Additive manufacturing (AM), also known as direct digital manufacturing (DDM), is the focus of two symposia at MS&T 2011, affording attendees an outstanding opportunity to update their knowledge of this high tech materials and processing topic (see sidebar). The “Mechanical Properties of Additive Manufactured Materials and Components” session discussed in this article focuses on the mechanical properties of metallic materials and components formed by additive manufacturing using lasers and the interrelationship of mechanical properties, microstructure, and processing. It addresses the question: What is needed to enable metallic products formed by additive manufacturing using lasers or other heat sources to become a baseline design option?

These symposia should be of interest to materials suppliers and system developers who realize the potential of AM, process simulators, corporations that seek to strategically exploit this technology, university researchers, and government organizations that stand to benefit from the insertion of this transformative technology into the U.S. industrial base.

What is needed to enable metallic products formed by direct digital manufacturing using lasers to become a baseline design option?

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Additive manufacturing of metallic materials and components

There are a number of manufacturing processes that are categorized as additive manufacturing. Although differing in details, all share common steps. They start with a computer-aided design (CAD) file—a computer generated three-dimensional representation of the component to be manufactured. Computer software slices the digital image into multiple layers. A machine reads the sliced digital image and builds the component layer by layer as illustrated in Fig. 1.

AM processes for producing metallic materials and components challenge conventional formative manufacturing processes, such as casting, rolling, forging, and fabrication, through efficient methods of consolidating metallic feed stock into highly complex shapes. AM processes are applicable to on-demand production of high-value components having complex shapes, while minimizing material waste and compressing the design-to-production cycle. The additive nature of AM processes also enables unique design features not possible using conventional manufacturing techniques, such as creating complex internal features, varying material functionality for load paths, and locally altering material for wear and corrosion resistance, to name a few. AM processes relevant to the manufacture of engineered parts include the use and manipulation of precise, high-energy heat sources, such as laser and electron beams, for consolidation of powder or wire stock provided at the point of addition or through a continually recharged powder bed.

Although all AM processes are capable of producing metallic shapes, attributes such as metallurgical properties, surface finish, deposition rates, and component size are important considerations in the economic and technical decisions that influence process selection. In general, processes that provide high deposition rates favor near-net-shape production that requires post-process machining; whereas, processes that use lower build rates offer superior quality. In all cases, the ability to quickly create near-net- or net-shape components through a distributed design, analysis, and manufacturing network offers a new paradigm for industry. Broad adoption of this technology...
will provide an immediate impact on the suitability, affordability, and availability of critical components throughout industry, as well as enabling the exploitation of innovative designs and materials not possible using traditional manufacturing methods.

For the U.S. industrial base to realize the potential of AM technology for production of highly engineered metallic components requires the collaboration and collective expertise of organizations involved in all aspects of the technology. Foremost, the reliability of the process and quality of the product must be guaranteed and capable of consistently producing components and structures that meet the intended performance requirements dictated by the application. Standardized practices, materials, and techniques for producing high-quality components must be identified and validated for AM, and advanced sensing and control technology offers enormous potential for improving and ensuring process consistency during extended operation. Management, design, and production functions within an organization, as well as the operational system, must be structured to accommodate AM design, manufacturing, and certification processes. As with any disruptive technology, full exploitation of additive manufacturing requires education and training of managers, engineers, and technologists involved in all aspects of the design, manufacturing, and insertion processes.

**Laser additive manufacturing (LAM)**

Discussions of presentations on AM at the “Laser Applications in Materials Processing (I)” symposium at MS&T 2010 identified the availability of mechanical properties data and standardized measurement methods as being barriers to the development of laser additive manufacturing, which led to the focus of this year’s symposium. The goal of the “Mechanical Properties of Additive Manufactured Materials and Components” session is to highlight current efforts to overcome these barriers. The speakers will address questions such as:

- What materials and properties are of current interest and why?
- How dependent are properties on deposition variables?
- How reproducible are mechanical property results?
- Can properties reliably be predicted by modeling?
- Where is the engineer to go for data to support selecting LAM materials and components?

Co-authors Ricky Martin, Kevin Slattery, and David Dietrich from the Boeing Co., St. Louis, Mo., will present the keynote talk giving the perspective of a corporation that has long been involved in efforts to exploit this technology. They point to verifying cost competitiveness and developing an industry-shared design property database to support component design and analysis as being the primary challenges to the broad implementation of metal additive manufacturing (MAM). They present an overview of MAM titanium technology development activities at Boeing, emphasizing recent accomplishments in overcoming the challenges to pervasive implementation of this technology.

Two presentations give the perspective of the AM systems suppliers. Co-authors Jyotirmoy Mazumder and Sudip Bhattacharyya (University of Michigan, Ann Arbor) and Bhaskar Dutta (POM Group Inc., Auburn Hills, Mich.) review the mechanical properties of materials and critical microstructures of a number of ferrous and nonferrous al-

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**Additive Manufacturing Technology at MS&T 2011**

The research described here will be presented during “Mechanical Properties of Additive Manufactured Materials and Components,” the Tuesday morning, October 18, session of the “Laser Applications in Materials Technology (II)” symposium organized by the Emerging Technologies Awareness Committee of ASM International. The reader’s attention is also directed to the “Additive Manufacturing of Metals” symposium comprising six sessions scheduled Monday afternoon, October 17, through Thursday morning, October 20.

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![Fig. 1 — Direct metal deposition of a titanium aerospace structure using electron-beam technology: (a) digital representation; (b) fabricated component. Courtesy of Sciaky Inc., Chicago.](image-url)
loys produced by direct metal deposition (DMD), an AM processes developed at University of Michigan and marketed by the POM Group. They will present data for aluminum, tool steel, copper-nickel, nickel-base superalloys, and titanium alloys. Co-authors John Smuggeresky (Sandia National Laboratories, Livermore, Calif.) and David Keicher and Richard Grylls (Optomec Design Co., Albuquerque, N. Mex.) will discuss mechanical property design using laser engineered net shaping (LENS), a process developed at Sandia and marketed by Optomec Design. For Type 316 stainless steel, they report tensile yield strengths between two to three times those of conventionally processed materials with little change in ductility.

Cost is clearly a challenge to the development of laser additive manufacturing. Co-authors Shawn M. Kelly, Michael J. Policelli, and Kenneth C. Meinert (Applied Research Laboratory, Penn State University, State College, Pa.) and Binky Sargent and Paul A. Prichard (Technology Center, Kennametal Inc., Latrobe, Pa.) investigate the possibility of using recycled Ti-6Al-4V powder for DDM. Tensile and high-cycle fatigue properties of virgin plasma rotating-electrode process (PREP) powder and recycled PREP powder are compared. Figure 2 shows a titanium foil shape being laser deposited at the Laser Process Div., Applied Research Laboratory, Penn State.

Standardization is an important cost-reduction strategy. David Bourell (University of Texas, Austin) will review efforts to predict, measure, control, and report mechanical properties with emphasis on three laser-based AM processes: stereolithography, laser sintering, and powder-based deposition processes. His presentation will provide broad coverage of the microstructural/mechanical property connection, processing effects on specific mechanical properties, and specification efforts of the ASTM F42 Committee on Additive Manufacturing. He is an active
member of ASTM Subcommittee F42.05 on Materials and Processes. The National Center for Manufacturing Science (NCMS), Ann Arbor, Mich., is very active in promoting laser additive manufacturing. Constance J. Philips (NCMS), who serves as Membership Chair of the ASTM F42 Committee on AM, will share NCMS program experiences from several R&D projects aimed at developing advanced laser-based technologies and inserting them in defense and commercial operations with the ultimate objective of seeing these technologies reach commercial production and market adoption. Co-authors, April Cooke (NIST, Gaithersburg, Md., and University of Maryland, College Park), John Slotwinski (NIST) and Kevin Ayers (Federal Bureau of Investigation) compare the mechanical properties of metal parts made by AM and tested using traditional methods to those determined using ultrasonic measurements. April Cooke is an active member of ASTM Subcommittee F42.91 on Terminology.

Co-authors Khershed Cooper (Naval Research Laboratory, NRL, Washington, D.C.) and Ralph Wachter (Office of Naval Research, ONR, Washington, D.C.), point out that manufacturing for DoD requires the process be accredited and certified. Most AM processes are not. They explore the potential of a new ONR basic research program, cyber-enabled manufacturing systems (CeMS), which add a computational “architecture” layer to better control the desired properties of a part during its manufacture by using real-time data, derived in-situ, to guide the manufacturing process and document every step. They suggest that CeMS has the potential of accelerating qualification, verification, and validation of additive manufacturing, making it as accepted and used as CNC machining is today.

Co-authors Mool Gupta, Tyson Baldridge, and Chen-Nan Sun (University of Virginia, Charlottesville) report on the investigation of laser and electron-beam sintering and cladding for processing ultrahigh-temperature ZrB2 and ZrB2-based ceramic metal composites. They report on material properties such as hardness, thermal expansion, thermal conductivity, heat capacity, and thermal diffusivity.

Additive manufacturing has the potential to enable on-demand fabrication and repair of damaged components in remote or inaccessible locations. Co-authors, Craig Brice, Karen Taminger, and Rob Hafley (NASA Langley Research Center, Va.), and Dalia Gonzalez (NASA Johnson Space Center, Houston) present the results of a recent experience to fabricate an aluminum tool component for an International Space Station servicing mission. Sean Kelly (Applied Research Laboratory) points out that DDM processes such as laser deposition are used for complete fabrication of new components, adding complex features to simple components, and for repair of existing high-value components. The thermal conditions resulting from each case are different, as is the ability to provide post-deposition heat treatment. As a result, different mechanical properties are anticipated. He reports on the use of laser deposition to produce thin wall repairs consisting of Ti-6Al-4V powder laser deposited onto Ti-6Al-4V plate. Tension and bending fatigue data are reported. ☞

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