

# PARTICLE AND CONTINUUM ASPECTS OF MESOMECHANICS

Mesomechanics 2007

edited by  
**George C. Sih**  
**Moussa Naït-Abdelaziz**  
**Toan Vu-Khanh**

ISTE

First Published in Great Britain and the United States in 2007 by ISTE Ltd

Apart from any fair dealing for the purposes of research or private study, or criticism or review, as permitted under the Copyright, Designs and Patents Act 1988, this publication may only be reproduced, stored or transmitted, in any form or by any means, with the prior permission in writing of the publishers, or in the case of reprographic reproduction in accordance with the terms and licenses issued by the CLA. Enquiries concerning reproduction outside these terms should be sent to the publishers at the undermentioned address:

ISTE Ltd  
6 Fitzroy Square  
London W1T 5DX  
UK

ISTE USA  
4308 Patrice Road  
Newport Beach, CA 92663  
USA

[www.iste.co.uk](http://www.iste.co.uk)

© ISTE Ltd, 2007

The rights of George C. Sih, Moussa Naït-Abdelaziz and Toan Vu-Khanh to be identified as the authors of this work have been asserted by them in accordance with the Copyright, Designs and Patents Act 1988.

---

Library of Congress Cataloging-in-Publication Data

Particle and continuum aspects of mesomechanics/edited by George C. Sih, Moussa Naït-Abdelaziz, Toan Vu-Khanh.

p. cm.

Includes bibliographical references.

ISBN-13: 978-1-84704-025-1

1. Fracture mechanics--Congresses. 2. Continuum mechanics--Congresses.
3. Microstructure--Congresses. 4. Micromechanics--Mathematical models--Congresses.
- I. Sih, G. C. (George C.) II. Naït-Abdelaziz, Moussa. III. Vu-Khanh, Toan.

TA409.P377 2007

620.1'1292--dc22

2007014815

---

British Library Cataloguing-in-Publication Data

A CIP record for this book is available from the British Library

ISBN 13: 978-1-84704-025-1

---

Printed and bound in Great Britain by Antony Rowe Ltd, Chippenham, Wiltshire.

## List of sponsors

---



**Polytech'Lille**  
École d'ingénieurs

LABORATOIRE  
de MECANIQUE  
de LILLE

UMR CNRS 8107



  
**LA VISION**  
WE COUNT ON PHOTONS

---

# Mesoscopic Model for Electroactive Composite Films and Its Applications

D. Roy Mahapatra<sup>a</sup> and R.V.N. Melnik<sup>b</sup>

<sup>a</sup>*Department of Aerospace Engineering,  
Indian Institute of Science, Bangalore 560012  
droymahapatra@aero.iisc.ernet.in*

<sup>b</sup>*Mathematical Modelling and Computational Sciences, Wilfrid Laurier University,  
Waterloo, ON N2L3C5, Canada  
rmelnik@wlu.ca*

---

**ABSTRACT:** A mesoscopic model to analyze various effects of electroactive and flow related properties of piezoelectric copolymer-ceramic composite thin film is reported in this paper. A three-phase composite with piezoelectric particulate phase, electroactive polymer phase and graft polymer-matrix phase is considered. The proposed homogenized constitutive model takes into account the local transport of cations in polymer, electrostriction and anhysteretic polarization. A finite strain description is given, which includes the mesoscopic dispersion of the copolymer chains. Finite element simulation is carried out by considering a P(VDF-TrFE)-PZT-Araldite thin film. Numerical simulations reveal diagonal shear band like patterns with small scale flow-induced regions.

---

**KEY WORDS:** Piezoelectric, polymer, mesoscopic, finite strain, thin film

## 1. Introduction

Polymer semiconductors and their composite variants with significant piezoelectric effect are considered as promising candidates, often as an alternative to the silicon based technology. Piezoelectric copolymer composite films, such as ultra-thin Langmuir-Boldgett films of PVDF and its copolymer with trifluoroethylene (P(VDF-TrFE)) (Palto *et al.*, 1995), ionic polymer (Shahinpoor, 2003) and electrostrictive elastomers (Pelrine *et al.*, 1999) have several potential applications, especially in photonics, bio-medical devices, macromolecular assembly and smart structures. The category of polymer composite we are interested in this paper is the one in which the piezoelectricity, the electrical charge and the polymer dispersion interplay to produce a desired functionality. Detailed discussions on the merits and the demerits of various piezoelectric copolymer composites can be found in the published literature (see Harrison and Ounaies, 2001; Furukawa, 1997; Shahinpoor, 2003). Computational models have been developed in literature for polymer chains in solvent, as they are solidified (Chow, 2000). Substantial efforts have been devoted to the analysis of the equilibrium conformations of the polymer chains and their interactions in a solvent. Pelletier *et al.*, 1997 studied a network of block copolymer and its entanglement and derived a scaling law, which indicates significant viscosity of shear modulus and its fractional power law based dependence on the stretching of the polymer chains. Based on the analysis reported by Pelletier *et al.*, 1997, for a sol-gel processing of electroactive copolymer film, one can approximate the typical size ( $\xi_0$ ) of the unit block of a network entangled between parallel electrodes as in Gennes, 1979.

$$\xi_0 \approx \bar{a} \left( \frac{Dd^2}{N_a \bar{a}^3} \right)^{\frac{\nu}{3\nu-1}}, \quad (1)$$

where  $D$  is the separation between the two parallel electrode surfaces,  $d$  denotes the average distance between the anchor point of two neighboring chains on the electrode surfaces,  $N_a$  is the number of C-C backbone segments in a polymer chain and  $\nu$  is the Flory exponent ( $\approx 3/5$  for a good solvent). Subsequently, the elastic modulus corresponding to the normal stress across the electrode surface can be expressed as

$$E \sim \frac{Dk_b T}{\bar{a}^2 N_a d^2} \left( \frac{Dd^2}{N_a \bar{a}^3} \right)^{\frac{1-\nu+\frac{1}{2}\beta}{3\nu-1}}, \quad (2)$$

where  $k_b$  is the Boltzmann constant and  $T$  is the absolute temperature. The relaxation time ( $\tau_p$ ) for the polymer network is estimated as

$$\tau_p \sim \frac{\eta_s}{k_b T} N_e \xi_0^2 D ,$$

where  $\eta_s$  is the solvent viscosity and  $N_e$  is the average number of concentration blocks in the entanglement. For a harmonic strain with frequency  $\omega$ , a liquid like behaviour is observed in the range  $\tau_p\omega \ll 1$  and a rubber like behaviour is observed in the range  $\tau_p\omega \gg 1$ . The storage part ( $G'$ ) and the loss part ( $G''$ ) of the complex shear modulus is estimated as

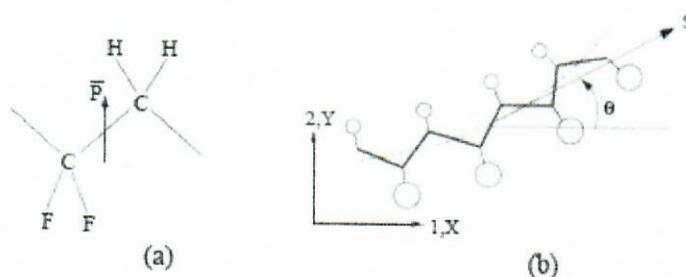
$$\tau_p\omega \ll 1 \quad \begin{cases} G' \sim \frac{\omega^2 \eta_s^2 \bar{a} N_e}{k_b T} D^2 \left( \frac{Dd^2}{N_a \bar{a}^3} \right)^{\frac{\nu}{3\nu-1}} \\ G'' \sim \frac{\omega \eta_s}{\bar{a}} D \left( \frac{Dd^2}{N_a \bar{a}^3} \right)^{\frac{\nu}{1-3\nu}} \end{cases}, \quad (4)$$

$$\tau_p\omega \gg 1 \quad \begin{cases} G' \sim \frac{k_b T}{\bar{a}^3 N_e} \left( \frac{N_a \bar{a}^3}{Dd^2} \right)^{\frac{3\nu}{3\nu-1}} \\ G'' \sim \frac{1}{\bar{a} \eta_s D \omega} \left( \frac{k_b T}{\bar{a}^3 N_e} \right)^2 \left( \frac{N_a \bar{a}^3}{Dd^2} \right)^{\frac{5\nu}{3\nu-1}} \end{cases}. \quad (5)$$

However, it may be noted that the elastic moduli are based on the small strain assumption for the polymer chain and a Newtonian type solvent. Use of large deformation assumptions in obtaining similar scaling law has not been successful till date, and numerical simulation is the most reliable way to predict the flow properties during processing as well as for the properties of the solidified states under dynamic loading. In the solid state, the dynamics of a piezoelectric copolymer film is likely be governed by the deformation of the polymer chains. These polymer chains (conformational structures) also undergo electrical polarization and transport of the electronic charge. Due to this coupled dynamics, the transport of the electronic charge with the dynamical changes in the conduction band of the polymeric network is of importance in photonics related applications. On the other hand, electrostriction induced mechanical motion and high flexibility of the piezoelectric copolymer film is of importance for smart structural applications. Molecular level modeling of the dynamics and related observations have been reported by Carbeck and Rutledge, 1996, and Young *et al.*, 1999. Macroscopic effects of linear piezoelectricity and electrostriction in piezoelectric composite structures have been studied widely. However, in polymer composite, various effects which are important in the small scale applications (e.g., flexible thin film device for sensing of strain or electromagnetic fields) have not been well analyzed in the published literature. Among these effects, the most important are (1) the large stretching of the polymer chains and the resulting macroscopic deformation and (2) contribution of various piezoelectric phases (i.e., piezoelectric nano-particles dispersed within the polymer network) on the large deformation behaviour.

## 2. Constitutive model

Here, we first discuss a general formulation of the piezoelectric polymer-ceramic (piezoelectric nano-particle) composite thin film problem. Electrical excitation to the film is generally given by surface electrodes. From the microscopic point of view, the mechanism of electrical excitation by electrode is not well defined. This is due to the fact that the electrode material remains in a diffused state with the polymeric system and there is a lack of crystalline surfaces. Therefore, at the microscopic scale, the interaction is three-dimensional. On the other hand, for device level analysis and design optimisation, a thin film type geometry requires a reduced dimensional model. By employing a mesoscopic modeling approach, we reduce the problem complexity of a three-dimensional polymeric composite system. In order to derive the dynamics in this mesoscopic modeling approach, we first construct a three-dimensional constitutive model and homogenize corresponding to a quasi-three dimensional situation.



**Figure 1.** (a) A PVDF molecular structure with local polarization vector  $\bar{P}$  and (b) oriented polymer chain

Let us first consider the components of stress ( $\sigma$ ), strain ( $\varepsilon$ ), electric charge displacement ( $D$ ), electric field intensity ( $E$ ), magnetic flux ( $B$ ) and the magnetic field intensity ( $H$ ) in the Cartesian coordinate system ( $x, y, z$ ). Here  $z$  denotes the thickness direction for the film. Our objective is to construct a constitutive model of the form

$$\sigma = c\varepsilon + \tau c'\dot{\varepsilon} - \tau\dot{\sigma} - \sigma(E)_p, \quad D = \epsilon E + P(\varepsilon, E), \quad B = \mu H + \mu_0 M(\varepsilon), \quad (6)$$

where  $c$  is the stiffness,  $c'$  is the flow coefficient,  $\tau \sim \tau_p$  is a strain relaxation time constant,  $\sigma_p$  is the electric polarization induced stress,  $\epsilon$  is the dielectric permittivity,  $P$  is the electrical polarization vector due to transformation and deformation of the macro-molecular structure,  $\mu$  is the magnetic permeability and  $M$  is the magnetic polarization vector due to the molecular spin. There can be several other effects depending on the composition of the piezoelectric polymer (e.g., inclusion of

ferromagnetic particles, index, etc.). However, experimentally measured on the bulk sample is in the thin film limit. Then we then to perform a more detailed nature of the coupling next consider individual model. We split the model into two parts as

where  $\rho_c$  is the true conduction current density,  $\rho_m$  is the molecular current density

and the local continuity condition

The true charge continuity condition

Eq.(ref)(eq;eq)  
chemically active polar groups in the polymer composite (Shahinpoor et al., 2002).

where  $N$  is the Avogadro's number. Further, the migration of ions should then follow the Nernst equation neglecting the piezoelectric thermodynamics, or

and the solvent transport

ferromagnetic particles, inclusions of left-handed material systems with negative index, etc.). However, in this way, an increasing complexity would restrict the use of experimentally measured material constants, since such experiments are performed on the bulk sample without the effects of constraints on the network formation in the thin film limit. The only straightforward but computationally prohibitive method is then to perform a molecular dynamic simulation. With the basic assumptions on the nature of the coupling between the mechanical and the electromagnetic fields, we next consider individual part of the linear and the nonlinear terms in the constitutive model. We split the total charge density  $\rho_{\text{total}}$  and the total conduction current  $J_{\text{total}}$  as

$$\rho_{\text{total}} = \rho_c + \rho_p \quad J_{\text{total}} = J + J_p + J_m , \quad (7)$$

where  $\rho_c$  is the true charge density,  $\rho_p$  is the bound charge density,  $J$  is the true conduction current,  $J_p$  is the conduction current due to bound charge,  $J_m$  is the molecular current density. Then the local conservation law is described by the form

$$\nabla \cdot P = -\rho_p , \quad \nabla \times M = J_m , \quad (8)$$

and the local continuity condition reads

$$\nabla \cdot J_p = -\dot{\rho}_p . \quad (9)$$

The true charge density  $\rho_c$  is related to the conduction current  $J$  by the continuity condition

$$\nabla \cdot J = -\dot{\rho}_c . \quad (10)$$

Eq.(ref{eq: eq7c}) is significant mainly for polymer semiconductor and chemically active polymers. The bound charge density  $\rho_p$  is obtained from the molar concentration ( $c_n$ ) of cations and the molar concentration ( $c_{\text{group}}$ ) of charge groups in the polymer (e.g., the sulfonic or the carboxylic groups in ionic polymer composite (Shahinpoor, 2003}), which can be written as

$$\rho_p = (c_n - c_{\text{group}})Ne , \quad (11)$$

where  $N$  is the Avogadro's number and  $e$  is the elementary charge of an electron. Further, the migration of cations can be important for certain polymers, which should then follow the Onsagar theory or irreversible thermodynamics. By neglecting the piezoelectric coupling in the constitutive model for this local thermodynamics, one can write the ion transport equation as

$$J_p = \sigma_c E - L\nabla p , \quad (12)$$

and the solvent transport equation as

$$Q = L^T E - K\nabla p , \quad (13)$$

where  $p = \frac{1}{3}\text{Tr}(\sigma)$  is the hydrostatic stress,  $Q$  is the solvent flux,  $\sigma_c$  is the electric conductance,  $K$  is the Darcy permeability and  $L$  is a symmetric positive definite coefficient matrix obtained experimentally. By assuming that the solvent flux is negligible for solid-state applications, the local conservation equation due to the migrating charge is expressed as  $eE \approx k_b T \nabla (\ln(c_n))$ . The continuity equation for the migrating charge finally becomes

$$\frac{\partial}{\partial t}(c_n N) e = \frac{\sigma_c}{e} k_b T \nabla^2 [\ln(c_n)] - \frac{1}{3} \nabla \cdot (L \nabla [\text{Tr}(\sigma)]) . \quad (13)$$

Furthermore, for the piezoelectric polymer blends, it is reasonable to adopt an averaging approach to obtain the true charge density and the effective dielectric properties. To this end, for the present study, we also neglect the spin polarized current; that is, we assume  $J_m = 0$ . In the polymer blends, the poling can be done through network of metallic wires embedded in the solidified matrix phase. In such a case, the conduction current induced charge density may show special type of distribution depending on the type of interaction between the piezoelectric particles and the polymer-metal legands.

### 3. Mesoscopic kinematics

Here we first define the displacement field as

$$u = u_{ep} + \frac{1}{m} \sum_{i=1}^m v_i , \quad (14)$$

where  $u_{ep} = \{u_x \ u_y \ u_z\}^T$  denotes the displacement vector due elastic deformation of the predominantly piezoelectric particulate-matrix phase,  $m$  is the number of copolymer chains present in the volume element,  $v_i$  denotes displacement due to the kinematics of the segment of the chain with length  $m' a_0$  centered at a material point  $i$  with coordinate  $(x_i, y_i)$ , where  $m'$  is the number of blocks in the segment of the chain and  $a_0$  is the C-C bond length in the backbone. The  $i$ th segment of the chain is assumed to be oriented at an angle  $\theta_i = \theta$  as shown in Fig. 1(b). We describe the kinematics in the following form:

$$v_i = m' a_0 [1 - \cos(\theta(x_i, y_i)_i - \theta(x_i, y_i)_i^0)] \begin{Bmatrix} \cos \theta(x_i, y_i)_i^0 \\ \sin \theta(x_i, y_i)_i^0 \\ 0 \end{Bmatrix} , \quad (15)$$

where  $\theta(x_i, y_i)_i^0$  denotes the saturation conformation under the applied mechanical and electrical loading. In general, the flow in the copolymer phase in terms of its distribution  $\bar{v}_i$  should follow a kinetic law (e.g., the Smoluchowski equation of dispersed colloidal system (Chow, 2000)). However, solving the mesoscopic dynamics including this dispersion effect is not an easy task. Instead, in the present

model, we p  
then we solv

### 4. Numerical

COMSO  
used for fi  
governing p  
TrFE) cou  
numerical si  
square film  
discretized i  
stepping sc  
Material pr  
Harrison an  
on the def  
sinusoidal d  
edges  $x =$   
piezoelectri

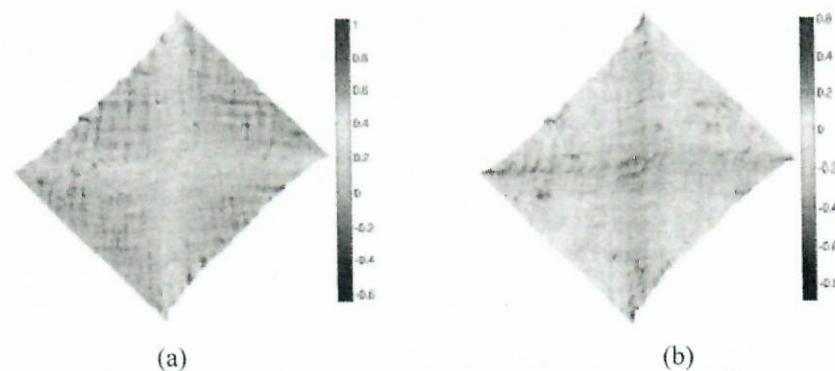
### 5. Conclusi

A meso  
properties i  
paper. The  
cations for  
simple com

model, we prescribe a distribution of the saturation conformation in terms of  $\theta_i^0$  and then we solve the equations of motion by using finite element method.

#### 4. Numerical Simulation

COMSOL multiphysics modelling software package~\cite{bib:comsol} has been used for finite element simulation with right-hand side coupling terms in the governing partial differential differential equations. Material properties of P(VDF-TrFE) copolymer blend with araldite as the matrix phase are considered for numerical simulations. PZT is considered as the piezoelectric particulate phase. A square film geometry of size  $L_x = L_y = 0.005\text{m}$  and thickness  $h = 2\text{mm}$  is discretized by tetrahedral Lagrangian finite element with second order accurate time stepping scheme. A deterministic distribution of chain angles  $\theta$  has been used. Material properties are used from the published literature (Gomez *et al.*, 1998; Harrison and Ounaies, 2001). Effects of the increase in copolymer volume fraction on the deformation under mechanical loading are shown below for applied sinusoidal displacement of amplitude 2.5mm uniformly and normal to the parallel edges  $x = 0, L_x$ . The figures reveal the flow pattern with shear bands for the piezoelectric composite film at the mesoscopic and macroscopic scales.



**Figure 2.** (a) Longitudinal strain  $\varepsilon_{xx}$  and (b) lateral strain  $\varepsilon_{yy}$  distribution at the onset of the tensile half cycle of loading

#### 5. Conclusions

A mesoscopic model to analyze various effects of electroactive and flow related properties in piezoelectric copolymer composite thin film has been developed in this paper. The three-phase constitutive model takes into account the local transport of cations for ionic polymer, electrostriction and anhysteretic polarization within a simple constitutive averaging scheme. A finite strain formulation is carried out

while modelling the kinematics of the copolymer chains. This is a new approach to deal with the polymer network. Finite element simulation is carried out by considering a P(VDF-TrFE)-PZT-Araldite thin film. Numerical simulations indicate that an increasing copolymer content substantially changes the deformation behaviour of the film, along with the flow-induced diagonal shear band like patterns.

## 6. References

- Banno, H. and Saito, S., "Piezoelectric and dielectric properties of composites of synthetic rubber and PbTiO<sub>3</sub> or PZT", *J. Appl. Phys.*, 22(2), 67, 1983.
- Carbeck, J.D. and Rutledge, G.C., "Temperature dependent elastic, piezoelectric and pyroelectric properties of  $\beta$ -poly(vinylidene fluoride) from molecular simulation", *Polymer*, 37(22), 5089-5097, 1996.
- Chow, T.S., "Mesoscopic Physics of Complex Materials", Springer-Verlag, NY, 2000.
- COMSOL, "Multiphysics User's Guide", COMSOL AB, Burlington, MA, 2005.
- de Gennes, P.D. Scaling concepts in polymer physics, Cornell University Press, Ithaca, 1979.
- Furukawa, T., "Structure and functional properties of ferroelectric polymer", *Advanc. Colloid and Interface Sci.*, 1997, 183-308, 1997.
- Gomez T.E. and Espinosa, F.M. and Levassort, F. and Lethiecq, M. and James A. And Ringgard E., and Millar, C.E. and Hawkins, P., "Ceramic powder-polymer piezocomposites for electroacoustic transduction: modeling and design", *Ultrasonics*, 36, 907-923, 1998.
- Harrison, J.S. and Ounaies, Z. "Piezoelectric Polymers", ICASE Report No. 2001-43, NASA/CR-2001-211422, 1-26, 2001.
- Palto, S., Blinov, L., Bune, A., Dubovik, E., Fridkin, V., Petukhova, N., Verkhovskaya, K., Yudin, S., "Ferroelectric Langmuir-Blodgett films", *Ferroelectric Lett.*, 19, 65, 1995.
- Pelletier, E., Belder, G.F., Hadzioannou, G. and Subbotin, A., "Nanorheology of Adsorbed Diblock Copolymer Layers", *J. Phys. II France*, 7, 271-283, 1997.
- Pelrine, R., Kornbluh, R. and Joseph, J., "Electrostriction of polymer dielectrics with compliant electrodes as a means of actuation", *Sensors and Actuators A: Phys.*, 64, 77-85, 1999.
- Shahinpoor, M., "Ionic polymer-conductor composite as biomimetic sensors, robotic actuators and artificial muscles - a review", *Electrochimica Acta*, 48, 2343-2353, 2003.
- Smith, R.C. and Hom, C.L. "A domain wall theory of ferroelectric hysteresis", *J. Intelligent Mater. Sys. Struct.*, 10(3), 195-213, 1999.
- Young, J.A., Farmer, B.A. and Hinkley, J.A., "Molecular modeling of the poling of piezoelectric polyamides", *Polymer*, 40, 2787-2795, 1999.

## TABLE OF CONTENTS

<b>Section I: Physical Mechanisms of Multiple Damage . . . . .</b>	1
Multiple hierarchical scale-dependency on physical mechanisms of material damage: macromechanical, microstructural and nanochemical – G.C. Sih . . . . .	3
Surface layers and inner interfaces as functional subsystems of solid – V.E. Panin, V.V. Panin and A.V. Panin . . . . .	37
Microstructural evolution in dual-phase steels at high strain-rates – V. Besson and A.G. Odeshi . . . . .	45
Plastic deformation in single crystal Ni <sub>3</sub> Fe (thin and thick plates) – V.A. Starenchenko, V.A. Starenchenko and I.P. Radchenko . . . . .	55
Observations of physical aging in polypropylene – G. Guero and T. Vu-Khan. .	63
<b>Section II: Physical, Mesoscopical and Multiscale Models . . . . .</b>	73
Finite element homogenization for the determination of the RVE size for viscoelastic Polycrystalline Materials – H. Haddadi and A. Salahouelhadj .	75
An incremental energy based fatigue life calculations method for metallic structures under multiaxial amplitude loadings – J. Benabes, N. Saintier, C. Pâle-Luc and F. Cocheteux . . . . .	83
Microscopic fatigue crack growth involving crystal structure and crack geometry – G. Tsakalopoulos and G. Chliveros . . . . .	91

Development of a nonlinear homogenization method: evaluation and application to a rubber-reinforced material – V. Bouchart, M. Brieu, D. Kondo and M. Naït-Abdelaziz . . . . .	105
Cavitation of rubber toughened polymer: numerical and experimental investigation N. Belayachi, N. Benseddiq and M. Naït-Abdelaziz . . . . .	113
Ductile damage by interface decohesion – N. Bonfoh, S. Tiem and P. Lipinski . . . . .	123
A multiscale discussion of fatigue and shakedown for notched structures G. Bertolino, A. Constantinescu, M. Ferjani and P. Treiber . . . . .	131
Two scale approach for the defect tolerance fatigue design of automotive components – H. Gadouini and Y. Nadot . . . . .	145
<b>Section III: Film, Layer and Interface . . . . .</b>	153
Plastic deformation and fracture of thin metallic films on annealing in terms of the multilevel model of a deformed solid – A.V. Panin and A.R. Shugurov . . . . .	155
Mesoscopic model for electroactive Composite Films and its applications D. Roy Mahapatra and R.V.N. Melnik . . . . .	163
Interfaces of one-way glass/epoxy composite in inflexion – A. Djebbar and L. Vincent . . . . .	171
Point defects of the elastic properties of layered structured nano-materials T.E. Karakasidis, C.A. Charitidis and D. Skarakis . . . . .	183
DFT study of interactions of water on Kaolinite and Goethite surfaces D. Tunega . . . . .	191
Nanolayered MAX phases from <i>ab initio</i> calculations – R. Ahuja. . . . .	199
<b>Section IV: Crack Models and Solutions . . . . .</b>	205
Fracture initiation at re-entrant corners: experiments and finite fracture mechanics predictions – A. Carpinteri, P. Cornetti, N. Pugno, A. Sapora and D. Taylor . . . . .	207
Buckling analysis of cracked columns subjected to lateral loads – L. Nobile . . . . .	217

Micro-cavity et plasticity – M. I. M. Naït-Abdelaziz

Effect of microplasticity – B. E. B. Serier and M.

Stress intensity Y. Bao, G. Chu

T-stress by stress and Z. Azari . . . . .

Elasto-inelastic M. Radi and A.

Crack propagation and M.A. Khalek . . . . .

Elastoplastic so forces – X. Zhao . . . . .

J-integral and G

Oscillating crack . . . . .

**Section V: Nanomaterials**

Mechanical properties of amorphous carbon F. Chouliaras, C.

Extension of the indentation test K. Matsuda . . . . .

Multi-scale modeling of composites – K.

Mechanical, thermal and K. Matsuda-Jindal . . . . .

SWNT reinforced U. Shim, S. Oh . . . . .

This title brings together a variety of papers presented at Meso 2007, a conference focussing on mesomechanics and threshold phenomena of organic and inorganic substances. Topics covered include the following:

- Flow through capillary tubes in contrast to pipes
- Laminar and turbulent flow transition
- Heat convection of thin wires in contrast to cylinders
- Electrical conductance of macro- and nano-circuits
- Rubber and glass polymers
- Single and poly-crystal behavior
- Strength of wires and round cylindrical bars
- Uni-axial and multi-axial material: linear and non-linear response
- Thin and thick plate behavior
- Brittle and ductile fracture
- Small and large crack growth behavior
- Low and high temperature effects
- Local and global material property characteristics
- Small and large bodies: size and time effects
- Specimen and structure
- Nanomaterials



[www.iste.co.uk](http://www.iste.co.uk)

A standard one-dimensional barcode is located in the top left corner of the white rectangular area. To its right, the ISBN number is printed vertically.

9 781847 040251