



Journal of  
MATERIALS RESEARCH

VOLUME 34 • NO 13  
JULY 15, 2019

FOCUS ISSUE

**Intrinsic and Extrinsic Size  
Effects in Materials**

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

**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: Intrinsic and Extrinsic Size Effects in Materials**

Shuozhi Xu, *University of California, Santa Barbara, USA*

Marat I. Latypov, *University of California, Santa Barbara, USA*

Jaafar A. El-Awady, *Johns Hopkins University, USA*

Irene J. Beyerlein, *University of California, Santa Barbara, 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*

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*

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, *Editorial and Production Associate, Materials Research Society, Warrendale, PA*

Eileen M. Kiley, *Director of Communications, Materials Research Society, Warrendale, PA*

**INTRINSIC AND EXTRINSIC SIZE EFFECTS IN MATERIALS**

2147 Introduction

Shuozhi Xu, Marat I. Latypov,  
Jaafar A. El-Awady, Irene J. Beyerlein

**INVITED PAPER**

2148–2160 Size-dependent vibration analysis of carbon nanotubes

Wu-Rong Jian, Xiaohu Yao,  
Yugang Sun, Zhuocheng Xie,  
Xiaoqing Zhang

**INVITED REVIEW**

2161–2176 Size effects on material yield strength/deformation/fracturing properties

Ronald W. Armstrong

**INVITED PAPER**

2177–2193 Size effect on mechanical properties in high-order hierarchically nanotwinned metals

Jicheng Li, Ke-Gang Wang

**ARTICLE**

2194–2200 Gamma radiation induced compressive response of silicon rubber foam: Experiments and modeling

Huyi Wang, Yong Qiu, Wenjun Hu,  
Yongmei Chen

**INVITED FEATURE PAPER**

2201–2208 Kinetic control of CeO<sub>2</sub> nanoparticles for catalytic CO oxidation

Bingqi Han, Huixia Li, Liping Li,  
Yan Wang, Yuelan Zhang,  
Guangshe Li

**INVITED PAPERS**

2209–2217 Grain size effects on dynamic fracture instability in polycrystalline graphene under tear loading

Yuxin Zhao, Yunfei Xu, Xiaoyi Liu,  
Jun Zhu, Sheng-Nian Luo

2218–2228 An in situ study on Kr ion-irradiated crystalline Cu/amorphous-CuNb nanolaminates

Zhe Fan, Cuncai Fan, Jin Li,  
Zhongxia Shang, Sichuang Xue,  
Marquis A. Kirk, Meimei Li,  
Haiyan Wang, Xinghang Zhang

2229–2238 Grain size effects on Ni/Al nanolaminate combustion

Brandon Witbeck, Douglas E. Spearot

2239–2251 Irradiation resistance of nanostructured interfaces in Zr–Nb metallic multilayers

Elton Y. Chen, Chaitanya Deo,  
Rémi Dingreville

2252–2262 High-rate dislocation motion in stable nanocrystalline metals

Jeffrey T Lloyd

2263–2274 Grain boundary strengthening of FCC polycrystals

R. Arturo Rubio, Sarra Haouala,  
Javier LLorca

**ARTICLE**

2275–2284 Size-independent strength of amorphous–HCP crystalline metallic nanolayers

Mohammad Abboud, Sezer Özerinç

**INVITED PAPERS**

2285–2294 3D multiscale modeling of fracture in metal matrix composites

Yan Li, Leon Phung, Cyril Williams

(Continued)

- 2295–2305 **Effect of Xe bubble size and pressure on the thermal conductivity of  $\text{UO}_2$ —A molecular dynamics study** Weiming Chen, Michael W.D. Cooper, Ziqi Xiao, David A. Andersson, Xian-Ming Bai
- 2306–2314 **A multiscale study of misfit dislocations in PbTe/PbSe(001) heteroepitaxy** Yang Li, Zhaochuan Fan, Weixuan Li, David L. McDowell, Youping Chen

**ARTICLE**

- 2315–2324 **A new exponential function to represent the effect of grain size on the strength of pure iron over multiple length scales** K.S. Ravi Chandran

**INVITED PAPERS**

- 2325–2336 **Interfacial plasticity governs strain delocalization in metallic nanoglasses** Bin Cheng, Jason R. Trelewicz
- 2337–2346 **Anomalous size effects in nanoporous materials induced by high surface energies** Justin W. Wilkerson

**ARTICLE**

- 2347–2369 **Analysis of local grain boundary strengthening utilizing the extrinsic indentation size effect** Prasad Pramod Soman, Erik G. Herbert, Katerina E. Aifantis, Stephen A. Hackney

**INVITED FEATURE PAPER**

- 2370–2383 **Fracture properties of ultrafine grain chromium correlated to single dislocation processes at room temperature** Inas Issa, Anton Hohenwarter, Reinhard Fritz, Daniel Kiener

**INVITED PAPERS**

- 2384–2397 **Size effects on thermomechanical failure of layered structure with generalized particle dynamics multiscale methods** Jinghong Fan
- 2398–2405 **Grain size effect on deformation twin thickness in a nanocrystalline metal with low stacking-fault energy** Yusheng Li, Liangjuan Dai, Yang Cao, Yonghao Zhao, Yuntian Zhu