Message from the Assistant Deputy Administrator for Research, Development, Test, and Evaluation, Dr. Kathleen Alexander

This issue of the Stockpile Stewardship Quarterly focuses on additive manufacturing (AM), or three-dimensional (3D) printing from digital models. To significantly reduce cost and schedule risk associated with the development and production of components, the National Nuclear Security Administration (NNSA) laboratories and sites are exploring the development of an array of advanced technologies, including AM and 3D printing. This issue introduces representative work on AM at the NNSA national laboratories and Kansas City National Security Campus (KCNSC).

Los Alamos National Laboratory provides us with an introduction to AM and describes the key challenge of qualification of an AM material for an application using this innovative new approach. The article also describes the latest work with AM metal processing using advanced diagnostics. The next article from Lawrence Livermore National Laboratory (LLNL) describes the history of AM and current programs. LLNL is combining materials in new ways, creating materials with properties not found in nature. Specifically, LLNL is pursuing a comprehensive modeling and simulations strategy for accelerating parts qualification based on a successful multiscale modeling framework. Sandia National Laboratories (Sandia) is transforming the way that non-nuclear components are developed and produced using AM. The article, written in close collaboration with KCNSC, details the extensive material testing and characterization that has been performed to quantify material properties and process variations. KCNSC closes the quarterly with an article describing the interesting history of how Honeywell encouraged the adoption of AM. It also takes us through the detailed methodical process that KCNSC uses to create AM parts.

As you can see from this issue, exciting things are happening within the nuclear security enterprise. We also highlight two Sandia Presidential Early Career Awards for Scientists and Engineers recipients, as well as our university partnerships (see photo above). Continue to do great work.

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Additive manufacturing (AM), or three-dimensional (3D) printing as it is more commonly known, is defined as the process of joining materials by fusing or solidifying a material—usually in a layer-by-layer fashion—via a 3D printing process. Unlike traditional subtractive manufacturing processes, such as cutting, drilling, or milling, AM processes do not remove material from a pre-existing shape. Instead, new material is added in a layer-by-layer fashion to create a final part. This process is characterized by its ability to produce complex geometries with high accuracy and precision, making it suitable for a wide range of applications from rapid prototyping to direct manufacturing.

As noted above, the driving force behind AM processes is the ability to create complex parts that are difficult or impossible to produce using traditional manufacturing methods. These parts can be designed to have intricate internal structures and variable properties, enabling innovative designs that could not be achieved using traditional techniques. The flexibility of AM processes is particularly advantageous in industries where customization and rapid prototyping are required, such as aerospace, automotive, and medical device manufacturing.

In terms of process science to material and property characterization, the rapid cooling and solidification rates associated with AM processes can result in unique microstructures and properties that are distinct from those produced by conventional manufacturing methods. The challenge for AM scientists is to understand and control the microstructure and properties of AM materials to optimize their performance for specific applications.

Historically, AM research has focused on developing process control strategies to improve part quality and reduce defects. However, the recent emphasis on material science has opened up new avenues for innovation in AM processes. By combining process control with microstructure and property characterization, researchers can develop new AM materials and processes tailored to specific applications.

The challenge for qualifying AM parts is to define the conditions under which the part will meet performance requirements. This requires a comprehensive understanding of the microstructure-property relationships, which can be achieved through experimental and computational modeling.

Figure 1 provides a schematic of the experimental and modeling efforts that are ongoing at Los Alamos National Laboratory (LANL) to develop a process science strategy for AM materials. The blue arrow indicates the path of the material as it is deposited layer by layer, while the yellow arrows indicate the location of the material as it cools and solidifies. The black box shows the location of the measurement. The yellow box shows the location of the measurement, which is a critical linkage needed for the process science strategy to material and property characterization.

Figure 2 provides an example of the data collected during an experiment to characterize the microstructure of a specific AM material. The graph shows the evolution of austenite fraction during cooling and final austenite fraction is location dependent. The yellow arrows in Figure 2 indicate the specific location where the austenite fraction was measured. The blue arrow indicates the path of the material as it is deposited layer by layer, while the yellow arrows indicate the location of the measurement. The black box shows the location of the measurement, which is a critical linkage needed for the process science strategy to material and property characterization.

Figure 3 provides a 3D model of the material as it is deposited layer by layer, with the yellow arrows indicating the location of the measurement. The black box shows the location of the measurement, which is a critical linkage needed for the process science strategy to material and property characterization.

In conclusion, the successful development of AM processes requires a multidisciplinary approach that integrates process science, materials science, and computational modeling. By combining these efforts, researchers can develop new AM materials and processes that are optimized for specific applications.

Additive manufacturing (AM), the layer-by-layer creation of three-dimensional (3D) parts and components from digital models, is sparking a worldwide revolution in manufacturing. Described and defined in this article is AM and the unique role of Lawrence Livermore National Laboratory (LLNL) in this rapidly expanding research and development area.

Additive Manufacturing History

AM, better known as 3D printing, is not new; in fact, one of the longest-running technical conferences on the topic just held its 27th annual meeting. For much of its history, most additively manufactured objects were made from polymers. Additively-manufactured metal parts were first demonstrated in the 1990s, but were slow to catch on, as the poor state to the final solid state and create within the AM material.

Layer by layer, with more data in hand, a prediction in time evolution will be studied in both the initial layer deposited and the subsequent layers. With more data available, the predictive simulation is foresee where the final microstructure (and, therefore, the properties and performance) can be known a priori. This is an important step in turning the promise of AM into reality. References


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LLNL’s Emerging Role

LLNL is presently playing a leading role in AM by advancing the science of AM, combining materials in new ways, and creating materials with properties not found in nature. At LLNL, deep experience in precision engineering, materials science, and high-performance computing combines with a dedicated research and development program to enhance and advance this technology and its applications.

LLNL has been using AM for years to make scale models with acrylonitrile butadiene styrene (ABS) plastic. The more recent move—since 2011—into metals, ceramics, semiconductors, and other materials, opens new opportunities.

Advantages, Disadvantages, and Costs

AM provides a number of advantages compared with traditional subtractive manufacturing, including access to new levels of complexity, reduced need for tooling, weight reduction, part consolidation, and reduction also in production steps. Disadvantages, however, include slow build rates, relatively high production costs, high cost of process optimization, relatively poor surface finish and dimensional accuracy, and limited part size. Given these tradeoffs, AM is particularly appealing for manufacturing involving low-volume, high-value parts, including parts that simply cannot be made by other methods. An example of such a part is a lattice, which is a type of cellular periodic structure with dimensions in the range of a few millimeters.

Generally speaking, AM will be cost effective for low volume, high complexity production. The cross-over point where conventional manufacturing will become more cost effective than AM is a function of the recurring cost of the manufacturing process.3 A driver for cost is the slow build rate in powder bed fusion systems. An important, but perhaps less tangible, consideration is AM's versatility. Small lots of high-value, complex parts can be produced very quickly, and if a change is needed (assuming that the part can be qualified), only the computer-aided design need be changed before building the new parts.

LLNL’s Role in Ensuring Fulfillment of Qualification Requirements

Part qualification for any industry can be costly and take a long time (up to a decade)—attributes that offset the speed, versatility, and adaptability of AM. Thirty-two percent of manufacturers surveyed indicated that uncertain quality of the final product was a barrier to adoption of AM.4 Most road maps for AM suggest that modeling and simulation will play a key role in accelerating qualification.5,6 LLNL is pursuing a comprehensive modeling and simulation strategy for accelerated parts qualification based on the successful multiscale modeling framework illustrated in Figure 1. This strategy includes:

- Powder dynamics. A discrete element model of the spreading of the powder layer.
- Powder model. A finite element model of the interaction of the laser with the powder bed, melting of the powder, flow of the molten metal, and solidification.7
- Microstructure model. A phase field model of the solidification of the liquid and development and evolution of the grain structure.8
- Effective medium model. A finite element model based on a LLNL code that models the building of a complete part and predicts residual stress and distortion.9

- Intelligent feed forward algorithms. A new methodology focused on improving part quality using advanced models.

The multiscale modeling strategy employs an information-passing methodology with critical information shown in the arrows being passed between scales. The output of our process models can feed into models that are used for prediction of material properties and performance of materials. Because simulations are only as useful as the models and the input data, our simulations are underpinned by validating experiments. Over the last four years, our experimental work has provided important insights into how the laser interacts with the metal powder.10 High-speed imaging of the melting process has revealed missing physics in the powder model that is now being added.11 Extensive material characterization, including density measurements, metallography, x-ray diffraction, electron backscatter diffraction imaging, transmission electron microscopy, focused ion-beam microscopy, and mechanical testing play a critical role in understanding the role of processing parameters in controlling part properties and performance.

LLNL has demonstrated a significant improvement in part quality compared with the current approach using an early version of model-based intelligent feed forward. Following is a discussion of the critical need for part qualification and how model-based intelligent feed forward can help.

Qualification has three major components: physics and engineering qualification, production qualification, and materials qualification. Because with AM the material is being created at the same time as the part, materials qualification becomes an issue. The experimentally validated models describe what can be expected from a build carried out with specific input parameters, but such predictions alone do not provide the accelerated qualification that is required. Today (Figure 2a), LLNL uses extensive, iterative experimentation to optimize input parameters such as the laser power, speed, and beam size for the process. However, because the thermal boundary conditions change as a function of the part geometry, the parameters required to achieve desired part quality will also be a function of geometry. In current powder bed fusion systems, geometry-specific process parameters can be entered only for simple geometries such as overhangs or thin vertical walls. During the build, data are collected from in situ process sensors. In situ sensors and feedback schemes aid...
specified uncertainty, it likely will be and the experiment agree within some build. After the build is complete, the used to correct the simulation-based to be perfect, feedback control will be Because simulations cannot be expected the machine how to build the part approach, the simulation will be used to in controlling the process. Using this layer diagnostic monitoring, have the with high-performance computing Modeling and simulation, combined control, Figure 2b.

References


Additive Manufacturing’s Benefits for Product Development

Sandia National Laboratories (Sandia) is using additive manufacturing (AM), or as sometimes called three-dimensional (3D) printing, to transform the way that components are developed and produced. The ability to rapidly generate complex parts directly from a computer model provides agility that is invaluable to product design and development. Small lot quantities of prototypes, test hardware, tools, and fixtures can often be fabricated more quickly and less expensively than through traditional manufacturing methods. Therefore, risks are reduced since designs can be conceptualized, manufactured, evaluated, and improved quickly and cost effectively. The number of 3D printers in use at Sandia is growing due to their benefit for rapid prototyping. Sandia has a rich history of pioneering AM technologies to impact engineering design as developed two of the first processes to print metals and ceramics, Laser Engineered Net Shaping (LENS®) and Robocasting®. These and other processes have been used since for prototypes to shorten development schedules. Recent efforts are addressing barriers associated with AM material quality and reliability. Researchers are also developing new capabilities to increase Sandia’s ability to quickly and reliably respond to new requirements. Two examples are representative of the impact AM has provided to our efforts. Recently, Sandia and Los Alamos National Laboratories collaborated to fabricate a prototype that was cheaper and faster than prior prototypes by roughly 75%. The unit was assembled using printed plastic parts, was the earliest ever realized in a design cycle, and allowed engineers to quickly and easily evaluate assembly. Similarly, Sandia rapidly adopted AM to support tooling, molds, and fixtures for development and production activities, resulting in reduced costs.

Producing Stockpile Components Using Additive Manufacturing

Since AM has routinely provided reductions in development costs and schedules, there is motivation to realize similar gains for other parts, not just support hardware. Multiple parts have been explored for the recent development programs to evaluate opportunities and challenges associated with AM. Opportunities for metal parts have focused on housings with geometries that can only be fabricated by AM. This work is also being leveraged by the program to explore AM to realize cost, schedule, and performance gains.

A critical challenge in applying AM to parts is to ensure that printed parts and materials satisfy requirements. Material and part geometry are formed simultaneously in AM. While this presents revolutionary opportunities, it introduces the potential to generate defects during fabrication and/or unacceptable material variations.
Changing the Engineering Paradigm Using Additive Manufacturing

Although improvements to experimental methods are necessary and invaluable, a new paradigm is being explored at Sandia to further accelerate the development cycle. This vision will simple high-throughput manufacturing techniques, knowledge of process physics, sophisticated computer models, more advanced design tools and data analysis tools to optimize, predict, and control the performance of additive processes and materials. Process models are in development for metal and ceramic processes that describe the physics at multiple size scales. Work on materials models is capturing the influence of internal, microscopic material structures which is crucial for predicting part performance and variability. Since AM machines provide minimal information during fabrication, researchers are also investigating various sensing technologies combined with data analysis techniques to detect, control, and/or eliminate performance-degrading part defects. When realized, this vision will provide an unparalleled capacity to rapidly ensure that AM products will reliably meet performance requirements.

While AM provides the ability to generate complex geometries and materials that cannot be realized using traditional manufacturing techniques, existing design tools are incapable of fully exploiting this potential. Therefore, Sandia is working to develop analysis-driven design tools that can capture and leverage the full potential of AM.

High-throughput techniques for material characterization[2] Figure 1 shows an automated tester and subsequent test “cartridge” with 25 material samples that measures the strength of structural materials with test times of one to two minutes per sample, compared to one to two hours for traditional techniques. As a result, the statistical variations in additive materials can be captured quickly and cost effectively.

Digital Manufacturing at the Kansas City National Security Campus

Digital manufacturing is paying huge dividends for the NNSA’s Kansas City National Security Campus (KCNSC). Digital Manufacturing includes additive manufacturing (AM) or three-dimensional (3D) printing, as its central element, but also includes design, simulation, validation, and analysis. At its highest level, AM may be defined as manufacturing by creating objects from melting, sintering, or fusing material by layers following a 3D computer model. In 2016, the KCNSC celebrated its 25,000th 3D-printed development article created within the Digital Manufacturing Initiative, providing more than $45 million in cost benefit.

The KCNSC, managed by Honeywell, first started rigorously exploring the use of 3D printing, or AM, in 2013 as a way to accelerate the fabrication of development articles and parts in support of NNSA’s national security mission. This effort produced the Digital Manufacturing Initiative. Digital manufacturing has significantly reduced cycle times for development articles, capitalized on new design processes like computer-aided organic design, and provided better ergonomic and technical solutions to transform nuclear weapons manufacturing. All of the technologies that encompass Digital manufacturing and the systematic approach to their use are necessary for AM to be successfully implemented and maximally effective at the KCNSC. These technologies have far reaching and rapidly increasing implications for the nuclear security enterprise.

Your Opinion Matters!

What do you think about this issue of the Stockpile Stewardship Quarterly? We want to know. Please send your comments and suggestions for future issues to Terri Stone at terri.stone@nnsa.doe.gov. Requests to be added to our mailing list should include your full name, email address, and affiliation/organization.

References


Digital Manufacturing is a systematic approach that takes the concept of rapid prototyping and all of the advantages AM provides, including speed, highly specific geometry, evaluation of fit and function, visualization, increased cycles of learning, and low cost, among others, and supports it with all of the technologies necessary for success. Practical this includes a change in thinking, and simulation and inspection technologies. The goal of digital manufacturing is the ability to turn an idea or concept for a fixture, mold, tool, or part into something tangible that a partner, collaborator, or customer can reliably use, as fast and efficiently as possible. At the KCNSC, digital manufacturing consists of the five concepts of “Think it,” “Simulate it,” “Print it,” “Validate it,” and “Use it.”

Think it: It is often stated that with AM “complexity is free.” The statement is meant to imply that many of the restrictions imposed by traditional subtractive manufacturing on part shape and geometry no longer apply. However, subtractive manufacturing was what the initial practitioners were used to, so early additive high-level designs tended to look a lot like subtractive ones. Parts and assemblies that could be combined into a single article were considered to be the most efficient as it maintained a familiar rectilinear look. A change not just in thinking, but in culture was needed. This change, the KCNSC purchased approximately 3D Makerbots (desktop 3D printers) with the goal of making them available for everyone to use and to explore. This approach was highly successful in expanding the our collective, internal thought processes, while promoting the use of AM. The concept of “complexity is free” is tailor-made for a host of computational design techniques, including topology optimization (TO) (see “Simulate it” below), which goes beyond the capability of the human mind. As a result, some of the designs have an alien look, and for many who may adopt, use, and rely upon parts designed in such a way the required change in thinking is a work in progress.

Simulate it: If complexity is truly free, then with few limitations, designs that could not easily be manufactured or not manufactured at all are suddenly possible. This includes what can be imagined, but potentially more significantly what can be derived computationally. Computational science, specifically simulation and modeling, have become the manufacturing toolbox at the KCNSC for some time. TO is a newer technique that combines simulation and design. With TO, an article or part can be rendered in a simulated environment and have the stresses that the part might see in processing or use applied to it. Simultaneously, the design can be optimized in a variety of ways, individually or even in combination. For example, design can be optimized for weight, strength, load, center of gravity, harmonic frequency, or any of a variety of other constraints, through the selective elimination of material. In many cases, the final designs derived this way could only be made additively (see Figure 2).
tools are adequate for traditional and destructive analysis and inspection. Validate it.

Traditional non-destructive and destructive analysis and inspection tools necessary for AM parts will include computed tomography and other x-ray techniques, and 3D light scanning. Commercial machines and associated software allow x-ray and 3D-scanned AM objects to be rendered computationally and compared to the model-based rendering of the article or part, and ultimately highlighting where the object is out of dimensional tolerance, and even the location of certain voids and imperfections. The accuracy of the different scanning processes is an area of continued research and development. Use it. “Use it” for development, prototypes, evaluation of fit and function, visualization, and non-critical tooling. For critical tooling and War Reserve (WR) more research, development, evaluation, and characterization is needed before such articles and parts can be certified and qualified for these applications. Realistically, even the comfort level of potential customers and end users of AM articles and parts must, and will, grow as the scientific evidence and financial cases for AM use grows. Implications There are a number of practical and positive implications for manufacturing with respect to AM. The production environment within the nuclear security enterprise is ideal for the early adoption of AM and the support technologies needed to make it work. The KCNSC is no exception where the mix of work could generally be described as consisting of high quality, low volume, and high diversity development and production manufacturing. Much of the work involves the research and development associated with preparing for production. The area where AM was applied early and continues to have significant impact is development tooling. When tooling, fixtures, assembly aids, molds, housings, and the like are being developed for production, AM accelerates development and cycles of learning by enabling rapid validation and testing at low cost. Tools made this way may not ultimately be used in production. The next area where AM is being applied is associated with critical tooling, tooling that will be used in production. Finally, the ultimate goal is to use AM to produce parts additively. Impact The impact of AM at the KCNSC has been significant. Over the last three fiscal years (FYS), FY 2014 to FY 2016, the KCNSC has printed approximately 34,000 AM articles and derived approximately $64M in total cost benefit. AM now touches nearly every aspect of development at the KCNSC. The rapid adoption of new technology and close collaboration and cooperation with federal agency counterparts, academia, and industry to derive benefits for customers are the hallmarks of the KCNSC. Along with the Digital Manufacturing initiative comes other technology strategies that have proven successful in generating new and exciting technology breakthroughs in support of national security missions. Validate it. Traditional non-destructive and destructive analysis and inspection tools are adequate for traditional subtractive manufacturing. However, with AM designs that are derived computationally, these traditional methods for determining tolerances, and properties and performance are no longer adequate or no longer apply. The inspection and characterization tools necessary for AM parts will include computed tomography and other x-ray techniques, and 3D light scanning. Commercial machines and associated software allow x-ray and 3D-scanned AM objects to be rendered computationally and compared to the model-based rendering of the article or part, and ultimately highlighting where the object is out of dimensional tolerance, and even the location of certain voids and imperfections. The accuracy of the different scanning processes is an area of continued research and development. Use it. “Use it” for development, prototypes, evaluation of fit and function, visualization, and non-critical tooling. For critical tooling and War Reserve (WR) more research, development, evaluation, and characterization is needed before such articles and parts can be certified and qualified for these applications. Realistically, even the comfort level of potential customers and end users of AM articles and parts must, and will, grow as the scientific evidence and financial cases for AM use grows.

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Impact

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Two Sandia National Laboratories Scientists to Receive Top Award

The Office of Research, Development, Test, and Evaluation congratulates Sandia National Laboratories researchers Stephanie Hansen and Alan Kruizenga on being selected to receive Presidential Early Career Awards for Scientists and Engineers (PECASE).

Hansen studies the behavior of atoms in extreme environments and is working under a five-year Early Career Award from the Department of Energy (DOE) Office of Science. Her work contributes to the tools used to model and interpret data from high-energy-density experiments and astrophysical plasmas. Kruizenga currently leads investigations into materials compatibility, materials selection, and efficiency-generating technology for solar power systems and advanced reactor concepts. His research, funded by DOE, provides fundamental understanding of corrosion mechanisms and associated data for design and use of molten salt and liquid metal-based materials in high temperature solar thermal and nuclear reactor systems. Hansen and Kruizenga are among the 102 individuals selected to receive the 2017 PECASE award. Each recipient of the once-in-a-career award will receive a citation and plaque and will continue to receive DOE funding for up to five years to advance his or her research.

Highlights

Brig. General Lutton and Dr. Njema Frazier Tour Massachusetts Institute of Technology (MIT) HED/ICF Division

While visiting MIT in January, Brigadier General Michael J. Lutton, NNSA Principal Assistant Deputy Administrator, and Dr. Njema Frazier, Acting Assistant Director of Inertial Confinement Fusion, were shown the scope of student and staff research at: the National Ignition Facility (Lawrence Livermore National Laboratory [LLNL]); Omega Laser Facility (University of Rochester Laboratory for Laser Energetics [LLE]); Z machine (Sandia National Laboratories); and MIT High Energy Density/Inertial Confinement Fusion (HED/ICF) laboratory.

The outstanding PhD work of the students was highlighted. Two recent NNSA-supported MIT PhD graduates were awarded the 2016 and 2014 Rosenbluth Outstanding Thesis in Plasma Physics: Mike Rosenberg and Mario Manuel, respectively. At the heart of MIT’s program has been its multi-year collaboration with LL, LLNL, and the National Nuclear Security Administration in support of the latter of which funded critical major components of large diagnostics that MIT has interfaced with its many collaborators at LL and LLNL. The MIT HED/ICF graduate students were able to present their thesis material and engage in wide-ranging discussions with Brig. General Lutton and Dr. Frazier.

At the MIT HED Experimental Facility (left to right): NNSA Stewardship Science Graduate Fellowship awardee Hong Sio, General Lutton, Postdoctoral Associate Dr. Cody Parker, graduate student Neel Kohadi, Dr. Frazier; and graduate students Raspberry Simpson, Greame Suttelfie, Brandon Lahmann, and Chris Wink. Hong Sio will be presenting his PhD research at NNSA Headquarters on May 9, 2017.
Joule Award 2017. The National Nuclear Security Administration's Office of International Nuclear Safeguards presented this year's Joule Award "in recognition of outstanding contributions made for transferring: $^{19}\text{F}(\alpha,n)^{22}\text{Na}$ Cross Section for Uranium Enrichment to international partners." The Versatile Array of Neutron Detectors at Low Energy, also known as VANDLE, array of plastic scintillators, developed with Stewardship Science Academic Alliances funds, was critical to the success of this project. Also important were the students and postdoctoral associates supported in part by the Rutgers University Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science, an NNSA academic partner, who helped take the data. The final report for this exciting work, entitled "A Kinematically Complete, Interdisciplinary, and Co-Institutional Measurement of the $^{19}\text{F}(\alpha,n)$ Cross Section for Nuclear Safeguards Science" is available online at http://www.osti.gov/scitech/servlets/purl/1263500. Currently, the data are being processed by researchers in the Nuclear Data Section of the International Atomic Energy Agency for use in nuclear safeguards work.