Instrumented Laser Joining Workshop – Meeting Agenda and Abstracts

(National Institute of Standards and Technology, Boulder Colorado, USA)

July 11, 2017 (Tuesday)

Introduction

9:00-9:15 Welcome (John Lehman/Marla Dowell, NIST)

Session I: Critical parameters for laser welds

9:15-9:45	The Instrumented Weld – Establishing a Benchmark for Laser Processing Thermal Simulations	Brian Simonds, NIST
9:45-10:15	Traceable non-contact temperature measurement for advanced manufacturing	Klaus Anhalt, PTB
10:15-10:45	Laser power measurement – the state of the art	Josh Hadler, NIST

Break (Sponsored by Ophir)

11:00-11:30	Understanding Focus Behavior for High-Power Laser Welding	Stan Ream, EWI
11:30-12:00	A Facility for Emittance and Absolute Temperature Measurements of the Selective Laser Melting Process	Steven Grantham, NIST
12:00-12:15	Comments from the audience	

Lunch (Sponsored by Coherent, Inc.)

Session II: Modelling

13:30-14:00	Physics-based Model for Laser Additive Manufacturing - Needs for Material Property Data and in-situ Experimental Measurement	Wei Zhang, OSU
14:00-14:30	The Leap from Trial and Error to Accurate Predictive Modeling in Industrial Laser Welding & Bonding of Metals	David Plourde, Preco, Inc.
14:30-15:00	Multi-scale Modeling of Process Dynamics and Microstructure Development in Laser Keyhole Welding	Wenda Tan, U. of Utah

Break

15:15-15:45	Integration of Heat Transfer and Fluid Flow with Keyhole Modeling to Understand Laser Welding Processes	Todd A. Palmer, PSU
15:45-16:00	Laser Welding and Process Monitoring of Medical Devices	Neil Ball, Directed Light, Inc.
16:00-16:15	Laser Process Monitoring – Where we are now, where we want to be, and what is needed to get there	Mark Rodighiero, Amada Miyachi
16:15-16:30	Comments from the audience	

Poster session:

16:30-17:30 Poster interaction

Adjourn

July 12, 2017 (Wednesday)

Session III: Current metrology research for laser joining

9:00-9:30	Inline Coherent Imaging: Direct 3D Imaging of Laser Processes	Paul Webster, LDD
9:30-10:00	Residual stress measurements by neutron scattering	Daniel Hussey, NIST
10:00-10:30	Understanding light-matter interaction dynamics at the onset of keyhole mode laser materials processing	Manyalibo Mathews, LLNL
10:30-11:00	Additive Manufacturing Metrology Testbed (AMMT) Support for AM Process Reference Data	Brandon Lane, NIST
11:00-11:30	The Exascale Additive Manufacturing Project (ExaAM): Building on Decades of Experience and Research in Welding	John A. Turner, ORNL

Break

Summary and Report Discussion
11:45-12:30 Moderated by Paul Williams and John Lehman

Lunch

NIST Lab tours:
14:30-16:00 Tour groups
- Precision Imaging Facility
- Weld Instrumentation Lab
- Weld Metrology Lab

Workshop Close

Presentation Summaries and Speaker Biographies:

The Instrumented Weld – Establishing a Benchmark for Laser Processing Thermal Simulations

Brian Simonds (*National Institute of Standards and Technology*)

Abstract: Past research has demonstrated that laser energy transfer into metal alloys during welding can vary over an unusually broad range compared to more conventional joining techniques. Widely varying estimates of energy transfer efficiency (estimates range from ~20 % to 90 %) depend on heat absorption mechanisms and heat flow behavior in the melted region. Variations and instabilities in transfer of energy affect every material phenomenon related to metals joining including solidification mode, cooling rate, phase transformation behavior, and material properties. We demonstrate a measurement apparatus that will enable the first traceable measurements of energy transfer efficiency during laser spot welding. Our aim is to provide accurate data with known and low uncertainties for material properties and temporally-resolved energy coupling efficiency that can be used to rigorously test laser weld models. This will provide a benchmark for laser process models thus enabling more rapid refinement of laser joining processes. Improved thermal simulations of materials processing including laser welding and laser additive manufacturing can be made by simply changing out the reference material.

Biography: Brian received his Ph.D. in Applied Physics at the Colorado School of Mines in 2012. After completing a postdoctoral appointment at the University of Utah in 2014, he came to NIST as a National Research Council Postdoctoral Fellow. Currently a NIST physicist, he is developing advanced spectroscopic tools for studying industrial laser-materials processing. He has published research in wide range of subjects including single electron transistors, quantum dots, thin-film solar cells, laser processing of semiconductors, and now laser welding.
Email: brian.simonds@nist.gov

Traceable non-contact temperature measurement for advanced manufacturing

Klaus Anhalt (*Physikalisch-Technische Bundesanstalt*)

Abstract: For advanced manufacturing techniques, such as additive manufacturing, laser joining or surface heat treatment by laser a precise measurement and control of the absolute surface temperature is essential to achieve a reproducible quality in industrial applications.

Radiation thermometers and thermal imaging systems, typically measuring in the wavelength range between 700 nm and 2000 nm, are often used to measure the temperature. For the example of laser hardening the achievable accuracy of industrial temperature measuring devices has been investigated and systematically been improved at PTB and Fraunhofer IWS, Dresden Germany. A temperature deviation of more than 5 to 10 Kelvin can cause instable processes and heavy melting of the surface during the processing of special high alloyed steel grades or cast iron materials. Measurement uncertainties of this order can be difficult to achieve due to the non-linear signal damping by the laser optics in the case of co-axial view of the measurement device or the wear of optical components (e.g. caused by processing fumes) during their lifetime resulting in a continuous drift of the measurement signal.

On-site calibration is necessary as the temperature measurement devices are often mechanically and electrically integrated into complex and large machine systems. For this reason, a mobile calibration technique with inductively heated high temperature fixed points has been developed and tested in different industrial set-ups. Additionally, the influence of the emissivity on the uncertainty of the temperature measurement has been investigated for steel and cast iron.

Biography: Klaus Anhalt studied experimental physics in Marburg, Manchester and Berlin and obtained a PhD from the Technische Universität Berlin in 2008. He is a researcher at the Physikalisch- Technische Bundesanstalt, the national metrology institute in Germany, in the division “Detector Radiometry and Radiation Thermometry”. He has more than 15 years experience in the fields of radiometry, radiation thermometry above 1000 °C, high-temperature fixed-points, and emissivity measurements. He is co-opted member of the CCT working group on Radiation Thermometry for his expertise in high-temperature fixed-point research and absolute radiometric temperature measurement.
Email: klaus.anhalt@ptb.de

Laser Power Measurement – the State of the Art

Josh Hadler (*National Institute of Standards and Technology*)

Abstract: The needs of laser welding and additive manufacturing processes are already pushing the limits of conventional laser power measurement technologies. This talk will discuss aspects of the nature of laser power measurement technology and application to laser joining practices: What the current state of the art can deliver, where current industry practices typically are, what limitations already exist, and where the next generation of laser power measurement technology may be able to be implemented.

Biography: Josh Hadler is a physicist in the Sources and Detectors Group in the Physical Measurement Laboratory of the National Institute of Standards and Technology. He is the calibration leader for the High Power Laser Measurement Service at NIST, providing laboratory calibration services up to 10 kW cw. He also serves as the NIST Laser Safety Officer.
Email: josh.hadler@nist.gov

Understanding Focus Behavior for High-Power Laser Welding

Stan Ream (*EWI*)

Abstract: When multi-kilowatt, CO_2 lasers emerged in the early '70s, the techniques for finding and quantifying focal spots were crude at best. "Lucite" burns were a common solution to all sorts of beam quality questions. These were far from accurate and did not illustrate steady state conditions. Decades later, as shorter wavelength, higher beam quality lasers broke into the multi-kilowatt regime, the business of focal spot characterization became much more important. The introduction of the Primes Focus Monitor marked a turning point in our understanding and quantification of focus quality. And, now, with the recent emergence of Ophir's Beam Watch instrument, we can observe and quantify real-time focus behavior. These two instruments are providing essential understanding and insight into previously misunderstood laser welding behavior.

Biography: Stanley Ream is an internationally recognized expert in industrial lasers, process development and analysis, and manufacturing systems design and performance. As Laser Technology Leader at EWI, Mr. Ream focuses his experience on solutions to the joining challenges facing all EWI industry sectors.

Mr. Ream is a pioneer in the development of laser materials processing technologies. Starting in the '70s with his participation in high-power laser welding development for the Air Force, Navy, and NASA, Mr. Ream has continued to contribute to a broad range of laser applications and production implementations. Through his previous diverse employment experiences, including Sciaky Bros., AVCO Everett Research Laboratories, IIT Research Institute, Battelle, Amada, GE Fanuc, and Worthington Industries (TWB), and Edison Welding Institute, Mr. Ream has gained a broad perspective on the technological and marketing forces that have shaped the laser materials processing world.

Mr. Ream holds twelve patents in laser and electron beam technologies, and a B.S. and M.S. in Welding Engineering from The Ohio State University. He is a Fellow of the Laser Institute of America (LIA) and a Senior Member of AWS, SME.
Email: sream@ewi.org

A Facility for Emittance and Absolute Temperature Measurements of the Selective Laser Melting Process

Stephen Grantham (*National Institute of Standards and Technology*)

Abstract: The National Institute of Standards and Technology (NIST) is currently developing a facility for the study of the process of selective laser melting (SLM) used in powder-bed fusion for additive manufacturing. The Temperature and Emittance of Melts, Powders and Solids (TEMPS) system is currently under development to complement the Additive Manufacturing Metrology Testbed (AMMT). The TEMPS facility will expand its established emittance and radiance measurement capabilities to include higher sample temperatures and more sample forms including powder and liquid and provide traceability for primary functions of the AMMT.

For measurement of the temperature distribution of the SLM melt pool, it is understood that radiometry in the SLM environment may encounter numerous potential difficulties and TEMPS is designed to overcome this challenge. In this paper, we shall describe the techniques incorporated to meet the requirements for high temperature radiometry during the SLM process. Further, we shall present the optical design of the system which spans the 400 nm to 10,000 nm wavelength range along with results from the table top commissioning of the TEMPS optical system.

Beyond SLM, the TEMPS system provides a platform for high temperature emittance measurements on materials in various forms, both solid and liquid, and under either vacuum or an inert gas atmosphere environment. This will enable NIST's Physical Measurement Laboratory the capability to cater to customers' requirements that are currently out of reach. Our goal is to provide emittance and absolute temperature measurements at high temperatures well beyond our current capabilities, for the SLM community as well as for participants in other high temperature materials applications.

Biography: Steven Grantham joined NIST in 1999 after receiving his PH.D. in Optical Science and Engineering from the University of Central Florida's Center for Research and Education in Optics and Lasers (CREOL). He has over a decade of experience laser-matter interactions as well as optical and Optomechanical instrument design. He is part of NIST's Physical Measurement Laboratory's team for development of the Additive Manufacturing Metrology Testbed (AMMT) and the Temperature and Emittance of Melts, Powders and Solids (TEMPS) system.
Email: steven.grantham@nist.gov

Physics-based Model for Laser Additive Manufacturing - Needs for Material Property Data and in-situ Experimental Measurement

Wei Zhang (*The Ohio State University*)

Abstract: Physics-based model is essential to establish the fundamental understanding of process-microstructure-property relations for laser additive manufacturing. Such relations, in turn, are crucial for certification of parts built by additive manufacturing. Important material property data inputted to the model includes thermal conductivity, specific heat, surface tension and viscosity as a function of temperature and chemical composition. Moreover, in-situ experimental measurement of laser intensity profile, absorptivity, temperature distribution and molten pool boundary is important to validate and improve the physics-based model. In this talk, a molten pool model for laser powder bed fusion is described. Results of preliminary high-speed video and infrared thermography are presented. Needs for material property data and in-situ measurement are discussed.

Biography: Associate Professor in Department of Materials Science and Engineering at The Ohio State University. Ph.D. in Materials Science and Engineering from Pennsylvania State University in 2004. Research area in multi-physics modeling of welding and additive manufacturing processes, and microstructure-mechanics constitutive behaviors.
Email: zhang.3978@osu.edu

The Leap from Trial and Error to Accurate Predictive Modeling in Industrial Laser Welding & Bonding of Metals

David Plourde (*Preco, Inc.*)

Abstract: Mr. Plourde will discuss a potential roadmap to enhancing the commercial laser welding process by development of cost effective, predictive, weld models as integrated into and harmonized by predictive capability models of the laser welding machine tool. The presentation will address select variables deemed necessary for successful implementation of critical laser welding applications. Issues addressed will include requirement of desired joining specification, metallurgy, selection of a specific laser technologies, material handling, joint design, joint preparation, process control, post processing considerations, inspection techniques, in situ monitoring and inspection, post inspection and post weld laser machine tool monitoring and maintenance verification.

Biography: David G. Plourde has a Master of Organizational Leadership from the University of Northwestern St. Paul Minnesota and more than 30 years' experience in industrial laser welding. Mr. Plourde is the Executive Vice President of Preco Inc., Somerset, Wisconsin, and supports the commercial development, and implementation, of industrial laser

welding machine tools and laser processes. Preco Inc. supports a wide range of industries and educational institutions, including energy, aerospace, automotive, medical and defense.
Email: dplourde@precoinc.com

Multi-scale Modeling of Process Dynamics and Microstructure Development in Laser Keyhole Welding

Wenda Tan (*University of Utah*)

Abstract: Laser keyhole welding is a complex process that involves multi-scale, multi-phase, and multi-physics phenomena. Numerical modeling has been used as an important approach to assist experimentation in understanding laser keyhole welding process. A comprehensive modeling framework has been established to this end. A 3-dimensional macro-scale model is used to simulate the laser-matter interaction, keyhole evolution, and heat transfer and fluid mechanics; a meso-scale model is used to simulate the 3-dimensional grain growth during the solidification of the entire molten pool; and a micro-scale model is used to simulate the dendrite morphology evolution within the grains. The models are used to reveal the effects of welding parameters on some critical issues, such as pore formation and microstructure development, both of which are critical to the property and performance of the weldment.

Biography: Dr. Wenda Tan is an assistant professor of Mechanical Engineering at the University of Utah. He received his BS and MS degrees in Mechanical Engineering from Tsinghua University, China, and his PhD degree in Mechanical Engineering from Purdue University. His major research interests include the computational heat transfer, fluid mechanics, and materials in laser-based manufacturing processes, including but not limited to laser welding and additive manufacturing.

Integration of Heat Transfer and Fluid Flow with Keyhole Modeling to Understand Laser Welding Processes

Todd A. Palmer (*Pennsylvania State University*)

Abstract: Keyhole mode laser welding is characterized by the combination of a rather large number of simultaneous physical phenomena that make accurate prediction of the resulting weld pool geometry and the thermal history produced by the laser welding process difficult. Previous efforts at modeling the formation and growth of the keyhole have consistently integrated a number of simplifying assumptions into the models, resulting in the inability to accurately predict weld pool geometry and temperatures for different material systems. A comprehensive model that integrates a point-by-point heat balance of the keyhole profile with a turbulent heat transfer and fluid flow calculations has been demonstrated to accurately calculate weld pool cross sections for a range of materials. Using the temperature and fluid flow outputs of this model, a deeper understanding of the complex solidification structures as well as the formation of a range of defects in deep penetration laser and laser-arc hybrid welds has been obtained. The promise of integrating this comprehensive modeling approach with diagnostic tools is great, particularly to increase the understanding of temporal keyhole formation and events which lead to keyhole collapse. With the growing use of laser-based joining processes in a variety of industries from shipbuilding to the medical device industry, a comprehensive understanding and ability to predict weld geometries as well as defect formation is needed. However, much of the utility of these modeling approaches is currently limited by a dearth of accurate high temperature thermo-physical properties for alloy s of interest.

Biography: Todd A. Palmer is currently a Senior Research Associate and an Associate Professor of Materials Science and Engineering at the Pennsylvania State University. Previously, he was a metallurgist at Lawrence Livermore National Laboratory. He is the author of more than 70 articles and reports, and his current research focuses on the laser and electron beam joining and additive manufacturing of metallic materials. He is currently chair of the C7 Committee on High Energy Beam Welding and Cutting and a member of the newly formed D20 committee on additive manufacturing, the Welding Handbook, and Welding Research and Development Committees for the American Welding Society

(AWS). He is a member of the editorial board for *Science and Technology of Welding and Joining* and a key reader for *Metallurgical and Materials Transactions* as well as a principal review for the *Welding Journal Research Supplement*. Email: tap103@arl.psu.edu

Laser Welding and Process Monitoring of Medical Devices

Neil Ball (*Directed Light, Inc.*)

Abstract: This presentation will examine existing techniques for weld monitoring and process controls in the welding of implantable devices as well as other medical instruments and surgical tools. In addition I will explore future advancements and methods for improving production control and increase yields.

Biography: Neil Ball is the president of Directed Light Inc, of San Jose, California. Directed Light Inc is a laser technology company serving the industrial, medical and scientific laser communities worldwide since 1983. Neil has devoted his adult working life to the industrial laser industry. He began his career in 1985 as an application technician in the contract manufacturing sector at LaserFab, Inc. in California. After developing his laser knowledge, he moved to Systron Donner Inertial and became involved in the production of inertial guidance packages, accelerometer, gyroscopes and inclinometers. Neil joined Directed Light Inc in 1993 to assist in applications development, system design, and component/service support. In 2005 he became President of Directed Light Inc. He is still active in systems and applications development. Neil has led the marketing and developing sales plans for both national and international arenas and is the resident methodologist, working on projection of future industry trends.

Neil is a Fellow and sits on the Board of Directors for The Laser Institute of America. In addition he is a member and Educational Council Director for the Industrial Laser Community of the Society of Manufacturing Engineers. In addition he holds memberships with The American Welding Society, Fabricators and Manufactures Association, and The American Society of Lasers in Medicine and Surgery.
Email: neil.ball@directedlight.com

Laser Process Monitoring – Where we are now, where we want to be, and what is needed to get there

Mark Rodighiero *(Amada Miyachi America, Inc)*

Abstract: Over the years, there have been many attempts to correlate measurable phenomena produced by laser processes to quality characteristics of the end results. Measurable phenomena studied have included back-reflected IR (laser wavelength) and a few fairly broad slices of optical and acoustical spectra produced by laser - material interaction. Simple aggregation calculations (e.g., RMS, Peak, mean value) and boundary comparisons (upper and lower limits) have been applied to the collected data and correlated to laser process quality measures. In most cases, however, we are nowhere near able to classify the quality of desired process characteristics with sufficient accuracy to reduce or eliminate expensive manual inspection, to guarantee aggressive production defect rates, or to identify the root cause of the defects.

In this presentation, we will explore why our present methods yield such unsatisfying results and what is missing from our present data collection and analysis toolsets. We will show how new tools for data gathering and modern approaches to data analysis will allow us to make much better use of the measured data and achieve a much higher process defect classification accuracy. We will then outline a path forward to collecting more meaningful data and achieving superior process quality classification.

Biography: Mark Rodighiero - EVP, Technology and Business Development – Amada Miyachi America, Inc., Monrovia, CA. Current activities include developing and commercializing new technology and methods for material processing, including laser-based material processing, precision control systems, and advanced process monitoring methods. Thirty-five years of R&D engineering and management experience, including power and control systems, RF subsystems,

computer hardware and software development, communications and networking, mathematical pattern recognition, and machine learning. BSE, California State University, Los Angeles; MSEE, University of Southern California
Email: Mark.Rodighiero@amadamiyachi.com

Inline Coherent Imaging: Direct 3D Imaging of Laser Processes

Paul Webster (*Laser Depth Dynamics*)

Abstract: Laser processes have no shortage of advanced imaging techniques available for visualization. However, few of them boast the ability to provide 5 µs time resolution, micron-scale spatial resolution and the ability to be directly transferred out of the lab and into serial production. Inline Coherent Imaging (ICI) provides this unique array of benefits to keyhole laser welding and many other laser processes. While it is an emerging industrial product for the welding market, the understanding of the dynamics revealed by ICI are still in the early stages, especially for newer additive processes. This talk will be an overview of the technique, the kinds of data that can be produced and the current state of our interpretation of the results.

Biography: Paul Webster completed his doctoral degree with James Fraser at Queen's University in 2012. There he held an Alexander Graham Bell Canada Graduate Scholarship and authored many journal articles and conference papers on the topic of coherent imaging of laser processes. He is an inventor of the patented Inline Coherent Imaging laser weld monitoring technology which he is commercializing as the CTO of Laser Depth Dynamics and for which he was awarded the 2012 Martin Walmsley Fellowship for Technical Entrepreneurship.
Email: pwebster@laserdepth.com

Residual stress measurements by neutron scattering

Daniel Hussey (*National Institute of Standards and Technology*)

Abstract: Neutrons readily penetrate through a few centimeters of thickness of most metals and are non-destructive. Using Bragg-edge imaging one can map the strain along the beam direction with high spatial resolution (50 µm) with reasonably high strain resolution (100 µε). An example of a hybrid weld examined by Bragg-edge imaging will be given. Using dark-field neutron imaging, one can also measure porosity and grain structure over length scale ranges from 10 nm to 1 µm. This is like a small angle scattering image, where each 50 µm pixel contains a SAS pattern to reveal the underlying microstructure. This method has been used to examine an additively manufactured sample that has undergone torsional stress and there is evidence of the beginning of a crack formation. In both cases, the measurements require about an hour of acquisition time.

Biography: Dr. Daniel S. Hussey joined NIST as an NRC Postdoc in 2004 applying neutron imaging to measuring water in operating hydrogen fuel cells. His research focus is the development and application of quantitative neutron imaging methods for energy and material science research. He was awarded a PECASE in 2009 and the Arthur S. Flemming award in 2016.
Email: daniel.hussey@nist.gov

Understanding light-matter interaction dynamics at the onset of keyhole mode laser materials processing

Manyalibo Matthews (*Lawrence Livermore National Laboratory*)

Abstract: Accurate prediction of the material response associated with any laser materials processing technology depends on precise knowledge of the energy coupling mechanisms active during the laser-matter interaction. For example, in deep penetration laser welding, complex hydrodynamics driven by vapor recoil and Marangoni convection lead to liquid metal interfaces that are steeply curved thereby affecting Fresnel absorptivity (keyhole mode absorption). On the other hand, deep keyholing during laser powder bed fusion processing can lead to part defects and is generally

avoided, although vapor recoil is still a dominant mechanism in the laser-material interaction. To clarify the complex physics and provide data for model validation, an experimental set up is required that is capable of studying the melting and vaporization process with sufficient energy, spatial and temporal resolution. In the present work, a laser calorimetric test bed is developed and used to study changes in energy coupling as a function of laser power above the melting point for bulk metal plates and metal powder layers of 316L stainless steel, aluminum and tungsten. High speed optical imaging is used to capture morphological changes during laser weld track experiments and is compared with finite element simulations of the keyhole formation process. The measurements and analysis presented here offer new insights into the changes in optical absorptivity as a function of laser parameters which might be exploited to improve efficiency and overall process quality.

Biography: Manyalibo ("Ibo") J. Matthews currently serves as Deputy Group Leader in the Optical Materials and Target Science group in MSD. He holds a PhD in Physics from MIT, and a BS in Applied Physics from UC Davis. His research interests at LLNL include novel applications in laser-assisted material processing (e.g. metal additive manufacturing, laser-based CVD, nano-coarsening of metal films, non-contact laser polishing of glass), optical damage science, vibrational spectroscopy and in situ optical characterization of transient processes. Prior to LLNL he was a Member of Technical Staff at Bell Labs, Lucent Technologies in Murray Hill, New Jersey and worked on materials characterization of optical devices using novel spectroscopic techniques, stress-induced birefringence management in planar optical devices and research in advanced broadband access networks. Dr. Matthews is a Fellow of the Optical Society of America.
Email: ibo@llnl.gov

Additive Manufacturing Metrology Testbed (AMMT) Support for AM Process Reference Data

Brandon Lane (*National Institute of Standards and Technology*)

Abstract: NIST's Engineering Laboratories and Physical Measurement are jointly developing the Additive Manufacturing Measurement Testbed (AMMT) / Temperature and Emittance of Melts, Powders and Solids (TEMPS) facility. This facility enables research into monitoring, controls, and process development for laser powder bed fusion additive manufacturing (AM) and similar processes, with a goal of traceable, true temperature measurement of the laser-induced melt pool and heat affected zone. In this talk, the high-level system design is reviewed, with emphasis on the optical system design for AM process monitoring and temperature measurement. Finally, the metrology requirements for true temperature melt pool thermometry are reviewed, with discussion system design, measurement process approach, and initial test results.

Biography: Brandon Lane is a Mechanical Engineer in the Intelligent Systems Division of the NIST Engineering Lab, and leads the Real-Time Monitoring and Controls for Additive Manufacturing project. He co-leads development of the Additive Manufacturing Metrology Testbed (AMMT), and has expertise in applied thermography and radiometric thermometry of high temperature manufacturing processes.
Email: brandon.lane@nist.gov

The Exascale Additive Manufacturing Project (ExaAM): Building on Decades of Experience and Research in Welding

John A. Turner (*Oak Ridge National Laboratory*)

Abstract: Additive manufacturing (AM), or 3D printing, of metals is transforming the fabrication of parts by reducing the weight of final parts, reducing waste (and hence energy) in the manufacturing process, and dramatically expanding the design space, allowing optimization of shape and topology. However, there remain challenges in qualification of AM parts due to the unique physical phenomena inherent in AM processes. Although the physical processes involved in AM are similar to those of welding, a field with a wealth of experimental, modeling, simulation, and characterization research over the past decades, the failure rate for new AM parts is often as high as 80%. While modeling approaches and simulation tools for welding and similar processes are quite mature, and have been calibrated to the point that they are approaching predictive capability, they are proving to be inadequate for AM processes. We believe this is in part due to the fact that

the process-structure-property-performance relationship is typically treated in an uncoupled manner, relying on tabular databases and hence unable to adequately capture the rapid dynamics and non-equilibrium nature of AM processes.

The Exascale Additive Manufacturing Project (ExaAM) is a collaboration between U.S. Dept. of Energy laboratories as part of the Exascale Computing Project (ECP). ECP is a broad program including research efforts in hardware component and system design, system software, system acquisition and deployment, and science application development to deploy a computational ecosystem capable of delivering at least fifty times the performance of today's largest systems.
ExaAM is one of the applications selected for the development and implementation of models that would not be possible on even the largest of today's computational systems. With the prospect of Exascale computing resources in mind, one of the goals of ExaAM is to remove some of the limitations noted above by coupling high-fidelity sub-grid (mesoscale) simulations within continuum-scale process simulations to determine microstructure, properties, and hence performance using local conditions.

We briefly describe the overall goals and elements of ECP as well as the technical approach being taken in ExaAM and plans for verification and validation through collaboration with efforts such as AM-Bench, a set of benchmark test problems under development by a team led by NIST.

Biography: Dr. John A. Turner has almost 25 years of experience applying computational science to challenging problems ranging from nuclear energy and stockpile stewardship to battery safety. He is a Distinguished R&D Staff Member at Oak Ridge National Laboratory (ORNL), and serves as Group Leader for Computational Engineering & Energy Sciences, Chief Computational Scientist for the Consortium for Advanced Simulation of Light-Water Reactors (CASL), Principal Investigator for the Consortium for Advanced Battery Simulation (CABS), and ORNL lead for the High Performance Computing for Manufacturing (HPC4Mfg) Program. He is a Joint Faculty Professor in both the Bredesen Center for Interdisciplinary Research and Graduate Education at the Univ. of Tennessee in Knoxville and the National Center for Computational Engineering at the Univ. of Tennessee in Chattanooga. John received his Ph.D. in Nuclear Engineering from North Carolina State University in 1990. Until 1997 he worked at Los Alamos National Laboratory (LANL), when he joined Blue Sky Studios, earning credits on the Academy Award nominated feature film "Ice Age" and the Oscar-winning short animated film "Bunny". In 2001 he returned to LANL, and since 2008 has been at ORNL.
Email: turnerja@ornl.gov