Out of Bounds **Additive Manufacturing**

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The Big Area Additive Manufacturing system has the potential to manufacture parts completely unbounded in size.

Lockheed Martin and Oak Ridge National Laboratory (ORNL) are working on an additive manufacturing (AM) system (Big Area Additive Manufacturing, or BAAM) capable of manufacturing components measured not in terms of inches or feet, but multiple yards in all dimensions (Fig. 1). It has the potential to manufacture parts completely unbounded in size. Lockheed Martin pioneered the development of advanced materials, equipment, and processes for AM, and continues to be an industry leader in the field, realizing a vision that started in the late 1990s for manufacturing advanced thermoplastic composites of arbitrary size and shape. To further this goal, Lockheed Martin teamed with ORNL to leverage the lab's historic expertise in materials development and processing through the recently established U.S. Department of Energy's (DOE) Manufacturing Demonstration Facility (MDF). The partnership will accelerate the maturation and eventual commercialization of the Big Area Additive Manufacturing (BAAM) system.

Fig. 1 — *Big Area Additive Manufacturing (BAAM) system at ORNL's Manufacturing Demonstration Facility.*

AM benefits

Most current AM systems are confined to a limited build envelope defined by a powder bed or an enclosed deposition zone, such as an oven. By contrast, BAAM is not confined by a controlled-deposition chamber or restricted to a single deposition head. Instead, the system is designed to accommodate a team of coordinated robots working in an open-air environment to produce components and structures unbounded in size. The system not only expands the working volume of AM, but also enables the use of advanced polymer composites, multiple materials within a single component, multifunctional materials, and automated insertion of dedicated subcomponents, enabling a "CAD-to-system" approach rather than a "CAD-to-part" philosophy.

Most conventional manufacturing techniques (e.g., drilling, milling, and turning) are classified as subtractive because they involve removing material from a block of raw stock. Alternatively, AM refers to a suite of rapid, fully automated manufacturing technologies based on additive principles. AM enables production of complex structures directly from three-dimensional (3-D) CAD models in a layer-by-layer process using metals, polymers, and composite materials. Selective laser sintering (SLS), fused deposition modeling (FDM; Stratasys Inc., Eden Prairie, Minn.), and electron beam melting (EBM; Arcam AB, Mölndal, Sweden) are just a few examples of AM technologies. Unlike subtractive techniques that require time and energy to remove material, AM makes very efficient use of energy and raw materials, depositing material only where it is needed. This leads to significant time, energy, and cost savings in the manufacture of complex components for the automotive, biomedical, aerospace, and robotic industries.

AM volume capabilities

A number of AM systems can make components in the range of inches to several feet. For example, commercial systems currently available from Stratasys (Fortus 900) and ExOne (M-Print) produce polymer and metal components, respectively, measuring two to three feet along a side. The German company Voxeljet recently unveiled a continuous powder bed system (VXC800) that allows building and unpacking processes to occur simultaneously, effectively producing unbounded parts along a single dimension. In the Netherlands, an artist is using a robotically controlled, extruded polymer-deposition system to make freeform designs several feet long.

The BAAM system at ORNL's MDF deposits high-performance engineered thermoplastics and customized thermoplastic composites via melt extrusion processing. BAAM leverages industry standard feedstock materials, such as polymer pellets, powders,

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Fig. 2 — *Robotically controlled extrusion-deposition head on the BAAM system.*

Fig. 3 — *ORNL gantry deposition system used for additive manufacturing of concrete structures.*

fiber reinforcements, and specialty additives rather than requiring pre-extruded filament feedstock commonly used in industry standard extrusion-based systems, such as FDM. A benefit of eliminating filament as feedstock material is the ability to create high-performance composite materials, such as compounds containing significant amounts of carbon-fiber reinforcement. Extruding filaments made of highly reinforced compounds flexible enough to be wound on a spool is very challenging, and is a major limitation to implementation in functional end-use structures. Therefore, the deposition head of the BAAM system is designed to combine melting, compounding, and extruding functions to deposit a high-performance polymer compound at a controlled rate. Deposition-head positioning and movement are controlled using a multiaxis robotic arm (Fig. 2), which can either be stationary or mounted to a large multiaxis gantry system, similar to automated fiber-placement technologies. The deposition head could also be mounted directly to a conventional three-axis gantry (Fig. 3). In previous research at ORNL, this gantry system was used to demonstrate freeform deposition of concrete structures. Figure 4 illustrates a composite structure where deposited concrete defines the internal and external surfaces of a wall structure, and the internal volume is filled with either insulating or structural materials.

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TC-PRISMA
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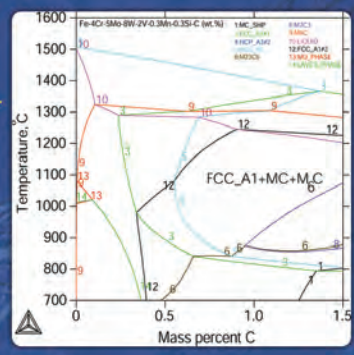
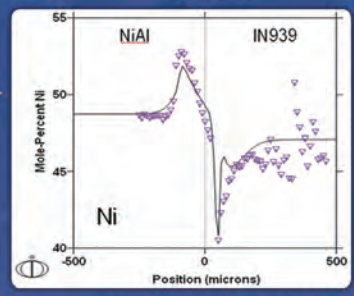
✓ Concurrent nucleation, growth/dissolution, and coarsening of precipitates
✓ Temporal evolution of particle size distribution
✓ Time-Temperature-Precipitation (TTP) diagram

Calculation of an isopleth


Diffusion in ordered phases


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Part size not a limitation

The BAAM system is designed to produce parts that are completely unbounded in size. It can deposit material at any point within a build volume defined by a specific range of motion, followed by the coordination of neighboring build volumes to produce very large components. In this configuration, a single deposition head is primary responsible for a specific region of the component, but coordinates with neighboring deposition systems to merge overlapping sections. In practice, multiple robotically controlled deposition systems are configured according to the overall dimensions of the desired component, simulating a "swarm" of deposition robots, each responsible for a given area, but coordinating with its neighbor to produce the overall component. Figure 5 illustrates the concept for the manufacture of an unmanned aerial vehicle.

Validation of the BAAM system will be initially demonstrated for the application of large, low-cost tooling. Several process-optimization tasks will be addressed in parallel throughout the advancement of BAAM, such as flow control, spatial resolution, geometric tolerances, advanced materials, and thermal control. Follow-on work will involve expanding the concept beyond the manufacture of large scale polymer components. Because AM enables incorporating multiple materials and multifunctional systems directly into a component structure, further developments will involve placement of reinforcing materials for structural applications, conductive materials for on-board electronics, and pick-and-place of specific subsystems (such as navigation, communication, and energy storage). The BAAM platform can also be extended to metallic-materials deposition.

BAAM potentially can revolutionize AM for large scale, highly complex systems, and radically impact tomorrow's fleet of aerospace vehicles. Imagine a full-scale squadron of unmanned aerial vehicles (UAVs) being produced directly from a CAD file in a "lights out" facility by a swarm of BAAM robots—from "file-to-flight" in a matter of days. Lockheed Martin and ORNL are accelerating technology to realize this vision through numerous innovations on the BAAM platform.

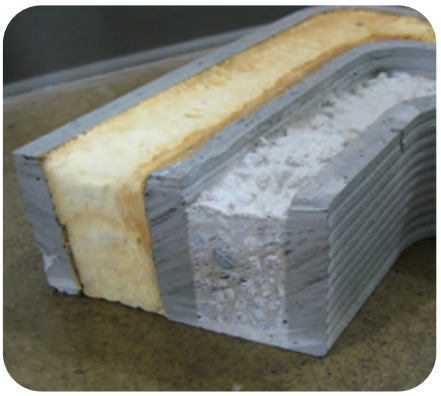

Fig. 4 — *Composite concrete wall structure deposited using AM.*

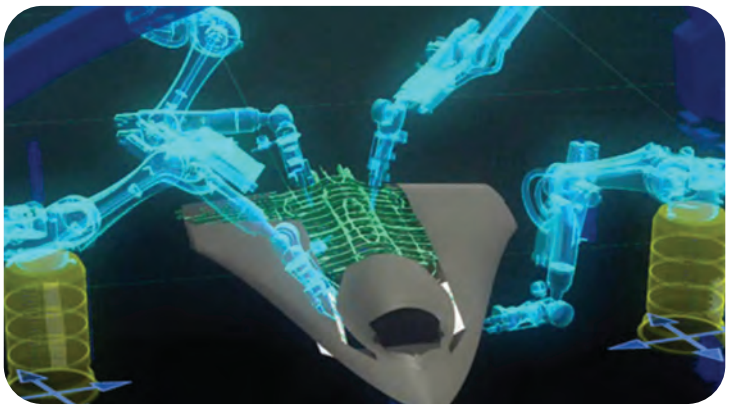

Fig. 5 — *Conceptual illustration of using coordinated multiple BAAM robots to manufacture a large, complex system.*

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