Lallit Anand

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Professor Anand's career-long contributions have helped establish the theoretical and computational foundations for modeling large inelastic deformations across a wide range of engineering materials — metals, polymers, glasses, granular media, and gels — with many of his theories now embedded as standard tools in commercial finite-element software used worldwide.

Lallit Anand's contributions span continuum theories of plasticity, fracture, and coupled multi-physics behavior. His work integrates theory, experiment, and computation, and has influenced both fundamental research and engineering applications, including implementation in widely used finite-element software.

Lallit Anand received his B.Tech. in Mechanical Engineering from the Indian Institute of Technology, Kharagpur in 1970, and earned his PhD degree in 1975 from Brown University. The same year he joined the Mechanical Sciences Division of the Fundamental Research Laboratory of the U.S. Steel Corporation, and served successively as Research Scientist and Senior Research Scientist until 1981. In 1982 he joined the faculty of the Massachusetts Institute of Technology (MIT) as an Assistant Professor, and currently is the Warren and Towneley Rohsenow Professor of Mechanical Engineering. Anand teaches undergraduate and graduate subjects related to solid mechanics at MIT. He was elected to the National Academy of Engineering in 2018.

At MIT he has served as the Head of the Area for Mechanics (2008–2013). During 1994–1999, he served on the Executive Committee of the Applied Mechanics Division of ASME. In addition, during September 1989 through August 1991 he served as Program Director for the Mechanics of Materials Program and the Manufacturing Processes Program in the Engineering Directorate of the National Science Foundation.

He has pursued a broad-ranging research program in mechanics of materials that integrates theory, experiment, and computation to model the large inelastic deformation of a wide variety of engineering materials, including polycrystalline metals, granular materials, amorphous metals, and polymers. Many of his theories have been numerically implemented in finite-element-based computer programs and are widely used for structural and materials-processing design.

His research over the last ten years has focused on:

- Gradient-damage (phase-field) theories for fracture of elastomers, amorphous polymers, quasi-brittle materials, rock-like materials, and steels subject to hydrogen embrittlement.
- Coupled electro-chemo-elasticity theories for ionic polymer–metal composites, polyelectrolyte gels, and hydrogel ionotronics.
- Coupled magneto-viscoelasticity theories for hard- and soft-magnetic elastomeric composites, as well as magneto-elasticity for electrically conducting materials under the eddy-current approximation.

He has published over 125 archival journal papers and advised 28 PhD students at MIT. His publications have been cited over 24,000 times, with an h-index of 74 (Google Scholar). Seventeen of his PhD students hold or have held faculty positions worldwide, while others have pursued careers in national laboratories, industry, and consulting.

He has also published four books:

1. Anand, L., Gurtin, M., Fried, E. (2010). *The Mechanics and Thermodynamics of Continua.* Cambridge University Press.
2. Anand, L., Govindjee, S. (2020). *Continuum Mechanics of Solids.* Oxford University Press.
3. Anand, L., Kamrin, K., Govindjee, S. (2022). *Introduction to Mechanics of Solid Materials.* Oxford University Press.
4. Anand, L., Stewart, E., Chester, S. (2026). *Introduction to Coupled Theories in Solid Mechanics.* Oxford University Press.

Honors

Major honors include:

- Member, National Academy of Engineering, 2018.
- Daniel C. Drucker Medal, ASME, 2014.
- William Prager Medal, Society of Engineering Science, 2018.
- J. P. Den Hartog Distinguished Educator Award, MIT, 2017.

Additional honors include:

- Eric Reissner Medal, 1992.
- Fellow, ASME, 2003.
- Khan International Plasticity Medal, 2007.
- Warren and Towneley Rohsenow Professor, MIT, 2009–.
- Distinguished Alumnus Award, IIT Kharagpur, 2011.
- Brown University Engineering Alumni Medal, 2018.
- Fellow, Society of Engineering Science, 2024.

Leadership and Service

- Program Director, Mechanics of Materials Program and Manufacturing Processes Program, NSF (1989–1991).
- Executive Committee, ASME Applied Mechanics Division (1994–1999), Chair in 1999.
- Graduate Admissions Officer, MIT (1997–2001).
- Graduate Officer, MIT (2005–2008).
- Head, Mechanics Area, MIT (2008–2013).

1 Publication highlights since 2015

1.1 Books

1. Anand, L., Govindjee, S., 2020. **Continuum Mechanics of Solids**. Oxford University Press, Oxford, UK, ISBN 978-0-19-886472-1

   This book on *Continuum Mechanics of Solids* presents a unified treatment of the major concepts in Solid Mechanics for beginning graduate students in the many branches of engineering. The major topics covered in this book include: *Elasticity*, *Viscoelasticity*, *Plasticity*, *Fracture*, *Fatigue*, and *Finite elasticity.* In addition to these standard topics in Solid Mechanics, because of the growing need for engineering students to have a knowledge of the coupled multi-physics response of materials in modern technologies related to the environment and energy, the book also includes chapters on *Thermoelasticity*, *Chemoelasticity*, *Poroelasticity*, and *Piezoelectricity.*

2. Anand, L., Kamrin, K., Govindjee, S., 2022. **Introduction to Mechanics of Solid Materials**. Oxford University Press, Oxford, UK, ISBN: 9780192866080.

   Introduction to Mechanics of Solid Materials offers a unified presentation of the major concepts in Solid Mechanics for junior/senior-level undergraduate students in the many branches of engineering — mechanical, materials, civil, and aeronautical engineering among others.

   The book begins by covering the basics of kinematics and strain, and stress and equilibrium, followed by a coverage of the small deformation theories for different types of material response: (i) Elasticity; (ii) Plasticity and Creep; (iii) Fracture and Fatigue; and (iv) Viscoelasticity. The book has additional chapters covering the important material classes of: (v) Rubber Elasticity, and (vi) Continuous-fiber laminated composites. The text includes numerous examples to aid the student. A substantial volume with example problems is also available on the book's companion website.

3. Anand, L., Stewart, E. M., Chester, S. A., 2026. **Introduction to Coupled Theories in Solid Mechanics**. Oxford University Press, Oxford, UK, ISBN: 9780198986218.

   Introduction to coupled theories in solid mechanics is concerned with the formulation of some coupled theories of solid mechanics which form the basis for a wide range of engineering applications. These theories require a knowledge of the foundational balance laws of mechanics, thermodynamics, and electrodynamics of continua, together with a knowledge of the structure and properties of the materials which are provided by particular constitutive models for the so-called "smart-materials", and the materials used in the many applications that involve thermo-, poro-, electro- and/or magneto-mechanical coupling.

   This book reviews the basic kinematics, balance laws, thermodynamics and constitutive equations for the large deformation theories of elasticity, viscoelasticity, thermoelasticity, poroelasticity, electroelasticity, and magnetoelasticity. The governing partial differential equations are formulated, and suitable boundary conditions are discussed. For specificity, attention is directed towards formulating coupled theories for elastomeric materials.

   The large deformation coupled theories discussed in this book have been numerically implemented in the open-source finite element program FEniCSx, and representative simulations which illustrate key coupled behaviors are presented for each theory. The FEniCSx codes used for these simulations are freely available online on the book's companion website.

1.2 Journal papers

The following groups of papers, published since 2015, represent major thematic contributions spanning: (i) poroelasticity of elastomeric gels, (ii) fracture of elastomers and gels, (iii) mechanics of Li-ion batteries, (iv) gradient-damage theories of fracture, (v) coupled electro-chemo-mechanics, and (vi) coupled electromagneto-mechanics.

1.2.1 Poroelasticity and elastomeric gels

The body of work in the papers listed below establishes a rigorous and unifying framework for the coupled diffusion-deformation behavior of polymeric gels and porous materials, grounded in continuum thermo-mechanics. Beginning with a modern derivation of classical small deformation poroelasticity from chemoelasticity, which replaces the traditional pore-pressure formulation with a chemical-potential-based framework, these works systematically generalize the theory to large deformations and inelastic behavior. The development of finite-deformation poroplasticity for microporous polymers provides one of the first physically-based frameworks for materials in which fluid transport, evolving porosity, and viscoplastic deformation are strongly coupled. Complementing these theoretical advances, the formulation and open dissemination of robust finite element implementations for coupled diffusion–deformation problems in gels has enabled practical simulation capabilities for large-scale boundary value problems. The framework is further extended to capture the nonlinear viscoelastic behavior of polymeric liquids and complex gel architectures, including double-network hydrogels with rate-dependent dissipation and internal damage mechanisms, and to quantitatively reproduce experimentally observed swelling and transport phenomena in double-network hydrogels under varying deformation modes. Collectively, these contributions have significantly advanced the theoretical foundations and computational modeling of soft materials and gels, providing predictive tools that are now widely used in the analysis and design of the diffuso-mechanical response of gels, membranes, biological tissues, and other diffusion-active materials in engineering and biomaterials science.

- Anand, L., 2015. A derivation of the theory of linear poroelasticity from chemoelasticity. ASME Journal of Applied Mechanics 82, 111005.

- Chester, S.A., Di Leo, C.V., Anand, L., 2015. A finite element implementation of a coupled diffusion-deformation theory for elastomeric gels. International Journal of Solids and Structures 52, 1–18.

- Anand, L., 2016. A theory for non-Newtonian viscoelastic polymeric liquids. International Journal of Plasticity 83, 273–301.

- Anand, L., 2017. A large deformation poroplasticity theory for microporous polymeric materials. Journal of the Mechanics and Physics of Solids 98, 126-155.

- Mao, Y., Lin, S., Zhao, X., Anand, L., 2017. Large deformation viscoelastic model for double-network hydrogels. Journal of the Mechanics and Physics of Solids 100, 103–130.

- Stewart, E.M., Narayan, S., Anand, L., 2022. On modeling the infiltration of water in a PEG-DA hydrogel and the resulting swelling under unconstrained and mechanically-constrained conditions. Extreme Mechanics Letters, 101775.

1.2.2 Fracture of elastomers and elastomeric gels

This body of work develops a physically grounded, multiscale framework for fracture in elastomers and polymeric gels by directly linking macroscopic failure to molecular mechanisms of bond rupture. Beginning with a unified single-chain theory that reconciles entropy-dominated elasticity with energy-driven fracture through bond scission, these contributions establish that the internal energy stored in stretched molecular bonds — not configurational entropy — is the fundamental driver of damage and rupture. This insight is systematically elevated to the continuum scale through the development of thermodynamically consistent gradient-damage (phase-field) theories that capture progressive damage, flaw sensitivity, and rupture in elastomers under large deformations. The framework is further extended to account for distinct failure mechanisms, including both chain scission and crosslink failure, leading to new scaling laws for toughness beyond classical Lake–Thomas theory, and to polymeric gels where fracture is strongly coupled with fluid diffusion and swelling. Collectively, these works provide one of the first predictive continuum theories of fracture in soft materials rooted in molecular physics, significantly advancing the understanding and modeling of failure in elastomers, gels, and biological soft materials.

- Mao, Y., Talamini, B., Anand, L., 2017. Rupture of polymers by chain scission. Extreme Mechanics Letters 13, 17–24.
- Talamini, B., Mao, Y., Anand, L., 2018. Progressive damage and rupture in polymers. Journal of the Mechanics and Physics of Solids 111, 434–457.
- Mao, Y., Anand, L., 2018. A theory for fracture of polymeric gels. Journal of the Mechanics and Physics of Solids 115, 30–53.
- Mao, Y., Anand, L., 2018. Fracture of elastomeric materials by crosslink failure. ASME Journal of Applied Mechanics 85, 081008.

1.2.3 Mechanics of Li-ion batteries

The papers listed below address the diffusion–deformation framework for modeling the response of classical lithium-ion batteries, and also the response of more recent all solid-state batteries with lithium anodes and ceramic electrolytes. Beginning with a continuum theory that couples Cahn–Hilliard-type diffusion with large elastic deformations, this work provides a basis for analyzing phase separation and stress evolution in electrode materials. The framework is extended to address key degradation mechanisms, including the growth of solid-electrolyte interphase (SEI) layers and the associated evolution of stresses and interfacial integrity during electrochemical cycling. Complementary constitutive models for the large-deformation elastic–viscoplastic response of lithium enable analysis of lithium metal anodes and their interaction with solid electrolytes, while subsequent developments address the mechanics of inhomogeneous plating and stripping and their role in interfacial damage and short-circuiting. Together, these contributions provide a predictive, computationally implemented framework for analyzing the coupled electro-chemo-mechanical processes in lithium-ion-based batteries, with relevance to the design and reliability of next-generation energy storage systems.

- Di Leo, C.V., Rejovitzky, E., Anand, L., 2015. Diffusion-deformation theory for amorphous silicon anodes: the role of plastic deformation on electrochemical performance. International Journal of Solids and Structures 67-68, 283–296.

- Rejovitzky, E., Di Leo, C.V., Anand, L., 2015. A theory and a simulation capability for the growth of a solid electrolyte interphase layer at an anode particle in a Li-ion battery. Journal of the Mechanics and Physics of Solids 78, 210–230.
- Narayan, S., Anand, L., 2018. A large deformation elastic–viscoplastic model for lithium. Extreme Mechanics Letters 24, 21–29.
- Anand, L., Narayan, S., 2019. An Elastic-Viscoplastic Model for Lithium. Journal of The Electrochemical Society 166, A1092-A1095.
- Narayan, S., Anand, L., 2020. On modeling the detrimental effects of inhomogeneous plating-and-stripping at a lithium-metal/solid-electrolyte interface in a solid-state-battery. Journal of The Electrochemical Society 167, 040525.

1.2.4 Gradient-damage theories of fracture

These works formulate a class of gradient-damage theories for modeling fracture across a wide range of materials, including quasi-brittle solids, polymers, metals, and geomaterials. Using the virtual-power framework, these theories introduce coupled macro- and microforce balances together with thermodynamically consistent constitutive relations that depend on both a damage variable and its gradient, thereby incorporating an intrinsic length scale for regularizing the damage-to-fracture response of the material. The framework is systematically specialized to different material systems, including quasi-brittle materials such as concrete, metals undergoing hydrogen embrittlement through coupled diffusion–deformation–damage processes, and amorphous polymers where competing mechanisms such as crazing and network disentanglement govern brittle and ductile fracture. More recent developments extend the approach to rock-like materials, integrating plasticity and damage to model both tensile cracking and compressive shear banding. Together, these contributions provide a unified continuum framework for damage and fracture that is broadly applicable across material classes, and which enables predictive simulation of crack initiation, propagation, and interaction in complex geometries.

- Narayan, S., Anand, L., 2019. A gradient-damage theory for fracture of quasi-brittle materials. Journal of the Mechanics and Physics of Solids 129, 119–146.
- Anand, L., Mao, Y., Talamini, B., 2019. On modeling fracture of ferritic steels due to hydrogen embrittlement. Journal of the Mechanics and Physics of Solids, 122, 280–314.
- Narayan, S., Anand, L., 2021. Fracture of amorphous polymers: A gradient-damage theory. Journal of the Mechanics and Physics of Solids 146, 104164.
- Anand, L., 2025. Fracture of rock-like materials: a gradient-damage theory, International Journal of Solids and Structures, 194, 113739.

1.2.5 Coupled electro-chemo-mechanics

This body of work develops continuum theories for modeling the coupled electro-chemo-mechanical behavior of ionically active polymers and polyelectrolyte gels. These contributions establish a unified framework in which deformation, ionic transport, and electric fields are treated in a fully coupled manner, based on balance laws for mass, charge, and momentum together with appropriate constitutive relations for the free energy. The framework is applied to ionic polymer–metal composites, where it captures the migration of hydrated ions, the resulting differential swelling, and the associated actuation response, and is subsequently extended to polyelectrolyte gels to model their swelling and deswelling behavior under changes in pH and ionic strength, including transient kinetics and cross-diffusion effects. More recent developments apply these ideas to hydrogel ionotronic devices, where the theory accounts for ion transport, electrostatic interactions, and large deformation to model sensing and actuation mechanisms based on electric double layers. Together, these contributions provide a predictive framework for analyzing coupled electro-chemo-mechanical processes in soft functional materials, with direct relevance to emerging applications in soft robotics, bioelectronics, and responsive material systems.

- Narayan, S., Stewart, E.M., Anand, L., 2021. Coupled electro-chemo-elasticity: Application to modeling the actuation response of ionic polymer-metal composites. Journal of the Mechanics and Physics of Solids 152, 104394.
- Narayan, S., Anand, L., 2022. A coupled electro-chemo-mechanical theory for polyelectrolyte gels with application to modeling their chemical stimuli-driven swelling response. Journal of the Mechanics and Physics of Solids 159, 104734.
- Stewart, E.M., Narayan, S., Anand, L., 2023. An electro-chemo-mechanical theory for hydrogel ionotronics: application to modeling a capacitive strain sensor and a dynamic large strain actuator. Journal of the Mechanics and Physics of Solids, 105196.

1.2.6 Coupled electromagneto-mechanics

The papers listed below formulate and numerically implement continuum theories for magneto- and electromagneto-mechanical coupled response of soft magnetorheological materials and also deformable conductors, with emphasis on large deformations and dynamic effects. These contributions establish continuum frameworks that couple mechanical deformation with magnetic fields, magnetization, and—in the case of conducting solids—induced eddy currents and accompanying Lorentz forces, based on appropriate balance laws and free-energy formulations. The framework is applied to hard- and soft-magnetic elastomeric composites, where it captures magnetically induced deformation, viscoelastic effects, and instabilities such as snap-through and magnetostriction, including geometry-dependent responses arising from demagnetization effects. More recent developments extend the theory to fully coupled dynamic electromagneto-elastic problems, enabling the modeling of actuation, damping, and levitation phenomena in deformable conductors under time-varying electromagnetic fields. Together, these contributions provide a predictive framework for analyzing coupled magneto-mechanical interactions in functional materials, with relevance to soft robotics, adaptive structures, and electromagnetic actuation systems.

- Stewart, E.M., Anand, L., 2023. Magneto-viscoelasticity of hard-magnetic soft-elastomers: application to modeling the dynamic snap-through behavior of a bistable arch. Journal of the Mechanics and Physics of Solids, 105366.
- Eric M. Stewart, Lallit Anand, 2025. Magnetostriction of soft-magnetorheological elastomers, Journal of the Mechanics and Physics of Solids, Volume 194, 105934.
- Stewart, E. M., Anand, L., 2026. Electromagneto-elasticity in the eddy-current approximation and its numerical implementation in FEniCSx. Computational Mechanics, `https://doi.org/10.1007/s00466-026-02791-w`.

2 Publication highlights prior to 2015

The following groups of papers, published prior to 2015, represent major thematic contributions spanning: (i) crystal plasticity, (ii) high-temperature viscoplasticity, (iii) shear-band localization instabilities, (iv) shape-memory metals, (v) plasticity of metallic glass, (vi) strain gradient plasticity, (vii) amorphous polymers, (viii) elastomeric gels, and (ix) phase-field theory for species diffusion coupled with large elastic-plastic deformations.

Polycrystalline plasticity and crystallographic texture evolution

His research highlights are best illustrated by the following two papers with his former students Surya Kalidindi and Curt Bronkhorst on polycrystalline plasticity and crystallographic texture evolution in fcc metals:

- Kalidindi, S.R., Bronkhorst, C.A., Anand, L., 1992. Crystallographic texture evolution in bulk deformation processing of fcc metals. *Journal of the Mechanics and Physics of Solids* 40, 537–569.
- Bronkhorst, C.A., Kalidindi, S.R., Anand, L., 1992. Polycrystalline plasticity and the evolution of crystallographic texture in fcc metals. *Philosophical Transactions of The Royal Society London A* 341, 443–477.

Prior to the publication of these two papers, the topic of constitutive modeling, numerical implementation, and experimental validation of polycrystalline plasticity — based on single crystal deformation — had appeared in various differing, incomplete, and widely-disparate formats in the technical literature. In contrast, Anand and his students provided a comprehensive set of pedigreed experimental stress-strain curves on polycrystalline copper undergoing large deformation in tension, compression, and simple-shear, together with x-ray pole-figure measurements which documented the corresponding evolution of crystallographic texture. They showed that a modern version of a polycrystal theory, first developed by G.I. Taylor, when numerically implemented within a finite element program was able to successfully predict the stress-strain response and the evolution of crystallographic texture. Moreover, using their theory and its numerical implementation they successfully predicted the overall force-displacement curve and the spatially non-homogeneous evolution of crystallographic texture in a plane strain forging experiment. This pair of papers represent a significant milestone in the successful integration of modern continuum mechanics, physical-mechanism-based constitutive modeling, experimentation, and computation.

The crystal plasticity theory and the numerical algorithms developed by Anand and his students have been successfully incorporated into commercial finite element codes and are currently widely-used by researchers across the world.

High-temperature viscoplasticity of metals

An important example of Anand's work in developing modern large-deformation constitutive equations are his papers on high-temperature viscoplasticity of metals:

- Anand, L., 1982. Constitutive equations for the rate-dependent deformation of metals at elevated temperatures. *ASME Journal of Engineering Materials and Technology* 104, 12–17.
- Anand, L., 1985. Constitutive equations for hot-working of metals. *International Journal of Plasticity* 1, 213–231.

- Brown, S.B., Kim, K.H., Anand, L., 1989. An internal variable constitutive model for hot working of metals. *International Journal of Plasticity* 5, 95–130.

These papers, and a companion paper (Weber and Anand, Computer Methods in Applied Mechanics and Engineering 79, 173-202, 1990, see below), form the basis of the finite-element implementation of high-temperature plasticity in the widely-used commercial code ANSYS, where it is called the *Anand Viscoplastic Model.* Anand's viscoplasticity model has also been implemented as a *standard option* in three other widely-used commercial finite element programs ABAQUS, ADINA, and COMSOL. Since Anand's viscoplastic model is a built-in material modeling option in the widely-used finite element programs, it is now routinely used in industry for applications ranging from reliability prediction of solder-joints and thermal design of electronic packaging and surface mount technology, to the computational design of three-dimensional hot-deformation processing operations. Of all of Anand's publications, his papers on high-temperature viscoplasticity of metals have had the most impact in engineering practice.

Computational plasticity

Another example of Anand's work in developing modern constitutive equations and robust numerical time-integration algorithms for large deformation plasticity is the following paper with his student Gustavo Weber:

- Weber, G., Anand, L., 1990. Finite deformation constitutive equations, and a time integration procedure for isotropic, hyperelastic viscoplastic solids. *Computer Methods in Applied Mechanics and Engineering* 79, 173–202.

This computational-mechanics paper — whose focus is large deformation isotropic, hyperelastic-viscoplasticity — has several novel features. Weber and Anand (i) Used the Kroner-Lee $\mathbf{F} = \mathbf{F}^e\mathbf{F}^p$-based decomposition of the deformation gradient $\mathbf{F}$. (ii) Used a strain energy function based on the logarithmic elastic strain as the most appropriate hyperelastic generalization of the infinitesimal isotropic linear elasticity for moderately large elastic deformations (ASME Journal of Applied Mechanics 46, 78-82, 1979). (iii) Resolved the intrinsic indeterminacy of the $\mathbf{F} = \mathbf{F}^e\mathbf{F}^p$-based decomposition, by using rigorous continuum mechanics symmetry arguments to motivate the assumption of $\mathbf{W}^p = \mathbf{0}$ for an isotropic material. (iv) Used a rate-dependent plasticity theory using a single scalar internal hardening variable (ASME Journal of Engineering Materials and Technology 104, 12-17, 1982; International Journal of Plasticity 5, 95-130, 1989). (v) Developed a novel numerical time-integration procedure which is simple and automatically numerically-objective. In contrast to the then widely-used hypoelastic-rate-independent-plasticity framework for large deformation plasticity, the hyperelastic-viscoplastic framework of Anand and Weber is not only thermodynamically consistent and therefore more satisfying on fundamental physical grounds, it is also of increasing current practical importance in accounting for the large elastic volumetric deformation accompanying shock and ballistic applications. The theory and numerical time-integration algorithm presented in this paper have been widely adopted by several researchers, and have also been implemented in several commercial non-linear finite-element programs.

Shear band localization instabilities

An early example of Anand's research contributions is a paper on "shear bands" with a former colleague Bill Spitzig, while both were at US Steel Research in the late 1970s:

- Anand, L., Spitzig, W.A., 1980. Initiation of localized shear bands in plane strain. *Journal of the Mechanics and Physics of Solids* 28, 113–128.

A common observation during large plastic deformations of ductile solids is that a general non-homogeneous but smoothly varying deformation pattern often gives way rather abruptly to a pattern exhibiting a loss of smoothness in the form of jump discontinuities in the displacement gradients across certain curved surfaces, while the displacements themselves remain continuous across these surfaces. Experiments show that these surfaces often bound narrow bands, the deformation within each band being predominantly one of shear parallel to the interface between the band and the adjacent material. When this occurs, the deformation is said to have been localized within "shear bands." If such a jump discontinuity in the displacement gradients across the interface between a band and the adjacent material is formed, and if it persists, then it is usually an important precursor to an occurrence of a jump in the displacements themselves (fracture) across the bounding surfaces of these shear bands. In this paper, Anand and Spitzig studied the initiation of localized shear bands in plane-strain tension and compression. By conducting carefully-crafted experiments on a high-strength maraging steel, they showed that their experiments supported the physical relevance of a theoretical framework by Rudnicki & Rice and Hill & Hutchinson, which viewed the initiation of shear bands as a bifurcation phenomenon from a homogeneous equilibrium field in an elastic-plastic solid. Anand and Spitzig showed that the predictions of the theory were in good qualitative agreement with their experimental observations. This paper has been widely cited in the literature on plastic instabilities and shear band localizations.

Shape-memory metals

Shape-memory alloys, such as Ni-Ti, are widely used as functional/smart materials for a variety of applications, including arterial stents. The individual grains in these polycrystalline materials can abruptly change their lattice structure in the presence of suitable thermo-mechanical loading. This capability of undergoing a solid-solid, diffusionless, displacive phase transformation leads to the technologically important properties of pseudoelasticity and shape-memory. In the publications,

- Thamburaja, P., Anand, L., 2001. Polycrystalline shape-memory materials: effect of crystallographic texture. *Journal of the Mechanics and Physics of Solids* 49, 709–737, and
- Anand, L., Gurtin, M.E., 2003. Thermal effects in the superelasticity of crystalline shape-memory materials. Journal of the Mechanics and Physics of solids 51, 1015–1058.

Anand, with Thamburaja and Gurtin formulated and numerically implemented a crystal-mechanics-based large-deformation constitutive theory for shape-memory materials accounting for thermal effects, and demonstrated that their theory was able to capture the major features of the experimentally-measured effects of crystallographic texture on pseudoelasticity of a polycrystalline Ti-Ni alloy in a variety of proportional and non-proportional loading experiments under both isothermal and thermo-mechanically coupled situations. The structure of the theory has also been found to be of use for modeling the elastic-plastic response of other systems which undergo austenite-martensite phase transformations.

Plasticity of metallic glasses

Over the past forty years, certain amorphous metallic alloys which can be solidified in relatively large section sizes under moderate cooling rates have been developed. Such disordered metals, referred to as bulk metallic glasses, represent a new class of materials which possess impressive mechanical and magnetic properties. These materials hold promise for several potential applications in engineering. The micro-mechanisms of inelastic deformation in bulk metallic glasses are not related to dislocation-based mechanisms that characterize the plastic deformation of crystalline metals. Because of the lack of long-range order in the atomic structure of these materials, the plastic deformation of amorphous metallic glasses is fundamentally different from that in crystalline solids. Computer simulations in the literature show that at a micromechanical level, inelastic deformation in metallic glasses occurs by local shearing of clusters of atoms (≈ 30 to 50 atoms); this shearing is accompanied by inelastic dilatation that produces strain-softening, which then leads to the formation of shear bands. In

- Anand, L., Su, C., 2005. A theory for amorphous viscoplastic materials undergoing finite deformations, with application to metallic glasses. *Journal of the Mechanics and Physics of Solids* 53, 1362–1396,

Anand, with his student Su, developed the first physical-mechanism-based continuum-level finite deformation plasticity theory for metallic glasses. The flow-rule in this theory is a rate-dependent generalization of "double-shearing" flow-rule used in soil mechanics (Anand, L., Gu, C. JMPS 48, 1710–1733, 2000).

A particularly important characteristic of metallic glasses is their intrinsic homogeneity to the nanoscale because of the absence of grain boundaries. Also, since metallic glasses are amorphous materials, they exhibit a glass transition, and at temperatures above this glass transition, they soften dramatically and are therefore amenable to net-shape thermoplastic forming processes. This characteristic, coupled with their unique mechanical properties, makes them ideal materials for fabricating nano and microscale components. This was very nicely demonstrated in two recent papers by Anand and his co-workers (Acta Materialia 56, 3290–3305, 2008; Journal of Micromechanics and Microengineering 19, Article Number: 115030, 2009).

Strain gradient plasticity

A number of experimental results published over the last twenty-five years, concerning the strength of micron-dimensioned metallic components undergoing inhomogeneous plastic flow, show that this strength is inherently size-dependent, with smaller being stronger. Because conventional plasticity theories do not contain intrinsic material length-scales, such theories cannot describe size-dependent phenomena, a drawback that has led to the recent development of theories that attempt to capture such phenomena via dependencies on plastic-strain gradients. Working together with Mort Gurtin of Carnegie Mellon University, Anand has published several theoretical papers on strain gradient plasticity, of which the two major ones are:

- Gurtin, M.E., Anand, L., 2005. A theory of strain-gradient plasticity for isotropic, plastically irrotational materials. Part I: small deformations. *Journal of the Mechanics and Physics of Solids* 53, 1624–1649.

- Gurtin, M.E., Anand, L., Lele, S.P., 2007. A gradient single-crystal plasticity with free energy dependent on dislocation densities. *Journal of the Mechanics and Physics of Solids* 55, 1853–1878.

These papers have been very well received in the literature on size-dependent plasticity.

Amorphous polymers

Amorphous thermoplastic polymers are important engineering materials widely used in a variety of applications. The papers by Anand and his students listed below formulate a thermo-mechanically coupled large-deformation constitutive framework for the elastic–viscoplastic response of amorphous polymers, incorporating strain-rate and temperature effects, as well as internal variables to represent back-stress and chain alignment. The theory is supported by systematic experiments over wide ranges of strain, strain rate, and temperature, and has been implemented in the finite element program Abaqus. Numerical simulations based on this framework reproduce key features of polymer behavior, including yielding, strain softening, strain hardening, and thermo-mechanical coupling. The predictive capability of the theory has been validated through detailed comparisons with experimental results, including stress–strain responses and deformation patterns.

Subsequent work extended the framework to temperatures spanning the glass transition, enabling modeling of polymer processing operations and thermally actuated shape-memory responses.

This body of work has provided a basis for predictive simulation of amorphous polymers in both structural applications and manufacturing processes. By combining constitutive theory, experimental calibration, and numerical implementation, it has been used by other researchers as a reference framework for modeling rate- and temperature-dependent behavior of polymers.

- Anand, L., Ames, N.M., Srivastava, V., Chester, S.A., 2009. A thermo-mechanically coupled theory for large deformations of amorphous polymers. Part I: Formulation. International Journal of Plasticity 25, 1474–1494.

- Ames, N.M., Srivastava, V., Chester, S.A., Anand, L., 2009. A thermo-mechanically coupled theory for large deformations of amorphous polymers. Part II: Applications. International Journal of Plasticity 25, 1495–1539.

- Srivastava, V., Chester, S.A., Ames, N.M., Anand, L., 2010. A thermo-mechanically-coupled large-deformation theory for amorphous polymers in a temperature range which spans their glass transition. International Journal of Plasticity 26, 1138–1182.

- Srivastava, V., Chester, S.A., Anand, L., 2010. Thermally actuated shape-memory polymers: Experiments, theory, and numerical simulations Journal of the Mechanics and Physics of Solids 58, 1100–1124.

Elastomeric gels

There are numerous elastomeric materials which can absorb large quantities of suitable fluids without the essential skeletal network structure of the elastomer being disrupted by the action of the fluid. Such a polymer network, together with the fluid molecules, forms a swollen aggregate called an elastomeric gel. Elastomeric gels are ubiquitous; they are found in foods and medicines, and they find use in several important and diverse applications including valves for microfluidic devices, and tissue engineering. Indeed, many body parts in humans and other animals are gel-like in constitution.

Anand, with his students, has formulated a continuum-mechanical theory to describe the various coupled aspects of fluid permeation, heat transfer, and large deformations (e.g., swelling and squeezing) of thermally-responsive elastomeric gels. They have also numerically implemented their theory, and solved several interesting boundary-value problems of engineering interest.

- Chester, S.A., and Anand, L., 2010. A coupled theory of fluid permeation and large deformations for elastomeric materials. Journal of the Mechanics and Physics of Solids 58, 1879–1906.

- Chester, S.A., and Anand, L., 2011. A thermo-mechanically-coupled theory for fluid permeation in elastomeric materials: application to thermally-responsive gels. Journal of the Mechanics and Physics of Solids 59, 1978–2006.

- Chester, S.A., Di Leo, C.V., Anand, L., 2015. A finite element implementation of a coupled diffusion-deformation theory for elastomeric gels. International Journal of Solids and Structures 52, 1–18.

Phase-field theory for species diffusion coupled with large elastic-plastic deformations

Anand and his students have developed a unified framework of balance laws and thermodynamically consistent constitutive equations which couple Cahn-Hilliard-type species diffusion with large elastic-plastic deformations of a body, and account for the swelling and phase segregation caused by the diffusing species. A technologically important area of application of the theory is in the chemo-mechanical analysis of the evolution of large stresses which develop because of the volume changes associated with the diffusion of lithium ions in the active electrode particles of lithium-ion batteries during charge-discharge cycles.

- Anand, L., 2012. A Cahn-Hilliard-type theory for species diffusion coupled with large elastic-plastic deformations. Journal of the Mechanics and Physics of Solids 60, 1983–2002.
- Di Leo, C.V., Rejovitzky, E., Anand, L., 2014. A Cahn-Hilliard-type phase-field theory for species diffusion coupled with large elastic deformations: application to phase-separating Li-ion electrode materials. Journal of the Mechanics and Physics of Solids 70, 1–29.
- Di Leo, C.V., Rejovitzky, E., Anand, L., 2015. Diffusion-deformation theory for amorphous silicon anodes: the role of plastic deformation on electrochemical performance. International Journal of Solids and Structures 67-68, 283–296.

These are a few highlights of Anand's publications. He has published numerous additional widely cited papers across solid mechanics and materials physics:

- **Granular materials** (JMPS 31, 105–122, 1983; JMPS 48, 1701–1733, 2000; IJP 17, 147–209, 2001).
- **Crystal plasticity with combined slip and twinning in fcc and hcp materials** (JMPS 46, 671–696, 1998; IJP 19, 1843–1864, 2003).
- **Nanocrystalline metals** (JMPS 52, 2587–2616, 2004; Acta Materialia 54, 3177–3190, 2006);
- **Oxidation of metals with application to thermal barrier coatings** (IJP 27, 1409-1431, 2011; Acta Materialia 61, 399–424; Surface and Coatings Technology 222, 68–78, 2013).