohn, Montroll, Tinkham, Simmons, Roach and various Mines personnel. It developed from this conference and analysis that the Materials Research Council study had indeed led to concrete ideas which should and could be tried. At present the Mines group is seriously limited in both personnel and budget and therefore cannot proceed. We hope, since this is an important technology for our long term national interests, that the recent research proposals from the Bureau of Mines to study these questions will receive careful attention and be funded.

<u>TREES</u> Although the Council did not devote major attention to the problems of TREES, relevant aspects were presented at the spring briefing session. In July, the ARPA Office became aware of the desire of people at NOL to discuss one particular knotty problem with the members of the Council. On short notice, arrangements were made for two NOL scientists, H. S. Belson and V. L. Kenyon, to come to the conference for an ad-hoc meeting.

The problem presented concerned the relaxation time of conduction electrons in a solid. Professor Schrieffer was the principal contributor during this discussion and was able to answer the question posed to the complete satisfaction of NOL investigators. At issue was the necessity of starting a major experimental program to answer certain questions empirically for the particular material of interest, unless a definite theoretical prediction could be made.

This encounter illustrates one highly successful output of the Council. The members are available for consultation on urgent technical matters, and because of their stature in the various fields represented, they can be relied upon for authoritative opinions within their areas of competence. Occasionally, as in this case, they can be expected to contribute technical advice or opinions which will have great immediate value regarding various DOD programs.

Follow-On Activities

Toward the latter part of the Summer Project period, it became apparent that many of the topics under consideration had been receiving competent short-range treatment, usually as part of an on-going, high priority and complex defense science system but we had some inputs to be made. We could see however, in addition, long range generic problems which need to be pursued on a continuing basis. To take care of each of these needs, we established procedures for sub-groups of the participants to visit DOD installations or DOD contractors in order to continue their studies. Work in shock propagation in materials, extreme condition constitutive relations and in composite materials will be carried forward in this way.

The longer range problems are being investigated by individuals at their home institutions in preparation for continued analysis and development at the next summer conference.

Plans for 1969 Conference

Work will continue in the areas of shock and extreme condition constitutive relations as well as in composite materials. Studies will be initiated in the EMP area, which is related to the shock problem. Materials problems in the high-power laser area will also be examined. The non-destructive test area takes on added significance when one looks at composite materials and should receive the attention of the participants. Corrosion, or more generally, environmental effects on materials is another important area to be examined in view of our interests in surfaces and interfaces.

Other problem areas such as fracture analysis, plasticity, polymers, graphite chemistry, etc., will be considered for continuation by the Steering Committee.

APPENDIX

Abstracts

Research Reports for General Distribution

Wave Propagation through Dispersive Media

J. Robert Schrieffer
W. H. Flygare
C. P. Slichter

Some elementary equations and order of magnitude computations are given for the disposition of X-rays in a RV. The shock waves and trajectory errors produced by blowoff are discussed. The advantage of a centrally located graded-z, X-ray absorber is pointed out. Geometric absorbers of sound waves are proposed to dissipate the shock energy. Several types of acoustical filters are discussed in detail. Several general results on wave propagation in solids are also given.

Underground Sensing

M. Tinkham

This report considers electrical methods of sensing what is ahead of a tunnel face, with the objective of assisting in rapid excavation operations. For this consideration, the rock is characterized almost entirely by its electrical conductivity, which in turn is strongly affected by water content, a highly relevant parameter for mining operations. Three classes of techniques are considered: DC resistivity, electromagnetic wave, and electromagnetic induction. It is concluded that DC resistivity measurements offer little hope of sensing further than one tunnel diameter ahead, although they provide a valuable short-range characterization of the rock at the tunnel face. Electromagnetic wave ("radar") techniques are limited in range to about one foot for frequencies high enough ($\gtrsim$ 1GH$_z$) to allow any directionality; hence they seem to have very little promise. Electromagnetic induction techniques in the frequency range 1-100 kHz appear to offer more promise, particularly for detecting highly conducting (e.g. wet) regions hidden behind material of lower conductivity. Even so, the practical range will probably be limited to something like the tunnel diameter, and it would be hard to get much directional information. Although not treated in detail in this paper, "sonar"-type acoustic measurements seem to offer greater promise of directional information at a useful range.

Wave Front Analysis in Composite Materials*

E. H. Lee
T. C. T. Ting

The propagation of an initially sharp plane pressure pulse through a linear elastic composite medium is analyzed. Wave front and ray theory analogous to geometrical optics is shown to determine the change in shape of the leading wave front and also the stresses immediately behind it. For certain circumstances the stress amplitudes on this front, or the corresponding tensile stresses on its reflection at the free back surface of a slab, may be critical in design. Examples are presented of an initially sharp plane pressure pulse transmitted through an elastic circular cylinder and an elastic spherical inclusion. The method can be applied to more general composite configurations, and can be extended to determine the stress gradient behind the front. For the latter, general formulae are derived by which the reflection and transmission coefficients can be determined for the stress gradient and the higher order derivatives at an arbitrary interface.

*Sponsored jointly by the ARPA Materials Research Council and by the Ballistic Research Laboratories on a contract with Stanford University.

Plastic Failure of Fiber-Reinforced Materials

W. Prager

The paper is concerned with failure by plastic flow of the matrix of a fiber-reinforced composite sheet. For undirectional reinforcement, a completely general state of plane stress in the median plane of the sheet is discussed, but for a two-ply laminate with an arbitrary angle between the two systems of reinforcing fibers only simple tension in any direction to the fibers is investigated.

A Simple Composite Problem

J. P. Hirth
J. A. Krumhansl
E. H. Lee

An analysis is presented of a layered composite composed of an isotropic matrix and thin anisotropic interspersed layers. The investigation had the two purposes of investigating the macroscopic elastic behavior of such a composite and of determining local stresses at the interfaces in the composite. The model is used as the basis for the discussion of the role of elastic anisotropy in composite failure; in particular, the influence on crack propagation.

A Survey of Non-Mechanical Applications of Composites

M. B. Bever
P. E. Duwez
W. A. Tiller

This memorandum surveys potential non-mechanical applications of composites. These applications are considered systematically in terms of the basic characteristics of composites. A large array of promising and useful materials and devices becomes apparent. A detailed analysis is recommended for the near future.

Scanning Electron Micrographs of Spall Fracture*

J. Joyce
J. T. Viola
F. A. McClintock

Stereo-scanning micrographs taken of spall fractures in 6061-T6 aluminum alloy sheet in which the fractures were induced by the electrically induced impact of a Mylar flyer are presented.

*The work report herein is presented for the purpose of stimulating discussion and does not necessarily represent a final, well-considered view of the authors.

A General Scheme for the Characterization of Composite Materials

M. B. Bever

In this memorandum the general features of the characterization of a material are briefly described. Special problems encountered in the characterization of composites are outlined. A scheme for the characterization of composites is presented.

Segregation of Solutes in Stressed Solids

H. Reiss

A reasonably careful thermodynamic analysis of segregation in stressed solids is performed employing a standard Gibbs analytical approach (using partial differentiation rather than cyclic analysis). Some of the unclear points made by earlier workers are clarified. Some model statistical mechanical analyses are performed for dilute solid solutions.

The elastic strain problem for a rigid spherical misfitting inclusion in an incompressible isotropic medium under external stress is solved for use in a typical example.

It appears as though external stress (in view of low yield limits) cannot cause much solute segregation. On the other hand misfit inclusions of high curvature can induce appreciable segregation near their surfaces. This effect may be important for composites with fibres of small diameter. It may be of general importance in the heat treatment and annealing of alloys.

Turning the coin around, the existence of atomically dispersed solutes at high supersaturations can induce high strain energies which may produce yielding and various side effects when high gradients of concentration are involved.

Research Reports for Restricted Distribution

Atomic Models of Shock Fronts in Solids

J. J. Gilman
G. H. Vineyard

Most of the work that has been published on shock waves considers the material as a continuum. This suffices for many purposes, but overlooks interesting phenomena on the atomic level. In particular, the thickness of the shock front, the role that may be played by dislocations, and the typical atomic motions in the front have remained mysterious. A better picture at this level would give better insight into phase changes, chemical reactions, and the production of lattice defects in the shock, as well as the survival of structural or electronic changes after passage of the shock. The thickness of the shock front itself is a matter of conjecture at this time.

Recently a plausible model for the elastic precursor of moderate shocks has been developed* and indicates the role that is played by dislocations in this part of a shock. Some similar model remains to be provided for the case of strong shocks. This model might also be of importance in understanding detonation waves.

In the short period of this summer study we have only begun looking at shocks on an atomic scale. As an introduction and as a means for aiding intuitive understanding, we have worked on the simplest possible analogue; a shock in a single line of atoms. Here some progress is possible by straightforward analytical methods. Three models were considered: a line of hard spheres (exactly soluble

*Reviewed by J. J. Gilman, "Dislocation Dynamics and the Response of Materials to Impact" - Applied Mechanics Reviews, <u>21</u>, 767 (1968) and exhibiting true shock behavior but unrealistic); a line of atoms interacting with perfectly harmonic forces (exactly soluble, but not possessing true shock behavior); and a line of hard spheres supplemented with perfectly harmonic forces (approximately soluble and somewhat more realistic).

Next we have discussed the possibility that a shock front can be considered as a moving wall of dislocations, following a suggestion first advanced by Professor C. Smith. Conjectures about the formation of such a wall, and its stability, suggest that this may be a correct picture for strong shocks in ideal crystals, although the case is far from proved. Some ideas have been developed concerning a semi-quantitative theory, based on this picture and using the ideas of conventional dislocation theory. We are not yet able to formulate the theory completely.

It appears very desirable to carry out machine calculations for atomic models. We understand that such efforts are underway at Los Alamos (Richard Gentry and Frank Harlow; T Division) and at the National Bureau of Standards (Charles Beckett), but have no details of what those people are doing. Some of our own ideas about how the calculations might be done are outlined below. Some work of this kind may be undertaken at Brookhaven by Montroll and Vineyard later this year.

Experimental techniques for working with strong shocks should be further developed in a number of directions. Much more systematic work with carefully prepared mono-crystaline specimens is desirable. We speculate that specific crystalline effects may be observable, even in very strong shocks, if the right experiments are attempted.

We have benefited from many discussions with colleagues in the project and with consultants. In particular, we should like to acknowledge: J. P. Hirth, E. W. Montroll, E. H. Lee, F. A. McClintock, R. M. Thomson, B. M. Butcher, M. Wilkins, J. W. Taylor, and J. T. Viola.

Sonar Search for Faults Ahead of Tunnelling Operations

W. Kohn
E. Montroll

No Abstract

Worthwhile Problems in the Theory of Mechanical Properties of Composite Materials

B. Budiansky
W. Prager

This memorandum briefly indicates a number of projects concerning the theory of mechanical properties of composites that, in the authors' opinion, would be particularly worthwhile. For easy scanning, one-sentence descriptions of these projects have been underlined.

Non-Local Stress Analysis in Composites
F. A. McClintock

Introductory examples are given of several ways in which the fiber structure of composites may lead to action at a distance and to couple stresses on a macro-scale, which are not included in the classical theory of elasticity.

Problems in the Mechanics and Fracture of Composites
F. A. McClintock

No Abstract

Graphite Thermodynamics
J. L. Margrave

Literature data on the sublimation, melting and vaporization of graphite have been reviewed. Several areas deserving further study have been identified, including the importance of negative ions in the equilibrium vapor, the need for high-temperature enthalpy increments, the lack of information on the kinetics and mechanism of sublimation, and the lack of information regarding molecular geometries and basic parameters for polymeric species.

Preparation of Oriented Graphite Filaments
H. S. Gutowsky

Low strength carbonaceous filaments are converted into high strength oriented graphitic filaments by high temperature heat treatment under tension in at least part of the cycle. The atomic level processes responsible for the increased strength apparently are not at all clear. Though difficult, investigations directed towards this question should have high priority. A relatively easy though indirect approach is proposed, namely the introduction of reactive atmospheres during the graphitization cycle. Significant effects would result if cross linking and/or growth in size of graphitic domains by diffusion and combination with smaller, more reactive species are important features of the graphitization mechanism. Such effects could lead to improved filaments and more economical production methods. Other aspects of the problem are discussed.

Current Status of Composite Fibers

P. E. Duwez
J. A. Krumhansl
M. J. Sinnott

This memorandum presents the current status of development of typical candidates for fibers to be used in composites. The consensus is that graphite fibers offer the greatest potential for future use in composites.

X-ray Absorption and Wave Propagation through Dispersive Media*

W. H. Flygare
W. Kohn
J. R. Schrieffer
C. P. Slichter

Some elementary equations and order of magnitude computations are given for the disposition of X-rays in a RV. The shock waves and trajectory errors produced by blowoff are discussed. The advantage of a centrally located graded-z, X-ray absorber is pointed out. Geometric absorbers of sound waves are proposed to dissipate the shock energy. Several types of acoustical filters are discussed in detail. Several general results on wave propagation in solids are also given.

*CLASSIFIED