Title
THE THREE APPROACHES TO MECHANICAL PROPERTIES OP MATERIALS

Permalink
https://escholarship.org/uc/item/7q61915w

Author
Dorn, John E.

Publication Date
1967-08-01

UCRL-17181

University of California

Ernest O. Lawrence Radiation Laboratory

THE THREE APPROACHES TO MECHANICAL PROPERTIES OF MATERIALS

Proceedings of the Conference on
Materials Science Education

UCRL-17181
Preprint

UNIVERSITY OF CALIFORNIA
Lawrence Radiation Laboratory
Berkeley, California

AEC Contract No. W-7405-eng-48

THE THREE APPROACHES TO MECHANICAL PROPERTIES OF MATERIALS

John E. Dorn

September, 1966

THE THREE APPROACHES TO MECHANICAL PROPERTIES OF MATERIALS

John E. Dorn

Inorganic Materials Research Division, Lawrence Radiation Laboratory,
and Department of Mineral Technology, College of Engineering,
University of California, Berkeley, California

Prepared for presentation at the
Conference on Materials Science Education
held at
Indian Institute of Technology
Kanpur

September 2 - 10, 1966

I. INTRODUCTION

The mechanical behavior of materials is an area of primary interest within the general scope of materials science. By far the greatest tonnage of engineering materials is destined for applications in structures and machines that must resist either static or dynamic loading. In contrast the production of materials for electronic, chemical, nuclear and other miscellaneous applications is quite small; this fact, however, in no way detracts from the great importance of these applications. But even when the major issue of utility depends on other properties, e.g. electronic, nevertheless the mechanical properties, e.g. strength, fatigue, and shock resistance, continue to have significance in their engineering applications.

Engineers are dedicated to the efficient and economic utilization of materials for the benefit of man. Because of its universal application, all engineers, regardless of their individual fields of specialization, require a substantial background for coping with the diverse aspects of the mechanical properties of materials.

II. THREE APPROACHES OF INSTRUCTION IN MECHANICAL PROPERTIES OF MATERIALS

The subject of mechanical properties of materials can be presented to students from one or several of three viewpoints. These might be classified as follows:

1. Continuum Mechanical
2. Microstructural
3. Molecular and Atomistic

Each of these require clarification relative to their meaning within the context of this discourse.

1. Continuum Mechanical. This approach refers to the application of the now classical methods of the mathematical theories of elasticity and plasticity to a description of the mechanical behavior of materials under combined stresses. Its development took place over the past 2000 or more years; but the major advances in utilizing this analytical method have matured over about the last 100 years. It provides a venerable and time-tested method which, even today, constitutes the

principal proceedure for integrating mechanical design in terms of the mechanical properties of materials.

Usually this approach employs simplifying idealizations of the actual mechanical behavior of real materials. For example, it might assume the validity of the linear isotropic theory of elasticity and idealized plasticity with a constant deformation stress. On the other hand it has great flexibility, as its formulation can be generalized to accommodate non-linear elasticity, anisotropy, general conditions for strain hardening, the analyses of ductile, quasi-brittle and brittle fracturing, fatigue failures, and time-dependent deformations such as those encountered in creep of materials. Furthermore by employing Voight and Maxwellian models of materials it can accommodate in its analytical structure, damping capacity, creep recovery and the anelastic behavior of materials.

Despite its universality and well-documented utility this analytical approach, when used alone, has a number of serious limitations. In fact these limitations arise principally from its inherent empiricism and somewhat false attempt at universality. To apply this approach, extensive test data on the significant mechanical phenomena of known materials must be available in the form of parameters, such as moduli of elasticity, yield strengths, rates of strain hardening, endurance limits, etc. that need be incorporated into the theory. Consequently the continuum approach does not and, in general cannot, provide either the practical or theoretical basis for developing new and better materials. Nor, disregarding some minor exceptions, does it give the basis for judgement or prediction on how a given material might behave under new and untested conditions. Another limitation, somewhat associated with the above-mentioned empiricism and universality, arises because the analyses are structured in terms of continuum concepts whereas materials, in fact, are molecular or atomistic in nature. Therefore the macroscopic analyses smear out and average all of the significant atomistic and microstructural factors on which the mechanical behavior of real materials depend.

Whereas the continuum approach is invaluable for decisions on plastic forming of materials and the conversion of known mechanical properties into selection criteria and design limitations, it leaves a substantial vacuum regarding the mechanical behavior of materials in terms of their atomic bonding and microstructures. This vacuum needs to be filled by alternate approaches.

2. Microstructural. This approach was initiated in the latter half of the 19th century with the introduction of optical microscopy when the early metallographers, such as Sorby and Martens, first observed that the mechanical properties of metals depend not only on their chemical composition but also and in a very sensitive way on grain structure and the types and distribution of phases present in the microstructure. It soon became evident that how materials are put together on a microscopic basis determines, in large measure, their mechanical behavior when viewed on a continuum basis. Over the intervening years, the metallographic art has developed into an invaluable tool which is now used extensively in all engineering evaluations on the mechanical behavior of materials. Its utility has also been extended to include

ceramic and high polymeric materials in addition to metals. Recent developments in electron microscopy, principally those employing replica techniques but also those based on electron transmission, have now so extended the resolution to permit viewing of phases of submicroscopic sizes.

The metallographic approach permits a comparison of the ever-important continuum properties of materials with their microstructures. A few prosaic examples will serve to illustrate this point:

1. In a single phase of ductile material the yield strength increases and the rate of strain hardening decreases as the grain size is decreased.

2. Whereas some phases, e.g. alpha iron, are ductile, other phases, such as cementite, are brittle.

3. The continuum mechanical properties of a two-phase composite are dictated, at least qualitatively, by the properties of the continuous phase. When the continuous phase is brittle, the composite behaves in a brittle fashion; but when the continuous phase is ductile, the

composite also is somewhat ductile.

4. The continuum mechanical properties of a hard brittle phase distributed in a ductile matrix depends on the dispersion of the brittle phase. When the dispersed phase consists of closely spaced fine particles the yield strength is higher and the rate of strain-hardening is at first higher and then lower than for a more widely separated dispersion of coarse particles.

Several important features of the metallographic approach become apparent in terms of these examples of its utility:

1. It provides a new and deeper insight into the origin of mechanical properties. When, for example, theoretical continuum mechanics are applied to calculate the effects of grain size and dispersions on mechanical behavior, the theory suggests that such effects should not exist. Obviously classical continuum mechanics, as it now stands, is incompetent to describe the nature and origin of the mechanical behavior of materials.

2. On the other hand the metallographic approach is never a substitute for the continuum mechanical approach. It is always used in

conjunction with knowledge of the continuum properties and supplements this knowledge with detailed information on microstructural effects.

3. Furthermore the metallographic approach is highly empirical and qualitative; only occasionally is it semi-quantitative.

In spite of its empirical, comparative and qualitative nature, the metallographic approach is an invaluable supplement to the continuum mechanical approach. In the hands of a competent materials engineer it is an invaluable tool for control of heat treatments, obtaining optimum microstructures, uncovering undesirable microstructures, and in revealing the origin of failures. All engineers require a sound background in this area, not only for specific problems but equally for general indoctrination in the important relationship between microstructure and mechanical properties of materials.

On the other hand even when the metallographic approach is used to supplement the continuum mechanics approach, many important questions are left unanswered. A few of such questions will illustrate this point:

1. Why are single crystals of f.c.c. metals so soft and those of

diamonds so hard?

2. Why do crystalline materials deform by slip in the directions of closest atomic packing and on planes that are also most densely packed with atoms.

3. Why does the flow stress of some crystalline materials increase very rapidly with an increase in strain rate and in others only modestly or not at all.

4. What causes strain hardening?

5. Why do metals first exhibit high creep rates at temperatures above about one-half of their melting temperature?

It is interesting to note that these questions remain unanswered by the continuum and metallographic approaches not because these approaches need additional development. Regardless of how highly developed these approaches become, they will remain forever incompetent to answer these questions because they were never constructed so as to provide the detailed vehicle that is needed to answer these questions. Their answer lies not in the continuum realm and not in the microscopic realm but rather in the much finer details of atomic bonding, the molecular structure of crystals, glasses and polymeric materials, coupled with their defects and thermal perturbations.

3. Atomistic. The atomistic approach is based on three major complementary advances in our knowledge. It might be said to have started in 1913 when Bragg, and von Laue and Knipping first demonstrated that crystalline solids consist of ordered arrays of atoms or groups of atoms on three-dimensional lattices. Although the atomic bonding in ionic solids was soon thereafter developed by Born and Madelung, a general and unified approach to atomic bonding had to wait until about 1926 when Schroedinger first postulated wave mechanics which finally led to the electronic band theory of solids. These concepts alone permit analyses of the origin of the cohesion and elastic properties of materials but were unable to account for their significant plastic behavior. But in 1934 as a result of the efforts of Dehlinger, Orowan and G. I. Taylor, it became known that the motion of linear lattice defects, now known as dislocations, were the responsible structural

details for glide in crystals. Over the same period of time it was found that the mechanical behavior of liquids, glasses and high polymers could be rationalized in terms of diffusive motion of molecules or chains of atoms that comprise their less regular structure.

At first progress was very slow because first dislocations had not yet been seen and secondly because of their extreme versatility. How the same dislocations that permit slip to occur in single metal crystals at the low flow stress of 100 lbs/in^2 could also account for the high strength of 100,000 lbs/in^2 or more in severely work hardened metals seemed to pose a paradox. With the advent of electron-transmission microscopy and several alternate techniques that have been developed to "see" dislocations the doubt concerning the existence and importance of dislocations vanished and most of the paradoxes have been resolved. Remarkable strides have been made particularly over the past 15 years in rationalizing on the atomistic basis the mechanical behavior of many materials. On the other hand, such advances as have been made, have usually uncovered more areas for research than were thought to exist originally. Dislocation mechanics is yet in its early stages of development but it is now certain it is a fruitful avenue of approach to the understanding, correlation, and rationalization of the mechanical behavior of crystalline materials from a basic atomistic viewpoint. Dislocation theory is now being extensively applied to the development of new and better engineering materials. This is most in evidence in the development of ausforming steels of remarkable strength and good ductility and in engineering development, for future high temperature applications, of intermetallic compounds.

The elements of dislocation theory are easily taught to engineering students at an early stage in their education. Dislocations are merely linear elastic strain-energy fields. As such elastic strain-energy fields move under the action of shear stresses, the crystal undertakes plastic deformation. Thus plastic deformation is no longer a new and different area of knowledge but is merely an easily explanable extension of classical theory of elasticity to include the motion of linear elastic strain centers. The most powerful approach to dislocation theory is via work or energy principles. These methods are well known to engineers and their utilization in dislocation theory are readily grasped.

On the other hand a firm grasp of the principles of atomic bonding requires extensive knowledge of the more sophisticated wave mechanics theory. Fortunately many of the concepts on atomic bonding might be presented in a qualitative way in a first course on dislocation theory. Thus some knowledge on dislocation theory can be presented at an early stage of an engineers program of study.

III. PREREQUISITE DISCIPLINES

In the preceeding discussion some of the essential disciplines for understanding the mechanical properties of materials were briefly mentioned. Here the interdisciplinary nature of the subject as outlined in Table I will be more completely scrutinized.

As shown, the Continuum Mechanical approach is rather narrowly defined in terms of a single discipline, namely applied continuum mechanics. Although the subjects listed are essential to an understanding of the mechanical response of materials, they are not, in themselves alone,

Table I

Disciplines Essential to Mechanical Behavior

A. Continuum Mechanical

1. Newtonian mechanics
2. Strength of materials
3. Mechanical testing
4. Theory of elasticity
5. Theory of plasticity
6. Mathematics: Partial differential equations
   Potential theory
   Numerical analyses

B. Microstructural

1. Crystal structure: Crystal lattices
   X-ray and electron diffraction
   Atomic bonding (qualitative)
   Packing of atoms
   Stacking faults
2. Statistical thermodynamics: Boltzmann statistics
   Phase equilibria
   Surface tension
   Order-disorder equilibria
   Point defects
3. Fermi statistics: Quantum mechanics
   Bond theory
   Stability of phases
4. Kinetics of solid state reactions: Diffusion
   Nucleation and growth
   Martensitic reactions
5. Microstructures and properties: Optical microscopy
   Replica electron-microscopy

Table I continued

Transmission electron-microscopy
Correlation with Mechanical properties

C. Dislocation Theory
  1. Athermal mechanisms
  2. Thermally activated mechanisms
  3. Viscous behavior of dislocations
  4. Relativistic conditions
  5. Electron-transmission microscopy

---

materials science. They merely indicate the engineering utility of mechanical properties and do not and can not provide information on the physical and chemical origin of such properties.

The orientation of interest toward the materials science aspects are first emphasized in the microstructural approach which provides a correlation of atomic bonding, crystal structure and microscopy with properties. Here also the basic interdisciplinary nature of materials science becomes evident in the direction of knowledge on continuum mechanics, the physics and chemistry of bonding, crystal structure, phase equilibria, kinetics of reactions and microstructure toward a comparative study of the mechanical behavior of materials.

The basic rationalization of the physical and chemical origin of the mechanical behavior of materials begins with the Atomistic approach. It must be understood that this approach is superimposed on top of the microstructural approach. Consequently all topics under the microstructural approach have even greater impact on the atomistic approach.

IV. BALANCED INSTRUCTION

Because of its interdisciplinary nature and its requirements of a broad engineering and scientific background it is difficult to achieve an adequate balance of desired breath and sufficient depth of instruction in mechanical properties for all engineers. This problem is not unique to the engineering profession; it is also prevalent in the medical, legal, and all other highly developed professions. As in these professions, so likewise in engineering we need the general practitioner and also the specialist. The success of their cooperation depends on the general practioners early recognition that he needs expert help in depth in an area where his general knowledge is too shallow to permit him to solve the problem alone.

The specialist of materials science on the mechanical behavior of materials usually requires a broad and diversified background in engineering, physics, chemistry, mathematics and the various special subjects of materials science per se. In addition he must be trained in the area of research. It appears unlikely that this objective can be achieved with less than the Ph.D. degree in the area of specialization.

On the other hand a materials engineer whose duties might involve advice to his colleagues on selection of materials, control of casting, welding, fabrication and heat treatment, and inspection of failures might be adequately trained at the B.S. or M.S. levels. In contrast to the Materials Scientist he need not be trained in research methods; furthermore he has little need for great depth in the physics of atomic bonding and crystal structure or dislocation theory. He should have a good background in phase diagrams and some knowledge of equilibria and kinetics of reactions. His major forte should be concerned with microstructural approach more as an engineer than as a scientist.

As mentioned previously, all engineers have a vital interest in the mechanical behavior of materials. As general practitioners, however, they will not be able to delve very deeply into the subject of mechanical properties. Undoubtedly all will have some background in strength of materials, theory of elasticity, and mechanical design. In addition many may have some instruction in the theory of plasticity. Very likely they will have time only for one year course instruction on materials science per se. In this event major emphasis should be given to the microstructural aspects of mechanical behavior, including crystal structure, atomic bonding, phase diagrams, equilibria, kinetics of reactions, heat treatment and microscopy. Although dislocation theory should be deemphasized, some beginning instruction in this field is nevertheless desirable in order to give the student some basis for judgement on the atomistic nature of plastic deformation.

It is indeed difficult to prescribe the needed ratio of production of students in the three categories that have been mentioned. Perhaps it is not too wrong to suggest that for each 1000 mechanical engineers, there be about 50 materials engineers and about 5 materials scientists.

V. SUMMARY

1. All engineers work with materials and therefore need some instruction on the mechanical behavior of materials.

2. There are three major approaches to the mechanical behavior of materials: continuum mechanical, microstructural and atomistic.

3. All three approaches are essential to a basic understanding of the nature and origin of the mechanical behavior of materials.

4. Materials science is an interdisciplinary subject covering engineering and the physics and chemistry of solids.

ACKNOWLEDGMENT

This report was prepared as part of the activities of the Inorganic Materials Research Division of the Lawrence Radiation Laboratory of the University of California, Berkeley, and was done under the auspices of the U. S. Atomic Energy Commission.