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Report on Additive Manufacturing for Large-Scale Metals Workshop

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OAK RIDGE NATIONAL LABORATORY
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Manufacturing Demonstration Facility

WORKSHOP REPORT ON ADDITIVE MANUFACTURING FOR LARGE-SCALE METAL COMPONENTS – DEVELOPMENT AND DEPLOYMENT OF METAL BIG-AREA-ADDITIVE-MANUFACTURING (LARGE-SCALE METALS AM) SYSTEM

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ABSTRACT

Additive manufacturing (AM) is considered an emerging technology that is expected to transform the way industry can make low-volume, high value complex structures. This disruptive technology promises to replace legacy manufacturing methods for the fabrication of existing components in addition to bringing new innovation for new components with increased functional and mechanical properties. This report outlines the outcome of a workshop on large-scale metal additive manufacturing held at Oak Ridge National Laboratory (ORNL) on March 11, 2016. The charter for the workshop was outlined by the Department of Energy (DOE) Advanced Manufacturing Office program manager. The status and impact of the Big Area Additive Manufacturing (BAAM) for polymer matrix composites was presented as the background motivation for the workshop. Following, the extension of underlying technology to low-cost metals was proposed with the following goals: (i) High deposition rates (approaching 100 lbs/h); (ii) Low cost (<$10/lbs) for steel, iron, aluminum, nickel, as well as, higher cost titanium, (iii) large components (major axis greater than 6 ft) and (iv) compliance of property requirements. The above concept was discussed in depth by representatives from different industrial sectors including welding, metal fabrication machinery, energy, construction, aerospace and heavy manufacturing. In addition, DOE's newly launched High Performance Computing for Manufacturing (HPC4MFG) program was reviewed. This program will apply thermo-mechanical models to elucidate deeper understanding of the interactions between design, process, and materials during additive manufacturing. Following these presentations, all the attendees took part in a brainstorming session where everyone identified the top 10 challenges in large-scale metal AM from their own perspective. The feedback was analyzed and grouped in different categories including, (i) CAD to PART software, (ii) selection of energy source, (iii) systems development, (iv) material feedstock, (v) process planning, (vi) residual stress & distortion, (vii) post-processing, (viii) qualification of parts, (ix) supply chain and (x) business case. Furthermore, an open innovation network methodology was proposed to accelerate the development and deployment of new large-scale metal additive manufacturing technology with the goal of creating a new generation of high deposition rate equipment, affordable feed stocks, and large metallic components to enhance America's economic competitiveness.

1. OVERVIEW OF GOALS, NEEDS AND CAPABILITY

Additive manufacturing (AM) is considered an emerging technology that is expected to transform the way industry can make low-volume, high value, complex structures for replacement of existing components, as well as, bring innovation for new components with increased functional and mechanical properties. The Department of Energy's Manufacturing Demonstration Facility (MDF), established at ORNL by Energy Efficiency and Renewable Energy (EERE), helps industry adopt new AM technologies to reduce life-cycle energy and greenhouse gas emissions, lower production cost, develop new products, and increased opportunities for high-paying jobs. This report outlines the outcome of a workshop on large-scale metal additive manufacturing. The workshop started with welcome and introductory comments by Dr. Thomas Zacharia, Deputy Director of Science and Technology at ORNL. He stressed the need for interdisciplinary research and development involving process, process control, materials science, computing, neutron science, as well as, the need for open innovation [1] based on sharing ideas and technologies to propel the US industry for global competitiveness.

1.1 PERSPECTIVE OF DOE-ADVANCED MANUFACTURING OFFICE AND CHARTER FOR THE WORKSHOP

The workshop was kicked off by Dr. Blake Marshall, Technology Manager for the Advanced Manufacturing Office (AMO) at DOE's Office of Energy Efficiency and Renewable Energy (EERE). He outlined the vision, mission, and goals of EERE and AMO. The fundamental vision of EERE focusses on developing a strong and prosperous America powered by clean, affordable and secure energy. The mission is to create and sustain American leadership in the transition to a global clean energy economy. The goals of EERE include the following activities: (i) Sustainable transportation: Accelerate the development and adoption of sustainable transportation technologies; (ii) Renewable power generation: Increase the generation of electric power from renewable sources; (iii) Energy efficiency: Improve the energy efficiency of our homes, buildings and industries; (iv) **Clean energy manufacturing: Stimulate the growth of thriving domestic clean energy manufacturing industry**; (v) Grid modernization: Enable the integration of clean electricity into a reliable, silent and efficient electricity grid; (vi) Federal sustainability: Lead efforts to improve federal sustainability and implementation of clean energy solutions; (vii) High-performing culture: Enable high-performing, results driven culture through effective management approaches and practices. The topic of this work shop on large-scale metal additive manufacturing fits under the clean energy manufacturing initiative. Dr. Marshall provided a charter for the workshop attendees to evaluate the technology with five basic questions related to impact, additionality, openness, enduring economic impact, and proper role of government as given below.

- Is this a high-impact problem?
- Will EERE funding make a large difference relative to existing funding from other sources, including the private sector
- Are we focusing on the broad problem we are trying to solve and open to new ideas, approaches and performers?
- How will EERE funding result in economic impacts for the United States?
- Why is this investment a necessary, proper, and unique role of government rather than something best left to the private sector?

Dr. Marshall highlighted the successful example of the development and deployment of Big Area Additive Manufacturing (BAAM) for polymer composites (see Fig. 1). The project started with a prototype demonstration of an idea (Fig. 1a) and led to a cooperative research and development agreement (CRADA) with Cincinnati Incorporated that resulted in the launch of a new product line, BAAM-CI (Fig. 1b). This system was then used to make a commercial demonstration of a 3D printed car (Fig. 1c) with Local Motors, called the Strati; followed by another demonstration of (Fig. 1d) a 3D Shelby

Cobra replica. This effort led to the design and deployment of the 2nd version of the commercial system (Fig. 1e) with an increased size envelope that enabled ORNL to demonstrate the Additive Manufacturing Integrated Energy, or AMIE project (Fig. 1f), an integrated house and vehicle with innovative energy management.

Figure 1: Trajectory of technology development, evaluation, demonstration, technology transfer and improvement of capability related to big area additive manufacturing of polymer matrix composite structures at MDF in an open innovation model with various industries and universities

The success of these initiatives, accomplished in a rapid timeline from concept to deployment, resulted in a new product line for the 100- year old American Automotive business within 3 years, has propelled the ORNL researchers to extend the concept to metallic systems with the following goals: (i) High deposition rates (100 lbs/h); (ii) Low cost (<$10/lbs) iron, steel, aluminum, nickel, as well as, higher cost alloys, such as titanium and Inconel; (iii) Large components [major axis greater than 6 ft]; and (iv) Meet the target property requirements. Dr. Marshall requested the attendees evaluate these targets and provide feedback on the challenges and approaches to achieve these targets through an open innovation model.

1.2 CASE OF LARGE-SCALE ADDITIVE MANUFACTURING OF METALS

<u>Presenter</u>: Dr. Lonnie Love

In the next presentation, Dr. Lonnie Love presented a case for development of large-scale additive manufacturing of materials. Currently, most of the common metallic parts made by additive manufacturing are rather small (< 1 ft^3) and are built with slow deposition rates (1 in^3/hr.) and relatively expensive feedstock material ($100/lbs). As a result, metallic AM has been adopted primarily by the Aerospace (improve buy to fly ratio) and biomedical (small and complex capability need) industries. This success adoption of AM in these industries has highlighted the need to extend this capability onto large structures. The reasons for extending AM onto large-scale components are justified based on (i) efficiencies through part consolidation, (ii) reduced time to realize large structures, (iii) low production rate of large components, and (iv) relatively high manufacturing costs of large components. Dr. Love articulated that with these drivers, new methods of additive manufacturing were required to achieve the promise of large scale AM. As an example, innovations on the polymer material and extruder design that occurred during the previous work enabled and BAAM-Ci (See Fig. 1e). These innovations led to three orders of magnitude increase in deposition rates of polymer composite within 12 months, starting from 1 in3/h to 2500 in^3/hr (100 lbs/h). Based on the industry feedback before the meeting, Dr. Love provided candidate target metallic applications including construction equipment, tooling, buildings, trucks and components for oil and gas, as well as, energy applications. He also expressed the challenge of printing a boom for excavator (see Fig. 2), as a forcing function. He discussed some of the gaps to achieving this goal including (i) CAD to Part, (ii) modeling and simulation of residual stresses and distortion, (iii) custom design of alloys, (iv) rapid qualification through in-situ and ex-situ characterization and (v) open innovation network at MDF through collaboration across various engineering solutions providers.

Figure 2: Challenge demonstration problem of printing a boom for excavator has been identified to force the development and evaluation of a large-scale metal additive manufacturing

1.3 INDUSTRY SECTOR DISCUSSIONS AND FEEDBACK

In this session, representatives from varying industrial sectors including, equipment manufacturers, welding industry, power generation, aerospace, and heavy manufacturing were invited to provide feedback and lead panel discussions. Salient points of these discussions are summarized below.

1.3.1 Metal Fabrication Machinery Perspective: Role of Existing Manufacturing Processes

<u>Presenter</u>: Mr. Rick Neff

This topic was led by Rick Neff, Manager of Market Development at Cincinnati Incorporated. Fabrication of big sheet metal is routinely performed in many industrial sectors by prudent use of cutting and welding. High productivity cutting and welding are routinely achieved by high speed gantry style manipulators. As a result, the goal of increasing the productivity of large-scale additive manufacturing can be achieved by leveraging existing expertise and technology in fabrication machinery community. Furthermore, these industries already have the required capital, infrastructure, training, sales and marketing distribution chains that allows for deployment of these technology. The above hypothesis was indeed proven by the rapid deployment of big area additive manufacturing (BAAM) infrastructure for polymer composites. In addition to gantry style robotic systems, new extruder technologies were also developed. BAAM has been deployed within emerging companies like Local Motors, material companies like Sabic, as well as, aerospace companies such as Textron Aviation. The introduction of BAAM allowed Local Motors to introduce a new 3D printed car, i.e. SWIM (see Fig. 3).

Figure 3: Introduction of 3D Printed car named as "SWIM" by Local Motors at SEMA in 2015

The extension of existing BAAM infrastructure to metal (referred as *Large-Scale Metals AM* in the rest of the document) may allow the traditional manufacturing community to innovate faster, increasing competitiveness and time to market. Although, the concept of large-scale metallic structures through electron beam and laser blown powder methodologies have been demonstrated for high-value added metallic (e.g. Titanium alloys) components, the adoption of *Large-Scale Metals AM* for commodity materials suffers from lack of business case. Some of the preliminary survey suggested the following business cases including realization of complexity, flexibility, precision replication, part consolidation, reduced lead time and waste, tapping workforce with wide range of skill set, and minimal constraints in commodity materials. Furthermore, the *Large-Scale Metals AM* can be easily transported to sites with minimal cost and can go from material feedstock to on demand part production. Possible targets of *Large-Scale Metals AM* technology may involve variety of metals and alloys (< $10/lbs) with local shielding that eliminates the need for box-like protective environments. The *Large-Scale Metals AM* can potentially leverage the existing supply chain for welding consumables, i.e., solid-wire, cored wire (with encapsulated alloy powders, ores, oxides, sponges), strips and foil. Similarly, *Large-Scale Metals AM* can use the existing welding energy sources including Electron Beam, Arc, Plasma, Laser, or a Combination of Arc, Plasma and Laser. Interestingly, there are emerging trends to use induction and microwave heating as auxiliary sources. In principle, existing solid-state processes like ultrasonic additive manufacturing (see Fig 4) developed by Fabrisonic®, cold-spray technologies, and friction stir processing can also be grouped within the lexicon of *Large-Scale Metals AM*. Alternatively, borrowing from the Binder Jet process, to use material feedstocks from metal injection molding (MIM) in conjunction with BAAM for polymer composite has also emerged as an alternative approach. However, this technology would indeed require high-temperature post-process operations like resin burn-off and sintering technologies. Due to this flexibility, *Large-Scale Metals AM* could potentially be developed for wide range of metallic systems including steel (ferritic and austenitic), magnesium alloys, aluminum alloys, Zn-base kirksite, copper, brass, Invar, and emerging low-cost Fe-base metallic nanomaterials, while satisfying the high value added components made up of titanium alloys.

Figure 4: Photograph of the largest ultrasonic additive manufacturing system developed by Fabrisonic. The SonicLayer® 4000 has a bed of 24" x 36" while the SonicLayer® 7200 can accommodate parts 6 ft x 6 ft x 3 ft

Based on the above discussions, availability of processing and material supply chain, one could conclude that there exists the business case. Nevertheless, the industry also recognizes challenges including residual stress, distortion, stability of the build platform, post processing and initial capital cost. The above discussion provided the backdrop for the technology presentations.

1.3.2 Modeling of Additive Manufacturing Processes: Role of High Performance Computing

Presenter: Dr. Peg Folta

Based on ensuing consensus across practitioners and researchers, it is clear that most of the additive manufacturing technologies are not matured enough to meet the public expectation of "plug and play." There are many trial and error optimization efforts made before a final part can be deployed in a real life application. As mentioned earlier, the *Large-Scale Metals AM* compresses various technical tasks including design, process selection, process parameter optimization and control, material selection, qualification and validation into a compressed time frame, driving the need to predict the interactions between various physical processes in a robust and timely manner. In this regard, DOE has launched a new program known as HPC4MFG which focuses on collaborative research between industries, national laboratories, and academia utilizing the existing high-performance computing infrastructure and software in DOE national laboratories. The director of the HPC4MFG, Dr. Peg Folta, provided an outline of ongoing projects relevant to the simulation of solidification grain texture during laser powder bed. One project focuses on understanding the roles of temperature gradient (G) and liquid-solid interface velocity (R) on the transition from columnar to equiaxed grains in nickel base alloys. Furthermore, other projects focus on predicting the residual stress and distortion in welding. Dr. Folta also provided information to participations, who may have already some form of *Large-Scale Metals AM* technology based on welding, on they could to apply for this HOC4MFG program to get access to existing computational capabilities.

1.3.3 Joining Community View Point: Role of existing welding and cladding processes

Presenter: Dr. Shawn Kelly

In discussions prior to this workshop, many industry members identified a viable pathway to realizing *Large-Scale Metals AM* capability by leveraging Arc based directed energy deposition technologies and building on the existing welding and joining infrastructure. This perspective was discussed by Dr. Shawn

Kelly from EWI, who directs the Additive Manufacturing Consortium (AMC). In his talk, Dr. Kelly indicated electric arc welding based additive manufacturing is not a new concept, having been introduced by a patent developed by Baker in 1920 for making decorative objects. However, the technology was never adopted for structural applications due to the emergence of robust and high quality machining and milling technologies. Dr. Kelly also concluded that, in principle, the underlying physical processes in any fusion (melting and solidification) based additive manufacturing processes are indeed the same as welding, which includes heat and mass transfer, solidification, solid-state transformation, evolution of residual stress and distortion, and heterogeneous properties. In the context of the targets proposed earlier, he compared different welding/cladding processes (see Fig. 5) in terms of their deposition rate ranges. It is clear from the data presented in this graph that in order to meet the 100 lbs/h, only electro-slag process is suitable as a single deposition head. He suggested that it is possible to use multiple tandem gas metal arc welding (GMAW) to arrive at the target speeds and deposition ranges, however, this would require the coordinated motion of robots. Dr. Kelly also reviewed some of the early demonstrations conducted by EWI using Gas Metal Arc Welding (GMAW), Gas Tungsten Welding (GTAW), Plasma Transferred Arc Welding (PTAW), and Electron Beam Welding (EBW). Some of these experiments showed that material wastage can be reduced by 85% when using arc welding based additive manufacturing.

Some of the limitations of using welding for AM led to the following challenges. The cleaning operation in between layers reduced the overall productivity. For example, in one experiment, for every 15 hours of arc-on time, 2 hours are used for the inter pass cleaning operation. Additional longer term challenges were observed related to (i) geometry of the walls with reference to distortion, (ii) planarity of each layer, (iii) tie-in near to the edge (see Fig. 6), (iv) sensitivity to welding consumable composition, (v) non self-correcting tool path which may affect final machining, (vi) challenges in tracking complex shapes and contours, (vii) complex nuances like arc-weaving and staggering of stop and start of welding with reference to arbitrary geometry, and (viii) long-winded path operation due to lack of robust robotic codes. Some suggested mitigation techniques included improved bead sequencing, part design, fixtures, base plate thickness tailored to expected heat input, pre-camber positioning, load balancing, and use of multiple energy sources and multiple robots.

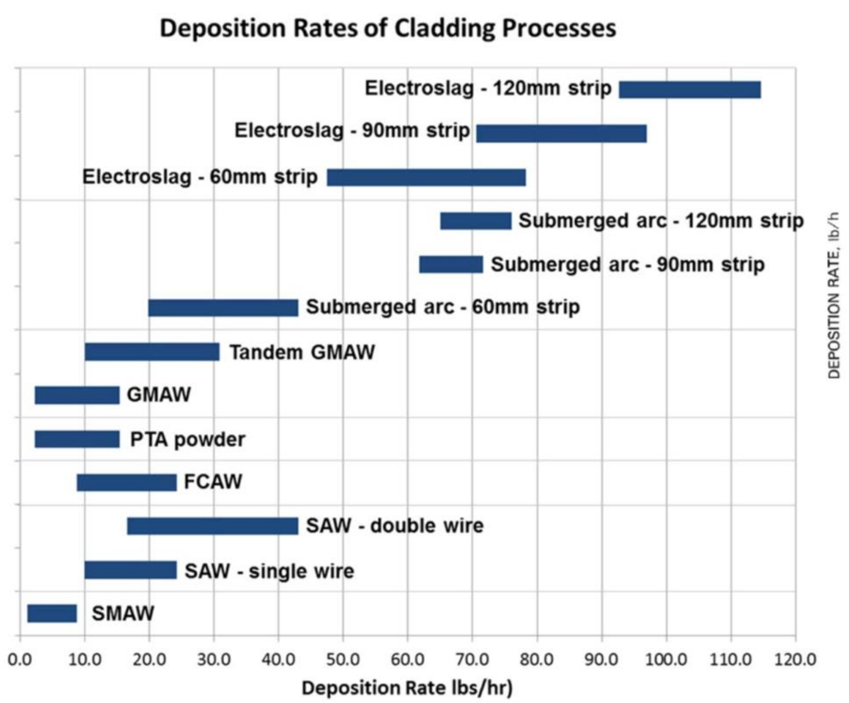

Figure 5: Comparison of deposition rates of various welding and cladding process.

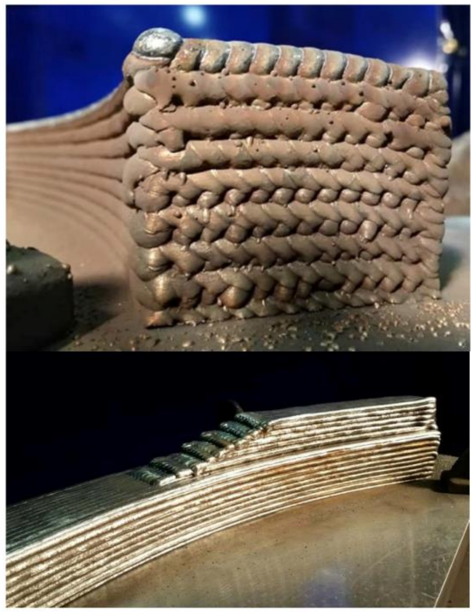

Figure 6: Photograph showing the potential defects along the edges of the wall where the tie-in between weld beads can be seen.

1.3.4 Energy Industry View Point – Challenges in Qualifying Large AM Parts

Presenter: Mr. David Gandy

Both the U.S. nuclear and fossil fuel industries face challenges when it comes to the design and manufacturing of large-scale parts in a timely manner due to a dwindling forging supply chain. This challenge was discussed by Mr. David Gandy from EPRI within the context of addressing it via two competing technologies i.e., powder metallurgy and additive manufacturing. High value components that can be made by these two processes are compared in Fig. 7. The table clearly shows that current additive manufacturing processes are not relevant for big components such as an SMR containment vessel due to limited envelope size. On the contrary, large-scale near-net shaped powder metallurgy technology has been proven to be feasible. Furthermore, this process has been used for developing functionally gradient materials for valves. Based upon this case study, if the proposed direct *Large-Scale Metal AM* technology can be proven, many potential components for nuclear reactor internals could be fabricated in this manner including: fuel assemblies (see Fig. 8), control rod drive internals, alignment pins, small spray nozzles, instrument brackets, stub-tube housing, steam separator inlet swirler, flow detectors, and generation IV reactor cooling channels. However, Mr. Gandy did identify critical challenges to mature the *Large-Scale Metals AM* for adoption on nuclear applications including (i) the limitation of chamber size, (ii) deposition rates, (iii) physical defects like porosity and lack of fusion, (iv) residual stress/distortion, (v) need for post processing and (vi) need for layer-by-layer qualification. Based on the above challenges, Mr. Gandy insisted the need to demonstrate the technology on real-life components within the associated qualification framework before pragmatic adoption by industry can occur.

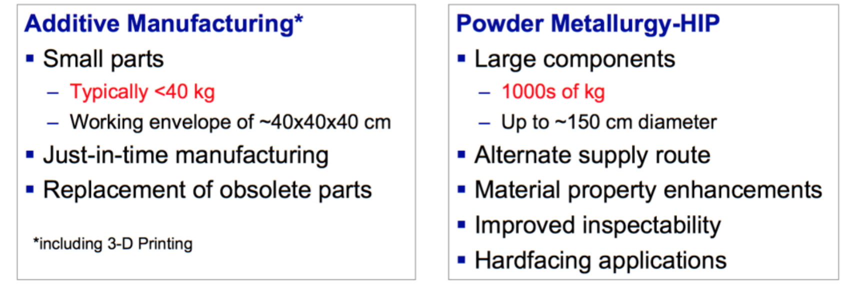

Figure 7: Scope comparison of additive manufacturing and powder metallurgy HIP processes

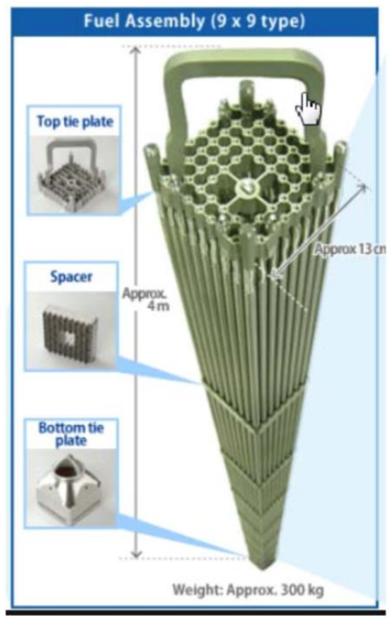

Figure 8: Possible application of Large-Scale Metals AM once it is matured.

1.3.5 Aerospace Industry Viewpoint – Business Case for Light Weight Metal Alloy Construction

Panel Session lead by Dr. David Dietrich, Dr. Slade Gardner, Mr. Brian Thompson

During this session, a panel was chaired by representatives from Boeing, Lockheed Martin and GKN Aerospace. Overwhelming focus on large-scale metal additive manufacturing for the Aerospace industry is related to the fabrication of Titanium components. The business case for AM against traditional manufacturing is related to reduced manufacturing cost, particularly the reduction of Titanium wastage during machining, i.e., improving the buy-to-fly ratio. Typical titanium billets can cost approximately \$25/lb whereas the recycle value of the machined chips is approximately \$1/lb. Typical buy-to-fly ratios are 10:1 or greater. As an example a 1 lb part would require 10 lbs of billet costing \$250 which after machining would result in 9 lbs of chips worth \$9. In addition, the machining Titanium is slow (typically 20 in^3/hr) requiring frequent tool changes (every 20 minutes). The following target requirements were suggested by the panel participants: (i) build envelope greater than 6-ft in any one direction ; (ii) tunable/increased deposition rates/feature resolution; (iii) improved deposited material properties

(Titanium); (iv) flexible and scalable equipment; (v) possible applications on unmanned aircraft components, (vi) standardization of machine; (vii) improved system robustness, (viii) reduction of lead time and (ix) focus on reducing end-to-end part manufacturing cost. The panel also reverberated many of the challenges identified by other speakers and recommended that these challenges should be addressed one step at a time via a phased introduction starting with non-critical structures and progressing to Class 1 critical applications.

1.3.6 Heavy manufacturing Industry View Point

Presenter: Dr. Nathan Parsons

Representative from Caterpillar discussed the required metrics before the adoption of *Large-Scale Metals AM* by the earthmoving equipment industry can occur. The first requirement is that the cost of *Large-Scale Metals AM* should be competitive to that of casting, in which case the target of $10/lbs may be appropriate. However, due to the need for good mechanical (fatigue) properties, the focus on cost reduction should be a secondary target. In contrast to the Aerospace industry, the weight reduction is not as important, rather the weight distribution is more crucial. Interestingly, the introduction of new alloys into the heavy manufacturing industry is rather easier compared to the automotive and energy industries. The discussion ensuing after the presentation validated the need for a demonstration project (see Fig. 2) to allow the community to understand the real challenges associated with transitioning *Large-Scale Metals AM* to various industries.

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2. TOP 10 CHALLENGES AND APPROACHES

Contribution: All the attendees of the workshop

After the above industry specific sessions, all the participants were encouraged to identify a list of top 10 challenges related to the development and deployment of *Large-Scale Metals AM*. The feedback from the audience was grouped under the following categories: (i) Computer Aided Design (CAD) to Part (ii) Selection of Energy Source, (iii) Systems, (iv) Material feedstock, (v) Process planning, (vi) Residual stress and distortion, (v) Post-processing, (vi) Qualification of parts; (vi) Supply chain, and (vii) business case development. Challenges in each of these categories are presented below along with possible paths forward to overcoming the same. The discussions in each category were captured under three different sub-categories of: specification, challenges, and approach (including the identification of possible partners who can provide tools to address this approach).

2.1 CAD TO PART

Specification

- Define the material, geometry, size ranges, expected properties and identify the sweet spot for the deployment of the *Large-Scale Metals AM* for each and every industrial sector.
- Develop robust, user friendly, deposition process specific (incorporation of design rules), design tools that will also allow for part consolidation

Challenges

- Non-planar fill up of the parts during additive manufacturing, e.g., leveraging the space filling algorithms like Hilbert curves and couple them with open domain 3D printing software
- Robust ways to define the material in specific locations does not exist.
- Commercial robotic path planning tools are not scalable to additive manufacturing arbitrary CAD, including non-gravity aligned modes.
- Surface finish definition is still a challenge.

Approach

- Design sacrificial supports to counteract the residual stress and distortion
- Develop and disseminate web-based guidance tools for CAD to PART for different classes of geometry and metallic materials

2.2 SELECTION OF ENERGY SOURCE

Specifications

- Due to the wide range of metallic systems, flexibility in energy density is necessary.

Challenges

- Not all applications may need expensive energy sources and the cost of capital will increase with introduction of laser and electron beam
- Flexible robotic cells to adopt arc, laser, plasma, and electron beam energy sources in a batch mode with or without vacuum conditions may be a prudent approach.
- Deposition rate influences final part resolution. Current DED technologies only have a narrow range of deposition rates/feature resolution. May be possible to broaden the deposition rate range on a single system through a combination of energy sources.

Approaches

- Develop systems that is capable of handling multiple energy sources depending upon the need final application, required properties, compliance to standards and also economic factors

2.3 SYSTEMS DEVELOPMENT

Specifications

- The systems should be capable of attaining on demand spatial resolution (μm to mm) within a robotic cell of many meters in size, as well as, out of plane deposition
- The systems should be scalable, flexible, and designed for use in a production environment (low cost, high rate, minimal operator interference, easily maintainable, safety, etc.)
- The systems should be capable of working in lights-out condition, i.e., with minimum manual supervision or error corrections.

Challenges

- A flexible robotic cell may not meet the required kinematics (velocity, acceleration, starting and stopping distance) when using a wide range of energy sources
- Existing welding robotic systems were not designed for high duty cycle conditions of 3D printing or additive manufacturing that may be in continuous operation for more than a day.
- With higher degrees of freedom and multiple robots, CAD to PART and path planning software becomes complex.
- Maintenance of robotic systems may require resources that may act against our aspiration to develop a low-cost system.

Approach

- Through open innovation and a collaborative approach, a comprehensive system must be developed and demonstrated that successfully integrates energy source(s), sensors (i.e. closed loop control), material feed (i.e., wire feed), robotics, material handling, instrumentation, inert environment, and data transfer for qualification.

2.4 MATERIAL FEED STOCK

Specifications

- The relevant alloy systems should include Titanium, steels, aluminum, nickel, copper and magnesium alloys.
- Need to develop a supply chain for low cost, highly reliable material feedstock
- One of the key requirements for the *Large-Scale Metals AM* is the mass customization of material feedstock (wire or sheet) that allows for improved control of the deposited microstructure, as well as, transformation strains relevant to the mitigation of residual stresses and distortion [ref].
- The magnitude of allowable impurities based on the qualification strategy for different industrial sector needs to be identified

Challenges

- How far back in the supply chain of material feedstock can we go, e.g., iron oxides within cored wire?
- Methods for recycling expensive materials (e.g. Titanium materials) needs to be developed.
- Cost should be lower than $2/lb (i.e steel based). for heavy manufacturing.

- Shielding gas costs may prove to be critical as the build size and background temperature increases.
- With titanium builds, there is a need to have a large enclosure with shielding to avoid oxidation and pick up of interstitials (C, N, O) as solid solutions – need to develop global or local shielding solutions

Approach

- The community may need to explore self-shielding consumables and slag-metal reactions for minimizing shielding gas costs for all metallic alloys. Possibility of leveraging expansive literature on extractive metallurgy.
- Also develop other alternative large-scale additive manufacturing technologies that are based on polymer matrix composition, e.g. metal injection molding resin as a material feed stock.

2.5 PROCESS PLANNING

Specifications

- The process planning, i.e., path of the energy source with reference to the CAD geometry and pre-existing substrate, has to consider innovative tools for in-situ mitigation of distortion and residual stress
- The path planning must be capable of changing the energy input and wire feed (composition selection and rate) for comprehensive control of surface finish, wall geometry, and microstructure
- Path planning should be capable of close integration with computational process modeling, as well as, sensor feedback.

Challenges

- Currently, all additive manufacturing technologies, including existing large-scale metal additive methodologies are open loop. They cannot recover from unexpected defects (e.g., wire feed rate problems) even with the presence of sensors. Current process controls lack the human imagination and decision making to allow for on-the-fly changes in process planning.

Approach

- A pragmatic approach for process planning needs to be developed to include:
    a. Step-by-step increases in complexity of integration with sensors
    b. Process modeling with demonstrated improvements in geometrical conformity
    c. Ability to program tailored properties for parts with increasing complexity.

2.6 RESIDUAL STRESS DISTORTION

Specifications

- The welding literature has demonstrated that it is impossible to eliminate residual stress and distortion due to inherent nature of thermal gradients and associated accumulated plastic gradients.

Challenges

- Although most of the residual stress and distortion can be predicted, the buckling distortion is hard to predict. This will be a critical issue during the manufacture of large-scale structures that are topologically optimized and/or those with embedded thin truss structures.

Approach

- The literature also shows pragmatic methods to reduce the magnitude of the residual stress and distortion through careful process planning, thermal management and local material compositions that lead to compressive stresses.

2.7 POST PROCESSING

Specifications

- In certain geometries and metal feed stocks, it would be impossible to eliminate debilitating microstructure heterogeneity and high residual stresses. Under these conditions, it will be necessary to use post-processing methodologies that fall under thermo-mechanical processing (e.g. heat treatment and local mechanical cold working).

Challenges

- The infrastructure for post-processing treatments of large-scale AM structures are not widespread.
- Need for post-processing will severely limit the stability of topologically optimized structures
- The notion of "complexity is free" within AM may not be achievable or more limited in large-scale structures.

Approach

- Develop pragmatic design rules for final geometry and material composition in the context of expected performance in order to minimize the need for global post-process heat treatment.
- Use of alternative local treatment techniques (e.g. high frequency impact treatment [2]), to counteract the tensile residual stresses in high stress concentration areas, should be considered.

2.8 QUALIFICATION OF PARTS

This topic was discussed extensively during the workshop. It is interesting to note that the discussions are not unique to *Large-Scale Metals AM*, rather relevant to all additive manufacturing technologies. Therefore, the challenges can be addressed synergistically by building on emerging solutions for direct energy deposition and power bed metal additive manufacturing.

Specifications

- The qualifications should include the standardization and curation of CAD to Part and Path Planning and process parameter designs, by building on welding procedure specifications and qualifications adopted by welding community.

Challenges

- Build quality between builds deposited by directed energy deposition technology is inconsistent. This is indeed a perennial problem even in welding [3].
- Uncertainty in assessing material performance [low- and high-temperature static and dynamic mechanical properties including tensile strength, creep strength, impact strength and fatigue limits], in different regions of (large and small-scale) complex geometry.
- The extent and magnitude of R&D required for achieving the qualification of AM components is open ended and often lacks consensus, even with emerging standards development within Standards Development Organizations.
- Currently, there are no cost-effective, non-destructive inspection technologies for inspection of large-scale parts. Even if it can be inspected, the location of defects leads to the significant scatter in material property data [4].
- Significantly high cost associated with qualifying materials in the Aerospace industry using traditional methods

- Lack of understand of effects-of-defects on material properties and part performance
- Lack of material database for materials deposited using AM (i.e. MMPDS)

Approach

- The qualification method can be based on the calibration of typical classes of geometries and extend to complex geometries by association or equivalency.
- There is a need to develop and disseminate design rules for leveraging the inherent anisotropic properties based on the geometric design of AM parts.
- Leverage ICME tools to develop rapid qualification methods.
- The open innovation network members should include the Standards Development Organizations including American Welding Society, ASTM, SAE, and ASME. Use demonstration articles to develop code packages for the development of standards for large-scale metal additive manufacturing of complex structures.

2.9 SUPPLY CHAIN

Specifications

- In order to deploy *Large-Scale Metals AM* across many industry sectors into small-, medium-, and large-scale companies, it is important to ensure a robust supply chain for material feedstock, robotic platforms, CAD to Part software, Process-Planning Software with Computational Models, sensors and controls and training and education.

Challenges

- There is no single organization or entry point to coordinate all the above activities in a seamless fashion without infringing on individual intellectual properties.
- The complexity increases when considering the need to standardize the CAD to Part software and aligning the same with the OPC foundation that focusses on interoperability standards [5].
- The developments have to be synchronized with emerging industry (e.g. cyber-physical systems, also known as internet of things) initiatives across the world.
- The equipment manufactures for each and every component needed for *Large-Scale Metals AM* equipment are fragmented. There is a need for an integrator organization or organizations that is/are able to deploy commercial units of *Large-Scale Metals AM* with viable, global, 24-hour support infrastructure.
- Safety requirements may prove to be a rate limiting step.

Approach

- Develop a flexible, but add-on type approach for the *Large-Scale Metals AM* system that allows for wide range of industry participation using open-innovation network approach (discussed further below).

2.10 BUSINESS CASE

Specifications

- The business case has to be made for each and every industrial sector including automotive, aerospace, energy, heavy manufacturing and commodity industries.
- *Large-Scale Metals AM* could be used for the development of spare parts and reducing inventory cost.
- The aerospace industry already has the business case for titanium due to the, high cost of raw material, high buy-to-fly ratios, slow machining time, and low value of recycled material.

Challenges

- Currently, the data does not exist for the complete definition of the market space for *Large-Scale Metals AM* across all industries.
- OEM acceptance may require demonstrations that cannot be executed easily by current Tier-1 suppliers.
- Cost of all-in-all machine with all engineering solutions may be cost prohibitive.
-

Approach

- Develop a “killer”, i.e. high-impact (hybrid or topologically optimized low-cost Fe- or Al- based materials). After proving the technology, extend the tools to high cost materials (e.g. Nickle, Titanium) and pragmatic (part consolidation) demonstration that shows the competitive nature of the *Large-Scale Metals AM* with respect to traditional manufacturing approaches such as casting, forging, and welded sheet-metal structures. Disseminate the results relevant to this challenge problem in open literature and web-sites in terms of design guidelines and business case.
- Although a favorable business case may drive the rate of adoption, the participants also indicated that BAAM for polymer matrix composites brought about its own applications (e.g. mass customization of cars by Local Motors). So the *Large-Scale Metals AM* should also focus on applications or innovations that cannot be met by traditional manufacturing.

3. OPEN INNOVATION NETWORK FOR TECHNOLOGY DEVELOPMENT AND TRANSFER

As discussed above, the workshop attendees provided comprehensive technology development, demonstration and dissemination methodologies for *Large-Scale Metals AM*. However, to realize all the above tools, one single organization cannot provide the solution. Furthermore, many small businesses cannot afford to pay membership to existing large consortium efforts. Therefore, the suggestion has been made to adopt the "open services innovation" (see Fig. 9) [1] model as presented by Dr. William Peter, Director of Manufacturing Demonstration Facility. The mission of this open innovation network will be to "*accelerate the development and deployment of new Large-Scale Metals AM, creating a new generation of high deposition rate equipment, affordable feed stocks, and large metallic components to enhance America's economic competitiveness*."

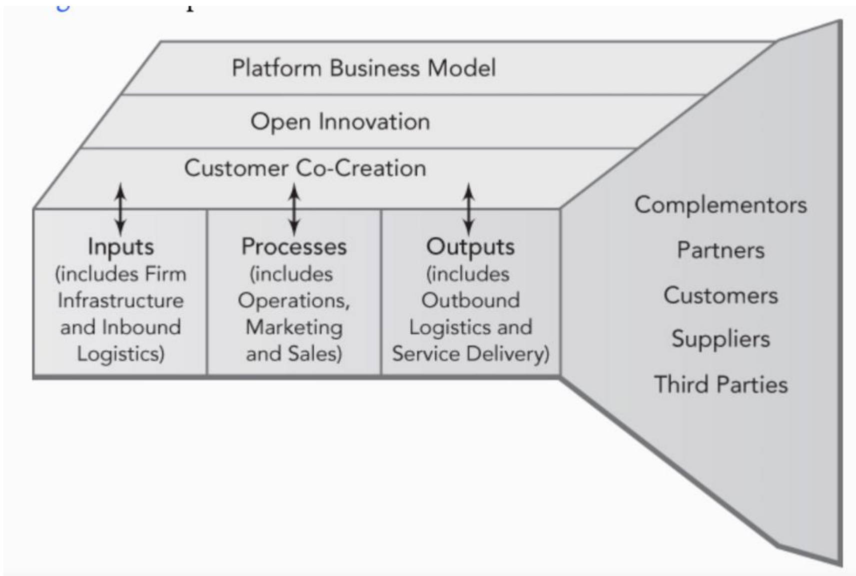

Figure 9: Reproduction of image from the book of Chesbrough which outlines the open services value chain for open innovation on cutting edge technology development

It is proposed that the open innovation network be operated by a non-profit organization with a steering committee. This network will serve as a platform for industry to develop a pre-competitive technology roadmap to accelerate the development and deployment of *Large-Scale Metals AM*. This will enable the industries to collaborate across the value chain to meet the mission outlined above. This network will be financed by a small membership fee (e.g. $ 5,000/year to $10,000/year) in order to organize this data flow and coordination across industries. The members will have access to all the open domain software and design guidelines that will be developed at ORNL's Manufacturing Demonstration Facility for *Large-Scale Metals AM*. To protect the intellectual property of all the participating members and still arrive at an integrated system for *Large-Scale Metals AM*, an innovative model for investment and revenue sharing will be developed (see Fig. 10). Such a business model has already been developed and deployed for integrated process modeling of welding, i.e., E-WeldPredictor® [6].

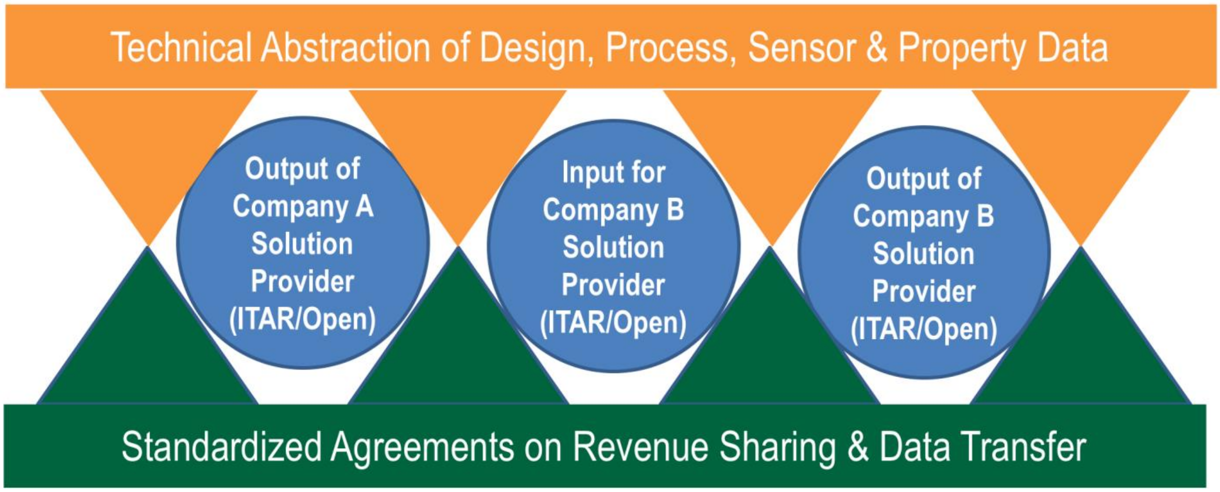

Figure 10: An emerging open innovation network model for Large-Scale Metals AM development and deployment across industries. A non-profit organization will allow for plug and play of different engineering solutions form different organizations that allow for revenue sharing and seamless technology transfer.

4. NEXT STEPS TASKS AND PROJECT PLANNING

The following section provides the approximate time line for the next steps in this initiative to develop and deploy *Large-Scale Metals AM*. This project planning was developed based on the experience of moving BAAM for polymer composites from concept stage to technology development to transfer to industries. The following tasks are planned.

(1) Workshop with stakeholders from industry and agencies (March 11, 2016) (completed)

(2) Complete the draft report based on the workshop (May 15, 2016) (Completed)

(3) Refine and publish report based on the feedback from the participants (July 1, 2016)

(4) Launch open innovation network non-profit organization

(5) Identify and design impactful demonstration article and functionality

(6) Select partners for the development of a system and material feed stock

(7) Mature the Open domain CAD Part to Software

(8) Finalize on the energy source and material feedstock

(9) Identify robust and rapid computational tool for analyzing the distortion and residual stress

(10) Develop process planning for the selected system and solicit feed-back from industries

(11) Integrate all the parts to arrive at a prototype system *Large-Scale Metals AM*-v1 with energy source, material feedstock delivery, sensors, process control, in-situ (thermal and geometry) data logging, and qualification strategies for a steel component

(12) Make simple (prismatic and hollow cylinder) and complex (cantilevers with trusses) geometries with steels

(13) Evaluate the geometric conformity and properties, as well as, functional performance of the structures in simple shapes

(14) Refine the system and move on to complex shapes relevant for all industrial sectors.

(15) Release the *Large-Scale Metals AM*-v1 system to U.S. industries through the open innovation network model

(16) Parallel efforts to export the low-cost metals-v1 (steels and aluminum alloys) to other metallic alloys (Stainless steels, nickel base alloys, Ti-alloys, and Mg-alloys) depending upon the business case

(17) Continued refining or transfer the system technology to an integrator who can take over the marketing and sales. The network steps down to activities involving dissemination, education and training and expanding to other cost-cutting technologies for high value added materials.

(18) A yearly demonstration of *Large-Scale Metals AM* during annual industry sponsored events (e.g. CONEXPO-2017, FabTech).

The time frame for the above tasks over a period of three years is presented in a Tabular format. The resources (i.e. funding, capital and expertise) have not been estimated currently. This will be finalized at the launch of the open innovation network for *Large-Scale Metals AM*.

Table 1: Proposed timeframe for completion of the above tasks.

Task	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
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Completed		In Progress		Planned		Milestone Demonstration Event	

APPENDIX 1: MEETING AGENDA

OAK RIDGE National Laboratory — AGENDA

MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

Final agenda 3-8-16

Additive Manufacturing for Large Scale Metals Workshop
Location: NTRC, 2360 Cherahala Blvd., Knoxville

Event contact: Bill Peter 865-241-8113 (office)			*Rita Ayers 865-946-3096(office)*
Friday, March 11, 2016			
Time	**Event**	**Lead**	**Place**
7:45-8:15am	**Arrive at NTRC (Badging)** **(Bagels and coffee available)**	Rita Ayers Stefani Pemberton	NTRC Lobby
8:15-8:25am	**Welcome and Overview of Manufacturing Activities**	Thomas Zacharia, ORNL	NTRC, CC01
8:30-8:55am	**Goals of Workshop & Charter- DOE Perspective**	Blake Marshall, DOE	NTRC, CC01
9:00-9:25am	**BAAM- Status and Technology Transfer Activities**	Lonnie Love, ORNL	NTRC, CC01
9:30-9:45am	**BAMM CI**	Rick Neff, Cincinnati Inc.	NTRC, CC01
9:45-9:55am	**Break**		
10:00-10:30am	**Tour of Manufacturing Demonstration Facility**	Bill Peter, ORNL Lonnie Love, ORNL	NTRC-2
10:45–11:00am	**Role of Arc Welding Advances**	Shawn Kelly, EWI	NTRC, CC01
11:05-11:20am	**Role of High Performance Computing**	Peg Folta, LLNL	NTRC, CC01
11:25-11:40am	**EPRI: Needs from Energy Industries Perspective**	Dave Gandy, EPRI	NTRC, CC01
11:45-12:00pm	**Boeing: Needs from Aerospace Perspective**	Dave Dietrich, Boeing	NTRC, CC01
12:20-12:35pm	**Caterpillar: Needs for Heavy Manufacturing Perspective**	Nathan Parsons, Caterpillar	NTRC, CC01
12:40-1:15pm	**Working Lunch: Consortium Models**		NTRC, CC01
1:15-1:30pm	**Break**		

APPENDIX 2: MEETING ATTENDEES

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