NIST Roadmapping Workshop: Measurement Science for Polymer-Based Additive Manufacturing

June 9-10, 2016

NIST Administration Bldg. (101), 100 Bureau Drive, Gaithersburg MD

Packet Contents

Workshop Sponsors

This workshop is sponsored by the National Institute of Standards and Technology (NIST) and the National Science Foundation (NSF)

Workshop Steering Committee

Kevin Jurrens (NIST)
Lonnie Love (ORNL)
Kalman Migler (NIST)
Zhijian Pei (NSF)
Ralph Resnick (NCDMM)
Richard Ricker (NIST)
Steven Schmid (ND)
Katherine Vorvolakos (FDA)

AGENDA

Thursday, June 9, 2016

7:30 am	Registration
8:30 am	Opening Plenary Session **Portrait Room** Moderator: ZJ Pei, National Science Foundation ▶ **Welcome** ~ Mike Molnar, Advanced Manufacturing Program Office, NIST ▶ **Workshop Scope and Objectives** ~ Kalman Migler, NIST ▶ **Current Status of Polymers Roadmapping** ~ Rob Gorham, America Makes
9:00 am	Panel Session: Characterization of Materials Throughout Their Lifecycle Moderator: Mark Dadmun, University of Tennessee-Knoxville ▶ Matthew Di Prima, Food and Drug Administration ▶ Angel Yanguas-Gil, Argonne National Laboratory ▶ Abraham Joy, University of Akron
10:15 am	*Break*
10:30 am	Panel Session: Process Models Moderator: Kalman Migler (NIST) ▶ Slade Gardner, Slade Gardner Advanced Manufacturing and Materials, LLC ▶ Peter Olmsted, Georgetown University ▶ David Roberson, University of Texas-El Paso
11:45 am	*Lunch and Posters* **NIST Cafeteria**
1:00 pm	Panel Session: In Situ Processing Measurements **Portrait Room** Moderator: Robert Maxwell, Lawrence Livermore National Laboratory ▶ Miriam Rafailovich, State University of New York at Stony Brook ▶ Jon Seppala, NIST ▶ Chris Williams, Virginia Tech
2:15 pm	Instructions for Breakout Sessions ▶ Joan Pellegrino, Energetics Incorporated
2:20 pm	*Move to breakout rooms*
2:30 pm	Breakout Session I: Targets/Capabilities for Polymer-based Additive Manufacturing *This round of concurrent breakout sessions will look at the envisioned future: desired capabilities, characteristics, and performance.* *Topic* — *Room* **Materials** — Heritage Room **Process Modeling** — Portrait Room **In Situ Measurements** — Lecture Room C **Performance** — Lecture Room D
3:15 pm	*Break*
3:30 pm	Breakout Session II: Challenges and Barriers to Achieving Targets/Goals *Participants will return to their breakout session to consider barriers limiting the broad use of polymer-based additive manufacturing and measurement and standards barriers, challenges, and gaps, and identify priority topic areas for the measurement roadmap.*
5:00 pm	Adjourn Day 1 — Hold onto your badge and remember to bring it tomorrow!

AGENDA

Friday, June 10, 2016		
8:00 am	Early Networking	
8:30 am	Welcome and Recap of Day 1	**Portrait Room**
8:40 am	Panel Session: Performance Moderator: Greg Kittlesen, FDA ► Courtney Fox, Carbon3D ► Bryan Vogt, University of Akron ► Gerald Grant, University of Louisville	
10:00 am	*Break and Move to Breakouts*	
10:15 am	Breakout Session III: Pathways for Measurement Science Roadmap *Participants will return to their breakout session and review and clarify top challenges and potential roadmap topics. After consensus on priority topics, small groups will work together to develop priority roadmap action plans and next steps, which will be presented in the afternoon plenary.*	
11:45 pm	*Lunch and Posters*	**NIST Cafeteria**
1:15 pm	Panel Session: Integration and Standards Moderator: Carl Dekker, Met-L-Flo ► Scott Fish, University of Texas ► Praveen Tummala, 3DSystems ► Lyle Levine, NIST	**Portrait Room**
2:15 pm	Breakout Group Reports	
2:45 pm	Workshop Wrap-up and Next Steps	
3:00 pm	Workshop Adjourns	

Definition of Measurement Science

The term "measurement science" is used in the context of creating **critical-solution enabling tools – metrics, models, and knowledge** – for U.S. manufacturers. This includes:

- Development of
  - Performance metrics
  - Measurement and testing methods
  - Predictive modeling and simulation tools
  - Knowledge modeling
  - Protocols
  - Technical data
  - Reference materials (e.g. data sets)
  - Artifacts
- Conduct of inter-comparison studies and calibrations
- Evaluation of technologies, systems, and practices
- Development of the technical basis for standards, codes, guidelines, and/or practices

Posters

Name: Joe Bennett
Title: Measuring the UV Curing Parameters of Commercially Available Photopolymers used in Additive Manufacturing
Institution: National Institute of Standards and Technology

Name: Chad Duty
Title: Infrared preheating - A strategy to enhance interlayer strength of Big Area Additive Manufacturing (BAAM) components
Institution: Department of Mechanical, Aerospace, and Biomedical Engineering, University of Tennessee, Knoxville

Name: Kirsten Kozlovsky, Matthew Kelly, Steven Schmid
Title: Economic Production of Next Generation Orthopedic Materials through Powder Reuse
Institution: Department of Mechanical Engineering, Notre Dame

Name: Joshua Land, Shawn Moylan, and Antonio Possolo
Title: Additive Manufacturing Round Robin Protocols: A Pilot Study
Institution: National Institute of Standards and Technology

Name: Ken Langley
Title: Advanced Polymer Chromatography - Method Development Tools for SEC Polymer Analysis
Institution: Waters

Name: Ming Leu, K. Chandrashekhara
Title: Characterization of Sparse-Build Tooling Fabricated by Fused Deposition Modeling
Institution: Missouri University of Science and Technology

Name: Claire McIlroy
Title: Modelling Polymer Behaviour in Fused Deposition Modelling
Institution: Department of Physics, Georgetown University

Name: Tina Ng
Title: Flexible Sensor Circuits Fabricated by Additive Printing
Institution: Department of Electrical and Computer Engineering, University of California San Diego

Name: Yayue Pan
Title: Continuous Printing of Large Objects with Wide Solid Cross Sections
Institution: Department of Mechanical and Industrial Engineering, University of Illinois at Chicago.

Name: Amy M. Peterson
Title: Residual Thermal Stresses and Interlayer Diffusion During Fused Deposition Modeling
Institution: Department of Chemical Engineering, Worcester Polytechnic Institute

Name: Steven Shpiner
Title: Additive Manufacturing of High Temperature Thermoset Resins
Institution: Prescient

Name: Matt Staymates, Lourdes Bobbio
Title: Printing parameter optimization for entry-level fused deposition modeling 3D printers
Institution: National Institute of Standards and Technology

Breakout Session Information and Assignments

Topic	*Key Issues*	*Room and Facilitator*
Materials	What measurements are needed to quantify AM materials throughout their life-cycle? What new measurement science tools must be developed to achieve this goal?	Heritage Room
Process Modeling	What types of models are required to achieve fundamental understanding of AM processes; to enable real-time control? What types of input data are required?	Portrait Room
In Situ Measurements	What parameters must be measured on-line in order to achieve closed-loop feedback or quality control? What new measurement methods must be developed?	Lecture Room C
Performance	What new types of performance measures are required for AM manufactured goods? What measures are needed to allow qualification, certification or regulation of such parts and products?	Lecture Room D

CHECK YOUR ASSIGNMENT

(it is okay to switch, but please stay with the group you choose to join)

First Name	LAST NAME	Organization	Breakout Session
Nicolas	**ALVAREZ**	Drexel University	Materials Characterization
Joseph	**BARTOLAI**	Penn State	Materials Characterization
Joe	**BENNET**	NIST	Performance
Jack	**BEUTH**	Carnegie Mellon University	Process Modelling
David	**BIGIO**	University of Maryland	Process Modelling
Daniel	**BOWEN**	Honeywell	Performance
K	**CHANDRASHEKHARA**	Missouri University of Science & Technology	Process Modelling
Robert	**CHISENA**	University of Michigan	Materials Characterization
Kevin	**CHOU**	The University of Alabama	In-situ measurements
Daniel	**COLE**	US Army Research Lab	Materials Characterization
Brian	**CZAPOR**	UDRI	Performance
Mark	**DADMUN**	Univ. of Tennessee	Materials Characterization
Anthony	**DECARMINE**	Oxford Performance Materials	Performance
Jeff	**DEGRANGE**	Impossible Objects LLC	In-situ measurements
Carl	**DEKKER**	Met-L-Flo Inc.	Performance
Matthew	**DI PRIMA**	FDA-CDRH	Materials Characterization
Chris	**DIMITRIOU**	Nike Inc	Materials Characterization
Chad	**DUTY**	University of Tennessee	Materials Characterization

First Name	LAST NAME	Organization	Breakout Session
Scott	**FISH**	Univeristy of Texax at Austin	Performance
Elizabeth	**FITZGERALD**	DOE National Security Campus	Materials Characterization
Courtney	**FOX**	Carbon3D	Performance
Slade	**GARDNER**	Slade Gardner Advanced Manufacturing and Materials, LLC	Process Modelling
Robert	**GORHAM**	NCDMM	Process Modelling
Scott	**GRANT**	Autodesk	Materials Characterization
Gerald	**GRANT**	Louisville	Performance
Yong	**HUANG**	University of Florida	Process Modelling
Irada	**ISAYEVA**	FDA	Materials Characterization
Terrence	**JOHNSON**	Army Research Laboratory	Performance
Abraham	**JOY**	University of Akron	Materials Characterization
Kevin	**JURRENS**	NIST, Intelligent Systems Division	Performance
Sung	**KANG**	Johns Hopkins University	In-situ measurements
Jennifer	**KELLY**	FDA	In-situ measurements
Matthew	**KELLY**	University of Notre Dame	Process Modelling
Jason	**KILGORE**	NIST	Process Modelling
Gregg	**KITTLESEN**	FDA-CDRH	Performance
Hilmar	**KOERNER**	Air Force Research Laboratory	In-situ measurements
Zhenyu	**KONG**	Virginia Tech	In-situ measurements
Anthony	**KOTULA**	NIST	In-situ measurements
Kirsten	**KOZLOVSKY**	University of Notre Dame	Performance
Mark	**KUJAWSKI**	BASF	Performance
kenneth	**LANGLEY**	Waters Corporation	Materials Characterization
Gary	**LARSON**	Stratasys Inc	In-situ measurements
Ming	**LEU**	Missouri University of Science and Technology	In-situ measurements
James	**LEWICKI**	Lawrence Livermore Natl. laboratory	Materials Characterization
Joao	**MAIA**	Case Western Reserve University	Materials Characterization
Blake	**MARSHALL**	DOE	Process Modelling
Robert	**MAXWELL**	LLNL	In-situ measurements
James	**MCGUFFIN-CAWLEY**	Case Western Reserve Univ	Materials Characterization
Claire	**MCILROY**	Georgetown University	Process Modelling
Kalman	**MIGLER**	NIST	Materials Characterization
Mike	**MOLNAR**	NIST	Performance

First Name	LAST NAME	Organization	Breakout Session
Stephanie	**MORAN**	Carbon3D	Performance
Ryan	**MURPHY**	Solvay	In-situ measurements
Tse Nga	**NG**	UC San Diego	Materials Characterization
Thao (Vicky)	**NGUYEN**	Johns Hopkins University	Process Modelling
Scott	**OLIG**	US Naval Research Laboratory	Materials Characterization
Peter	**OLMSTED**	Georgetown University	Process Modelling
Yayue	**PAN**	University of Illinois At Chicago	Materials Characterization
Brian	**PATTERSON**	Los Alamos National Laboratory	In-situ measurements
ZJ	**PEI**	National Science Foundation	Performance
Amy	**PETERSON**	Worcester Polytechnic Institute	Materials Characterization
Steven	**POLLACK**	Carbon 3D	In-situ measurements
Timothy	**PRUYN**	AFRL/RX	Materials Characterization
Miriam	**RAFAILOVICH**	Stony Brook University	In-situ measurements
Russ	**REVEY**	DOE National Security Campus	Materials Characterization
Rick	**RICKER**	NIST	Materials Characterization
Laura	**RICLES**	Food and Drug Adminstration	Performance
Mark	**ROBBINS**	Johns Hopkins University	Process Modelling
David	**ROBERSON**	UTEP	Process Modelling
Natalie	**RUDOLPH**	University of Wisconsin-Madison	Materials Characterization
Godfrey	**SAUTI**	NIA/NASA Langley	In-situ measurements
Christina	**SAVISAAR**	FDA	Materials Characterization
Jay	**SCHIEBER**	Illinois Institute of Technology	Process Modelling
Steve	**SCHMID**	Notre Dame	Process Modelling
Lester	**SCHULTHEIS**	University of Maryland	Performance
Jon	**SEPPALA**	NIST	In-situ measurements
Steven	**SHPINER**	Prescient	Materials Characterization
Christopher	**SPADACCINI**	Lawrence Livermore National Laboratory	Materials Characterization
Timothy	**SPAHR**	Arkema Inc	Materials Characterization
Thomas	**STARR**	University of Louisville	In-situ measurements
Daniel	**STOLYAROV**	Graphene 3D Lab Inc	Materials Characterization
Limin	**SUN**	FDA	Performance
Charles	**SWEENEY**	Texas A&M	Materials Characterization
Blake	**TEIPEL**	Essentium Materials	Materials Characterization
Mary	**TONEY**	NSF	Process Modelling

First Name	LAST NAME	Organization	Breakout Session
John	**TUMBLESTON**	Carbon3D	Performance
Praveen	**TUMMALA**	3DSystems	Performance
Anthony	**VAN BUUREN**	LLNL	In-situ measurements
Bryan	**VOGT**	Univ. of Akron	Performance
Katherine	**VORVOLAKOS**	FDA	Performance
Xiaoke	**WAN**	Sync Optics LLC	In-situ measurements
Todd	**WEISGRABER**	LLNL	Process Modelling
Christopher	**WILLIAMS**	Virginia Tech	In-situ measurements
Buzz	**WINCHESKI**	NASA LaRC	In-situ measurements
William	**YACKABONIS**	Autodesk	Performance

Presenters and Moderators

Mark Dadmun, University of Tennessee-Knoxville

Dr. Mark Dadmun (Paul and Wilma Zeigler Professor, Chemistry Department, received his B.S. in Chemical Engineering from the University of Massachusetts and a Ph.D. from the University of Massachusetts working with Prof. M. Muthukumar in Polymer Science and Engineering. He subsequently was awarded a National Research Council Post-Doctoral Fellowship, which was completed at the National Institute of Standards and Technology working with Dr. Charles Han. Prof. Dadmun then joined the faculty of the Chemistry Department at the University of Tennessee, where he is now a Full Professor. His current appointments include Joint Faculty at Oak Ridge National Laboratory in the Chemical Science Division and Associate Director of the UT/ORNL Joint Institute for Neutron Sciences. His current research interests focus on directing polymeric interfaces, the characterization, optimization, and control of the dispersion and morphology in multi-component polymeric materials, and understanding the superglue fuming of latent fingerprints.

Carl Dekker, Met-L-Flo

Carl K. Dekker serves as the President of Met-L-Flo, Inc., a growing Service Center for Additive Manufacturing located in Sugar Grove, IL. He has been actively involved in research and product development using current technologies and innovative methods. Currently the Chair of the ASTM F42 Committee on Standards for Additive Manufacturing and a Past Chairperson of the SME's Rapid Technologies and Additive Manufacturing (RTAM) Community (formerly the RPA), he also serves as the Chair of the Direct Digital Manufacturing Tech Group of the RTAM. Being actively involved in fostering education he teaches the Rapid Technologies and Additive Manufacturing Technologies Certificate Programs and also remains active in the Bright Minds Program as a member and Past Co-Chair. He holds a Master Certificate in Rapid Prototyping and is a proud recipient of the SLA "Dinosaur" award.

Matthew Di Prima, Food and Drug Administration

Dr. Matthew Di Prima received a bachelor's degree in Materials Science and Engineering from Rice University (2005) and his doctorate in Materials Science and Engineering from the Georgia Institute of Technology (2009) and is working as materials scientist at the Center for Devices and Radiological Health in the US Food and Drug Administration. His areas of research are investigating how the additive manufacturing process can alter material properties, the interplay between corrosion and durability testing, and explant analysis. Along with his research duties, he is the head of the Additive Manufacturing Working Group which is spearheading efforts across the Agency to address how this technology affects medical devices and other regulate medical products. These efforts include guidance and standards development, device review harmonization, and performing regulatory science with the intent to foster innovative and high quality products while maintaining that they have the same safety and effectiveness that Americans have come to expect.

Scott Fish, University of Texas

Dr. Fish has over thirty years of research and engineering experience, covering a broad range of technical areas including fluid mechanics, control systems and robotics, ballistics and armor protection, and multi-disciplinary modeling of ground and sea vehicle power systems and associated maneuverability. He is currently a Sr. Research Scientist at the University of Texas at Austin, exploring advanced methods of process monitoring and control for powder bed 3D printing with polymers and metals. He has extensive experience executing technical projects in government, academia, and industry. Dr. Fish has been with the University of Texas at Austin since 1993, with appointments both at DARPA developing robotics technology, and with the Army as its Chief Scientist. He also served as a Chief Engineer and Assistant Vice President for Technology at SAIC with focus on ground robotics development. Prior to UT, he served 9 years with the Naval Surface Warfare Center conducting research and development in naval architecture and weapon system control. Dr. Fish holds a PhD in Mechanical Engineering from the University of Maryland, Masters Degree's in Naval Architecture and Mechanical Engineering from MIT, and a Bachelor's Degree in Mechanical Engineering from UT Austin. Scott is a Private Pilot and is building a Cozy MKIV aircraft.

Courtney Fox, Carbon3D

Courtney is a Research Scientist on the Carbon Materials Team, and has developed their internal materials characterization program. Her work is focused on understanding the interrelationships between printer operation processes and material performance and mechanical properties. She completed her M.S. and Ph.D. in Chemical Engineering at Stanford as a NSF Graduate Research Fellow and National Defense Science and Engineering Graduate Fellow. In her spare time, she loves to cook, entertain, swim, run, and ride her bicycle.

Slade Gardner, Slade Gardner Advanced Manufacturing and Materials, LLC

Dr Slade Gardner is President of Slade Gardner Advanced Manufacturing and Materials LLC, a consulting firm focused on strategic planning, business opportunity case studies, technology development and special projects for customers seeking innovative solutions for manufacturing and materials. He has advised corporations, institutes, national laboratories and the US Government on strategy, priorities and development needs on incorporation and industrial application for advanced manufacturing. His technical background includes equipment configuration, materials development and engineering transition from laboratory to factory to customer for: large additive manufacturing, composite structures, nanomaterials, and thermoplastic composites. Through these technical avenues he has reached product implementation for customer benefit greater than $500M. His technology insertions can be found on spacecraft, aircraft, sophisticated ground systems and are currently reaching into sporting goods, watercraft and motorsport. Previously Slade served as Fellow at Lockheed Martin Space Systems and also Fellow at Lockheed Martin Aeronautics in the Skunk Works division. Prior to that he was a research engineer at Amoco Carbon Fibers at the global R&D headquarters. His PhD in Chemical Engineering is from Virginia Polytechnic Institute and

State University where he studied under fellowship from the National Science Foundation Science and Technology Center for High Performance Polymers and Composites. His BS in Chemical Engineering is from Lafayette College. Personal interests include traveling and dining with his wife, all seasons of mountain sports and he is an avid motorcycle enthusiast.

Rob Gorham, America Makes

Rob joined the America Makes team in 2013 as the Deputy Director of Technology Development and in May 2014 was promoted to Director of Operations. He has more than a decade of solid defense research and advanced manufacturing experience. Prior to joining America Makes, he was the Senior Manager of the Manufacturing Exploration and Development (MXD) group within the Advanced Manufacturing Systems and Prototyping (AMS&P) directorate of Lockheed Martin (LM) Aeronautics – Advanced Development Programs (ADP). In this position, Rob was responsible for leading the transition-focused development and the application of affordable manufacturing technologies for LM Aeronautics and other LM Business Areas across the corporation. He holds a B.S. in Aerospace Engineering from Texas A&M University and a M.S. in Engineering Management from Southern Methodist University.

Gerald Grant, University of Louisville

Dr. Gerald Grant received a dental degree from the University of Louisville school of Dentistry (1985) after which he began his career as a Navy Dental Officer, a certificate of training in Prosthodontics at the Navy Postgraduate Dental School (1995), a Masters in Oral Health from George Washington University of Health Sciences (1995) and a Certificate in training of Maxillofacial Prosthetics from the Navy Postgraduate Dental School (1999). In 2004 he became program director of the Maxillofacial Prosthetic Program at the Naval Postgraduate Dentals School in Bethesda, MD, where he began research in image capture, digital design and additive manufacturing of medical models and devices for craniofacial reconstruction of Wounded Warriors. He became the first "chief" of the 3D Medical Center at the new Walter Reed National Military Medical Center, where he expanded their services worldwide via an on-line accessible website to all DoD and federal medical/dental facilities. His experience outside of medical with AM include project leader for DARPA proof of concept for printing medical instruments in the field, project leader for the first training and use of a 3d printer on a Navy ship, and 3D print consultant to the NIH Digital files exchange. He has numerous publications and awards for use of digital capture, design, and additive manufacturing for medical devices, extra oral prostheses, virtual surgical techniques and validation of digital models. He recently retired from the Navy after 30 years and is presently is the Professor, Chair of Oral Health and Reconstruction at the University of Louisville School of Dentistry and continues his research in collaboration with the Speed School of Engineering and the Medical school in use of 3D Printing for medical and dental use.

Abraham Joy, University of Akron

Abraham Joy is an assistant professor of Polymer Science at the University of Akron. He obtained his Ph.D. in chemistry from Tulane University, working under the mentorship of Prof. V. Ramamurthy on organic asymmetric photoreactions. Following his doctoral work, he carried out his postdoctoral work at the Georgia Institute of Technology with Prof. Gary Schuster, working on charge migration in synthetic oligonucleotides. Subsequently, he was an NIH Ruth Kirschstein postdoctoral fellow at Rutgers University and the Univ. Pennsylvania working with Prof. Joachim Kohn and Prof. Christopher Chen. During that time, he worked on designing biomaterials for modulating cellular functions. In 2010 he joined the faculty of Polymer Science at The University of Akron as an assistant professor. The central focus of his research group is to develop materials for biomedical and engineering applications. The Joy Lab is engaged in developing: i) peptidomimetic biomaterials; ii) photoresponsive materials; and iii) self-assembled polymers.

Greg Kittlesen, FDA

Dr. Gregg Kittlesen conducts materials engineering reviews of novel neurosurgical devices at the FDA. Prior to joining FDA in 2013, Dr. Kittlesen's work spanned semiconductor process and device development and continued into reliability characterization of photonic components, materials, and electronic assemblies. Previous employers were DfR Solutions (2 years in Beltsville, MD), Ciena (9 years in Linthicum, MD), Ericsson Components (15 years in Stockholm, Sweden), and Analog Devices (1 year in Wilmington, MA). Dr. Kittlesen earned a Ph.D. in Inorganic Chemistry at the Massachusetts Institute of Technology, and a B.A. with a major in Chemistry at Kalamazoo College.

Lyle Levine, NIST

Dr. Lyle Levine is a physicist at the Materials Measurement Laboratory of the National Institute of Standards and Technology (NIST) where he leads the Additive Manufacturing of Metals Project. With a dual emphasis on world-leading, quantitative materials characterization and microstructure evolution modeling, this project provides experimental input and validation testing for both high-fidelity AM models and reduced order models for AM engineering design.

Robert Maxwell, Lawrence Livermore National Laboratory

Robert S. Maxwell is currently Division Leader for the Materials Science Division in the Physical and Life Sciences Directorate at LLNL. ROBERT has 17 years of experience at LLNL in numerous management and technical roles. Prior to his current positions, he has served the Group Leader for Forensics and Assessments within the Chemical Sciences Division, Dept. Program Lead for the Enhanced Surveillance Campaign. He has also served as Director of the LLNL NMR center, the Deputy Division Leader for Science and Technology for CSD, Associate Program Leader for GS, and served as a U.S. representative to the Organization for the Prohibition of Chemical Weapons Data Validation Group. He has served as Principle Investigator on numerous WCI, GS, and LDRD projects, including PI of the Transformation Materials Initiative, the largest LDRD ever funded at LLNL, focused on developing new materials and sensing platforms for the future stockpile. He currently serves as a senior member of the LLNL Additive Manufacturing team. He maintains research interests in Nuclear Magnetic Resonance, materials aging, and interfacial chemistry. He has over 100 peer-reviewed publications.

Kalman Migler, NIST

Dr. Kalman Migler is a staff scientist in the Polymers and Complex Fluids Group at the National Institute of Standards and Technology (NIST), where he leads the Additive Manufacturing of Polymers Project. His primary interest is in the measurement of non-equilibrium phenomena that occur during polymer processing. Before joining NIST, he was a postdoctoral research fellow at Exxon's Corporate Research Laboratory and at the Collège de France. He earned his Ph.D. in Physics from Brandeis University. He is a Fellow of the American Physical Society. http://www.nist.gov/mml/msed/polymers/kalman-migler.cfm

Mike Molnar, Advanced Manufacturing Program Office, NIST

Mike Molnar likes to be introduced simply as "a manufacturing guy from industry" with nearly 30 years of experience in advanced manufacturing. To help provide an industry focus in 2011 he was named the first Chief Manufacturing Officer of the National Institute of Standards and Technology. Today Mike leads the NIST Advanced Manufacturing Program Office for extramural manufacturing programs and also serves as the director of the interagency Advanced Manufacturing National Program Office. As called for by the Advanced Manufacturing Partnership initiative, the AMNPO's mission is to foster industry-led partnerships and to form a "whole of government" approach to strengthen competitiveness and innovation in U.S. manufacturing. Mike's experience includes leadership roles in advanced manufacturing, metrology, manufacturing systems, quality, technology development, sustainability and industrial energy efficiency. His credentials include service as a Federal Fellow in the White House Office of Science and Technology Policy, and election as Fellow of both the American Society of Mechanical Engineers and the Society of Manufacturing Engineers. He is a licensed Professional Engineer, a Certified Manufacturing Engineer and a Certified Energy Manager. He received a Master of Business Administration from the University of Notre Dame, and both a Master of Science in Manufacturing Systems Engineering and a Bachelor of Science in Mechanical Engineering from the University of Wisconsin. He is an active member of professional societies, consortia and volunteer organizations.

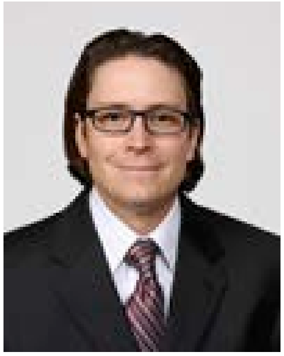
Peter Olmsted, Georgetown University

Peter Olmsted received an AB in Physics from Cornell (1984); and a PhD in Physics from the University of Illinois at Urbana-Champaign (1991), where he studied the theory of liquid crystal hydrodynamics and non-equilibrium phase transitions. Following post-docs at Exxon, Cambridge, and the University of Michigan, where he worked on a variety of soft matter physics topics (membrane, polymers, biophysics, liquid crystals and liquid crystalline elastomers), he moved to Leeds in 1996 for a University Research Fellowship. He became Professor in 2005, and led the Soft Matter Physics group in Leeds from 2008-2013. In 2014 he moved to Georgetown University in Washington DC, as Joseph Semmes Ives Chair in Physics, where he joined the new Institute for Soft Matter Synthesis and Metrology (ISM2). He is currently the Director of the Institute. Olmsted is a Fellow of the Institute of Physics (UK), and a Fellow of the American Physical Society (Division of Polymer Physics), and he was awarded the British Society of Rheology Annual Award in 2008. His research achievements include models for polymer crystallization at rest and under flow, explanations for shear banding in complex fluids such as polymer and surfactants, and an experimental-computational collaboration that revealed how mechanical force unfolds proteins. While in the UK he was in several European Union networks on Soft Matter, and led the EU Integrated Training Network DYNACOP (Dynamics of Architecturally Complex Fluids) from 2008-2012. He is the Secretary/Treasurer of the APS Topical Group on Soft Matter (GSOFT).

Miriam Rafailovich, State University of New York at Stony Brook

Miriam Rafailovich received her PhD from Stony Brook University in Applied Nuclear Physics. She then did her post-doctoral work at Brookhaven National Laboratory and the Weizmann Institute. Miriam was associate professor of Physics and Astronomy at CUNY, Queens College and is currently a distinguished professor at Stony Brook University in the Department of Materials Science and Engineering. Miriam is the director of the Garcia Center for Polymers at Engineered Interfaces. Her research interests span a broad spectrum which includes, Polymer nancomposites for additive manufacturing, biopolymers, biosensors, tissue engineering scaffolds, nanotoxicology, flame retardant composites, and polymers for green energy applications. Miriam is also known as a pioneer in the integration of research with education. She has graduated more than 60 PhD and Masters students and mentored several hundred undergraduate and high school students from across the United States and abroad. She is the co-author of more than 360 publications in peer reviewed journals and technical review articles, a Lady Davis Foundation Scholar and a fellow the American Physical Society.

David Roberson, University of Texas-El Paso



David A. Roberson, Ph.D. is an Assistant Professor in the Department of Metallurgical, Materials and Biomedical Engineering at The University of Texas at El Paso. He currently directs the Polymer Extrusion Lab in the W.M. Keck Center for 3D Innovation where he performs research related to the development of novel polymer matrix composites and polymer blends for additive manufacturing applications. Dr. Roberson has over twenty years of experience in materials characterization and electron microscopy techniques. Prior to his academic career, Dr. Roberson spent eight years working as an engineer in the semiconductor industry in the area of Defect Metrology for Intel Corporation (2001-2006) and Qimonda NA (2006-2009).

Jon Seppala, NIST

Jonathan Seppala is a chemical engineer in the Materials Science and Engineering Division at the National Institute of Standards and Technology (NIST). He is currently the technical lead in the additive manufacturing effort in the Polymer Processing and Rheology Project. His current research focuses on using infrared thermography, rheology, fracture mechanics, and neutron and x-ray reflectivity to study the polymer physics of thermoplastic additive manufacturing processes. Jonathan earned a B.S. in Chemical Engineering from Michigan Technological University and a Ph.D. in Chemical Engineering from Michigan State University studying the rheology and thermodynamics of polymer nanocomposites. Following his Ph.D., Jonathan worked as a Postdoctoral Researcher studying thin film self-assembly of block copolymers and equilibrium dynamics of amphiphilic micelles at the University of Delaware. Prior to joining the Polymer Processing and Rheology project, Jonathan studied ballistic witness materials and shear thickening fluids as part of the Personal Body Armor Project at NIST.

Praveen Tummala, 3DSystems

Praveen Tummala is a Manager, R&D Materials & Process at 3D Systems. In this role, he leads & manages projects related to development and launch of new materials and processes for SLS and PJP 3D Printing technologies. He is also heavily involved in creating the materials roadmap and strategically positioning the company's materials for these two technologies. While at 3D Systems, he invented a water soluble adhesive that can be used as a medium in between the print material and the print pad for the PJP technology, and an apparatus and accompanying process that will aid in controlled and faster cooling of the 3D printed parts built using SLS technology. Prior to joining 3D Systems, Praveen worked at an extrusion custom compounding company called Quality Thermoplastic Resins (QTR). While at QTR, he was responsible for custom developing polymer blends & alloys and engineering polymers using additives and filler to achieve specific end properties. Prior to joining QTR, Praveen was a Research Specialist at the Composite Materials & Structures Center at Michigan State University where he worked on developing biodegradable plastics and fabricating natural fiber composites. Praveen holds a Bachelor's Degree in Chemical Engineering from Andhra University (India) and a Master's Degree in Materials Engineering from Michigan State University. His Master's Degree thesis was on 'Ultraviolet Light Surface Treatment of Polymers & Polymer Composites for Enhancement in Surface Adhesion.''

Bryan Vogt, University of Akron

Bryan D. Vogt is a professor in the Department of Polymer Engineering at the University of Akron. He received his BS at Michigan Technological University in Chemical Engineering. He received his PhD in Chemical Engineering while working with Jim Watkins at the University of Massachusetts and was a NRC postdoctoral fellow with Wen-li Wu in the Polymers Division at NIST in Gaithersburg, MD. After 4 years at NIST, he joined the faculty at Arizona State University in Chemical Engineering in 2006. He received an NSF CAREER Award in 2008. He moved to the University of Akron as an Associate Professor of Polymer Engineering in fall 2011. His research interests focus on fundamental interface and self-assembly problems with an eye on potential applications and scalability for their commercialization. Areas of investigation include measurements of the mechanical properties of polymer thin films with potential impact on novel methods to improve the mechanical stability of nanostructures; combined neutron measurements and fracture mechanics to fundamentally understand the moisture resistance of polymeric adhesive joints; model porous materials for battery electrodes adsorbents and sensors to understand property-structure relationships; scalable routes to generate hierarchically porous composites for low cost sodium ion battery electrodes; nanoscale hydrogels based on supramolecular assembly; and new polymer processes for manufacture.

Chris Williams, Virginia Tech

Christopher Williams, Ph.D., is an Associate Professor and the Electro-Mechanical Corporation Senior Faculty Fellow in the Department of Mechanical Engineering at Virginia Tech. He is the Director of the Design, Research, and Education for Additive Manufacturing Systems (DREAMS) Laboratory, and the Associate Director of Virginia Tech's Macromolecules & Interfaces Institute. He is a recipient of a National Science Foundation CAREER Award (2013), the 2012 International Outstanding Young Researcher in Freeform and Additive Manufacturing Award, and the 2010 Emerald Engineering Outstanding Doctoral Research Award in the area of Additive Manufacturing. His research contributions have been recognized by eight Best Paper awards at international design, manufacturing, and engineering education conferences.

Angel Yanguas-Gil, Northwestern Argonne Institute of Science and Engineering

Principal Materials Scientist & Institute Fellow. Strong focus on the synthesis of nanomaterials for energy applications, ranging from fundamentals of materials growth and simulations to process development, and scale up of energy materials. Atomic Layer Deposition, synchrotron characterization techniques, plasma-surface interaction, wide bandgap semiconductors.

Abstracts

PANEL SESSION: CHARACTERIZATION OF MATERIALS THROUGHOUT THEIR LIFECYCLE

Moderator: Mark Dadmun, University of Tennessee-Knoxville

- Matthew Di Prima, Food and Drug Administration
- Angel Yanguas-Gil, Argonne National Laboratory
- Abraham Joy, University of Akron

FDA's perspective on 3D Printing of Medical Devices:

- Matthew Di Prima, Food and Drug Administration

While additive manufacturing (AM), commonly referred to as 3D Printing, was developed in the 1980's, it wasn't widely adopted by medical device manufactures until the new millennia. In the last few years there has been an increase in cleared medical devices made via AM. While there are a number of different AM technologies being used to make medical products; one aspect they have in common is that the final material is made at the same time as the device. This has led to greater emphasis on materials and process validation in AM devices to ensure that neither the AM technology nor the build parameters adversely affect the final performance of the additively manufactured device. This presentation will provide a high level overview of the AM devices that have been cleared by the FDA along with the technical considerations (focused on materials validation) that the Agency has when reviewing these devices.

Building to last: challenges in additive manufacturing going from prototype to functional component

- Angel Yanguas-Gil, Argonne National Laboratory

The adoption of 3D printing for the design of advanced functional materials comes with a number of challenges in terms of our understanding of the durability and performance in the field of manufactured parts. This can have a tremendous impact on any technoecomical analysis of processes relying on 3D printed parts.

In this talk I will focus on the challenges and unknowns of taking additive manufacturing from rapid prototyping to the fabrication of components with a core functionality. An important part of our research focuses on the modification of the surface chemistry of 3D printed polymer materials. Consequently, the chemical properties of 3D printed materials and their long term behavior, both in terms of their biocompatibility and their stability on chemically active environments, are critical for our applications. Based on our own experience, the development of capabilities to evaluate the materials in the field in a cost-effective manner, and the dissemination and adoption of standard techniques by non-specialists are two important gaps that need to be addressed.

3D printed polymers for biomedical applications

- Abraham Joy, University of Akron

The expanding role of 3D printing in biomedical applications has captured the imagination of both scientists and the general public. The potential of 3D printing custom biomedical products has been demonstrated by fabrication of splints for damaged tracheae, aortic valves, drug-loaded microneedles etc. Several 3D printing technologies and processes have been utilized to fabricate 3D printed polymers for these applications. This talk will briefly illustrate the various types of polymers used in 3D printing for fabrication of biomedical applications and contrast the advantages and disadvantages of each process. In addition, the talk will describe a contrasting approach developed in our lab where low modulus degradable polymers were designed to enable solvent-free 3D printing at room temperature. Irrespective of the technique or polymers used in designing polymeric 3D printed structures, translation of such scaffolds will be dependent upon their effective characterization and performance evaluation, both after fabrication and during its lifecycle. It is the intent of this presentation to catalyze this conversation.

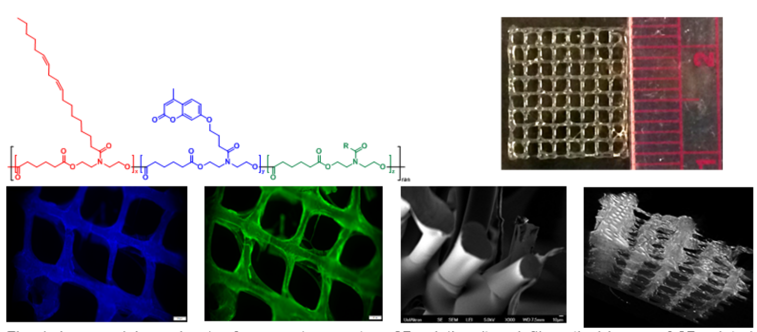


Fig. 1: Low modulus polyester for room temperature 3D printing (top, left); optical image of 3D printed structure (top, right); Fluorescence images of scaffold before functionalization with FITC (bottom); SEM and microCT images of the scaffold

PANEL SESSION: PROCESS MODELS

Moderator: Kalman Migler (NIST)

- Slade Gardner, Slade Gardner Advanced Manufacturing and Materials, LLC
- Peter Olmsted, Georgetown University
- David Roberson, University of Texas-El Paso

Elements of Generative Design Driving the Future of Process Modeling

- Slade Gardner, Slade Gardner Advanced Manufacturing and Materials, LLC

Although it is challenging, modeling polymer manufacturing processes has significantly improved the ability to produce high quality, reproducible, affordable and sophisticated articles. Additive manufacturing presents unique challenges for process models that include pseudo-controlled environment, variability of time between flow and substrate character of a material volume, absence of tooling to bound geometry, desire to change materials during a build, inconsistent start/stop and other difficult-to-control behaviors. The direction of additive design is headed towards collecting and using relevant mechanical, thermal and physical inputs for artificial intelligence driven design software and high performance computing machine learning to generate product designs that are mission inspired rather than based on legacy architectures. This capability is a tide that will raise all ships providing discrete digital information about each volume element of a structure – data that can be then incorporated in feed-forward process modeling algorithms. The challenges mentioned above for polymer additive beg the need for feed-forward modeling combined with process monitoring and feedback control in a rapidly responsive and adaptable control scheme that accounts for multiple time scales of interest. The process modeling of the future may need to occur first as a global description of the process (similar to the flow modeling of injection molding) to build confidence of high quality results and also in real time based on actual measured process circumstances. As a first step this may amount to inserting a process simulation algorithm into the feedback loop for process control variables but as high performance computing machine learning capabilities elevate, the use of artificial intelligence for process control may become the norm.

Polymer Processing issues in Additive Manufacturing

- Peter Olmsted, Georgetown University

Additive Manufacturing is exploding as a means for making personal products, with rapid design times and a multitude of evolving formats and functions. Arenas include metals, polymers, composites, biopolymers, and applications range from aircraft and automobile parts to medical implants and prototypes and tools for conventional manufacturing.
The desire and ability to create products rapidly and at small controlled scales are creating a revolution akin to the processing (such as lithographies) that underpins the electronics industry, which occurred in the 1950s-1960s. There are numerous methods for AM of polymeric materials. I will discuss some of the processing challenges faced with using polymers in the AM arena, and outline some of the specific issues that distinguish AM polymer processing from more familiar arenas of polymer processing, with a strong emphasis on fused deposition modeling (FSM).

Advanced Polymer Additive Manufacturing and Characterization

- David Roberson, University of Texas-El Paso

Increasing the disruptive nature of additive manufacturing (AM) occurs with the aid of advanced process and materials development. The following highlights efforts and achievements at the W.M. Keck Center for 3D Innovation related to polymer AM in the areas of both process and materials development. Key areas of discussion will be hybrid manufacturing techniques, novel polymer materials development, and burgeoning polymer materials characterization effort.

PANEL SESSION: IN SITU PROCESSING MEASUREMENTS

Moderator: Robert Maxwell, Lawrence Livermore National Laboratory

- Miriam Rafailovich, State University of New York at Stony Brook
- Jon Seppala, NIST
- Chris Williams, Virginia Teck

Polymer physics of weld formation during polymer extrusion 3D printing

- Jon Seppala, NIST

In polymer extrusion 3D printing, a material extrusion AM method, thermoplastic filament is extruded though a rastering nozzle onto previously deposited layers. The resulting strength of the 3D produced part is limited by the strength of the weld between each layer. While numerous factors can affect the weld strength, the temperature of the extrudate and the previous layer dictate the amount of interdiffusion and thus the weld strength. Temperature measurements were performed using infrared thermography. Isothermal weld times were calculated from temperature profiles, normalized using horizontal shift factors from offline rheological measurements. Weld strength was measured directly by mode III fracture. Since the processing conditions are known *a priori* this approach provides the data needed to estimate the final build strength at time of design. The resulting agreement between weld time estimates and weld strength for a range of printing conditions are discussed.

Molecules to Manufacturing: Expanding the Polymeric Materials Toolbox

- Chris Williams, Virginia Tech

In an effort to expand the selection of printable polymers, researchers at Virginia Tech's Macromolecules Innovation Institute (MII) are collaborating within a "Molecules to Manufacturing" paradigm. The centerpiece of this approach is shift away from tailoring AM systems for existing materials, and instead moving towards the design and synthesis of materials specifically for layer-wise processing. The research challenge with such a goal lies in the lack of formal scientific methodologies for materials screening and process parameter optimization. In this talk, we present our initial steps towards using analytical material measurements to screen materials and to efficiently identify process parameters. Examples of materials synthesized via the Molecules to Manufacturing approach will also be shared.

PANEL SESSION: PERFORMANCE

Moderator: Greg Kittlesen, FDA

- Courtney Fox, Carbon3D
- Brian Vogt, University of Akron
- Gerald Grant, University of Louisville

Functional Prototyping with Polymeric Materials

- Courtney Fox, Carbon3D

While plastics are used extensively to manufacture end-use parts through injection molding, polymeric materials for additive manufacturing have historically been limited to use as prototyping materials. Polymeric parts produced by additive manufacturing suffer from performance issues including anisotropy, surface defects, porosity, and poor mechanical properties. In particular, photopolymer systems like those used in stereolithography (SLA) are often brittle and rigid. Carbon has developed materials that can be used to rapidly produce parts with isotropic mechanical properties, layerless surfaces, and remarkable mechanical properties. These materials have been used to produce functional parts for medical, automotive, and consumer applications. In this talk we explore the performance of parts manufactured using Carbon's additive technology and propose metrics for establishing standards for manufacturing 3D printed parts.

Polymer Processing for FDM and Incorporating Functionality into 3D Printed Parts

- Brian Vogt, University of Akron

In this talk, I will briefly layout some of the processing specific challenges for FDM that impact the properties of the printed parts. These challenges tend to lead to poor mechanical performance in FDM printed parts. However, one can engineer anisotropy in these printed parts to accentuate certain failure directions, which can be normal to the applied load. The printing of cellular structures similarly provides a route to dramatically increase the impact strength of 3D printed parts. Measurements to assess the morphology, particularly void fraction in the parts, are illustrated. Finally, I will discuss the ability to control the macrostructure of responsive polymer parts through the print parameters used in generating the part.

Use of additive manufacturing in reconstruction and rehabilitation

- Gerald Grant, University of Louisville

The use of Additive manufacturing has been instrumental in the reconstruction and rehabilitation of wounded warriors. The use of imaging, digital design and printed models, implantable devices, surgical guides, extra oral prostheses, prosthetics accessories, and occupational devices have provided unprecedented opportunities to improve the wounded warriors quality of life. This presentation will include examples of how AM was used and a discussion on the need to improve printable materials, imaging, design, and more efficient workflow.

PANEL SESSION: INTEGRATION AND STANDARDS

Moderator: Carl Dekker, Met-L-Flo

- ► Scott Fish, University of Texas
- ► Praveen Tummala, 3DSystems
- ► Lyle Levine, NIST

Abstract for Integration and Standards Panel

- ► Scott Fish, University of Texas

I plan to discuss three topics from my perspective as a technology developer and partner with manufacturing industry for Polymer AM Adoption:

- Barriers adoption
- Standards as an aid to adoption
- Hard spots in standards development today

Examples will be cited for each in a quick 15-minute summary.

Factors Affecting the Adoption of SLS & PJP 3D Printing Technologies as Manufacturing Platforms – Accelerating the Adoption using Standards

- ► **Praveen Tummala, 3DSystems**

Selective Laser Sintering (SLS) and Plastic Jet Printing (PJP) are two 3D Printing technologies that are capable of delivering functional parts and hence are well positioned to be adopted as manufacturing platforms. However, both these technologies use thermoplastic polymers as print materials and hence face the complications associated with thermal processes like heating and cooling. These thermal related issues need to be overcome in order to achieve good part quality and uniform mechanical properties throughout the volume of the build. Factors like location of the parts and orientation of the parts along with commonly known factors associated with thermal and laser energy delivery have a profound effect on the final quality and properties of the parts. In situ monitoring and closed loop feedback controls can greatly help reduce the variability of these processes and make them more stable. Standards can mandate the requirement for better process controls to be in place and help achieve consistent and uniform quality and properties.

AM-Bench

- ► Lyle Levine, NIST

Dr. Levine will describe the Additive Manufacturing Benchmark Test Series (AM-Bench), that has the goal of developing highly controlled benchmark tests for validation of AM simulations by the scientific community. The AM-Bench organizing committee currently has 59 representatives from 40 organizations including five DoE labs, all three main DoD labs, four NASA centers, NIST, and numerous companies, institutes and universities.