MSE 4320/6320: Spring 2025

Origins of Mechanical Behavior of Materials: Deformation and Fracture of Structural Materials

Instructors:

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Logistics:

JH 171
T/Th: 1230-145

Office Hours Link

Sp25 – MSE 4320/6320 – Office Hours
- Meeting ID: 940 1560 5155
- Passcode: 43206320

Course website on UVa-Canvas
- Grades, homework, updates, recorded lectures, lecture notes, misc.

Objective and Approach:

The overarching objective of this course is to develop understanding of the phenomenology and fundamental principles describing the origins of material deformation and fracture in response to mechanical loading. Breadth of mechanical behavior and structural materials are emphasized over depth, which is covered in upper division courses. Engineering and scientific principles are integrated in an approach that includes: (a) governing continuum mechanics equations, (b) materials science principles at the atomic defect to microstructure scale, (c) examples of property phenomenology, (d) descriptions of test methods, and (e) problem solving to reinforce concepts and demonstrate applications. Each important mode of mechanical behavior is discussed in the context of a specific material; structure-property relationships are identified. After an introduction to elasticity, plastic deformation is considered based on dislocation concepts, leading to an understanding of strengthening mechanisms. Fracture is examined based on continuum fracture mechanics and microstructure damage leading to toughening mechanisms. Cycle-dependent (fatigue) and time-dependent (creep) plastic deformation processes are described and subcritical crack growth is discussed as the result of deformation-environment interactions. Modern predictive approaches are highlighted and the foundation for property modeling and component simulation is established.

Desired Outcomes:

- Course Objective 1: This course looks to provide the overarching outline to enable the students to distinguish and qualitatively explain a wide-range of macroscopic mechanical behavior by linking this behavior to the controlling microstructural features.
    - This requires the ability to identify and measure the material-mechanical attributes necessary for alloy performance and structural-design function.

- To understand how this behavior is influenced by strain rate, temperature and environment.
    - Provide the fundamentals necessary to excel at next-level courses that build on the materials science and solid mechanics principles of mechanical behavior.
- Course Objective 2: The technical content and evaluation material will reinforce engineering problem solving strategies. Relevant to:
    - Microstructural basis and 3D nature of elasticity
    - Physical understanding of plastic deformation

- Course Objective 3: The technical content and evaluation material will reinforce engineering problem solving strategies. Relevant to:
    - Fundamentals of fracture mechanics
    - Fundamentals of the fatigue damage process

- Course Objective 4: Help students to refine and build writing and presentation-style communication skills.

<u>Office Hours:</u>

Burns: Wed, 10-11, Zoom (Sp25 – MSE 4320/6320 – Office Hours)

TA: Mohammed Shabana mas5am@virginia.edu TBD:

If you need in-person discussions then please reach out directly to schedule with Burns.

<u>Grading:</u>

Course will be graded out of 550 (undergraduate) or 650 (graduate) total points

- Quizzes: 50 points (10 assignments)
- Homework: 100 points (4 assignments)
- Exam 1: 100 points
- Exam 2: 100 points
- Final Exam: 150 points
- Paper Critique: 50 points

Graduate Specific

- Extra HW: 20 points (EC for UG: up to 10)
- Extra Exam: 40 points (EC for UG: up to 20)
- Oral Final: 40 Points

Quizzes will be completed via Canvas and HW submission instructions will be provided. Exams are planned to be "take-home" assignments, further instructions will be provided. Any issues with grading should be addressed within 2 weeks of the return of the assignment.

Extra Credit:

All Students:

- Up to 20 Extra Credit Points will be assigned based upon the level of class participation, class attendance, office hours, etc.
- 10 points will be awarded if 100% of the class completes the Course Evaluation; 5 points will be awarded if >85% complete the Course Evaluations.

Undergraduates:

- Opportunities are available for completing the extra Graduate Specific HW/Exam questions.

Graduates:

- 25 points are available for completing a second paper critique

Late Assignments:

There is a zero tolerance for late submission of assignments; LATE ASSIGNMENTS WILL RECEIVE A ZERO. Individual cases will be subjectively evaluated, if mitigating circumstances are communicated to the instructor PRIOR to the deadline.

Course Text:

A complete set of course notes in PPT format will be incrementally provided via the UVa-Canvas website in the Resources section. These notes will provide a fully sufficient basis for learning, lecture note-taking, and open-notes exams; as such, a text book is not required.

However, the lecture notes are coordinated with sections of the following text books to (1) provide students with an alternate presentation of topics, or (2) serve as a future reference (recommended for those in the mechanics of materials field). These are not in-stock at the UVa bookstore but can be ordered via internet sources.

Deformation and Fracture Mechanics of Engineering Materials, Richard W. Hertzberg, Richard P. Vinci, and Jason L. Hertzberg, John Wiley and Sons, 5th edition, 755 pages (2013). This book provides an in-depth 6-credit undergraduate-graduate treatment of deformation and fracture mechanics from the materials science and fracture mechanics perspectives.

Mechanical Behavior of Materials Keith Bowman, John Wiley and Sons, 1st edition, 334 pages (2004). About 60% of the course follows the content of this text.

Mechanical Behavior of Materials, William F. Hosford, Cambridge University Press, 1st edition, 426 pages (2005). This book is strong in classic elasticity and plasticity descriptions applied to a wide range of materials.

Technical Outline:

1. Introduction
   - Course Logistics
   - Failure Modes
   - Great Failures
   - Misconceptions Regarding Materials Mechanical Behavior

2. Review of Stress/Strain
   - Definitions
   - Tensile test
3. Deformation: Elasticity
   - 3D Stress/strain states (tensors)
   - Atomic Considerations (basis, anisotropy)
   - Constitutive Laws
4. Yield/Failure Criteria
   - Tresca/von Mises
   - Brittle versus Ductile
5. Deformation: Plasticity
   - Phenomenological
     - Constitutive Laws
     - Plastic instabilities
   - Mechanistic
     - Dislocation review
     - Dislocation properties
     - Single Crystal Slip
     - Polycrystal Slip
6. Strengthening Mechanisms
   - Constraint based
   - Solid Solution
   - Grain size
   - Precipitation
7. High Temperature Deformation: Creep
   - Phenomenological
     - Trends, tests, empirical descriptions
   - Mechanisms
     - Dislocation Creep
     - Diffusion Creep
     - Deformation Map
8. Fracture Mechanics
   - Stress Concentration
   - Griffith Model
   - Stress Intensity
   - Similitude
   - Fracture Toughness
9. Fracture Modes
   - Phenomenological
   - Ductile Fracture (MVC)
   - Brittle Fracture (cleavage, intergranular)
   - Ductile to Brittle Transition
10. Fatigue

- High cycle fatigue
- Low cycle fatigue
- Fracture mechanics approach
- Engineering applications

11. Polymers (if time allows)
    - Polymer “terms”
    - Phenomenological
        - Deformation
        - Fracture
    - Overview of mechanisms
12. Special topics (if time allows)
    - Failure analysis example
    - Environmental cracking

<u>Helpful Reading Resources:</u>

Introduction:
Mechanical Tests; Failure Analysis
Bowman Ch. 1: pp. 1, 10-17, 211, 272-273
Hertzberg: pp. 251-253; 645-652; 683-684; 702-703; 708-710.

Deformation: Elasticity
Stress/Strain Definitions; Elastic Stress Analyses; Tensile (uniaxial and bend) Test
Bow Ch. 1: pp. 2-10, 17-26 Bow Ch. 3: pp. 103-104
Hertz: pp. 3-7; 17-34 Hosford Ch. 1: pp. 1-4, 9-12
Hosford Ch. 3, Ch. 4 (overview, do not consider details)

Atomic Effects in Elasticity; Rubber Elasticity; Physical Basis for Modulus Anisotropy
Bow Ch.1: pp. 26-30 Hosford Ch. 2: 24-27
Hertz: pp. 8-17

Linear-Elastic and Elastic-Plastic Constitutive Behavior; 3-Dimensional Stress and Strain States, Isotropic and Anisotropic Behavior
Bow Ch. 2: pp. 33-50, 51-67 (Overview; not responsible for tensor mathematics)
Hertz: pp. 34-40; 90-98; 100-102 Hosford: Ch. 2: 21-23, 27-35; Ch. 5: pp. 70-77

Yield/Failure Criteria:
Yield Criteria; Failure Criteria--Broken Chalk vs. Surgical Tools;
Bow Ch. 3: pp. 74-86 Hertz: pp. 88-90
Hosford Ch. 6: pp. 80-84, 86-87

Deformation: Plasticity
Stereographic Projection of Unit Cell; Shear Deformation of Crystalline Solids; Slip Geometry and Crystallography; Schmidt Factor for Single Crystals
Bow Ch. 2: pp. 67-70 Bow Ch. 3: pp. 94-96, 87-95
Hosford Ch. 8: pp. 120-132 Hosford Appendix B: p. 418-420
Hertz: 63-75

Schmidt and Taylor Factors for Polycrystals; Deformation Twinning
Bow Ch. 3: pp. 96-103 Hosford Ch. 11: pp. 170-181
Hertz: pp. 81-87; 102-105 Hosford Ch. 12: pp. 188-191

Definitions, Properties, and Characteristics of Dislocations in Crystalline Lattices
Bow Ch. 4: pp. 117-149 Hosford Ch. 9: pp. 139-154
Hertz: pp. 75-81; 111-117 Hosford Ch. 10: pp. 158-162, 166

Crystalline Solids--Obstacles to Slip; Strengthening Mechanism by Work Hardening; Single Crystal Stress-Strain Curve; LEDS
Bow Ch. 5: pp. 157-162 Hosford Ch. 10: pp. 158-162, 166

Hertz: pp. 143-155 Hosford Ch. 12: p. 194

Strengthening Mechanisms:

Stress Concentration; Strengthening Mechanism by Constraint; Examples: Notch Strengthening *vs* Notch Weakening for Strong Joints/Thin Films
Bow Ch. 5: pp. 152-156 Hertz: pp. 260-265

Strengthening Mechanism by Solid Solution Hardening and Particle Strengthening; Strengthening Mechanism by Grain Size Hardening
Bow Ch. 5: pp. 162-169 Hosford Ch. 12: pp. 195-199
Hertz: pp. 155-161; 164-172

Glassy Solids; Strengthening by Molecular Bonding and Orientation
Bow Ch. 5: pp. 172-175 Hertz: pp. 177-183

High Temperature Deformation: Creep

Creep and Stress Rupture in Metals, Polymers and Ceramics; Engineering Life Prediction
Bow Ch. 6: pp. 177-185 Hertz: pp. 189-195; 215-220; 291-294

Constitutive Behavior and Stress Relaxation
Bow Ch. 6: pp. 185-192 Hertz: pp. 195-202

Creep Deformation Mechanisms; Dislocation and Diffusional Processes
Bow Ch. 6: pp. 192-202 Hertz: pp. 202-205

Creep Deformation Mechanisms; Grain Boundary Sliding and Superplasticity
Bow Ch. 6: pp. 202-207 Hertz: pp. 205-208

Mapping Methods in Mechanical Behavior: Deformation and Fracture
Bow Ch. 8: pp. 248-266
Mapping Methods in Mechanical Behavior: Alloy Design and Selection
Bow Ch. 8: pp. 266-269 Hertz: 208-215

Fracture:

Stress Concentration; Elastic Crack Problem: Griffith Strain Energy Theory and G ; Irwin Crack Tip Stress Analysis and K
Bow Ch. 7: pp. 211-224, 243-244 Hertz: pp. 299-307; 315-318

Crack tip plastic zone; Catastrophic Fracture and Stress State Constraint; Elastic Compliance and G to K Equivalence
Bow Ch. 7: pp. 224-226 Hertz: pp. 330-334

Fracture Mechanics Similitude and Application; Stress Intensity Factors for Finite Bodies
Bow Ch. 7: pp. 227-230
Hertz: pp. 318-326; 326-330; 339-340; 719-721

Fracture Toughness Test Methods and Materials Data
Bow Ch. 7: pp. 230-237
Hertz: pp. 307-315; 336-355; 449-453

Fracture: Microscopic Damage Processes and Toughening
Macro-modes and Micro-mechanisms of Fracture; Brittle Fracture of Ceramics
Bow Ch. 7: pp. 237-242, 244-245
Hertz: pp. 254-260; 266-278; 383-388; 416-422; 434-440

Ductile Fracture and Microvoid Mechanisms; Microstructure-Property Relations
Hertz: pp. 278-282; 389-398; 402-404; 410-416

Brittle Fracture: Cleavage and Dislocation Mechanisms; Intergranular fracture; Microstructure-Property Relations
Hertz: pp. 398-402; 404-405

Fatigue:
Multiple Stages of Cumulative Fatigue Damage; Important Variables; Cyclic Stress *vs.* Strain Constitutive Behavior
Bow Ch. 9: pp. 272-280 Hertz: pp. 499-502; 529-538

Elastic SN Approach after Basquin; Plastic LCF Approach after Coffin-Manson; Method of Universal Slopes and Transition Fatigue Life
Bow Ch. 9: pp. 280-285 Hertz: pp. 503-510; 538-541

Fracture Mechanics Approach after Paris; Cyclic Plastic Zone
Bow Ch. 9: pp. 285-292 Hertz: pp. 559-563; 568-571; 578-590

Safe Life vs Damage Tolerance Prognosis; Example Problem in Component Fatigue and Fracture
Hertz: pp. 563-568

Microscopic Fatigue Mechanisms; Example Problem in Failure Analysis; Microstructure-Property Relationships
Hertz: pp. 572-577; 713-717

Polymers:
Coming soon…

Special topics:
Hydrogen Embrittlement; Property Relationships; Damage Mechanisms
Hertz: pp. 463-472

Stress Corrosion (Environmental) Cracking; Property Relationships; Damage Mechanisms
Hertz: pp. 472-487; 489-492; 661-664

THE HONOR SYSTEM:

Every student in this course must comply with all provisions of the UVa honor system. On tests and exams you are to pledge that you have neither received nor given unauthorized aid.

Your signature below this pledge affirms that you have not accessed notes, study outlines, old exams, answer keys, or textbooks while taking the tests and the exam and that you have not obtained answers from another student's exam.

Alleged honor violations brought to the attention of the professor will be forwarded to the Honor Committee. <u>If, in the professor's judgement, it is beyond a reasonable doubt that a student has committed an honor violation, that student will immediately receive a grade of zero for the affected work, irrespective of any subsequent action taken by the Honor Committee.</u>

From your Honor Reps:

<u>The Honor System and the School of Engineering and Applied Science</u>

The School of Engineering and Applied Science relies upon and cherishes its community of trust. We firmly endorse, uphold, and embrace the University's Honor principle that students will not lie, cheat, or steal, nor shall they tolerate those who do. We recognize that even one honor infraction can destroy an exemplary reputation that has taken years to build. Acting in a manner consistent with the principles of honor will benefit every member of the community both while enrolled in the Engineering School and in the future.

If you have questions about your Honor System or would like to report suspicions of an Honor Offense, please contact a SEAS Honor Committee member.

Statement on Disabilities

The University of Virginia strives to provide accessibility to all students. If you require an accommodation to fully access this course, please contact the Student Disability Access Center (SDAC) at (434) 243-5180 or sdac@virginia.edu. If you are unsure if you require an accommodation, or to learn more about their services, you may contact the SDAC at the number above or by visiting their website at http://studenthealth.virginia.edu/student-disability-access-center/faculty-staff.