Biomimetic Composites: Inspiration to Application

(a review)

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SEM Biological Systems and Materials Technical Division Chair

Outline

- Introduction to the SEM Biological Systems and Materials Technical Division
- "New Directions in Mechanics" *Mechanics of Materials* (2005)
- "The Future of Medicine: Biomaterials" *MRS Bulletin* (2000)
- Highlights of past and current work presented at SEM Biological Systems and Materials Technical Division:
  - Investigation of Organic Materials
  - Implant Materials
  - Inspiration
- Closing remarks

Your Technical Division

- **Biological Systems and Materials**
- **TD Focus:** Investigations, including experimental, of biological and biologically inspired materials and systems, with an emphasis on structure, property and process relationships
- **Officers**
  - *Chair*: Dr. Eric N. Brown
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    - Materials Science and Technology Division
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  - *Vice-Chair*: Prof. Michael Peterson
    - University of Maine
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  - *Secretary*: Prof. K. Jane Grande-Allen
    - Rice University
    - Dept Bioengineering
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Background

- The field of biological materials and systems is extensive, representing an interdisciplinary topic encompassing **mechanics**, materials science, and the breadth of engineering disciplines in conjunction with biology and medicine
- Within SEM this growing field resides in the Biological Materials and Systems Technical Division (TD), started as a series of sessions at the SEM annual meeting in Orlando, 2000
- This year: 4 sessions, 20 talks w/ 13+ topical talks in other sessions
- The growth of the field can be seen by its presence in the literature:
  - 111,822 publications “biological materials” (2000–2005)
  - 2,553 publications “biological composites” (2000–2005)
  - In both cases this is comparable the publications on these topics from 1950–1999
  - More than half-a-dozen journals specific to biological materials have been started in the last decade
  - Several broader journals—including *Experimental Mechanics*—publishing papers in the field
  - In December 2002 a special issue of *Experimental Mechanics* was published to focus on Biological and Biologically Inspired Materials

“New Directions in Mechanics” *

- Summary publication of the outcome from a US Department of Energy (DOE) sponsored workshop to “identify cutting-edge research needs and applications, enable by the application of theoretical and applied mechanics.”
- **Mechanics of Materials**; Feb.-March 2005; vol.37, no.2-3, p.231-59
- M.E. Kassner, S. Nemat-Nasser, Z. Suo, G. Bao, J.C. Barbour, L.C. Brinson, H.D. Espinosa, H.J. Gao, S. Granick, P. Gumbsch, K.S. Kim, W. Knauss, L. Kubin, J. Langer, B.C. Larson, L. Mahadevan, A. Majumdar, S. Torquato, F. van Swol

Underline indicates author has published in *Experimental Mechanics* and/or participated in a SEM annual conference

- Three primary areas proposed:

1. Self-assembly and fluidics
2. **Biological and bio-inspired mechanics**
3. Deformation and fracture


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Mechanics of Materials 37 (2005) 231–259

MECHANICS OF MATERIALS

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New directions in mechanics

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[2] Workshop participants.

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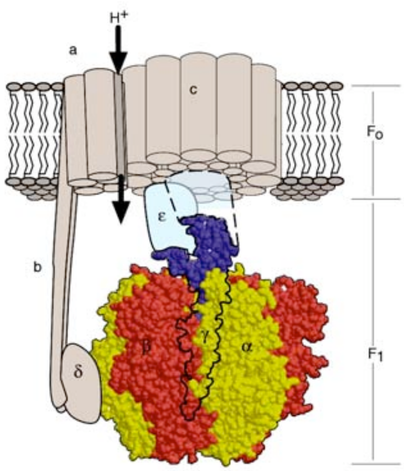
doi:10.1016/j.mechmat.2004.04.009

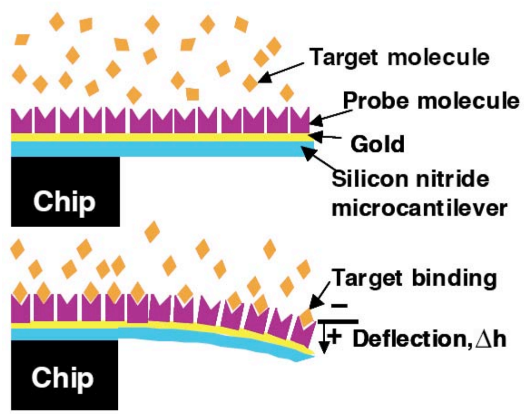
Biological and bioinspired mechanics *

- Protein machines
- Mechanics based biomolecular recognition
- Flaw insensitive structural design
- Rheology of cytoskeletal assemblies
- Thermal fluctuations
- Chemistry and mechanics
- Soft and hard



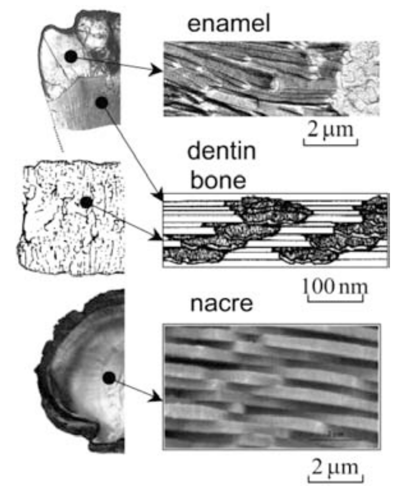
Energy transduction in the F1 motor of ATP synthase

H. Wang and G. Oster *Nature* (1998)



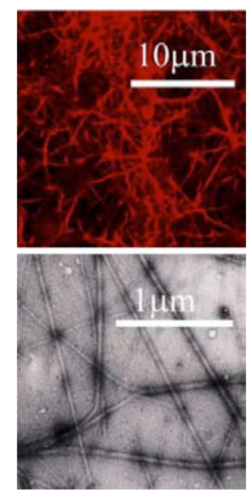
Bioassay of prostate-specific antigen (PSA) using microcantilevers

G.H. Wu, R.H. Datar, *et al. Nature Biotechnology* (2001)



Materials become insensitive to flaws at nanoscale: Lessons from nature

H.J. Gao, B.H. Ji, *et al. Proceedings of the National Academy of Sciences of the United States of America* (2003)



Highly crosslinked microstructures result from actin and tight crosslinker scruin

New Directions in Mechanics

M.E. Kassner, *et al. Mechanics of Materials* (2005)

Future directions *

- How to link from atomistic to micromechanisms in basic deformation modes and failure in nanostructured or biomaterials?
- How to combine atomistic, statistical and continuum approaches? For example, understanding protein folding and mis-folding; rheology of disordered networks. These problems involve coupling between multiple length and time scales.
- Development of new experimental techniques to accurately probe dynamical evolution of bionanomaterial response
  - improvement in temporal and spatial resolution (protein machine);
  - to discriminate single versus ensemble molecular events at surfaces/interfaces.
- Interconnection between experiment and theory/simulation is crucial to answering the open questions in nanobiomaterials.
- Nanomechanics at the interface between liquids and solids with biomolecules is critical for materials and mechanics research, especially for new biomaterials synthesis, friction and dissipation, and energy conversion.
- Possibility of fabrication and replication of nanostructures, e.g., using self-assembly.

“The Future of Medicine: Biomaterials”

- “Biomaterials is expected to become the dominant focus of materials research and that significant economic expansion will flow from this research.”
- H.R. Piehler, **MRS Bulletin**; Aug 2000; v.25, no.8, p.67-70
  - When and how does it become prudent to substitute a new, potentially safer and/or more effective biomaterial or biomaterial fabrication process for an older, perhaps less safe one?
  - How should physicians and engineers divide their efforts between new device development and surveillance of existing devices, particularly over the long term?
  - How should the normal information flow and decision making between physicians and engineers be influenced, if at all, by legal, regulatory, and risk management concerns, particularly in the case of new biomaterials or biomaterial fabrication processes?
  - What roles should physicians and engineers play in formulating and communicating biomaterial risk information to patients, particularly risks associated with new biomaterials and biomaterial fabrication processes?
- Topics:
  - **Orthopedic Implants**
  - **Regenerative Materials**
  - **Cardiovascular Stents**
  - **Nanotechnology in Medicine**
  - **Prosthetic Heart Valves**
  - Cardiac Pacemakers
- The TD already has people working in most of these areas

MATERIALS CHALLENGES FOR THE NEXT CENTURY

The Future of Medicine: Biomaterials

Henry R. Piehler

> The abdomen, the chest, and the brain will forever be shut from the intrusion of the wise and humane surgeon.
>
> —Sir John Eric Ericksen, British surgeon, appointed Surgeon-Extraordinary to Queen Victoria 1873.

> Those who forget the past are condemned to relive it.
>
> —Santayana

Introduction

One commonly used definition of biomaterials is any material that is used to replace or restore function to a body tissue and is continuously or intermittently in contact with body fluids.[1] It is widely perceived that there will be significant advances in the development and use of biomaterials in the near future. In fact, many believe that biomaterials will soon become the dominant focus of materials research and that significant economic expansion will flow from this research. The very breadth of this field precludes a comprehensive, in-depth projection in all areas of biomaterials, which currently include orthopedic, cardiovascular, neurological, drug delivery, and other applications.[2] Projected future applications include the use of microrobotic devices for disease detection, drug delivery, and neurological applications, for example. Gene therapy is also identified as an alternative approach to many of these same clinical problems. Some unanticipated biomaterials-related events and changes will continue to occur; two such events which occurred during the preparation of this article will be described in the case studies to follow.

In order to provide an overview of possible future directions in biomaterials, it is useful to focus on three time frames[3]:

- The past: removal of tissues
- The present: replacement of tissues
- The future: regeneration of tissues.

Tissues are currently replaced by transplants or implants. Transplants include autografts (as in vertebral fusion), homografts (human organ transplants), and heterografts or xenografts (tissues from other species). Implants are stabilized in the human body by either cement, biological, or bioactive fixation techniques. Transplants have problems such as their availability, the need for immunosuppressant drugs, and possible viral contamination. Today's implants have a variety of shortcomings related to their fixation, and, unlike living tissues, cannot self-repair or adapt to changing physiological conditions. Tissue regeneration has the potential for avoiding these problems associated with transplants and implants through the use of engineered tissues, regenerative bioactive materials, and gene therapy. While the tendency toward regeneration rather than replacement of tissues is clearly the ultimate long-term objective, I do not believe that we have exhausted the incremental improvements possible to improve the processing and properties of our existing tissue-replacement materials, which should not be totally neglected in our pursuit of tissue replacement.

Another issue not typically addressed when considering the performance of biomaterials is the general area of information, which again can be usefully divided into three separate categories:

- information regarding the *in vivo* performance and performance limitations of biomaterials, including areas of current uncertainty and significant disagreement within and among the scientific, engineering, and medical communities;
- increased usage of information-storage and data-processing capabilities in implantable medical devices; and
- the potential utility, if any, of information technology (IT) processes such as data mining to improve the safety and efficacy of biomaterials.

Finally, no assessment of the future of biomaterials would be complete without examining the societal context in which new biomaterials or biomaterials fabrication processes are introduced. In essence this focuses on the kinetics of change as well as the thermodynamics of change, which is largely engineering and biological in origin. The Medical Device Amendments of 1976 require that all new biomaterials used in applications (or existing biomaterials used in new applications) which are life-sustaining or involve significant risks to patients must undergo premarket approval to establish their safety and effectiveness. The basic requirements are that the material be biocompatible within the bodily environment in which it is used and that it perform its intended function safely and effectively in that environment. Clinical trials involving both animals and humans are typically part of the premarket approval process. Biocompatibility testing of a new material is an extensive and expensive procedure which is undertaken only when significant performance increases in biocompatibility and/or functionality are anticipated. The tort liability litigation system also influences innovations in the use of biomaterials in that lawsuits involving not only biomaterial production defects but also materials selection or design defects are still possible even though the material has successfully undergone premarket approval. These regulatory and legal processes are traditionally described as stifling to innovation in biomaterials and medical devices; however, innovations have occurred in response to information concerning device and biomaterial deficiencies which was generated by the regulatory and/or legal processes. A final influence on the continued use or substitution of biomaterials or fabrication processes is marketplace information. Manufacturers' sales representatives are constantly seeking information about deficiencies in their competitors' products and are not reticent about conveying this information to their current and potential customers.

A number of years ago I posed several questions to address the processes of innovation and change in medical technology[4] which I believe are equally applicable to innovation and change in biomaterials:

- When and how does it become prudent to substitute a new, potentially safer and/or more effective biomaterial or biomaterial fabrication process for an older, perhaps less safe one?
- How should physicians and engineers divide their efforts between new device development and surveillance of existing devices, particularly over the long term?
- How should the normal information flow and decision making between physicians and engineers be influenced, if at all, by legal, regulatory, and risk management concerns, particularly in the case of new biomaterials or biomaterial fabrication processes?
- What roles should physicians and engineers play in formulating and communicating biomaterial risk information to patients, particularly risks associated with new biomaterials and biomaterial fabrication processes?

Materials Challenges For The Next Century presents a series of articles speculating on the role of materials in society in the coming century and beyond.

MRS BULLETIN/AUGUST 2000

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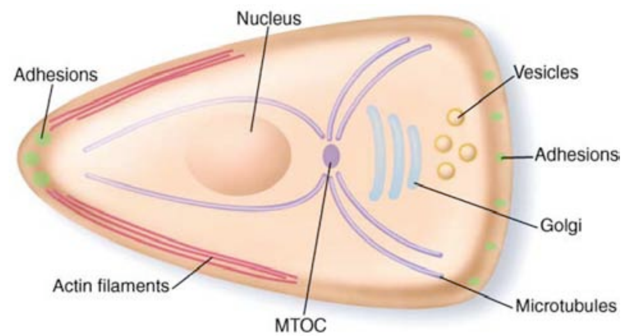
Taken from "A Workshop on New Directions in Mechanics" (2003)

Cell Migration *

A. Cell Polarization

Regulations of Polarity	
Side/Rear	**Front**
PTEN Myosin II	Activated Cdc42/PARs/aPKC PIP_3 Activated integrin MTOC/Golgi Microtubules



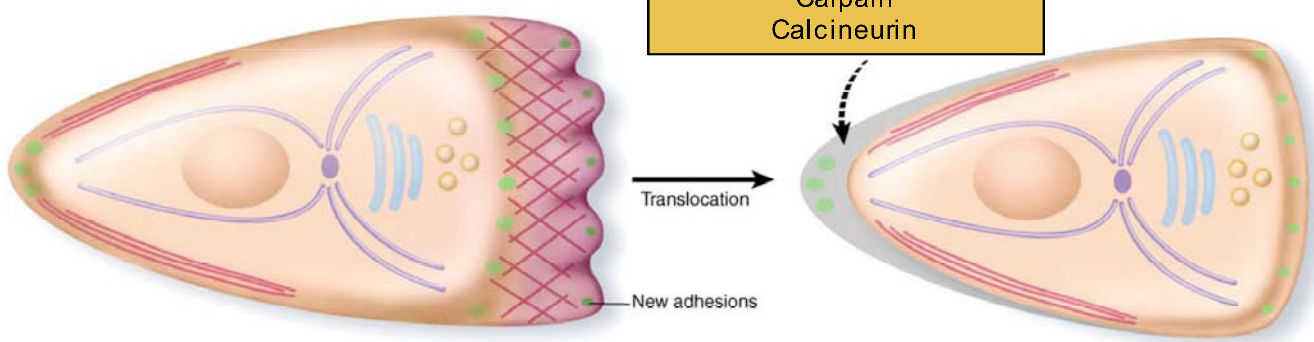
Energy transduction
Signal transduction
Mass transport
Deformation
Adhesion/deadhesion

B. Protrusion and Adhesion Formation

Actin Polarization	
Nucleation	**Polymerization/Organization**
Arp2/3 complex WAVE/WASP Rac/Cdc42	Profilin ENA/VASP ADP/Cofilin Capping proteins Cross linkers

C. Rear Retraction

Rear Retraction
Adhesion Disassembly and Retraction
FAK/Src/ERK Myosin II Microtubules Rho Ca^{2+} Calpain Calcineurin



Tissue Engineering Tools for Mechanical Modulation of Valvular Extracellular Matrix

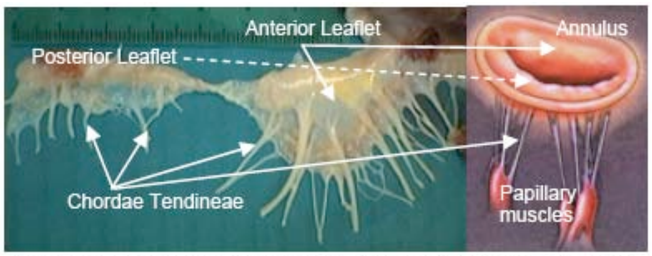


Figure 1: Normal mitral valve (left) cut open to show ventricular aspect and (right) closed position (right figure courtesy of Cochran, Kunzelman).

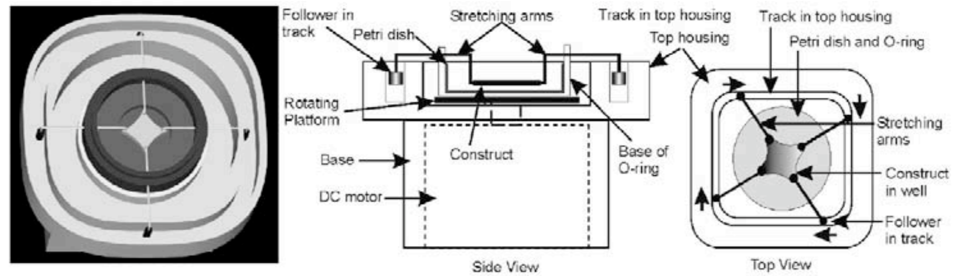


Figure 5: Diagram of the original design of the cyclic biaxial stretching device. Left: Pro-Engineer rendering. Center: side view. Right: top view. Note: the collagen holders and O-ring are not shown in detail, and the glass petri dish cover is not shown.

K. Jane Grande-Allen, Brian D. Lawrence, Vishal Gupta: *Rice University, Department of Bioengineering*

- Mechanical loading can induce remodeling of extracellular matrix components such as proteoglycans (PGs)
- In heart valves, PGs are produced by valvular interstitial cells during tissue development and remodeling
- PGs vary regionally and are altered in diseases such as myxomatous mitral valve degeneration
- To study loading effects on PG production by valvular cells, a bioreactor was designed to apply biaxial cyclic stretch to cells seeded within a collagen gel
- This device is easily sterilized, reusable, compact enough to fit into a lab incubator, and can provide a wide range of biaxial stretch magnitudes and cyclical stretch frequencies
- This device is being used to relate the type of loading experienced by valvular interstitial cells to the production of the PGs that can influence the tissue microstructure and mechanics

Mechanics of Materials Approach to Tooth Design

Dentine-Enamel Junction (DEJ)

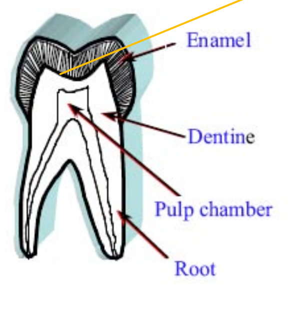


Figure 1. Schematic drawings of tooth

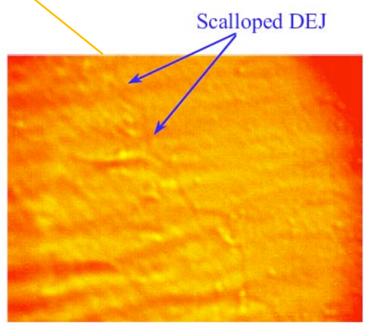


Figure 2. Picture of DEJ with optical Microscopic

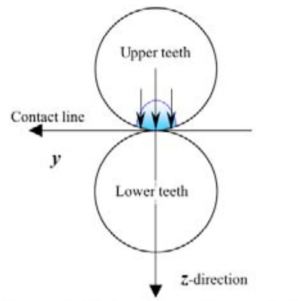


Figure 4. Simple mode of tooth contact

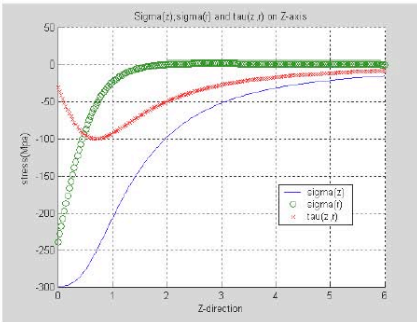


Figure 5. Stress on z-axis

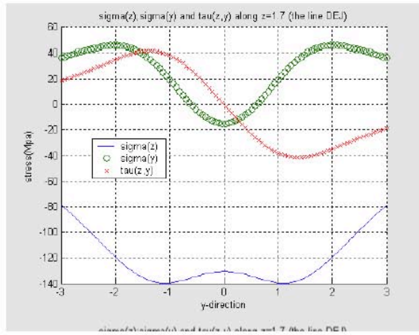


Figure 6. Stress on DEJ line

W. Du and J.D. Wood: *Clemson University*

- Teeth are amazingly complex in the design that have a lot of structural features such as the geometry, the contact surface, the orientation of dentin, the depth of enamel etc.
- All these features are strongly connected with mechanical properties of teeth to reach optimal results
- Fully understanding and analysis of these can aid in further designing restorative materials and composite materials
- The microstructure and macrostructure of tooth and its mechanical behavior under Hertz contact and with crack have been investigated, suggesting it is an optimal composite with high performance

Dynamic Response of the Intact and Prosthetic Intervertebral Disc

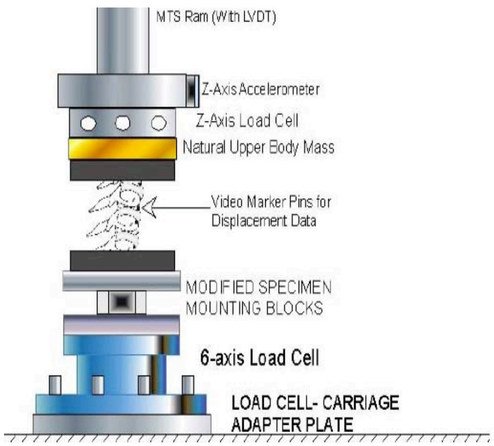


Figure 1. *Dynamic cervical spine testing apparatus. This illustration depicts the specimen in the middle with an inferiorly mounted 6-axis load cell. The MTS ram imparts displacements to the upper body mass fixture superiorly attached to the specimen where by loading the specimen.*

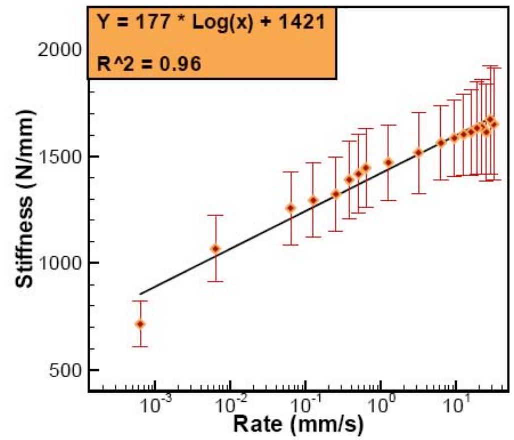


Figure 2. *The stiffness characteristics of the intact intervertebral disc demonstrate clear, significant rate dependence. The most notable changes in stiffness occurred from the quasi-static to the dynamic regime (0.001-mm/sec to 0.1-mm/sec).*

D.J. Nuckley, M.C. Dahland R.P. Ching: *University of Washington*

- Currently, most data on the cervical spine consists of quasi-static mechanical properties in spite of the dynamic nature of spinal loading *in vivo*.
- The dynamic response of the natural intervertebral disc, a prosthetic (replacement) disc, and spinal fusion (the current treatment) have been tested dynamically.
- Specimens were preconditioned, and a displacement controlled (0.25 mm) sinusoidal frequency sweep was imparted on the specimens from 15 Hz to 80 Hz using 2.5 Hz increments.
- Dynamic tests exhibited a logarithmically increasing stiffness with increasing frequency.
- Further, the intact, prosthetic, and fused cases exhibited dynamic stiffness, hysteresis, and damping characteristics which were interdependent.
- This research indicates that understanding the dynamic response of biologic tissues is imperative in the design of replacement materials.

A Novel Dissimilar Material Joint Inspired from Tree Mechanics

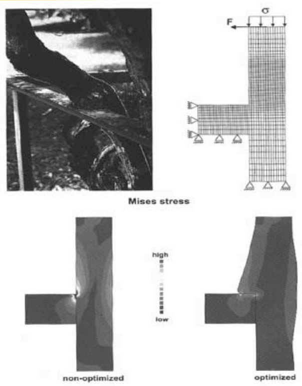


Fig. 2. Finite element stress analysis and corner optimization of a tree-steel railing interface/joint (Mattheck, 1998). The natural convex joint shows no stress concentrations/ singularities.

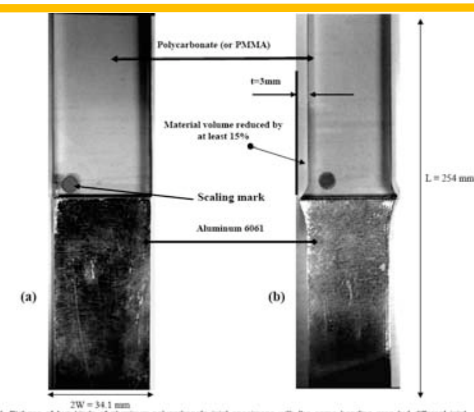
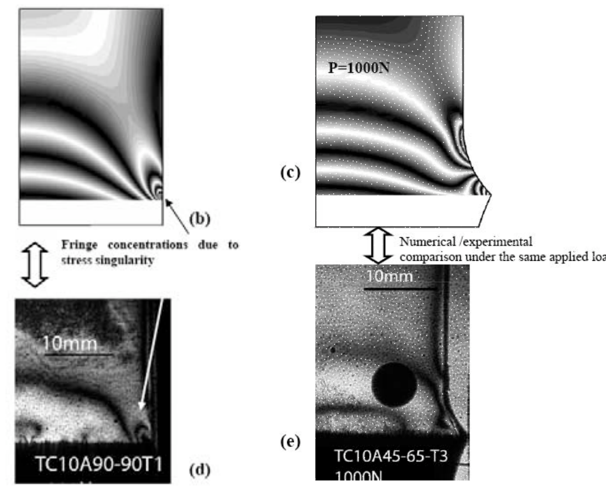


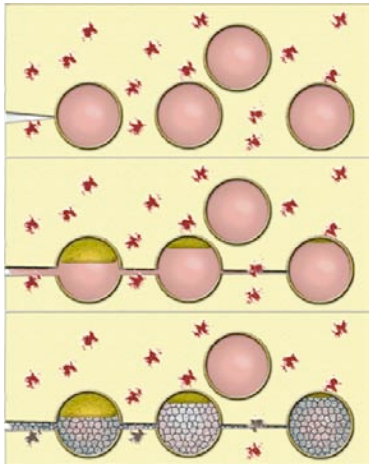
Fig. 4. Pictures of two kinds of aluminum-polycarbonate joint specimens with the same bonding area but different joint angles (a) straight edges (baseline) (b) shaped edges with least stress singularities.



L.R. Xu, S. Sengupta and H. Kuai: *Vanderbilt University*

- An integrated experimental and numerical investigation was conducted for removing the free-edge stress singularities in dissimilar material joints
- A convex interface/joint design, inspired by the shape and mechanics of trees, allows for least stress singularities at bi-material corners for most engineering material combinations
- In-situ photoelasticity experiments on convex polycarbonate-aluminum joints showed that the free-edge stress singularity was successfully removed
- The new design not only improves the static load transfer capacity of dissimilar material joints, but also yields more reasonable interfacial tensile strength evaluation
- For convex polycarbonate-aluminum and PMMA-aluminum joint specimens, the ultimate tensile load increased up to 81% while the total material volume reduced by at least 15% over that of traditional butt-joint specimens with severe free-edge stress singularities

Self-Healing Polymers



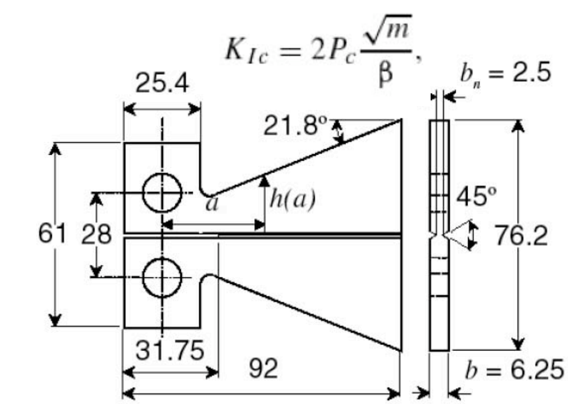


Fig. 3—TDCB geometry (dimensions in mm)

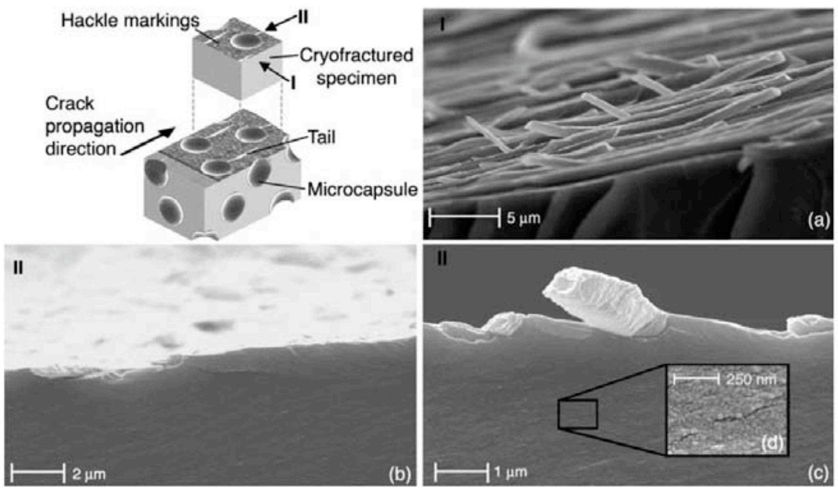


Figure 10 Scanning electron micrographs of cryofractured specimen as viewed from: (a) perpendicular to crack propagation and (b–d) opposite to the direction of crack propagation. Subsurface cracks forming hackle markings are shown in (b) and (c). Microcracks are shown in (d).

White, Brown *et al* Nature (2001)

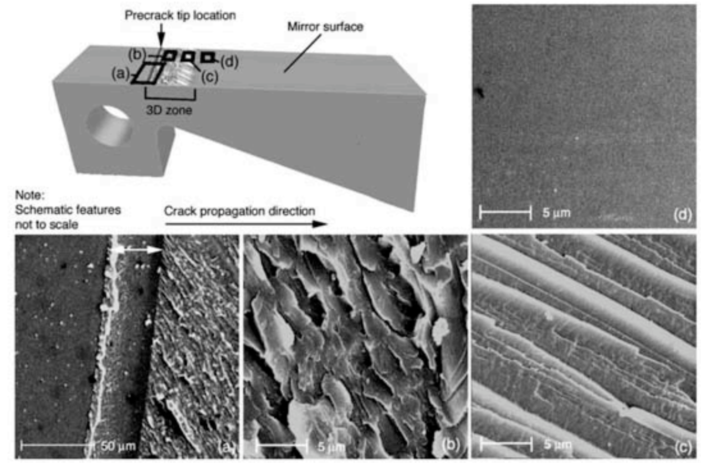


Figure 7 Scanning electron micrographs of fracture plane in neat epoxy: (a) Precrack tip location and 37.5 μm plastic zone denoted by arrow, (b) hackle markings following plastic zone, and (c) transition zone from hackle marking to mirror fracture surface, and (d) Mirror surface of brittle fracture plane extending the length of the specimen. Note: The crack propagation is from left to right in all images.

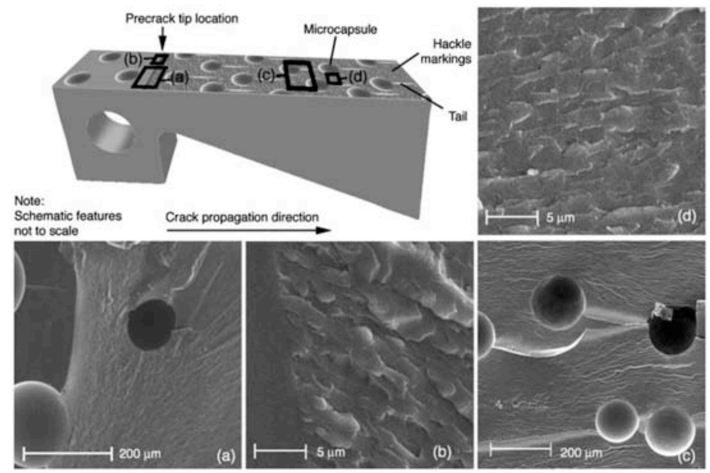
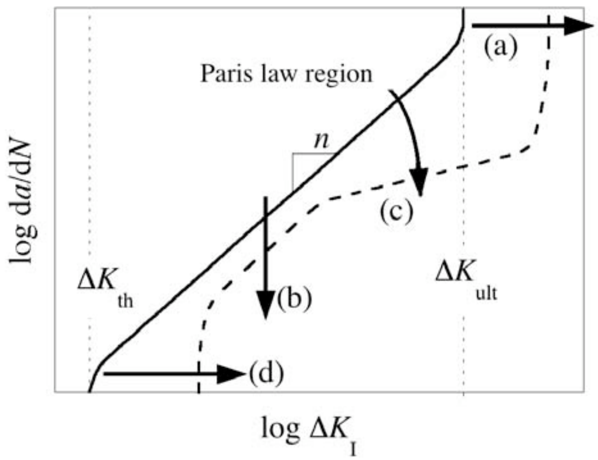
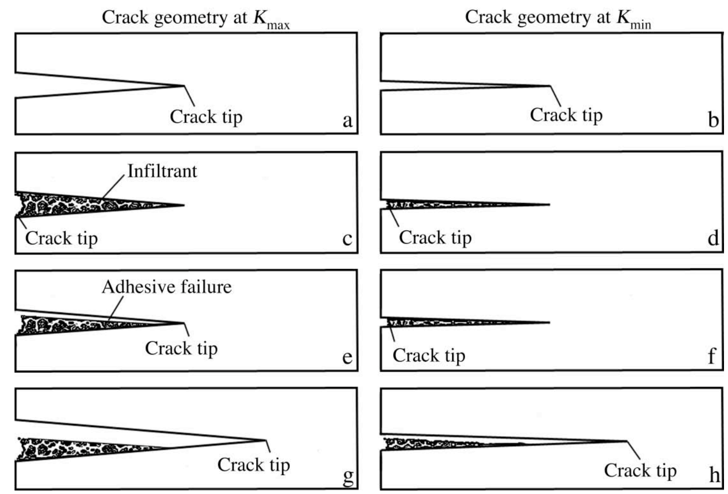


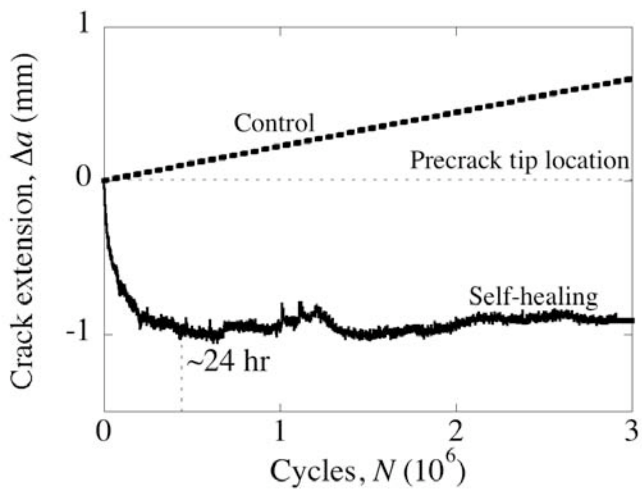
Figure 8 Scanning electron micrographs of fracture plane in epoxy with 11 vol% 180 μm UF microcapsules: (a) precrack tip in the presence of microcapsules lacking a defined plastic zone (b) (c) tails in the wake of microcapsules and (d) hackle marking presence 30 mm from precrack tip. Note: The crack propagation is from left to right in all images.

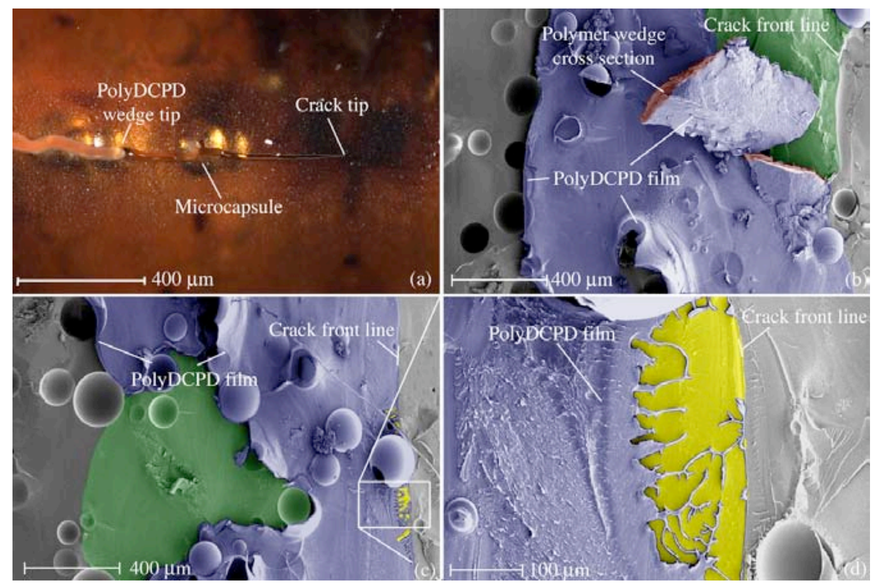
Brown, Sottos, White *Exp. Mech.* (2002)
Brown, White, Sottos, *J. Mater. Sci.* (2004)

Fatigue of a Self-Healing Polymer Composite









Brown, White, Sottos, *In Press.* (2005)

Stochastic and Multiscale Modeling for Superelastic NiTi Device Reliability

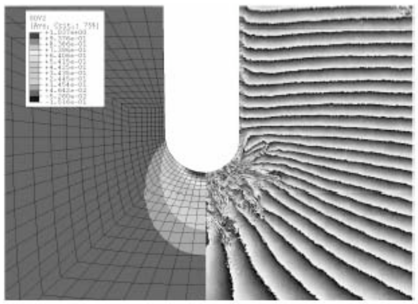


Figure 8. Comparison of martensitic transformation zone from FEA using user defined material subroutine (left) and phase shifted Moiré fringe patterns (right).

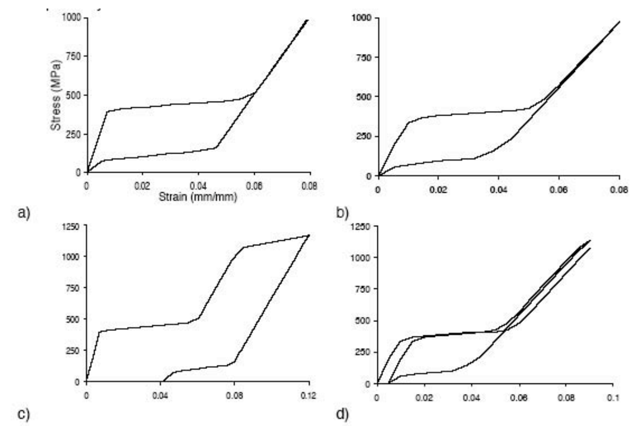


Figure 9 The stress-strain response a) before enhancements, b) including modeling of individual grains, c) accounting for martensite plasticity only, and d) combined effects of individual grains and martensite plasticity.

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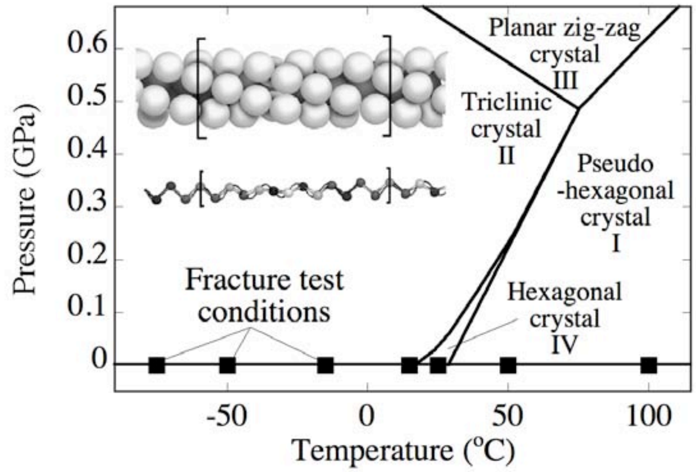
**University of Washington, **ECHOBIO*

- Over the past several years, NiTi alloys in both the shape memory and superelastic form have seen a tremendous increase in applications, which exploit the materials' ability to repeatedly recover inelastic strains up to 8 percent.
- Despite the current understanding of the relationship between the deformation modes and the transformations in NiTi, there is still not e a clear understanding of the fracture processes influencing fatigue limits.
- Research methodology have been developed to accurately obtain calibrated material constitutive relations and characterize the effects of the polycrystalline nature and grain size.
- A combination application of texture mapping, full-field strain measurements using Moire interferometry, and stochastic finite element modeling applied at different length scales have been employed.
- Effects of localized stress raisers such as notches and individual grains have been investigated, and the implications for medical device reliability have been discussed.

PTFE for Bioimplentation: Introduction

- PTFE (CF_2-CF_2) is semi-crystalline, with its linear chains forming complicated phases near room temperature and ambient pressure
- PTFE possesses a combination of desirable chemical and physical properties including:
  - excellent thermal stability
  - chemical resistance
  - dielectric properties
  - extremely low coefficient of friction
- Failure sensitive applications of PTFE include:
  - surgical implants
    - **total hip replacement (THR) (replaced w/ UHDPE)**
    - **pins in joint reconstructions**
    - **ossicular chain reconstructions**
    - **orbital floor reconstructions**
  - aerospace components
  - motor seals
  - barriers for hazardous chemicals



- This study focuses on PTFE 7C:
  - Molding powder (DuPont) is pressed and sintered by Balfor Industries according to the ASTM standard ASTM-D-4894-98a
  - Molding powder has the unique feature of consisting of small (~20 μm) irregularly shaped, fibrous particles
  - Molding powder is ~85% crystalline (by density)
  - Pressed PTFE is ~53% crystalline (by density)

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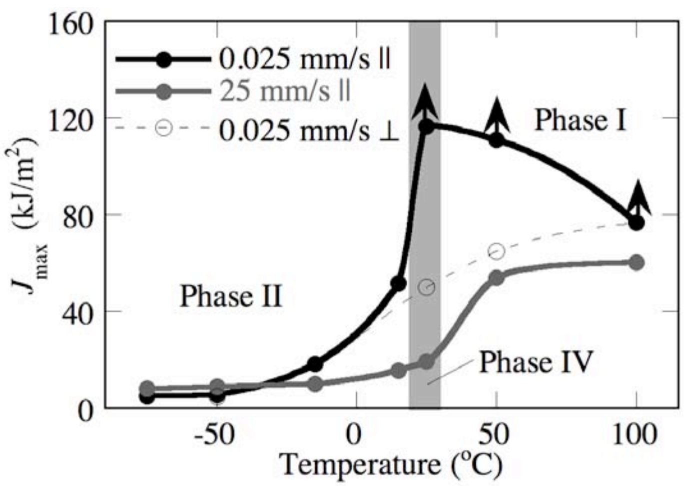
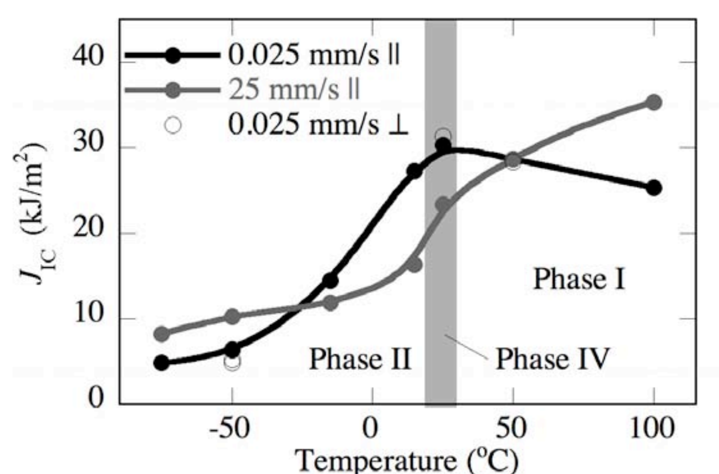
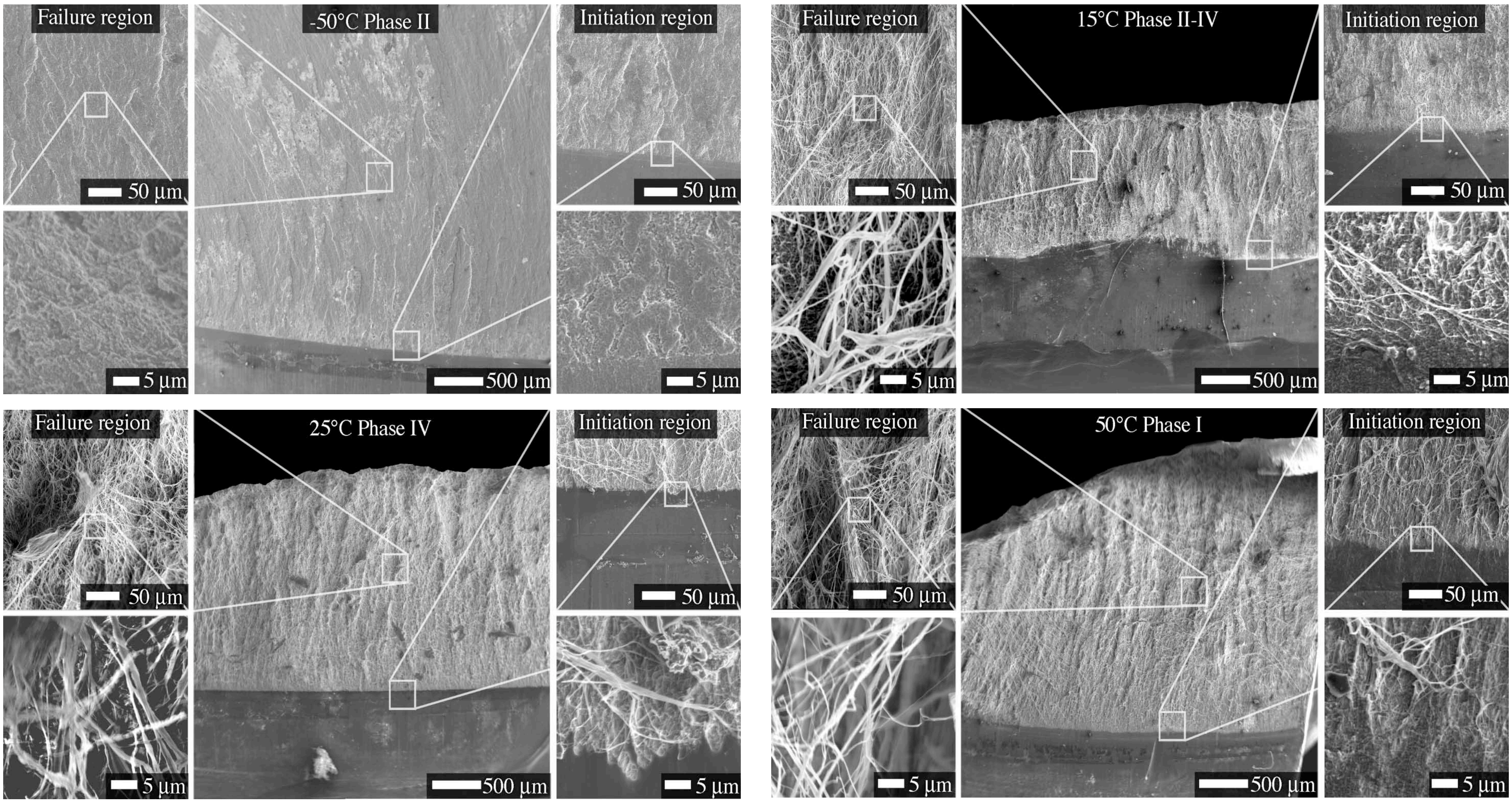
PTFE for Bioimplentation: Dependence of J on Temperature (Phase)

- Both J_{max} and J_{IC} exhibit strong dependence on temperature (phase) and rate
- J_{IC} is nominally dependent on sample orientation
- J_{max} is strongly dependent on sample orientation
- Crack propagation parallel to the pressing direction shows a much larger resistance to Crack propagation orthogonal to the pressing direction





PTFE for Bioimplentation: Fracture Morphology



Closing Remarks

- The biological world has evolved a diverse array of structures and materials that offer unique and desirable properties of significant interest to the engineering world
- By nature of the processes by which plants and animals form their structures, the resulting materials are often composites; as typified by nacre and wood
- Starting as early as the 1980s, researchers sought means to artificially manufacture biological composite materials that could be introduced into living organisms to replace damaged tissues, **this is becoming one of major future areas for mechanics**
- The field of biological materials and systems is extensive, representing an interdisciplinary topic encompassing **mechanics**, materials science, and the breadth of engineering disciplines in conjunction with biology and medicine
- The Biological Materials and Systems TD has a strong base in most of the developing areas of Biological Materials and Systems and bring a strong background of classical mechanics to:
  - Investigation of Organic Materials
  - Implant Materials
  - Inspiration
- **TD meeting at 4pm in the Medford Room**

Abstract

- The biological world has evolved a diverse array of structures and materials that offer unique and desirable properties of significant interest to the engineering world. By nature of the processes by which plants and animals form their structures, the resulting materials are often composites; as typified by nacre and wood. Starting as early as the 1980s, researchers sought means to artificially manufacture biological composite materials, such as bone, that could be introduced into living organisms to replace damaged tissues. Efforts to precisely recreate biological materials lead engineers to view the biological world as a source of inspiration. The Society for Experimental Mechanics formed the Biological Materials and Systems Technical Division to investigate biological and biologically inspired materials and systems, with an emphasis on structure, property, and process relationships. This paper provides a overview of biomimetic composites and the lessons learned by taking inspiration from biology. Recent successful applications of biomimetic composites have included such topics as self-healing polymers, micro air vehicles, and structural design for reduced local stresses.

- LAUR-04-7184

Biomimetic Composites: Inspiration to Application

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ABSTRACT

The biological world has evolved a diverse array of structures and materials that offer unique and desirable properties of significant interest to the engineering world. By nature of the processes by which plants and animals form their structures, the resulting materials are often composites; as typified by wood and nacre. Starting as early as the 1980's, researchers sought means to artificially manufacture biological composite materials, such as bone, that could be introduced into living organisms to replace damaged tissues. Efforts to precisely recreate biological materials lead engineers to view the biological world as a source of inspiration. The Society for Experimental Mechanics formed the Biological Materials and Systems Technical Division to investigate biological and biologically inspired materials and systems, with an emphasis on structure, property, and process relationships. This paper provides an overview of biomimetic composites and the lessons learned by taking inspiration from biology. Recent successful applications of biomimetic composites have included such topics as self-healing polymers, micro air vehicles, and structural design for reduced local stresses.

1. INTRODUCTION

The field of biological materials and systems is extensive, representing an interdisciplinary topic encompassing mechanics, materials science, and the breadth of engineering disciplines in conjunction with biology and medicine. Within the Society for Experimental Mechanics (SEM) this growing field resides in the Biological Materials and Systems Technical Division (TD), started as a series of sessions at the SEM annual meeting in Orlando, 2000. The growth of the field can be seen by its presence in the literature. Searches on "biological materials" and the subset of "biological composites" show 111,822 and 2,553 manuscripts respectively from 2000–2005, comparable to the number of publications on these topics from 1950–1999. More than half-a-dozen journals specific to biological materials have been started in the last decade, with several broader journals—including *Experimental Mechanics*—publishing papers in the field. In December 2002 a special issue of *Experimental Mechanics* was published to focus on Biological and Biologically Inspired Materials [1–7], exemplifying the breadth of research encompassed by the biomaterials field. While the broad interdisciplinary nature [8] of the biomaterials field has generated numerous highly specialized subfields, this paper focuses on three major areas research: organic materials, materials intended for introduction into biological systems, and materials inspired by nature.

2. INVESTIGATION OF ORGANIC MATERIALS

The quality of our natural tissue is often a governing factor in our quality of life. While our health has historically been the focus of the medical profession, characterization and modeling of biological tissue's mechanical constitutive response has proven to yield insight into the correlation of function with the structure of biological materials. Recent investigations with the application of mechanics to specific responses of human tissue for health purposes have ranged from the modeling of aortic valve incompetence brought on by Marfan syndrome [9] to correlation of pelvis fracture load with bone mineral density [10]. Biological tissues are generally composites with structural and compositional variations on length scales from nano- to meso-. Biomaterials commonly exhibit a complicated constitutive response arising from local variations in material composition and intricate hierarchical structures. More general studies have focused on the quasi-linear viscoelastic behavior of the human periodontal ligament [11], the bending response of auricular and costal cartilage, [12] and the anisotropy of cortical bone [13]. Merging of mechanics with anatomy and medicine has been able to generate critical data for understanding the force experienced during automotive accidents [14,15] and sports injuries [16], resulting in safer vehicles and equipment.

The growth processes of organic systems form complex soft and hard tissue composite materials. On the macro scale these materials are complex organic fiber/matrix composites. Soft tissues, such as muscle, are formed from elastin and collagen fibers within a cellular matrix [17]. Collagen is a helical protein formed from inelastic tropocollagen molecules

Proceedings of the 2005 SEM Annual Conference and Exposition on Experimental and Applied Mechanics, Session 10, Paper 3, Paper #253, Portland, OR, June 7-9, 2005.

consisting of glycine, proline, hydroproline and other amino acids. These helices are on the order of 0.3 μm in length and 1.5 nm in diameter with a pitch of 0.27 nm [18]. The tropocollagen molecules are built up in a multi length scale composite from nano-, through micro-, and into meso-scale structure. The molecular helices are aligned form microfibrils, which are subsequently organized in parallel to form 50 nm diameter collagen fibrils. The fibrils then twist together to form collagen strands [19]. Molecular cross-linking at each length scale generates high tensile strength [20]. Elastin is similarly formed to collagen but the amino sequence is primarily glycine, alanine and serine and lacks collagen's repetitive sequencing resulting in elastic fibers [20]. Cancellous bone and cortical bone are the two most important naturally occurring forms of bone. Cancellous bone is a nominally isotropic porous material, while cortical bone is highly anisotropic with reinforcing structures along its loading axis [18]. These hard tissues are formed from collagen fibers, hydroxyapatite (HA), ground substance, and water. Collagen fibers provide the framework and architecture of bone with HA particles between the fibers and matrix of the ground substance (proteins, polysaccharides and mucopolysaccharides). The collagen in bone has a similar microfibril structure as soft tissue with the addition of intre- and intra-fibril HA crystallites (20–40 nm in length by 5 nm thick) oriented along fibril [21,22], with the microfibrils either forming an immature woven or more mature lamellar bone structure [23]. Bone exhibits a wide range of constitutive responses due to the various microstructures of cancellous and cortical bone.

Other complex biological materials such as wood or nacre have similar hierarchical structures. In wood, the cell walls consist of 2.5 nm diameter crystalline cellulose nanofibrils embedded in an amorphous hemicellulose-lignin matrix. The nanofibrils are organized in several layers with helically aligned cellulose around the cell [24]. The helical structure—a function of angle and right handed, left handed, or crossed lamellae structure—varies by species and dictates the constitutive response [25]. At the cellular level wood is built up by tube-shaped cells oriented roughly parallel to the branch axis. Nacre on the other hand is hierarchical structure created by a process of biomineralization [26,27]. The abalone provides an organic material guide for nucleation of calcium carbonate. By controlling the precise crystal polytypes and growth habits the abalone creates a brick-and-mortar architecture with a repeat scale ~250 nm x 10 μm with a strength far exceeding that of inorganic calcium carbonate [28,29]. Unlike classic engineering materials that adopt highly homogeneous structures, or even classic composites that have a defined unit cell, these biocomposites have highly tailored structures to suit the needs of the organism.

3. IMPLANT MATERIALS

Inplant materials, like the organic materials they are designed to replace, frequently exhibit complicated constitutive responses. Since organic tissues perform specific mechanical functions in vivo, it is critical that the replacement biomaterials mimic the native material's constitutive response in order to reestablish mechanical functions. Moreover, whenever an artificial material is implanted into a living organism it will exhibit some reaction with the host tissues. When considering possible implant materials it is important to consider both the possible toxic or other harmful effects of the biomaterial on the host organism and the possible degradation of the implant leading to loss of functionality. The introduction of foreign materials in the form of implants is not new and parallels the evolution medicine. The ancient Romans, Chinese, and Aztecs used gold for rudimentary dental implants, while more recently Europeans and Colonial Americans used wood and ivory. By the mid-nineteenth century surgeons were attempting more invasive repair of the human body employing foreign materials. In 1890, the German surgeon T. Gluck employed ivory for arthroplasty implants [30]. The first metal prostheses were fabricated from Vitallium (a cobalt-chromium molybdenum alloy) in the late 1930's and used until 1960 when harmful corrosive effects where observed [31]. Numerous metals, polymers, and ceramics have been applied to implants to replace damaged or diseased parts of the anatomy, to aid in healing, to improve function of an organ, or to correct deformities [31]. Most biomaterials for implants have undergone long case studies and are regulated by the Food and Drug Administration (FDA) in the United States and ISO 10993 in Europe. As a result there is generally more focus on working with existing materials rather than developing new ones.

Selection of biomaterials for implants requires a balance of mechanical properties, inert response in vivo, and availability. An example of this balance occurred in the choice of polymer socket lining for the total hip replacement (THR). The THR is one of the most mechanically demanding implants, consisting of a polymer lining at the sliding interface between the prosthetic femoral head and socket. Early applications utilized polytetrafluoroethylene (PTFE) [32], commonly known as *Teflon*®, for the lining due to its strength and low sliding resistance. Although PTFE has excellent biocompatibility, it exhibits a low wear behavior and the resulting wear debris irritates the surrounding tissue. As a result THR implants now use ultra-high molecular weight polyethylene (UHMWPE) [33]. However, PTFE continues to be widely used for implants, including ball-and-socket joint reconstructions such as the temporomandibular joint [34–36], ossicular chain reconstructions [37–39], and orbital floor reconstructions [40,41]. Recent work on PTFE by the author has focused on the fracture behavior of PTFE [42] and the effect of crystalline content [43]. Several recent studies have focused on the mechanical behavior of bone cements [44–46] and the nickel-titanium shape memory metal Nitinol (NiTi) [47–49]. Bone cement materials have long been employed for affixing implants and are now considered promising osteoconductive substitutes for bone grafts. These cements are similar to acrylic cements with a range of fillers such as monocalcium phosphate, tricalcium phosphate and calcium carbonate. As an implant material the shape memory function of Nitinol provides the ability to prepare functional implants that are activated at body temperature, while its superelasticity withstand the large deformation required for implants such as stents better than conventional metals.

4. INSPIRATION

Constitutive behavior can also provide insight into the structure and functionality of biological materials. This provides unique insight into the correlation of function with structure that can lead to new advances in the development of engineered materials for nonbiological applications, i.e. bioinspired materials. Inspiration can come in many forms ranging from suggestions for specific microstructures to mimic, such those found in nacre for improved fracture resistance, to philosophies for design. Historically structural design has focused on homogeneous materials that are stiff, so as to deform little under imposed loads, and strong to withstand the high stresses that consequently arise under imposed displacements. Biology on the other hand tends to cultivate structures that posses a combination of strength and stiffness such that select deformation is possible to prevent large loads. Recent efforts have been made to understand the response biological systems to alleviate stress concentrations. This is achieved by both functional gradation of the materials constitutive response [50] and by adopting a geometry that minimizes points of stress singularity [51,52]. The heterogeneity of organic structure also facilitates complex interfaces, which can be used to design structures with directional strength and stiffness or multifunctional structures [53].

In addition to the challenge of recreating the complex configurations of natural structure, attempts to develop synthetic replicas have struggled to capture nature's ability to evolve and heal. With the exception of nerve tissues, all natural tissues are able to remodel due to change in its environment or to regenerate in response to damage. Processes of external intervention have been developed that can provide excellent recovery of structural integrity [54], but by definition they require user input. To counter this, a polymer composite material inspired by biological systems in which damage triggers an autonomic healing response has been developed that can heal itself when cracked [2,55]. The self-healing concept uses an epoxy matrix composite, which incorporates a microencapsulated [56] healing agent that is released upon crack intrusion. Polymerization of the healing agent is triggered by contact with an embedded catalyst. Once healed, the self-healing polymer exhibits the ability to recover as much as 90% of its virgin fracture toughness. Further work on this self-healing polymer has shown that the addition of DCPD-filled urea-formaldehyde (UF) microcapsules yields up to 127% increase in fracture toughness and induces a change in the fracture plane morphology to hackle markings [57]. Moreover, embedding the catalyst in wax microspheres has been demonstrated to provide superior healing efficiency with dramatically reduced catalyst concentrations [58].

5. CONCLUSIONS

The biological world has evolved a diverse array of structures and materials that offer unique and desirable properties of significant interest to the engineering world. The local variations in material composition and the intricate hierarchical structures of organic materials result in complicated constitutive responses. Characterizing and understanding these responses impact the field of medicine and provide inspiration for new materials and new areas of study. The unique requirements associated with implants provide opportunities to develop new materials and structures, and employ existing materials to new problems. By it nature the study of biomaterials requires an interdisciplinary approach encompassing mechanics, materials science, and the breadth of engineering disciplines in conjunction with biology and medicine. The membership of the Society for Experimental Mechanics, through the Biological Materials and Systems Technical Division, has embraced the opportunity to take on a central role in developing this new field as evidenced by the many publications referenced here.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the Los Alamos National Laboratory Director's Funded Postdoctoral Fellowship program for support. Dr. Ken Perry and Prof. Hugh Bruck are thanked for encouraging me to take on the role of TD Chair for the Biological Materials and Systems Technical Division, and many thanks to Prof. Michael Peterson and Prof. K. Jane Grande-Allen who are acknowledged for their support as the vice-chair and secretary. The author also wishes to recognize the session organizers and authors who make the Biological Materials and Systems Technical Division sessions possible.

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