

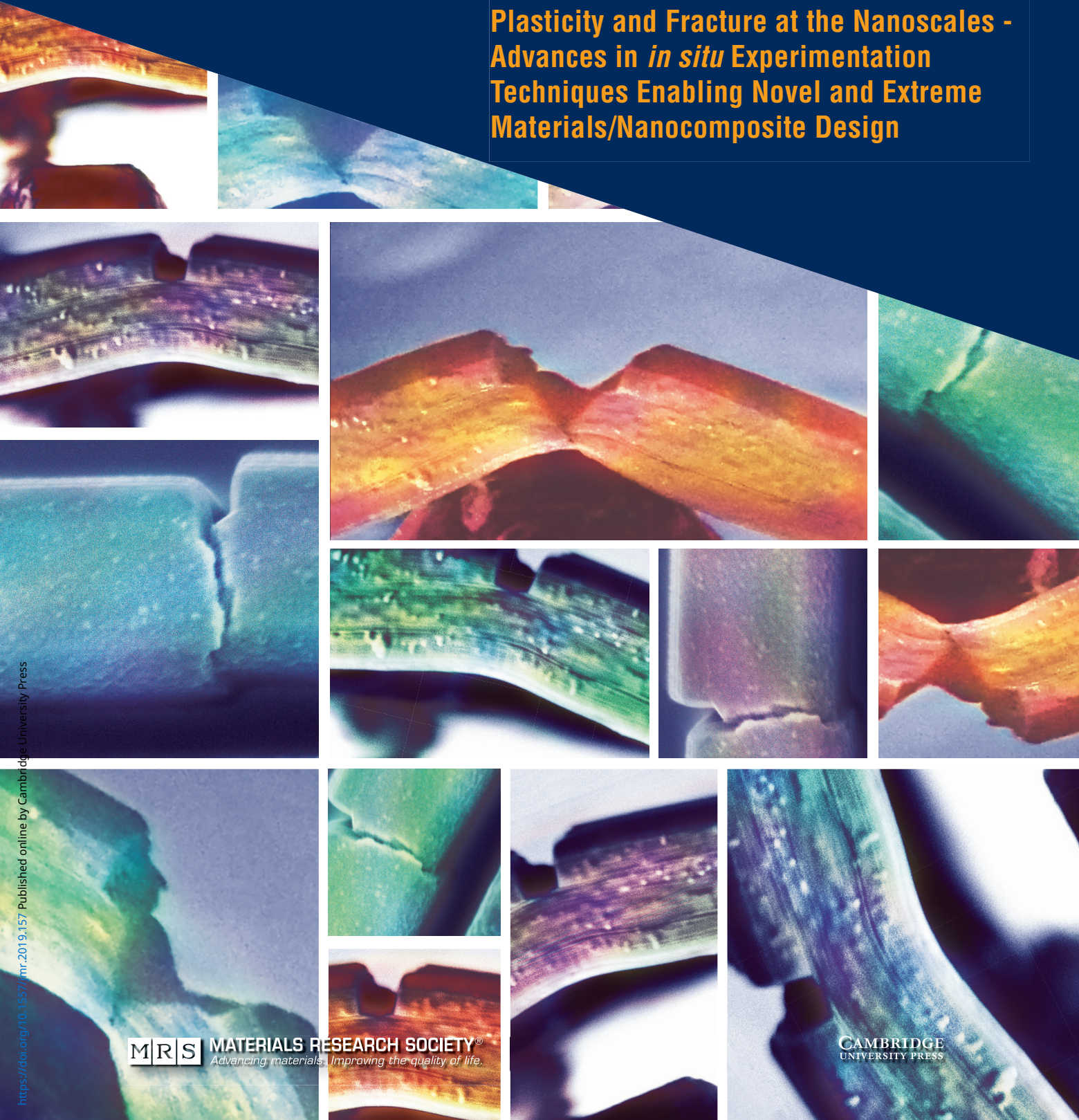


Journal of  
MATERIALS RESEARCH

VOLUME 34 • NO 9  
MAY 14, 2019

## FOCUS ISSUE

Plasticity and Fracture at the Nanoscales -  
Advances in *in situ* Experimentation  
Techniques Enabling Novel and Extreme  
Materials/Nanocomposite Design



**MRS** MATERIALS RESEARCH SOCIETY®  
Advancing materials. Improving the quality of life.

CAMBRIDGE  
UNIVERSITY PRESS

<https://doi.org/10.1557/jmr.2019.157> Published online by Cambridge University Press



# Journal of MATERIALS RESEARCH

**JOURNAL OF MATERIALS RESEARCH (JMR)** is an interdisciplinary journal serving the materials research community through publication of original research articles and invited reviews encompassing the synthesis, processing, characterization, properties, and theoretical description of materials.

**JMR** publishes new research that demonstrates a significant impact or advance of scientific understanding of interest to the materials research community. Engineering studies and applications to commercial products are beyond the scope of *JMR* and should be submitted elsewhere. Manuscripts that report data without giving an analysis, interpretation, or discussion are only acceptable if the data are sufficiently important that publication is expected to lead to significant new studies or advancements in science or technology.

**Manuscripts** must be submitted to the *Journal of Materials Research* electronically via ScholarOne manuscripts, at the following website address: <http://mc.manuscriptcentral.com/jmr>. Electronic submission expedites the review process and also allows authors to track the status of their manuscripts at any time. Complete instructions are available on the ScholarOne site and authors will be prompted to provide all necessary information.

Manuscripts must be prepared in English, using a word processing program, formatted to fit 8½ x11 in. paper, and saved as .doc or .pdf files. Separate graphics files (.eps and .tif) must be uploaded for each figure. Authors may also upload .xls or .ppt supplemental files as part of the manuscript submission process. All of these files will be converted to .pdf format. Detailed instructions are available on the submission web site. During submission, authors must enter all coauthor names and e-mail addresses. Manuscripts will not be considered for peer review until this information is provided. Authors must also enter manuscript keywords using the *JMR* keyword list (located on the submission web site). Authors who are not fluent in English must have their manuscript edited for correct English grammar and sentence structure before submission.

Authors are expected to follow the conventional writing, notation, and illustration style prescribed in *Scientific Style and Format: the CSE Manual for Authors, Editors and Publishers, 7th edition, 2006*. Authors should also study the form and style of printed material in this journal. SI units should be used. Authors should use an identical format for their names in all publications to facilitate use of citations and author indexes.

Manuscripts are accepted with the understanding that they represent original research, except for review articles, and that they have not been copyrighted, published, or submitted for publication elsewhere. Authors submitting manuscripts to *JMR* who have related material under consideration or in press elsewhere should send a copy of the related material to *JMR* at the time of submission. While their manuscripts are under consideration at *JMR*, authors must disclose any such related material. To expedite the review process, authors may provide names and contact information for up to four possible reviewers.

**Articles** are original research reports that include complete, detailed, self-contained descriptions of research efforts. All articles must contain an abstract and section headings.

**Commentaries and Reviews:** *Journal of Materials Research* occasionally publishes commentaries on topics of current interest or reviews of the literature in a given area. If an author proposes a review, the title, abstract, and a brief outline should be submitted to the Editorial Office via e-mail for prior consultation on the appropriateness of the topic.

**Color policy:** It is not necessary for authors to indicate that a figure should be displayed in color online. *JMR* will assume that any author who submits figures in color wants and agrees to their being produced in color online. Figures may be printed in color at the author's request for an additional charge. Color figures must be submitted before the paper is accepted for publication, and cannot be received later in the process. Authors cannot submit two versions of the same figure, one for color and one for black and white; only one version can be submitted. Authors need to carefully consider the following when submitting figures in color that will

be published in color online only: 1) The colors chosen must reproduce effectively and the colors should be distinguishable when printed in black and white; 2) The descriptions of figures in text and captions must be sufficiently clear for both online and print copy. When submitting figures to be in color online only, authors should include the phrase <<color online>> in the figure captions. This is the author's responsibility. Authors will see these color figures when viewing their author page proofs on screen. Authors should always print their page proofs in black and white to see how they will appear in print. Authors will NOT be allowed to submit color figures to replace black and white figures in the page proof stage. To maximize the probability that figures will be published in color online and also print as good quality black and white or grayscale graphics, authors are encouraged to follow these figure submission guidelines: 1) Submit a color graphic in Tagged Image File Format (.tif); 2) Submit color graphics with a resolution of at least 300 dpi (600 dpi if there is text or line art in the figure); 3) Submit color graphics in CMYK format; 4) Submit figures sized to fit the actual column or page width of the journal so that reduction or enlargement is not necessary; 5) Submit multipart figures in one single electronic file.

**Copyright © 2019**, Materials Research Society. All rights reserved. No part of this publication may be reproduced, in any form or by any means, electronic, photocopying, or otherwise, without permission in writing from Cambridge University Press. Policies, request forms and contacts are available at: <http://www.cambridge.org/rights/permissions/permission.htm>. Permission to copy (for users in the USA) is available from Copyright Clearance Center at: <http://www.copyright.com>, email: [info@copyright.com](mailto:info@copyright.com).

---

## **Journal of Materials Research Subscription Prices (2019)**

[includes on-line web access]

	USA and Poss.	Non-US	Online Only
MRS Regular and Student Members	\$260.00	\$351.00	–
Institutions	\$2329.00	\$2264.00	\$2043.00

---

*Journal of Materials Research* (ISSN: 0884-2914) is published twenty-four times a year by Cambridge University Press, One Liberty Plaza, 20th Floor, New York, NY 10006 for the Materials Research Society. Periodical Postage Paid in New York, NY and additional mailing offices. **POSTMASTER:** Send address changes to *Journal of Materials Research*, c/o Journals Dept., Cambridge University Press, One Liberty Plaza, 20th Floor, New York, NY 10006, USA.

**Subscriptions, renewals, address changes, and single-copy orders** should be addressed to Subscription Fulfillment, *Journal of Materials Research*, Cambridge University Press, One Liberty Plaza, 20th Floor, New York, NY 10006, USA (for USA, Canada, and Mexico); or Cambridge University Press, University Printing House, Shaftesbury Road, Cambridge, CB2 8BS, England (for UK and elsewhere). Allow at least six weeks advance notice. For address changes, please send both old and new addresses and, if possible, include a mailing label from a recent issue. Requests from subscribers for missing journal issues will be honored without charge only if received within six months of the issue's actual date of publication; otherwise, the issue may be purchased at the single-copy price.

**Reprints** of individual articles in *Journal of Materials Research* may be ordered. For information on reprints, please contact Cambridge University Press. Reprints of complete back issues older than the prior volume year may be ordered on an individual basis via Cambridge Core. To determine availability, visit the appropriate page for the *JMR* back issue desired ([cambridge.org/jmr](http://cambridge.org/jmr)).

**Individual member subscriptions are for personal use only.**

**Editor-in-Chief:** Gary L. Messing, *Ceramic materials, The Pennsylvania State University, USA*

**Associate Editor:** Susmita Bose, *Biomaterials, Washington State University, USA*

**Associate Editor:** Mathias Göken, *Advanced metallic materials, Friedrich-Alexander-University Erlangen-Nürnberg, Germany*

**Associate Editor:** Linda S. Schadler, *Polymeric materials, University of Vermont, USA*

**Guest Editors for Focus Issue: Plasticity and Fracture at the Nanoscales—Advances in *In Situ* Experimentation Techniques Enabling Novel and Extreme Materials/Nanocomposite Design**

Arief S. Budiman, *Singapore University of Technology & Design (SUTD), Singapore*

Nobumichi Tamura, *Advanced Light Source (ALS), Lawrence Berkeley National Laboratory, Berkeley, USA*

Nan Li, *Center for Integrated Nanotechnologies (CINT), Los Alamos National Laboratory, Los Alamos, USA*

Jessica Krogstad, *University of Illinois, Urbana-Champaign (UIUC), USA*

**2019 Principal Editors:**

Amit Bandyopadhyay, *Hard biomaterials, Additive manufacturing, Washington State University, USA*

Ricardo H.R. Castro, *Interfaces thermodynamics, Calorimetry, Ceramics, University of California, Davis, USA*

Jinju Chen, *Soft materials/thin films, Nanoindentation, Newcastle University, United Kingdom*

Xiaobo Chen, *Photocatalysis and batteries, University of Missouri-Kansas City, USA*

Yang-T. Cheng, *Mechanical behavior, Electrochemical energy storage, University of Kentucky, USA*

Sung-Yoon Chung, *Energy, Electron microscopy, Interface science, KAIST, Korea*

Paolo Colombo, *Pre-ceramic polymers, Porous ceramics, University of Padova, Italy; The Pennsylvania State University, USA*

Sylvain Deville, *Ceramic materials, Processing, Bioinspired materials, CNRS, France*

Franz Faupel, *Functional nanomaterials, VPD, Metallic glasses, University of Kiel, Germany*

Michael C. Gao, *High entropy alloys, Computational materials science, National Energy Technology Laboratory/AECOM, USA*

Erik G. Herbert, *Nanoindentation, Small-scale mechanical behavior Michigan Technological University, USA*

Jon Ihlefeld, *Ferroelectrics, Thin films, Ionic conductors, University of Virginia, USA*

Quanxi Jia, *Superconductors, Ferroelectric/magnetic materials, Thin films University of Buffalo, USA*

C. Robert Kao, *Metallic materials, Diffusion and joining, National Taiwan University, Taiwan*

Edson Roberto Leite, *Materials chemistry, Nanocrystals, Synthesis, Brazilian Nanotechnology National Laboratory, Brazil*

Lei Liu, *Semiconductors, Electronic structure, Spectroscopy, Changchun Institute of Optics, Fine Mechanics and Physics, China*

Jörg Löffler, *Metallic materials/synthesis and properties, ETH Zurich, Switzerland*

Michele Manuel, *Phase transformations, Materials design, University of Florida, USA*

Michael E. McHenry, *Magnetic materials, Carnegie Mellon University, USA*

Scott T. Misture, *In-situ diffraction, Electrochemically active ceramics, Alfred University, USA*

Sarah E. Morgan, *Polymer surfaces and interfaces, The University of Southern Mississippi, USA*

Lakshmi S. Nair, *Biomaterials, Tissue regeneration, Drug delivery, University of Connecticut, USA*

Akira Nakajima, *Photocatalysis, Surface wettability, Ceramic processing, Tokyo Institute of Technology, Japan*

Cewen Nan, *Ferroelectric, Multiferroic materials, Tsinghua University, China*

George M. Pharr, *Mechanical behavior, Nanoindentation, Texas A&M University, USA*

Ian M. Reaney, *Electroceramics, TEM, Thin films, The University of Sheffield, United Kingdom*

Joshua A. Robinson, *2D material synthesis and properties, The Pennsylvania State University, USA*

Fabrice Rossignol, *Ceramic processes, Additive manufacturing CNRS, France*

Edward M. Sabolsky, *Electroceramics, Electrochemistry, Processing, West Virginia University, USA*

Don W. Shaw, *Epitaxy, Vapor deposition, Semiconductors, The University of Texas at Dallas, USA*

Susan B. Sinnott, *Computational materials science, The Pennsylvania State University, USA*

Ziqi Sun, *Energy nanomaterials, Wet chemical synthesis, Queensland University of Technology, Australia*

Mitra Taheri, *Metallic materials, Semiconductors, Complex Oxides, Drexel University, USA*

Chongmin Wang, *Energy storage, Microscopy, In-situ/operando technique, Pacific Northwest National Laboratory, USA*

William J. Weber, *Radiation effects, Nuclear ceramics, University of Tennessee; Oak Ridge National Laboratory, USA*

Sam Zhang, *Thin films/coatings, Nanyang Technological University, Singapore*

Yanchun Zhou, *Structural ceramics, Electronic structure, Aerospace Research Institute of Materials and Processing Technology, China*

**Editorial Office:** Ellen W. Kracht, *Publications Manager, Materials Research Society, Warrendale, PA*  
Leslie Truver, *JMR Editorial Assistant, Materials Research Society, Warrendale, PA*  
Kirby L. Morris, *JMR Production Assistant, Materials Research Society, Warrendale, PA*  
Eileen M. Kiley, *Director of Communications, Materials Research Society, Warrendale, PA*

**PLASTICITY AND FRACTURE AT THE NANOSCALES—ADVANCES IN *IN SITU* EXPERIMENTATION TECHNIQUES ENABLING NOVEL AND EXTREME MATERIALS/NANOCOMPOSITE DESIGN**

1447–1448 Introduction

Arief S. Budiman,  
Nobumichi Tamura, Nan Li,  
Jessica Krogstad

**INVITED FEATURE PAPER—REVIEWS**

1449–1468 Advances in In situ microfracture experimentation techniques: A case of nanoscale metal–metal multilayered materials

Hashina Parveen Anwar Ali,  
Arief Budiman

1469–1478 An overview of interface-dominated deformation mechanisms in metallic nanocomposites elucidated using in situ straining in a TEM

Yuchi Cui, Nan Li, Amit Misra

1479–1488 A review on cyclic deformation damage and fatigue fracture behavior of metallic nanolayered composites

Guang-Ping Zhang, Fei Liang,  
Xue-Mei Luo, Xiao-Fei Zhu

**INVITED PAPER**

1489–1498 Revealing the ductility of nanoceramic MgAl<sub>2</sub>O<sub>4</sub>

Bin Chen, Yuanjie Huang, Jianing Xu,  
Xiaoling Zhou, Zhiqiang Chen,  
Hengzhong Zhang, Jie Zhang,  
Jianqi Qi, Tiecheng Lu,  
Jillian F. Banfield, Jinyuan Yan,  
Selva Vennila Raju,  
Arianna E. Gleason, Simon Clark,  
Alastair A. MacDowell

**ARTICLE**

1499–1508 In situ transmission electron microscopy investigation on  $\langle c + a \rangle$  slip in Mg

Dalong Zhang, Lin Jiang, Xin Wang,  
Irene J. Beyerlein, Andrew M. Minor,  
Julie M. Schoenung,  
Subhash Mahajan,  
Enrique J. Lavernia

**REVIEW**

1509–1532 Atomistic modeling of nanoscale plasticity in high-entropy alloys

Zachary H. Aitken, Viacheslav Sorokin,  
Yong-Wei Zhang

**ARTICLES**

1533–1541 Fracture resistance of Cu/Nb metallic nanolayered composite

Sixie Huang, Caizhi Zhou

1542–1554 Revealing deformation mechanisms in Mg–Y alloy by in situ deformation of nano-pillars with mediated lateral stiffness

Dalong Zhang, Lin Jiang, Xin Wang,  
Irene J. Beyerlein, Andrew M. Minor,  
Julie M. Schoenung,  
Subhash Mahajan,  
Enrique J. Lavernia

1555–1563 Crystal plasticity modeling the deformation in nanodominated heterogenous structures

Tianju Chen, Caizhi Zhou

1564–1573 Effect of multilayer interface through *in situ* fracture of Cu/Nb and Al/Nb metallic multilayers

Hashina Parveen Anwar Ali,  
Ihor Radchenko, Nan Li,  
Arief Budiman

(Continued)



- 1574–1583 **Microscale shear specimens for evaluating the shear deformation in single-crystal and nanocrystalline Cu and at Cu–Si interfaces** Jonathan G. Gigax, Jon K. Baldwin, Chris J. Sheehan, Stuart A. Maloy, Nan Li
- 1584–1594 **Dislocation spreading and ductile–to-brittle transition in post-irradiated ferritic grains: Investigation of grain size and grain orientation effect by means of 3D dislocation dynamics simulations** Yang Li, Christian Robertson, Xianfeng Ma, Biao Wang
- 1595–1607 **Strategies to tailor serrated flows in metallic glasses** Zhe Fan, Qiang Li, Cuncai Fan, Haiyan Wang, Xinghang Zhang
- 1608–1621 **Dynamic recrystallization initiated by direct grain reorientation at high-angle grain boundary in  $\alpha$ -titanium** Hao Wang, Qili L. Bao, Gang Zhou, J.K. Qiu, Yi Yang, Y.J. Ma, Chunguang G. Bai, Dongsheng S. Xu, David Rugg, Aijun J. Huang, Qing-Miao Hu, J.F. Lei, Rui Yang
- 1622–1631 **Stress evolution in silicon nanowires during electrochemical lithiation using in situ synchrotron X-ray microdiffraction** Sasi Kumar Tippabhotla, Ihor Radchenko, Camelia V. Stan, Nobumichi Tamura, Arief Suriadi Budiman