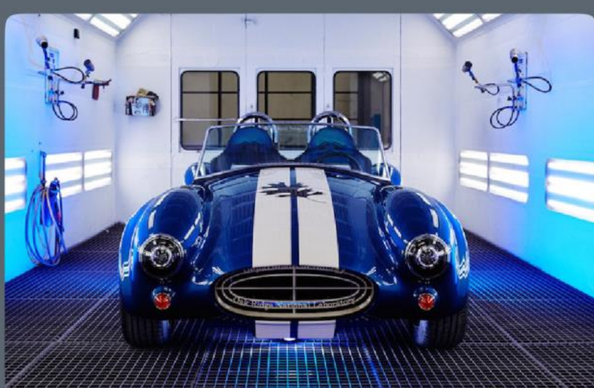
Spotlight

Additive Manufacturing: Building the Future

Updated July 2019



U.S. DEPARTMENT OF ENERGY | Office of TECHNOLOGY TRANSITIONS

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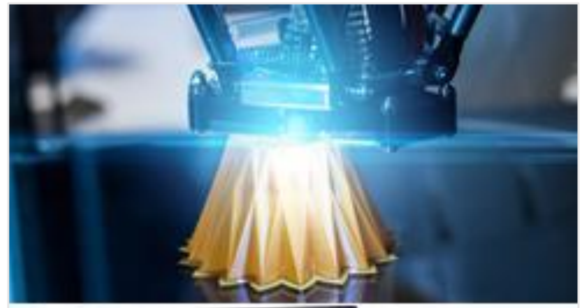
Critical Need for Additive Manufacturing

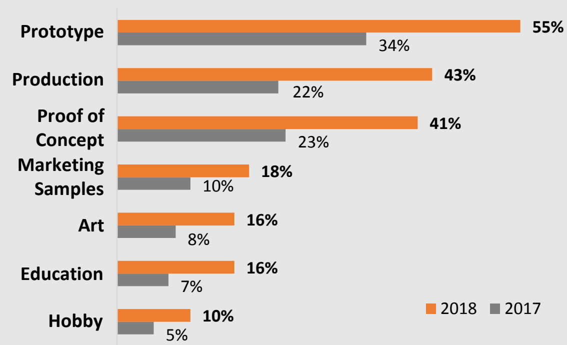
Additive manufacturing (AM), often called 3D printing,[1] uses a computer-aided design (CAD) file to precisely control layer-by-layer, or point-by-point, buildup of material into three-dimensional objects. The technology can vastly improve manufacturing processes by eliminating the design constraints and material waste of traditional processes like casting or machining. Ultimately, AM could produce parts energy efficiently that meet or exceed the functional requirements of existing products yet weigh far less. Today's AM technologies already benefit critical economic sectors, from buildings to aerospace and defense (A&D). Applications include rapid prototyping, tailored medical prosthetics, on-site part repairs, mold casting, and other consumer and industrial products.

Wider use of AM components is restricted, in part, by the inability to validate and verify AM part quality and structural integrity, particularly in tightly regulated industries like A&D, biomedicine, and transportation. In addition, materials costs can be high, and improvements are needed in process controls, surface finishes, and throughput to enable broader adoption of AM techniques and products. Despite these challenges, the potential economy-wide savings from broader adoption of AM systems are significant. The U.S. Department of Energy (DOE) estimates that (compared to traditional manufacturing) AM might slash waste and materials costs by nearly 90% and cut manufacturing energy use in half.[2] Today's AM industry is valued at over $14 billion globally and is expected to grow to $23 billion by 2022.[3]

DOE pursues research and development (R&D) to achieve these AM benefits, strengthen U.S. competitiveness, and create domestic manufacturing jobs. DOE and its National Laboratories form R&D partnerships with U.S. companies and universities to leverage resources and accelerate progress. Effective teamwork by the labs, industry, academia, and other agencies or organizations is moving AM toward broader commercial adoption.



AM Adoption is Rapidly Growing for Diverse Applications



Mostly used for prototyping, production and proof of concept, implementation of 3D printing technologies is increasing globally.

Sculpteo, "The State of 3D Printing, 2018." sculpteo.com/media/ebook/State_of_3DP_2018.pdf

[1] AM refers to many technologies, including subsets like 3D printing, rapid prototyping, direct digital manufacturing, layered manufacturing and additive fabrication.
[2] "What is Additive Manufacturing?" U.S. Department of Energy. October 2017. energy.gov/eere/articles/what-additive-manufacturing
[3] "Spending on 3D printing worldwide", Statista. September 2018. statista.com/statistics/590113/worldwide-market-for-3d-printing/

Challenges Facing Additive Manufacturing

DOE invests in early-stage research to advance technologies and develop next generation systems and materials that industry is unlikely to develop on its own. Ongoing R&D partnerships are working to advance AM processes by exploring new product designs, tailoring manufactured products, developing and rapidly deploying products with superior properties, improving process sustainability, and expanding or creating new end-use markets (e.g., regenerative medicine).[4]

Continued R&D efforts seek to fully exploit new design options; increase processing speeds; reduce costs; minimize environmental impacts; and enable confident validation and verification of AM parts. Advancements in these areas could accelerate the adoption of AM parts in the safety-critical fields of aerospace, biomedicine, and next generation energy systems (e.g., nuclear reactor designs, wind turbine blades)—encouraging wider use.[5]

DOE recognizes four key challenges to the widespread adoption of AM applications:[6]

Robust Modeling Could Validate AM Products


A testbed helps to enhance and advance AM processing systems.

Highly accurate computational models will improve the design and processing of AM products. To enable validation, models must be able to reliably predict exact product properties on the basis of processing parameters.

Addressing this challenge requires multi-modal measurements at high spatial and temporal resolutions. Robust tools, high performance computing, and experimental observations will help to verify existing models and identify new physical processes and their implications. DOE's Advanced Manufacturing Office (AMO) funds work on advanced data analysis, metrology tools, and an advanced AM testbed to accelerate model development and enable qualification of parts.

Learn more about DOE Advanced Manufacturing Office research projects: energy.gov/eere/amo/research-development

Process Control

Feedback control is challenging for AM given the rapid deposition rates. Physics-based models and simulations can help optimize part topology and increase throughput while maintaining consistency and high quality that are key to achieving economies of scale.

Dimensional Tolerances

Surface finishes for AM parts require further refinement as some potential AM applications require micron-scale accuracy in printing. Improved geometric accuracy could unlock benefits in high-value industries.

AM-Specific Materials

Material feedstocks are often costly, require preparation, and often need post-processing. Development of new metallic alloys and polymers designed for AM applications can help expand materials availability, lower feedstock costs, and improve performance of AM components.

Validation and Demonstration

Qualifying the structural integrity of AM parts may require extensive testing, demonstration, and data collection. This step is vital to meeting the stringent requirements of manufacturers and standards organizations for structural materials.

[4] 2015 Quadrennial Technology Review. U.S. Department of Energy. 2015. energy.gov/sites/prod/files/2015/11/f27/QTR2015-6A-Additive%20Manufacturing.pdf
[5] DOE, Advanced Manufacturing Office. "Draft Multi-Year Program Plan for Fiscal Years 2017 through 2021.". December 2016. energy.gov/sites/prod/files/2017/01/f34/Draft%20Advanced%20Manufacturing%20Office%20MYPP_1.pdf
[6] "Additive Manufacturing: Realizing the Promise of Next-Generation Manufacturing." Oak Ridge National Laboratory. 2017. ornl.gov/sci/manufacturing/docs/Advanced-Manufacturing-Brochure.pdf

Toward Reliable and Efficient Manufacturing

Manufacturers count on complex, defect-free manufacturing processes and dependable supply chains to deliver high-quality final products. Manufactured components must prove undisputed performance prior to use in highly regulated industries, where lives may be affected. AM products will become increasingly competitive with improvements in processing, throughput, scalability, affordability, and qualification. By improving these aspects of AM, DOE is enabling distributed AM to greatly increase supply chain efficiency.[7]

Strategic DOE R&D Focus Areas for Additive Manufacturing Systems


3D-printed excavator


Assembly of a 3D-printed house

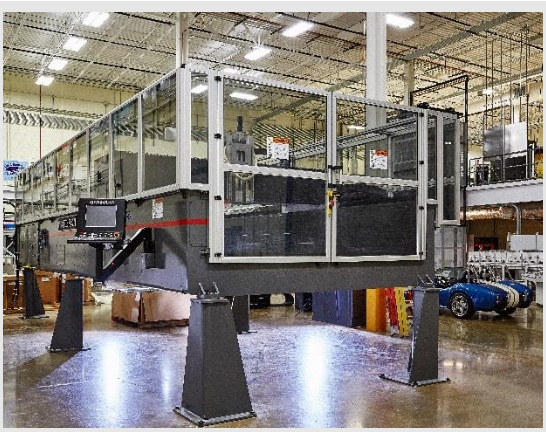

Coating the interior of a 3D-printed house

Optimization. Machine learning and data mining processes help build computational models that make use of thermal and optical measurements, design and build files, machine logs, and ex-situ characterization of residual stress and distortion. Collecting and analyzing process and performance data can advance understanding of AM process capabilities and limitations.

Process Controls. On large-scale AM systems, fully closed-loop controls with error detection and quality assurance/quality control (QA/QC) can improve the precision and reliability of AM processes and the quality of final products. Ensuring defect-free manufacturing with adaptive controls for responding to local build conditions can enhance the commercial viability of AM systems and their products.

Finishes. Surface finishes on AM components help achieve desirable tribological and aesthetic properties that can affect viability and lifecycle benefits in specific applications. Developing hardware and software capable of five-axis AM with variable nozzle sizes and free of support structures could streamline or eliminate the need for post-processing of products.

Certification. Use of physics-based modeling and rapid qualification tools for complex geometries can reduce the high costs associated with certification and qualification of components. Incorporating data from component characterization techniques into qualification tools can augment and expand the certification capabilities of AM systems.


ORNL's BAAM system at the MDF in Oak Ridge, TN.

BAAM!

The Big Area Additive Manufacturing (BAAM) system—jointly developed by ORNL and Cincinnati Incorporated—has printed automobiles (e.g., Shelby Cobra, Strati, the body of a military jeep), a house, a mold for a wind turbine blade, a submarine, and an excavator. A next-generation system under development will print two different materials onto a single object, enabling researchers to further tailor material properties for a given part. In addition, the new printer will have no top crossbeam, allowing the manufacture of taller objects and easier removal of objects after printing.

Learn more at: ornl.gov/blog/eesd-review/mdf-new-large-area-multi-material-printer-advance-research

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[7] DOE, Advanced Manufacturing Office. "Draft Multi-Year Program Plan for Fiscal Years 2017 through 2021." energy.gov/sites/prod/files/2017/01/f34/Draft%20Advanced%20Manufacturing%20Office%20MYPP_1.pdf

U.S. Supports Technological Advancements in Additive Manufacturing over 50 Years

DOE and its National Laboratories have a long history of working with industry, academia, and others to advance AM technologies that have the potential to revolutionize manufacturing by offering exceptional properties:

Durability: More durable, lightweight, and cost-effective materials for consumer and industrial products.

Performance: Products with fewer and more intricate parts that result in optimized performance.

Agility: Mobile AM systems can manufacture products closer to the site of materials or product need.

Sustainability: Reduced energy use and material needs produce broad benefits in various applications.

Design Innovation: Customized parts designed to meet specific customer needs enable new applications.

DOE R&D accomplishments demonstrate America's role in advancing the state of AM technology.

1967-1974

Battelle Memorial Institute (BMI) is first to attempt creating photopolymers using intersecting laser beams and a vat of resin.

1974-1991

BMI partners with a private company to generate a 3D object via photochemical machining. BMI leveraged DARPA funding to develop similar dual-laser techniques. The vat photopoly-merization process, known as stereolithography (SLA), is commercialized in 1987 as the first AM technology.

1991-1998

National Lab develops and licenses FastCast and MEMS SUMMiT AM processes. In addition, industry introduces the following AM technologies to commercial markets: fused deposition modeling (FDM), solid ground curing, laminated object manufacturing, and selective laser sintering.

1998-2010

National Labs license rapid solidification process (RSP) steel spray technique, laser-engineered net shaping (LENS) metal powder system, and RoboCast technology for fabricating ceramics in rapid prototyping applications. FDM patent expires, spurring growth in sales of consumer AM systems.

2010-2015

National Lab partners with industry to develop the Big Area Additive Manufacturing (BAAM) system, prints the largest solid 3D printed object in the world, and receives R&D 100 Award.

2015-2018

DOE's Critical Materials Institute (CMI) and two National Labs receive four R&D 100 Awards for innovations in coatings for AM products and AM-specific materials. Three National Labs were also awarded an Excellence in Technology Transfer Award for designing the first wind turbine blades fabricated from a 3D-printed mold.

DOE Focuses on Key Additive Manufacturing Technologies

DOE research focuses on the following processes classified by the American Society for Testing and Materials (ASTM) Committee F42 on Additive Manufacturing:

Electron Beam Melting: Powder bed fusion technique in which metal powder is melted in successive layers and bound together by a computer controlled electron beam.

Fused Deposition Modeling: Material extrusion process in which thermoplastic material is melted and deposited by a heated nozzle in a layered pattern to build a 3D part.

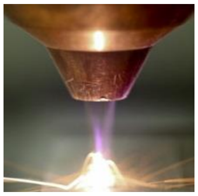
Direct Metal Laser Sintering: Another powder bed fusion process in which powdered material is fused by a laser that scans cross-sections on a metal powder bed surface.

Multi-Head Photopolymer: Photopolymers are jetted as liquid via inkjet print heads, and the material is solidified by UV lamp as layers are added on top in this photopolymerization process related to SLA.

Metal Laser Melting: Powder materials are fused by a fiber laser directed by a mirror-deflecting unit to make layer-by-layer components in this powder bed fusion technology.

Large-Scale Polymer Deposition: Polymer pellets at near-molten temperatures are extruded layer-by-layer onto a build platform outside the oven. This FDM process is used in the BAAM system.

Binder Jetting: A process in which powder particles are strategically layered by selectively depositing a liquid binding agent. Can be used with sand, polymers, metals, and other materials.



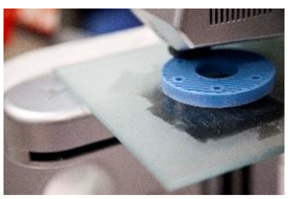
Laser Blown Powder Disposition: A directed energy deposition technique. Inert gas sprays powder into a melt pool created by a laser beam.

Enhanced Materials for Improved Products

Most materials currently used in AM processes have not yet been optimized for AM techniques. In addition, AM materials often cost more than those used in traditional manufacturing.[8] Improving component performance and driving down the cost of AM materials will require the identification and characterization of new metal, polymer, and ceramic materials; special formulations for AM materials could enhance application-specific properties, such as flexibility, conductivity, and transparency. Although R&D activities cover a variety of materials, DOE plans to strategically focus on metal-, polymer-, and ceramic-based AM.[9] This approach should help increase the range of high-performing materials and processes to exploit the potential of AM.

Strategic DOE R&D Focus Areas for Additive Manufacturing Materials and Products

AM and other equipment at ORNL's Manufacturing Demonstration Facility (MDF)



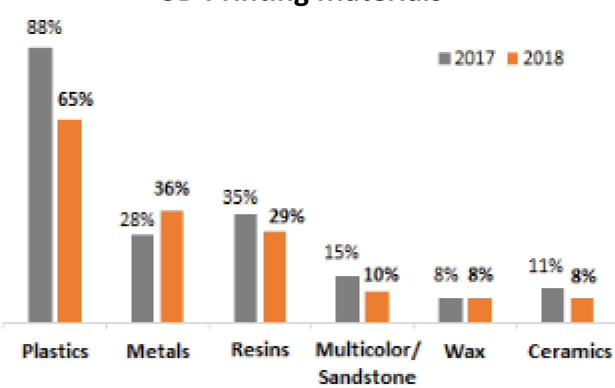
AM system used in the FIRST Robotics Competition

Materials Development. To enhance the properties of novel materials, AM-specific chemistries must be matched with tailored process controls to optimize fiber orientation (in polymers or carbon fiber) or tailor grain structure, size, shape, and orientation (in metals).

Design Tools. Designing and building files that specify component parameters for AM systems must leverage the capabilities of each paired material input and AM process. Computational tools that enable optimized designs based on underlying microstructures can advance process science and help meet specific material requirements or increase quality and throughput.

Improved Performance. Durability and structural integrity of components are paramount in sectors such as power generation, transportation, and A&D. Accelerating long-term testing protocols can expedite performance improvements in AM-built components and their subsequent qualification for use in highly regulated industries.

Metals Lead Growth in Use of 3D Printing Materials



Industry use of metal materials in 3D printing grew from 28% in 2017 to 36% in 2018—indicating expanded applications in product operations.

Sculpteo, "The State of 3D Printing, 2018." sculpteo.com/media/ebook/State_of_3DP_2018.pdf

In 2016, ORNL's BAAM printed the world's largest solid 3D-printed object: a trim-and-drill tool for Boeing.

Image: ORNL Manufacturing Demonstration Facility

AM Benefits to Aerospace Industry Are Sky High

The design-to-manufacture AM process shows the potential to dramatically reduce the buy-to-fly ratio (X amount of material needed to produce 1 pound of aerospace-quality material) from an industry average of 8:1 to nearly 1:1. This will reduce material and energy requirements while accelerating the fabrication of highly complex components.

"Realizing the Promise of Next-Generation Manufacturing." Oak Ridge National Laboratory. ornl.gov/sci/manufacturing/docs/Advanced-Manufacturing-Brochure.pdf

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[8] NIST. "Costs and Cost Effectiveness of Additive Manufacturing." nist.gov/nistpubs/SpecialPublications/NIST.SP.1176.pdf
[9] DOE, Advanced Manufacturing Office. "Draft Multi-Year Program Plan for Fiscal Years 2017 through 2021." energy.gov/sites/prod/files/2017/01/f34/Draft%20Advanced%20Manufacturing%20Office%20MYPP_1.pdf

Materials Solutions to Increase Reliability and Cut Costs

The high cost of material inputs are a key challenge facing the AM industry. A limited range of available materials are suitable, and the often required post-processing step can be costly.

DOE and the National Labs conduct R&D on metals, polymers, and ceramics to better understand ways to leverage these materials and unlock the vast potential benefits of AM products. Research includes the development of materials for specific AM processes and applications. The three main groups of AM materials are described briefly below.

METALS

Metal AM parts are fabricated for prototypes, casting shells, tooling, functional parts, and metal parts repair. These applications deliver benefits for the A&D, biomedical, automotive, robotics, electronics, oil and gas, and other industries. Metal AM products are typically complex components for end-use parts; applications in part repair are largely limited to aerospace.

Key Benefits:

- **Lightweighting.** Reliable as high-strength, lightweight structural material with energy savings potential in aerospace and automotive industries.
- **Rapid Prototyping.** Metal-based AM systems can fabricate components, molds, or repair metal parts in days, not months.
- **Examples:** Steel, aluminum, titanium, nickel, inconel, gold, silver, new noncrystalline metals

POLYMERS

Polymer AM products are mostly prototypes, casting patterns, soft tooling, and functional parts. Other current uses include consumer products, medical prosthetics, electronics, and parts for the automotive, and biomedical industries.

Key Benefits:

- **Affordable**. Polymer AM parts are cheaper than other materials and can be used in applications such as architectural models and automotive or aerospace components.
- **Versatile**. Some AM polymers are bio-degradable. Carbon fiber-reinforced plastics can enhance the strength and stiffness of materials.
- **Examples**: Thermoplastics (e.g., nylon, polyether ether ketone), resins (e.g., polyetherimide), and waxes

CERAMICS

Ceramic and glass AM parts are used in prototypes, casting patterns, high-temperature applications, and functional parts. Their electrical resistance, mechanical, chemical, and thermal properties support applications in industrial, home goods, and residential and commercial buildings markets. Advances in ceramic AM can enable end uses in bio- or food-compatible products.

Key Benefits:

- **Thermodynamics**. Ceramic AM materials have ideal thermal properties to withstand high-temperature operating environments (i.e., turbines).
- **Structural Integrity**. Structural properties of AM-fabricated ceramics strengthen aerospace, medical (i.e., dentistry), and consumer products.
- **Examples**: Ceramic paste (mixtures of ceramic powder, water, and trace amounts of chemical modifiers)

Partners Advance Additive Manufacturing with DOE

DOE invests in AM R&D to advance technology development and boost U.S. manufacturing competitiveness in global markets. Over the past decade, the DOE has supported AM research to accelerate deployment and commercial use of AM technologies.

DOE supports R&D via partnerships among the National Laboratories, industry, academia, federal agencies, and a range of public-private consortia.[10] These multi-institutional partnerships expedite the advancement of AM technologies for applications in a variety of industries, including power generation, transportation, medicine, and A&D. Consortia involving industry build on shared information and insights to create proprietary outcomes of commercial value. Consortia focus on achieving specific technology performance and cost thresholds required for commercialization and industry uptake, while basic research partnerships sustain leading-edge science and discovery to accelerate future technology advances and commercialization.

Additive Manufacturing Collaborative Research Institutes and Projects

America Makes is a Manufacturing USA Institute that is funded by the Department of Defense. This public-private partnership consists of roughly 40 companies, 9 universities, 5 community colleges, and 11 non-profit organizations that coordinate activities "to accelerate the adoption of [AM] technologies to increase domestic manufacturing competitiveness."[11]

Lightweight Innovations for Tomorrow (LIFT)—another Manufacturing USA Institute—collaborated with the Additive Manufacturing Standardization Collaborative (AMSC) to assemble dissimilar materials by joining them with AM components. The AMSC was launched by the American National Standards Institute (ANSI) in partnership with America Makes to develop AM roadmaps and standards and promote coordination, quality, and consistency across the industry.[12]

[10] "Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing—Supplemental Information." Quadrennial Technology Review 2015. DOE. 2017. energy.gov/sites/prod/files/2017/02/f34/Ch6-SI-Public-Private-Consortia-and-Technology-Transition-Case-Studies.pdf

[11] National Network for Manufacturing Innovation Program Annual Report. Executive Office of the President. February 2016. manufacturingusa.com/sites/all/assets/content/2015-NNMI-Annual-Report.pdf

[12] Manufacturing USA: A Third-Party Evaluation of Program Design and Progress. Deloitte. January 2017. dodmantech.com/Institutes/Files/MfgUSA_A-Third-Party-Evaluation-of-Program-Design-and-Progress_Jan2017.pdf

DOE Leverages Unique Advanced Manufacturing Research Facilities and Capabilities

DOE's scientific and technical capabilities are rooted in its system of National Laboratories—world-class institutions that constitute the most comprehensive R&D network in the world.

The DOE National Labs possess a unique collection of scientific expertise and highly specialized facilities. Collectively, these assets play a vital role in helping the United States maintain the science and technology leadership needed to sustain economic superiority in a dynamic and innovative global economy.

Core Additive Manufacturing Capabilities

Our National Laboratories use their world-class expertise and facilities to lead basic discovery research, technology development, and demonstrations. The following laboratories hold core capabilities in AM R&D:

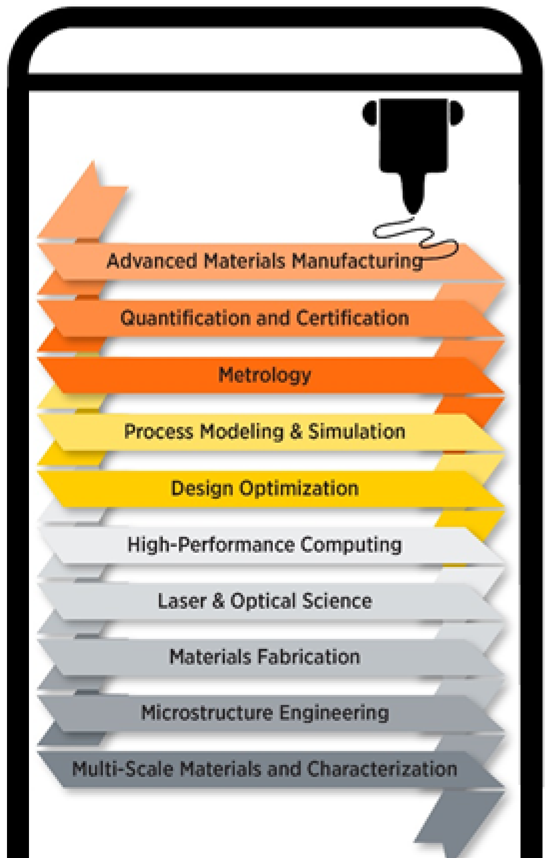
- Ames Laboratory
- Lawrence Livermore National Laboratory
- Oak Ridge National Laboratory
- Sandia National Laboratories

Learn more at energy.gov/downloads/annual-report-state-doe-national-laboratories and National Lab websites.

Researchers at the National Labs and other DOE-funded facilities actively collaborate with partners in industry, academia, and government to accelerate the development of transformational technologies, including those essential to AM. Prospective partner organizations can access the specialized expertise and facilities of the National Labs by entering into collaborative research agreements. A variety of partnership mechanisms are available to suit the diverse needs of the broad U.S. research community:

- Agreements for Commercializing Technology (ACT)
- Cooperative Research & Development Agreements (CRADA)
- Material Transfer Agreements
- Strategic Partnership Projects (SPP)
- Technical Support Agreements
- Technology Licensing Agreements
- User Agreements

Prospective public and private partners can use these mechanisms to engage the National Labs and access their AM-related capabilities (see list at right). DOE's laboratory network also includes two world-class facilities that possess AM-specific technology development and testing capabilities: ORNL's Manufacturing Demonstration Facility (MDF) and LLNL's Advanced Manufacturing Laboratory (AML), opening in late 2018.



DOE's National Laboratories dedicate substantial laboratory space, collaborative research groups, and multidisciplinary research efforts to accelerating the development of next-generation AM materials and technologies.

Collaborating with the National Laboratories

For more information on how to work with the National Laboratories, please refer to the *2016 Guide to Partnering with DOE's National Laboratories*, inl.gov/wp-content/uploads/2016/05/Revised-Guide-Partnering-with-National-Labs-Final.pdf

A Collaborative Approach to Additive Manufacturing Technology Development

Within the DOE's network of National Laboratories resides specialized expertise, equipment, and facilities that are dedicated to advancing AM technology and materials research. The National Labs highlighted below host unique capabilities, expertise, and facilities devoted to AM technologies and frequently collaborate with other National Labs for their technical expertise or needed equipment.

Ames Laboratory

Key capabilities and expertise:

- Materials discovery and development;
- Multi-scale materials and characterization; and
- Advanced material manufacturing and fabrication (i.e., metal alloy powders).

Ames' Laboratory (Ames) conducts materials science research and holds several patents in metal powder production and customization of alloys specifically for AM processing methods.

Ames' powder synthesis facilities allows researchers to design, verify, and fabricate metal powders and exercise control over the properties and quality of powders produced, which ultimately affects the quality of the final product.

Partnering with Ames on AM-related projects can provide industry-leading insights on material science and ensure high-quality materials in AM parts.

Lawrence Livermore National Laboratory

Key capabilities and expertise:

- Lasers and optical science;
- Physics-based modeling, simulation, and high-performance computing (HPC); and
- Metal AM component design optimization.

Lawrence Livermore National Laboratory (LLNL) is home to world-class HPC, simulation, and data science capabilities helping researchers understand and improve AM processes. LLNL's design optimization and materials development specialties also help generate novel AM-fabricated materials.

In late 2018, LLNL opens the Advanced Manufacturing Laboratory (AML), a new facility with specialized equipment for AM process and materials research. The AML is developing over 2 dozen partnerships with start-ups, multi-national corporations, and small- to medium-sized businesses.

Oak Ridge National Laboratory

Key capabilities and expertise:

- Modeling and simulation;
- AM process development and testing; and
- Materials development, characterization, and processing.

Oak Ridge National Laboratory (ORNL) has the infrastructure and expertise to advance the state of new manufacturing technologies and design methodologies. The Manufacturing Demonstration Facility (MDF) conducts research in partnership with 10 other DOE National Laboratories, in sponsorship or collaboration with 6 other Federal Agencies, and is a member or participates in 3 Manufacturing USA Institutes: America Makes, Lift, and IACMI.

As of 2018, the MDF has over 35 AM systems—including the BAAM—and 37 active CRADAs and 140 agreements in total (pending, active, complete) with industry partners, leading the way in AM research.

Sandia National Laboratories

Key capabilities and expertise:

- AM part qualification and testing;
- Metrology for AM parts and processes; and
- AM process simulation and design optimization.

Sandia National Laboratories (SNL) has years of experience in developing and advancing AM technologies. Leveraging its AM process and materials engineering expertise enables SNL to apply its multi-disciplinary capabilities to challenges facing today's AM process and materials.

SNL's strengths in metrology, for example, are improving final AM part quality and advancing part qualification and testing efforts to provide more confidence for manufacturer's seeking to benefit from use of AM technologies and components.

SNL's research is key to enabling a framework for part qualification to expand the range of applications for AM components and technologies.

Individual Additive Manufacturing Patents Available for Licensing

Process-Specific Innovations

Multi-orifice deposition nozzle for additive manufacturing
US 9821502, Oak Ridge National Laboratory

Article and process for producing an article
US 9796048, General Electric and DOE

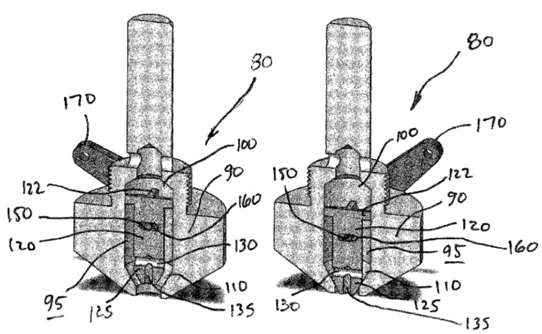
Reactive polymer fused deposition manufacturing
US 9650537, Oak Ridge National Laboratory

Additive manufacturing serialization
US 9626608, Savannah River National Laboratory

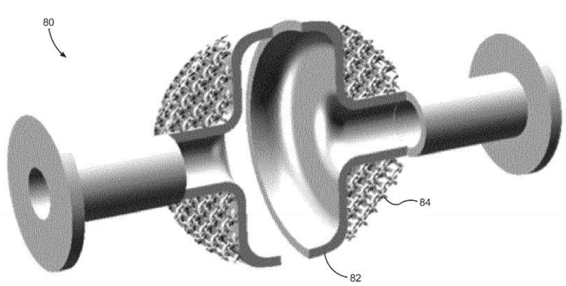
System and method for high power diode based additive manufacturing
US 9308583, Lawrence Livermore National Laboratory

Solid freeform fabrication using chemically reactive suspensions
US 6454972, Sandia National Laboratories

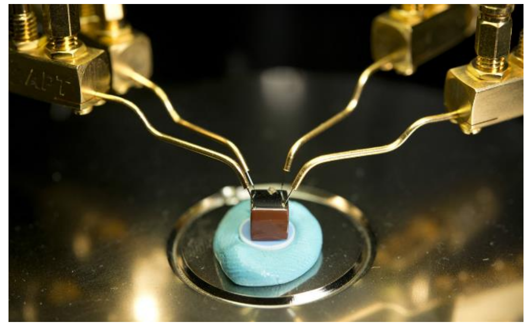
Method for net-shaping using aerogels
US 6258305, Sandia National Laboratories



Patent No. 9821502



Patent No. 9023765



Patent No. 9499406

Material- and Component-Specific Innovations

Dispersoid reinforced alloy powder
US 8864870, 9782827, 9833835, 7699905, 8603213, 8197574, Ames Laboratory

System and method for 3D printing of aerogels
US 9308583, Lawrence Livermore National Laboratory

Stability of gas atomized reactive powders through multiple step in-situ passivation
US 9650309, Ames Laboratory

Methods for the additive manufacturing of semiconductor and crystal materials
US 9499406, Consolidated Nuclear Security, LLC and DOE

Passivation and alloying element retention in gas atomized powders
US 9833837, Ames Laboratory

Sequential cooling insert for turbine stator vane
US 9611745, Florida Turbine Technologies, Inc. and DOE

Atomizer for improved ultra-fine powder production
US 9981315, Ames Laboratory

Effusion plate using additive manufacturing methods
US 9309809, General Electric and DOE

Additive manufacturing method for Srf components of various geometries
US 9023765, Thomas Jefferson National Accelerator Facility

Laboratory Partnering Service (LPS)

For up-to-date and additional information on all DOE available technologies, visit: labpartnering.org

Technology-to-Market Programs Strengthen the Innovation Ecosystem

Energy I-Corps

Energy I-Corps (EIC) pairs teams of researchers from the National Laboratories with industry mentors for an intensive two-month training where the researchers define technology value propositions, conduct customer discovery interviews, and develop viable market pathways for their technologies.

EIC is managed for The Office of Technology Transitions (OTT) by DOE's National Renewable Energy Laboratory (NREL), which leads curriculum development and execution, recruits program instructors and industry mentors, and assembles teams from the following national labs:

Energy I-Corps: Relevant Project Teams

AMAFT: Idaho National Laboratory (Cohort 5). AMAFT is an AM technique used to fabricate dense uranium silicide using a novel hybrid laser engineered net shaping process and multiple powder sources to form a pellet with required microstructure, chemistry, and properties.

Autonomous Concrete Printing: National Renewable Energy Laboratory (Cohort 4). This approach uses demonstrated concrete 3D printing technology in a novel configuration to manufacture ultra-tall wind turbine towers (i.e., over 200 meters) in-place without additional support structures.

Monolith: Sandia National Laboratories (Cohort 3). Monolithic technology can significantly reduce the cost, size, and manufacturing lead time of compact heat exchangers for a variety of applications, simultaneously improving performance, material options, and channel design possibilities.

For additional and up-to-date Energy I-Corps project teams and more information visit: energyicorps.energy.gov/

Technology Commercialization Fund

The Technology Commercialization Fund (TCF) leverages the Energy Department's annual R&D funding in the areas of Applied Energy Research, Development, Demonstration, and Commercial Application to mature promising energy-related technologies with the potential for high impact. TCF is implemented by OTT and its projects receive at least an equal amount of non-federal funds to match the federal investment to help businesses move promising technologies from DOE's National Laboratories to the marketplace.

Select TCF Projects Relevant to Additive Manufacturing

Accelerating Qualification of Additively Manufactured Metal Parts.
Lawrence Livermore National Laboratory.

Gas Atomization Nozzle Design for Controlled Particle Production.
Oak Ridge National Laboratory.

Additive Manufacturing as an Alternative Fabrication Technique for the Fabrication of Uranium Silicide Fuel.
Idaho National Laboratory.

Electrode Engineering Process for Solid Oxide Fuel Cell (SOFC) Commercialization.
National Energy Technology Laboratory.

Manufacturing of Advanced Alnico Magnets for Energy Efficient Traction Drive Motors and Generators.
Ames Laboratory.

For additional and up-to-date TCF projects and more information visit: energy.gov/technologytransitions/services/technology-commercialization-fund

Laboratory Partnering Service

DOE's Laboratory Partnering Service (LPS) is an online platform managed by OTT that enables access to world-leading DOE National Laboratory energy experts and DOE project awardee investible energy opportunities. Learn more at labpartnering.org/

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InnovationXLab^{SM} Summits

The DOE invests more than $10 billion per year in the 17 National Labs. The InnovationXLabSM series is designed to expand the commercial impact of this substantial investment in the Labs.

These summits facilitate a two-way exchange of information and ideas between industry and investors and National Lab researchers and DOE program managers with the following objectives:

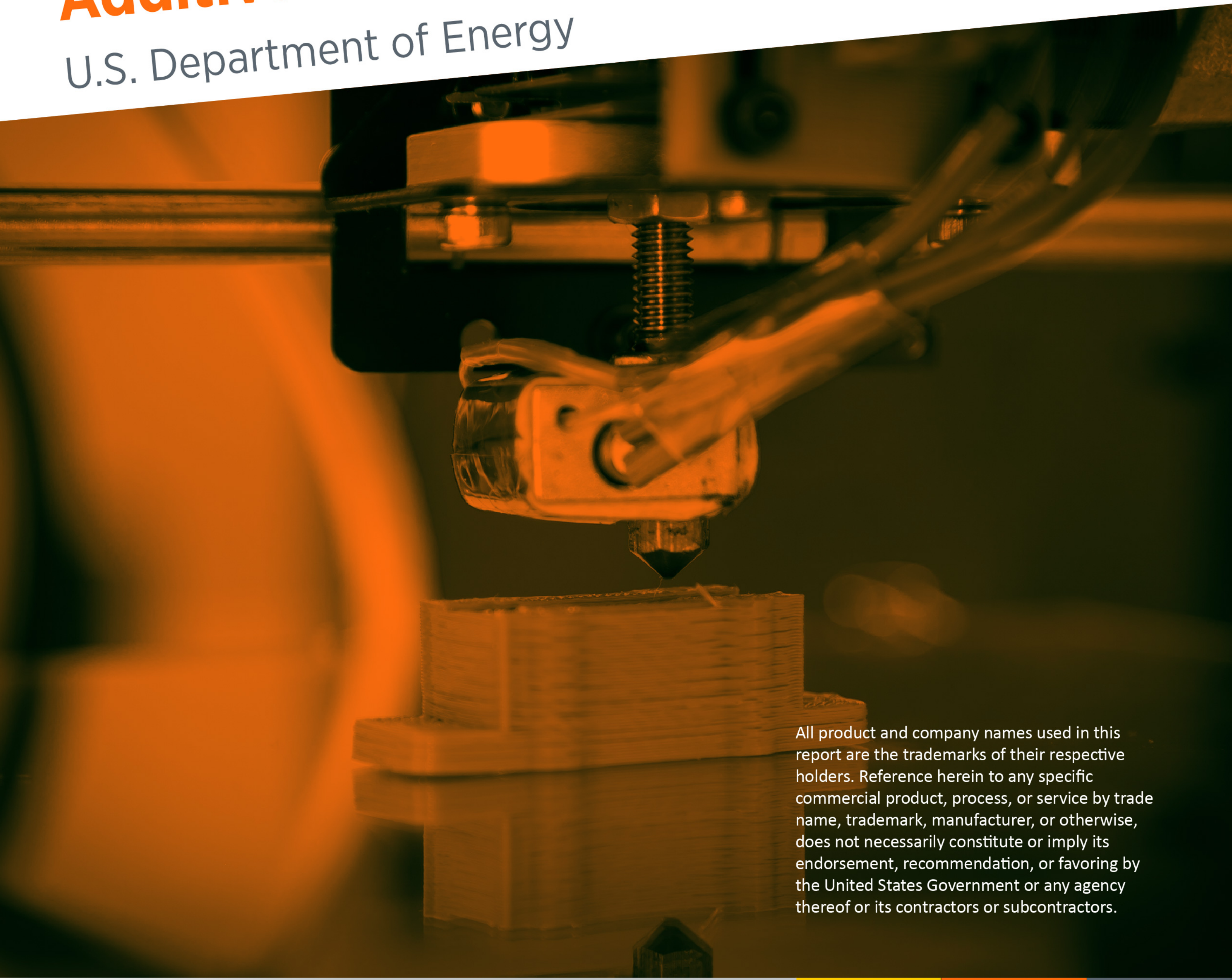
1) **Catalyze** public-private partnerships and commercial hand-offs utilizing DOE's extensive Lab assets: technology, intellectual property, facilities, and world-leading scientists and researchers;
2) **Engage** the private sector to ensure DOE understands industry's technical needs, risk appetite, and investment criteria, thereby incorporating "market pull" into DOE's portfolio planning; and
3) **Inform** DOE R&D planning to increase commercialization possibilities.

InnovationXLab^{SM} events are not technical workshops. They enable connections and commercialization opportunities at the decision-maker level.

3D-printed vehicle and home developed and assembled at Oak Ridge National Laboratory's BAAM system.

Additive Manufacturing Success Stories

U.S. Department of Energy



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U.S. DEPARTMENT OF ENERGY

Office of Technology Transitions

The Office of Technology Transitions develops DOE's policy and vision for expanding the commercial impacts of its research investments and streamlines information and access to DOE's National Labs, sites, and facilities to foster partnerships that will move innovations from the labs into the marketplace.

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Development of BAAM System Spurs Birth of an Industry

Oak Ridge National Laboratory in partnership with Cincinnati Incorporated and Strangpresse

Large-format 3D printer developed, licensed, and commercialized as industry adopts new additive manufacturing technology.

Innovation

Additive manufacturing (AM) processes had been widely limited by slow printing rates, a narrow range of source materials (e.g., extruded plastic), and small-volume product output capabilities. In 2014, Oak Ridge National Laboratory (ORNL) and Cincinnati Incorporated (CI) helped transcend these limits by developing the Big-Area Additive Manufacturing (BAAM) technology. Using new materials (carbon fiber-reinforced polymers), new processes (extruders) and controls, the team enabled an "out-of-oven" additive process that eliminated size constraints, enabled processing rates 500 times faster and build volumes 100 times larger than those of state-of-the-art commercial printing systems—with less material and energy waste.[1,2]

Outcomes

Technology Advancement

ORNL has used its large-area printers to demonstrate a variety of AM innovations ranging from full-scale prototype systems (cars, boats, submarines) to rapid low-cost tooling for the automotive, marine, aerospace, and construction industries. The system is the first to utilize plastic pellet feedstock reinforced with 20% carbon fiber, enabling production of stronger and stiffer parts. It has an 8-foot by 20-foot build area and can print structures up to 6 feet tall.[1,3]

Impact

ORNL licensed the BAAM technology and CI sold the first BAAM beta system in September of 2014. As of November 2017, CI has sold 14 BAAM systems to industries including aerospace, automotive, material providers, and tooling, among others. Since rolling out the BAAM, ORNL helped Cosine Additive with a medium-scale system, Strangpresse developed a line of BAAM extruders, Thermwood commercialized a large-scale additive manufacturing (LSAM) system, and ORNL partnered with Ingersoll to develop wide and high additive manufacturing (WHAM) machines.[4]

Using carbon fiber-enhanced polymers, the BAAM printer produced the frame and body of a full-scale Shelby Cobra in 2014; body panels feature a surface variation of 0.020 inches.
Photo: ORNL

"The auto industry could save energy and time with this type of additive manufacturing."[5]

Rick Perry,
U.S. Secretary of Energy

Timeline

February 2014: CI signs a partnership agreement with ORNL to develop new, large-scale AM system[1]

September 2014: Strati car printed live at the International Manufacturing Technology Show with the BAAM[4]

January 2015: ORNL presents 3D-printed Shelby Cobra at Detroit Auto Show[3]

September 2016: Ingersoll and ORNL partner to develop WHAM

October 2017: Strangpresse commercializes ORNL extruder technology

November 2017: CI has sold 14 BAAM systems[4]

[1] Press Release. wwwassets.e-ci.com/PDF/Press-Releases/CI-and-ORNL-Advancing-Large-Part-Additive-Manufacturing_Mar-2014.pdf

[2] EESD Review. ornl.gov/blog/eesd-review/mdf-new-large-area-multi-material-printer-advance-research

[3] ORNL Press Release. ornl.gov/sci/manufacturing/media/news/detroit-show/

[4] ORNL. energy.gov/eere/amo/downloads/amo-peer-review-july-17-19-2018

[5] Instagram. instagram.com/p/BXYgMtwgTPi/

BAAM System Demonstrates Potential for Innovation Across Multiple Industries

Oak Ridge National Laboratory in partnership with various industry partners and the U.S. Navy

Diversity of 3D-printing projects shows promise for revolutionizing the manufacture of transportation and construction machinery.

Innovation

Upon unveiling the novel large-scale 3D printer that enabled faster printing of larger objects with advanced materials, the Big-Area Additive Manufacturing (BAAM) has shown the range of innovative products it can fabricate. Thus far it has printed automobiles (e.g., Shelby Cobra, Strati, the body of a military jeep), a house, a submarine, a mold for a wind turbine blade, a boat hull mold, and a trim tool used in manufacturing wing tips for Boeing's 777X. These AM products used composite printing technologies to show the possibilities that AM technologies unlock.

Outcomes

Technology Advancement

These projects demonstrate the possibility to create customized vehicles and heavy machinery while saving time and money, a great benefit to the U.S. Navy in particular. In addition, these innovative designs and applications show the diversity of uses for AM products in residential, military, and construction industries. Exemplifying the versatility of the technology, the excavator project used a variety of 3D printing materials and processes, showing the seamless integration of AM parts into a large, working machine.[1,2]

Impact

In the case of 3D-printed submarines and watercraft, AM technology reduces the number of parts and cost compared to traditional manufacturing. The full-scale 210-square foot home and vehicle – both printed at ORNL's Manufacturing Demonstration Facility – and excavator integrate industrial components that involve complex shapes and patterns. These research projects provide solutions on a small scale, which will translate to significant reductions in energy use and corresponding increases in cost savings when ramped up to a national or global level.[1,5]

Images (clockwise from top-left): fully-functional AM-fabricated excavator; 3D-printed submarine; and AM-developed home and natural gas vehicle.

Photos: ORNL

"Additive manufacturing allows you to redesign things in ways we've never done before."

Dr. Lonnie Love,
Corporate Research Fellow, ORNL

Timeline

January 2015: ORNL conceptualizes new 3D-printed demonstration machine[1]

April 2015: Early production on the house and vehicle begins utilizing AM[2]

September 2015: Integrated home and vehicle energy system unveiled at EERE Industry Day at ORNL[3]

August 2016: Project partners began work on the 3D-printed submersible at a two-week rapid prototyping event[4]

March 2017: Excavator is showcased at the International Fluid Power Expo[5]

[1] DOE. energy.gov/eere/articles/navy-partnership-goes-new-depths-first-3d-printed-submersible
[2] ORNL. ornl.gov/sci/manufacturing/projectame/
[3] ORNL. https://web.ornl.gov/sci/eere/amie/
[4] U.S. Navy. navy.mil/submit/display.asp?story_id=101537
[5] 3D Printing Industry. 3dprintingindustry.com/news/project-ame-3d-printed-excavator-showcased-las-vegas-107482/

Large Scale Metal Printing Opens Doors for Localized Manufacturing

Oak Ridge National Laboratory in partnership with America Makes, Lincoln Electric and Wolf Robotics

Bringing advantages of AM to large, structural metal components for applications such as tooling, vessels, construction and more.

Innovation

After several technological breakthroughs in the area of large-scale polymer deposition, Oak Ridge National Laboratory (ORNL) teamed up with Lincoln Electric and Wolf Robotics to bring advantages of AM to large, structural metal components for the tool and die sector as well as construction and automotive applications.[1]

Outcomes

Technology Advancement

Wolf Robotics, Lincoln Electric and ORNL partnered to develop the materials and processes necessary to manufacture large (over 100 cubic feet) metallic structures at high deposition rates (>10 lbs/hr). Preliminary modeling efforts, validated through thermal imaging and neutron scattering, helped enabled the development of new materials and controls that provided a pathway to the rapid production of large-scale metal structures. Current efforts are expanding to multi-material and hybrid additive/subtractive processes.

Impact

ORNL showcased the impact of this system by fabricating the arm of a mini excavator at CONEXPO 2017, a construction expo with over 130,000 attendees. The excavator arm was fabricated from mild steel weld wire on the Wolf platform in about 5 days and illustrates how this novel system can be used to create single components with complex geometries. Specifically, it showcases the ability to embed hydraulic channels within the print.[2]

Recently, ORNL showcased the capabilities of the large-scale metal additive manufacturing by printing a new die every day that was machined, hard faced, and used to fabricate parts at the International Manufacturing Technology Show (IMTS) 2018. Whirlpool manufactured over 70,000 refrigerators using a 3D printed metal stamping die.

Top: The printed excavator stick – made of 927 layers printed continuously over 5 days – illustrated a 1.1mm height resolution in the Wolf Platform. Bottom: The same platform used to print the excavator stick demonstrated fabrication of steel dies for compression molding.

Photo: ORNL

"[The 3D printed excavator] will be a platform to demonstrate how the latest innovations and applied technologies are changing the future of the construction industry."

John Rozum,
IFPE Show Director

Timeline

August 2016: ORNL installs Lincoln Electric/Wolf Robotics MIG welder

March 2017: ORNL presents 3D printed excavator at CONEXPO

December 2017: Thermal mechanical models developed to predict distortion, thermal history of large-scale steel structures

August 2018: ORNL demonstrates multi-material printing using Wolf platform

September 2018: The team illustrates the concept of "Die in a Day" at IMTS 2018

[1] ORNL. ornl.gov/sci/manufacturing/projectame/

[2] University of Texas at Austin. utexas.edu/ChallengesinMakingComplexMetalLargeScale.pdf

New Generation of Miniaturized, High-Efficiency Heat Exchangers

DOE Building Technologies Office in partnership with the University of Maryland and 3D Systems

Printing a heat exchanger as a single, continuous piece allows novel designs at greater manufacturing efficiencies, with important implications for commercial products.

Innovation

Tube-fin heat exchangers have historically offered relatively high efficiency at low manufacturing cost—effectively constraining exploration of highly efficient alternative designs that would be too expensive to mass produce. 3D printing significantly accelerates the design-to-production process for complex heat exchangers, lowers production costs, and permits non-conventional shapes that can improve performance. Researchers at the University of Maryland's Center for Environmental Energy Engineering (CEEE) were able to design and manufacture an innovative heat exchanger in just weeks instead of months.[1]

Outcomes

Technology Advancement

Over the course of the project, CEEE researchers designed, prototyped, and additively manufactured a novel 1kW miniaturized air-to-refrigerant heat exchanger prototype that reduces energy losses by 20% relative to existing technologies and weighs 20% less. Compared to current advanced heat exchangers, it can also be manufactured much more quickly. A 10kW prototype was also fabricated and tested as part of this project.[1,3]

Impact

Heat exchangers are crucial components in residential and commercial heat pump systems (e.g., HVAC and refrigeration) that consume nearly 7 quadrillion Btu in the United States each year. The widespread commercial deployment of low-cost, high-efficiency heat exchangers can help to dramatically reduce this energy consumption and associated emissions. On a global scale, heat exchange is a multi-billion-dollar industry, impacting everything from consumer goods to automotive and aerospace engineering. As a result, improving the efficiency of a heat exchanger can improve the performance of a broad range of products.[1]

UMD's 3D-printed high-efficiency heat exchanger features high-precision design elements that would be impossible to efficiently manufacture with traditional technologies.

Photo: University of Maryland, Center for Environmental Energy Engineering

"The prototypes take much less time to build, enabling us to do test designs much earlier and more often during research."[2]

Dr. Vikrant Aute, CEEE Researcher

Timeline

March 2014: Heat exchanger design optimization completed[3]

June 2015: UMD researchers complete fabrication and testing of 1kW prototype high-efficiency heat exchanger[3]

January 2016: Project team completes fabrication and testing of 10 kW prototype as part of the same project[3]

[1] EERE. energy.gov/eere/success-stories/articles/eere-success-story-3d-printing-enables-new-generation-heat-exchangers

[2] University of Maryland. ceee.umd.edu/news/news_story.php?id=9709

[3] DOE Building Technologies Office. energy.gov/sites/prod/files/2016/04/f30/312103_Radermacher_040616-1505.pdf

Enabling Efficient Additive Manufacturing of Titanium Alloys

Ames Laboratory

Close-coupled high pressure gas atomization enabled by the "hot shot" pour tube energy-efficiently converts molten titanium into uniform fine spherical powders for use in manufacturing a broad range of products.

Innovation

Standard gas atomization methods for titanium (Ti) produce a wide range of sizes of spherical powder and only small yields of useful powders (diameters less than 45µm) resulting in extremely expensive fine powders of Ti-based alloys. The more efficient and uniform process of close-coupled gas atomization is needed, but required the design of a new modular pour tube heater to allow superheating of the Ti-alloy melt prior to immediate supersonic (cold) gas impingement, creating the best atomization conditions for the formation of high yields of fine spherical powders.[1]

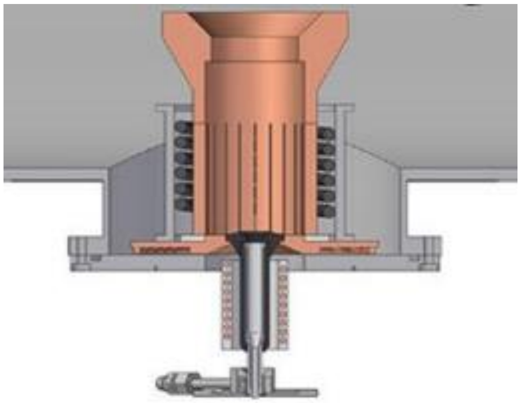
Outcomes

Technology Advancement

Given the rapid progress in 3D printing and additive manufacturing technology, ready access to affordable custom metal powders is likely to expedite further advancements in these energy-efficient production processes. Ti metal powders produced using this close-coupled gas atomization process open new possibilities for low-cost, high-volume additive manufacturing. This includes new opportunities in industrial, automotive, aerospace, and medical markets to revisit materials that industry and researchers had previously deemed too hard to work with.[2]

Impact

According to the *Powder Metallurgy Review* (August 2017), the Ti atomization process developed at Ames Laboratory may be 10 times more efficient than traditional powder-making methods and could lower manufacturing costs by 80%.[4] The Lab has acquired at least 16 patents for the process over the last two decades. In 2014, spin-off company Iowa Powder Atomization Technologies (IPAT) was acquired by Praxair, which now exclusively licenses Ames Laboratory's Ti atomization patents.[2]



Close-up of pour tube and gas nozzle
Image: Ames Laboratory

"This method enables us to revisit materials that have been around a long time, give them a second chance, and find new potential applications for them."
Dr. Iver Anderson
Senior Metallurgist, Ames

Timeline

Summer 2011: Iowa Powder Atomization Technologies (IPAT) spin-off company established to exclusively license Ames' Ti atomization patents[5]

Summer 2014: Praxair, Inc. – a Fortune 250 company – acquires IPAT

December 2015: Praxair Inc., in partnership with Ames Laboratory, begins large-scale production of Ti powder for use in AM and metal injection molding[3]

September 2017: Ames Laboratory's "hot shot" pour tube wins the 2017 Excellence in Technology Transfer Award[4]

1. Ames Laboratory: ameslab.gov/news/feature-stories/perfect-powder-ames-laboratory-perfects-metal-powders-manufacturing
2. Science News: sciencedaily.com/releases/2017/01/170112113847.htm
3. World Industrial Reporter: worldindustrialreporter.com/praxair-market-ames-labs-titanium-powder-additive-manufacturing/
4. Materials Today: materialstoday.com/metal-processing/news/award-win-for-powder-technology/
5. DOE. energy.gov/articles/iowa-start-may-be-america-s-next-top-energy-innovator

3D Direct Ink Writing with Graphene Aerogels

Lawrence Livermore National Laboratory in partnership with Virginia Polytechnic University

Novel process produces complex objects from a high-performing material for tailored applications in energy storage, aerospace, and other industries.

Innovation

Aerogel is a synthetic, porous, ultralight material formed by replacing the liquid component of a gel with a gas. Graphene aerogel, one of the least-dense solids in existence, is ideal for energy storage applications because of its high surface area, strength, and excellent mechanical properties, including high thermal and electric conductivity. Previous efforts to produce bulk graphene aerogels yielded only 2D sheets or basic structures with largely random pore structures, thwarting efforts to optimize the material's useful properties. Researchers have now successfully used an AM technique (*direct ink writing*) to create microlattices and other intricate structures for making graphene-based aerogels, opening a range of potential applications for this unique material.[1,2,3]

Outcomes

Technology Advancement

Researchers combined an aqueous graphene oxide (GO) suspension and silica filler to form a highly viscous ink, which can be extruded through a micronozzle to print a 3D structure.[1] After using ultrasound to break the GO hydrogel, researchers then added light-sensitive polymers and applied projection micro-stereolithography to create the desired solid 3D structures. The 3D structures were then heated to burn off the polymers and fuse the layers together. The resulting graphene aerogel structures were an order of magnitude finer resolution than ever before achieved (10 µm versus 100 µm).[3]

Impact

The ability to create graphene aerogels with tailored 3D macro-architectures paves the way to optimize key properties of graphene. Graphene aerogels are promising for applications in the automotive, aerospace, energy storage, chemicals, and nanoelectronics industries. Graphene aerogel microlattices could also find uses as thermal insulators, shock absorbers, battery electrodes, pressure sensors, and catalyst supports.[1,3,4]

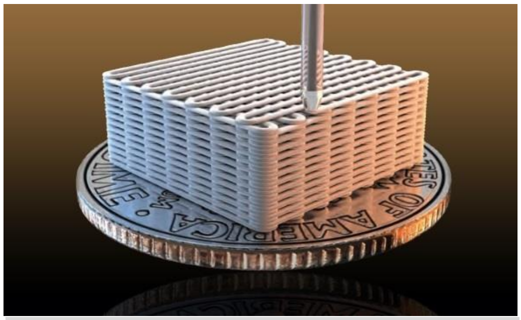


Image of graphene aerogel microlattice produced by a 3D printing technique known as direct ink writing.

Image: LLNL

"This development should open up the design space for using aerogels in novel and creative applications" [1]

Marcus Worsley
Engineer, LLNL

Timeline

April 2015: Project research is published in the journal, *Nature Communications*[4]

August 2018: Virginia Tech publishes article in *Nature* reporting on its work with LLNL.[4] Key findings are also published in *Materials Horizons.*[5]

[1] LLNL. lln.gov/news/3d-printed-aerogels-improve-energy-storage
[2] Graphene-Info. graphene-info.com/graphene-aerogel
[3] Virginia Tech. vtnews.vt.edu/articles/2018/08/engineering-3dprinted-graphene.html
[4] Nature Communications. nature.com/articles/ncomms7962
[5] Materials Horizons. pubs.rsc.org/en/content/articlehtml/2018/mh/c8mh00668g

Additive Manufacturing of Precast Concrete Molds for Construction Applications

Oak Ridge National Laboratory in partnership with Gate Precast and Precast/Prestressed Concrete Institute

Demonstrating how additively manufactured precast concrete molds outperform conventional molds.

Innovation

Polymer composite AM has reached new heights in recent years with the development of large-scale systems such as the Big Area Additive Manufacturing (BAAM) system and the Wide and High Additive Manufacturing (WHAM) machine. Oak Ridge National Laboratory (ORNL) has also made significant advances in working with industry to develop polymer chemistries for pellet feedstock material for use on these large-scale systems. To date, ORNL has successfully printed over 70 various fiber-reinforced polymers.

Outcomes

Technology Advancement

One of these materials, 20% carbon fiber-reinforced acrylonitrile butadiene styrene (CF-ABS) was used to 3D-print precast concrete molds to refurbish the façade of the Domino Sugar Building in Brooklyn, New York. ORNL, Gate Precast (a supplier of precast structural and architectural concrete), and the Precast/Prestressed Concrete Institute (PCI) demonstrated the feasibility of using the BAAM system to manufacture this tooling.[1]

Impact

Conventionally manufacturing the molds is a slow and expensive process with a shrinking workforce. The 3D-printed molds have been successfully used for 190 pours while still being usable – traditionally manufactured molds can only be used for 20 to 30 pours. In addition, the 3D-printed mold can provide the durability to complete precast concrete test samples with the required accuracy of less than 0.05 inch surface defects.[2]

3D printed precast concrete mold (9' long x 5.5' wide) printed on the BAAM system at ORNL's Manufacturing Demonstration Facility.
Photo: ORNL

"Additive manufacturing allows you to redesign things in ways we've never done before."

Dr. Lonnie Love,
Corporate Research Fellow, ORNL

Timeline

Summer 2015: ORNL and PCI initiate collaboration on advancing precast construction[1]

July 2016: Additive Engineering Solutions becomes a service bureau and purchases a BAAM system after interacting with ORNL, provides support to precast concrete project

July 2017: ORNL and Gate Precast design, manufacture, and evaluate 3D-printed mold prototypes[1]

August 2017: ORNL and Gate Precast begin production of molds and precast façade components[1]

[1] ORNL. ornl.gov/sites/publications/Files/Pub102721.pdf
[2] OSTI. osti.gov/servlets/purl/1471898

X-Rays Help Identify and Avoid Flaws in Laser Metal Deposition

SLAC National Accelerator Laboratory in partnership with Lawrence Livermore National Laboratory and Ames Laboratory

X-ray studies improve manufacturing of specialized metal parts for the aerospace, automotive, and health care industries

Innovation

Metal 3D printing can occasionally produce pits or weak spots if the metal cools and hardens unevenly as successive layers are deposited. Researchers at Stanford's Synchrotron Radiation Lightsource (SSRL) are working with Ames Laboratory and Lawrence Livermore National Laboratory experts to analyze every aspect of the process using X-rays and other tools. The aim is to find methods to eliminate pits, control the microstructure, and manufacture strong metal parts.[1] The research uses two types of X-rays. One studies the formation of layers at a micron level, while the other analyzes how particles change from solid to liquid and back again under the laser's path.[2]

Outcomes

Technology Advancement

To date, researchers have investigated lasers hitting standing layers of metal powder. Next, they will investigate an approach called directed energy deposition (DED) in which a laser beam melts metal powder or wire as it is being laid down. DED enables the creation of more complex geometric forms, which would be especially useful in making repairs.[1]

Next steps also include the incorporation of a high-speed camera into the experimental setup to document the manufacturing process. Researchers will then correlate the detailed photographic images with the X-rays to develop a clearer understanding of DED build-chamber behavior.[1]

Impact

Avoiding flaws in 3D-printed metal parts will help manufacturers more efficiently build more reliable parts on the spot. The need for vigorous qualification would diminish, and manufacturing costs could decrease.[1] The project can lead to an improved understanding of the laser fusion process and help to build industry confidence in metal 3D printing of critical parts for automotive and aerospace applications.[3]

SLAC staff scientists study metal 3D printing at SLAC's Stanford Synchrotron Radiation Lightsource (SSRL)

Image: SLAC

"We are providing the fundamental physics research that will help us identify which aspects of metal 3D printing are important."
Chris Tassone,
Staff Scientist, SSRL

Timeline

January 2018: Initial studies of the laser deposition process in making metal parts at SLAC's Stanford Synchrotron Radiation Lightsource (SSRL)

May 2018: The *Review of Scientific Instruments* publishes paper on the research and names it an "Editor's Pick."[3]

[1] SLAC. slac.stanford.edu/news/2018-01-30-slac-scientists-investigate-how-metal-3-d-printing-can-avoid-producing-flawed-parts

[2] 3D Printing Industry. 3dprintingindustry.com/news/slac-perfect-recipe-metal-3d-printing-investigation-lawrence-livermore-dept-energy-128231/

[3] LLNL. llnl.gov/news/llnl-researchers-use-x-ray-imaging-experiments-probe-metal-3d-printing-process

Additive Manufacturing of High Temperature Alloys for Energy Applications

Oak Ridge National Laboratory in partnership with Brayton Energy

Using AM to deposit complex, near net shape energy components of high temperature materials previously considered unweldable.

Innovation

Powder bed deposition AM techniques are useful for manufacturing commercial components, but are limited by the number of materials available for use in AM systems, especially for high temperature applications such as those used in the energy sector. Oak Ridge National Laboratory (ORNL) has made significant advances in developing high-temperature alloys using laser and electron beam melting (EBM). Developments in scan strategy, modeling of thermal histories of the deposited part, and in situ non-destructive evaluation techniques have enabled the fabrication of crack-free nickel (Ni) superalloy and refractory metal components.

Outcomes

Technology Advancement

ORNL has worked on the commercial deployment of Ni-based superalloy inconel 718 (IN718), as well as other Ni-based superalloy materials such as inconel 625, HastelloyX, and Haynes 282. More recently, ORNL has used unique EBM scan strategies based on input from simulation tools to deposit crack-free IN738 and MarM-247 in complex geometries; these alloys have traditionally been unweldable. The scan strategies developed by ORNL minimize the thermal gradients that lead to cracking, allowing for the deposition of a wider range of geometries from these advantageous materials.[1,2]

Impact

ORNL worked with Arcam to deploy IN718 – companies printing IN718 are likely using process parameters developed by ORNL. High temperature materials developments have led to successful deposition of MarM-247 and IN738, two high temperature materials previously considered unweldable. ORNL's various high temperature materials projects – enabling applications for gas turbines and fuel nozzle burners, among others – have enabled benefits such as higher operating temperatures, improvements in efficiency for energy generation, and lower NOx emissions.[1,2]

Represents IN738 turbine blades for industrial gas turbine engine using EBM technology.

Image: ORNL

Timeline

July 2012: ORNL initiates CRADA with Arcam to develop process parameters for IN718 on Arcam's EBM system

June 2014: Arcam launches IN718 for 3D printing off of ORNL process parameters

January 2015: Honeywell becomes the first company to use EBM to produce an aerospace component from IN718

May 2017: ORNL prints crack-free MarM 247 simple geometries

November 2017: ORNL and ECM Technologies complete trials on improving surface finish of IN738 using EBM

December 2017: GE acquires Arcam for $750 million

May 2018: ORNL completes 3D-printed crack free turbine blade using IN738

[1] ORNL 2017. ornl.gov/sci/manufacturing/docs/reports/web_Brayton%20Energy_MDF-TC-2015-075_Final%20Report.pdf

[2] ORNL 2018. ornl.gov/sci/manufacturing/docs/reports/web_MDF_TC_92_Final_CRADA_GTI_V3.pdf

[3] Arcam Press Release. arcam.com/ge-increases-its-shareholding-in-arcam-to-more-than-90-per-cent/

3D Printing Aerospace-Grade Carbon Fiber

Lawrence Livermore National Laboratory

3D printing of aerospace-grade carbon fiber composites enables greater control and optimization of this lightweight yet stronger-than-steel material.

Innovation

Lawrence Livermore National Laboratory (LLNL) researchers have found a way to successfully 3D print aerospace-grade carbon fiber composites (CFCs). These strong, lightweight, conductive, and temperature-resistant composites are restricted in applications today due to their high cost to manufacture, shape limitations (i.e., flat or cylindrical), and variable reliability in service. Now, with a modified form of 3D printing called direct ink writing (DIW), researchers are able to build complex shapes and rapidly cure the material to provide valuable mechanical properties.[1,2]

Outcomes

Technology Advancement

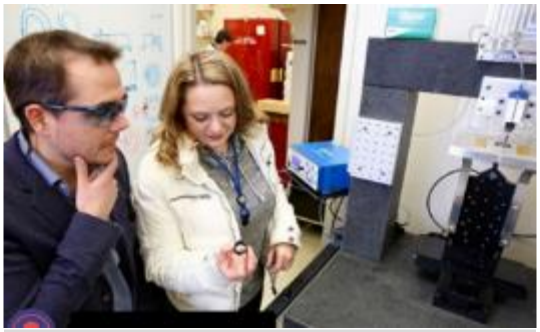
During DIW, a small nozzle extrudes custom carbon fiber-filled ink and lays it down precisely within a 3D build space to construct complex shapes.[2] With a patented new chemistry, the material cures in seconds instead of hours.[1]

Running on LLNL's supercomputers, computational models are able to simulate thousands of carbon fibers as they emerge from the nozzle. These models can help determine the best fiber lengths and alignments to optimize material properties and performance in finished parts.[2] Products with closely aligned microfibers may use two-thirds less carbon fiber and outperform CFC materials produced by other methods.[1]

Impact

LLNL researchers have entered discussions with commercial, aerospace, and defense partners to advance the development of this technology.[1] Future applications could include high-performance airplane wings, insulation for satellite components, and wearables that can draw heat from the body.[1,2]

Researchers believe parallelization of the process, using multiple print heads and advanced curing protocols, would allow larger, more complex parts to be produced in reasonable timeframes. If industrial partnerships are forged, these goals may be met within a three-to-five-year timeframe.[2]



LLNL researchers examine a carbon fiber part created using Direct Ink Writing.

Image: LLNL

"The mantra is 'if you could make every-thing out of carbon fiber, you would'— it's potentially the ultimate material. It's been waiting in the wings for years because it's so difficult to make into complex shapes. But with 3D printing, you could potentially make anything out of carbon fiber."

James Lewicki,
Scientist, LLNL

Timeline

March 2017: *Scientific Reports* publishes research on 3D-printed carbon fiber[1]

July 2017: Researchers are in discussion with possible partners to advance the development of 3D-printed carbon fiber composites.[2]

[1] LLNL. llnl.gov/news/3d-printing-high-performance-carbon-fiber

[2] EERE. energy.gov/eere/success-stories/articles/eere-success-story-new-3d-printing-aerospace-grade-carbon-fiber-method

3D Printing Enables Development of Cost-Effective Robotics

Sandia National Laboratories in partnership with Stanford University and LUNAR

Use of AM components in robotics can lead to significant cost savings.

Innovation

Dexterous robotic hands are expensive and can cost hundreds of thousands of dollars due to the cost of components, challenging assembly procedures, and relatively small scale of their manufacture. In a project funded by the U.S. Department of Defense's Defense Advanced Research Projects Agency (DARPA), Sandia National Laboratories (SNL) collaborated with LUNAR and Stanford University to develop a dexterous robotic hand that would cost significantly less than traditional robotic hands.[1,2]

Outcomes

Technology Advancement

AM played two key roles in the development of the hand. In the design and prototype stages, it allowed parts to be quickly fabricated and tested, facilitating rapid design iterations. Approximately 50% of the Sandia Hand components are 3D printed. In addition, due to the anthropomorphic design of the hand, many of the parts have complex geometries which are difficult to manufacture using traditional methods. The use of 3D printing technology permitted the hand – including components of the fingers – to be fabricated at a substantially lower price using a laser powder bed AM process.

The Sandia Hand consists of a frame that supports a set of identical finger modules that magnetically attach and detach from the hand frame. The finger modules consist of several sensor systems that enable the hand to perform complex manipulation tasks and is supported by several imaging systems to increase function and performance.[1]

Impact

The hand addresses challenges that have prevented widespread adoption of other robotic hands, such as cost, durability, dexterity, and modularity. 3D printing was a key enabler in cost-effective creation of the hand. Major cost reductions were achieved through a combination of inexpensive components, simplified assembly and maintenance procedures, and additive manufacturing methods.[1]

Sandia National Laboratories researcher Curt Salisbury demonstrates the dexterity of the Sandia Hand.

Image: SNL

"The Sandia Hand has 12 degrees of freedom, and is estimated to retail for about $800 per degree of freedom — $10,000 total — in low-volume production. This 90 percent cost reduction is really a breakthrough."

Curt Salisbury
Researcher, SNL

Timeline

2010: DARPA's Autonomous Robotic Manipulation (ARM) Program commences[2]

2011: The Sandia Hand, along with two other project teams, passes critical design review[2]

2012: Sandia Hand is developed and completes a full evaluation[2]

[1] SNL Fact Sheet. https://sandia.gov/research/robotics/_assets/documents/SandiaHand_Handout_Final.pdf

[2] Journal of the Robotics Society of Japan. jstage.jst.go.jp/article/jrsj/31/4/31_31_326/_pdf

Developing a New Qualification Framework for Additive Manufacturing

Oak Ridge National Laboratory in partnership the U.S. Air Force, other government agencies, and industry

Utilizing advanced characterization and data analytics to address challenges and cost barriers associated with adopting AM parts for transportation, defense, and energy applications.

Innovation

Although AM technologies have demonstrated the ability to fabricate complex products, few are currently being used in production environments due to the challenges and costs associated with the certification and qualification of parts and components. AM presents the advantage of building objects one element at a time. Developing technologies that can monitor, understand, and control AM processes can advance the industry toward certifying every single element independently and then merging this information to certify the final component.

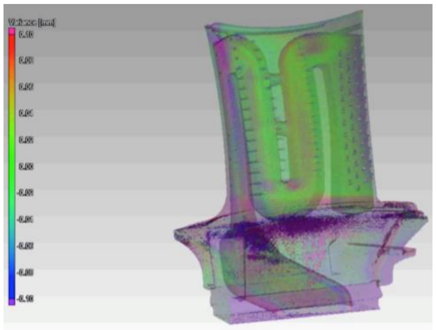
Outcomes

Technology Advancement

In order to establish a new AM certification platform, Oak Ridge National Laboratory (ORNL) developed new methods of information gathering and built software to analyze and visualize the quality of the additive component. Both hardware and software tools have been created to enable a data rich environment, capturing information from every stage of the production chain. ORNL then partnered with the U.S. Air Force using a data analytics framework (Dream3D) to visualize, analyze, optimize, simulate, and interpret the data. Since then, various data analysis and visualization software has been developed to analyze anamolies such as porosity, cracking, and microstructure evolution and link them with process variability. Artificial intelligence and machine learning software have been developed to minimize computational processing requirements and provide new tools to aid in predicting performance of AM components.[1,2]

Impact

Leveraging the AM database and various analytical tools, ORNL is working to develop a digital twin for each part fabricated which contains the relevant information toward certification. Projects in nuclear, fossil energy, and energy efficiency are using these new tools.



Using advanced characterization techniques and modeling to understand variance in AM builds for high temperature gas turbines.
Photo: ORNL

"We must revolutionize how we think about the certification process for additive manufacturing technologies to be widely implemented in industrial applications ... certify the process, not individual parts."
Dr. Vincent Paquit
Imaging Scientist and Data Analytics Lead
Manufacturing Demonstration Facility, ORNL

Timeline

April 2016: ORNL initiates a data analytics framework effort for certification and qualification of AM.

December 2017: ORNL completes project with Honeywell on residual stress determination of direct metal laser sintered inconel specimens and parts

June 2018: ORNL completes a collaboration with Rolls Royce to understand part-to-part variability during directed energy deposition processes using in situ and ex situ process characterization

Spring 2018: ORNL initiates projects with BWXT to use the digital qualification framework to evaluate components for the nuclear industry

[1] Computers and Graphics Journal. sciencedirect.com/science/article/pii/S0097849317300201
[2] C. Steed et al. csteed.com/publications/LDAV2016/LDAV2016-Abstract.pdf

3D Printing Metal Parts Faster than Ever

Lawrence Livermore National Laboratory

A technology originally developed to smooth out and pattern laser beams can be used to 3D print metal objects faster than ever before.

Innovation

Lawrence Livermore National Laboratory (LLNL) scientists have developed a new metal 3D printing process called Diode-based Additive Manufacturing (DiAM) which uses arrays of laser diodes, a Q-switched laser and a specialized laser modulator developed for LLNL's National Ignition Facility to flash print an entire layer of metal powder at a time, as opposed to other powder-based laser systems.

The result is that large metal objects could be printed in a fraction of the time compared to metal 3D printers on the market today, expanding possibilities for industries requiring larger metal parts, such as aerospace and automotive. The speed and degree of design flexibility afforded with the DiAM method is potentially "far beyond" that of current powder-bed fusion-based systems.[1]

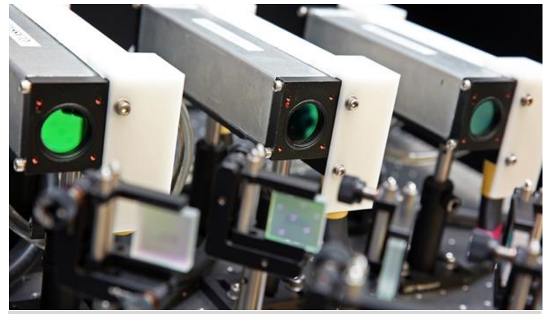
Outcomes

Technology Advancement

The benefit of the DiAM process is the implementation of a customized laser modulator called an Optically Addressable Light Valve (OALV), which contains a liquid crystal cell and photoconductive crystal in series. Much like a liquid crystal-based projector, the OALV is used to dynamically sculpt the high-power laser light according to pre-programmed layer-by-layer images. Unlike a conventional liquid crystal projector, the OALV is un-pixelated and can handle high laser powers.[1]

Impact

In 2016, Lawrence Livermore National Security (LLNS) LLC licensed patents for the system to Seurat Technologies, a startup company that envisions bringing an industrial metal printer to market with unparalleled speed and resolution. The Department of Energy awarded a grant to Seurat under the HPC4Manufacturing (HPCMfg) program in august of 2018 that will allow the company to use high-speed video, material analysis and multiphysics modeling performed at LLNL to optimize the printer. Seurat also closed a $13.5 million Series A round of funding in 2018 led by venture capitalist firm True Ventures that will be used to accelerate commercialization of the technology.



Diode-based Additive Manufacturing (DiAM) uses high-powered arrays of laser diodes and a specialized laser modulator developed for the National Ignition Facility (NIF) to flash print an entire layer of metal powder at once.

Image: LLNL

"By cutting the print time and having the ability to upscale, this process could revolutionize metal additive manufacturing."
Ibo Matthews
Scientist, LLNL

Timeline

2016: LLNS licenses patents for Diode-based Additive Manfacturing (DiAM) technology to Seurat Technologies

October 2017: *Optics Express* publishes research on DiAM

January 2018: Seurat closes $13.5 million Series A round of funding to accelerate commercialization of technology

August 2018: U.S. Department of Energy awards grant to Seurat Technologies under HPC4Manufacturing program allowing company to work with LLNL to optimize industrial metal printer

[1] LLNL. llnl.gov/news/nif-technology-could-revolutionize-3d-printing

[2] Seurat Press Release. seuratech.com/single-post/2018/08/17/Seurat-Technologies-Selected-for-HPC4Mfg-Award

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