Department of Defense Additive Manufacturing Strategy

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Office of the Under Secretary of Defense
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I. Introduction

Technology is changing how systems are manufactured and how production information and data is managed. This digital manufacturing revolution has far-reaching implications for the Department of Defense (DoD) and the defense industrial base. Additive manufacturing (AM), also known as three-dimensional (3D) printing, is a "process of joining materials to make parts from 3D model data, usually layer by layer."[1] AM creates the part and material at the same time. This improves production speed and flexibility, but requires careful control of the AM process. AM can be used to: build parts that cannot be made any other way; uniquely combine materials; produce obsolete parts; rapidly prototype; create tools and specialized job aids. AM is a powerful tool to enable innovation and modernization of defense systems, support readiness and enhance warfighter readiness.

AM is a form of digital manufacturing relying on 3D models and simulations to produce custom solutions. To take the lead in digital manufacturing, the United States will develop standards for digital manufacturing products and processes as well as for the digital environment needed to manage and secure them, as outlined in the *Department of Defense's Digital Engineering Strategy*.[2] The transformation of the engineering process from design-build-test to a model-analyze-build methodology is enabled by the rapid prototyping and unique manufacturing capabilities of AM.

Formerly American Society for Testing and Materials (referred to as ASTM International), a standards development organization, describes seven broad categories of AM that combine raw material and energy in different ways, summarized in Figure 1. These AM processes and related non-thermal techniques, such as cold spray,[3] allow for repair and production of a diverse set of materials relevant to DoD requirements. AM is used to create polymer, metal, ceramic, composite parts, and/or electronic elements (e.g., sensors, antennae) from ground to air systems. It is also being deployed in newer applications such as: biological material (e.g., Food and Drug Administration (FDA) approved tissues, organs) energetics, electronics, concrete and other building materials.

Figure 1: Seven industry recognized types of additive manufacturing processes (image courtesy of ASTM International).

[1] *ISO / ASTM52900-15, Standard Terminology for Additive Manufacturing – General Principles – Terminology*, ASTM International, West Conshohocken, PA, 2015 http://www.astm.org/cgi-bin/resolver.cgi?ISOASTM52900

[2] Office of the Deputy Assistant Secretary of Defense for Systems Engineering (ODASD(SE)). *Department of Defense Digital Engineering Strategy*. Washington, D.C.: U.S. Department of Defense 2018. https://ac.cto.mil/wp-content/uploads/2019/06/2018-Digital-Engineering-Strategy_Approved_PrintVersion.pdf

[3] *The Cold Spray Materials Deposition Process: Fundamentals and Applications*, Victor Champagne, editor. Cambridge, U.K., Woodhead Publishing, 2007. https://www.amazon.com/Cold-Spray-Materials-Deposition-Process/dp/1845691814

II. Alignment to DoD Mission

AM is a versatile technology that provides technical advantages across a range of defense applications in order to build a more lethal and ready force. AM can be used with more traditional materials like metals, ceramics and polymers; and in emerging areas such as electronics, energetics, and chemical and biological applications. It is a rapid, on-demand, and customizable manufacturing tool that is an enabler to the logistical and operational reforms described in the *Summary of the 2018 National Defense Strategy* (NDS) in three main ways.

1. Modernize National Defense Systems

AM is a powerful tool to "build a more lethal Joint force," a primary objective of the 2018 NDS.[4] AM fundamentally changes how a component is designed by integrating the material, machine and design process to enable part geometries that cannot be made using traditional manufacturing. These innovative designs can achieve greater operational performance. The performance of systems can also be improved by integrating printed material into or onto other components for sensors and electronic components.

Other design enhancements enabled by AM include the ability to combine many parts into a single assembly. This ability eliminates the need for joining, reduces part count, manufacturing cost, and weight while improving system reliability. The ability to combine parts, blend materials, create innovative lightweight structures, and build internal features all translate to the ability to create systems that perform better. AM supports rapid design and prototype cycles that can significantly reduce production timelines and increase speed to the warfighter for new systems.

2. Increase Materiel Readiness

Enterprise-wide use of AM will enhance mission readiness. As stated in the Summary of the NDS, "A rapid, iterative approach to capability development will reduce costs, technological obsolescence, and acquisition risk."[5] AM can reduce the time-to-use, ensuring Warfighters receive critical capabilities when needed. It enables the rapid production of prototypes; leading to decreased development times and faster iterations. An AM system is functionally a factory in a box, a digitally controlled production line that can be turned on or off easily. AM can expand our traditional vendor base by providing alternative manufacturers cost-effective operations. The flexible production of AM machines contributes to a reduced risk of obsolete parts and as part of proactive planning to mitigate diminishing manufacturing sources and material shortages (DMSMS).

AM production can be distributed and scaled across multiple machines and locations. AM also allows parts to be fabricated enabling production closer to the time and point-of-need. This can reduce equipment downtime, increased maintenance and repair efficiency, and reduced cost supporting the need for "resilient and agile logistics."[6] Where parts cannot be acquired and data is not available, reverse engineering and AM part production is an approach to support legacy systems and impact readiness.

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[4] Office of the Secretary of Defense. *Summary of the 2018 National Defense Strategy*. Washington, D.C.: U.S. Department of Defense, 2018. Pg. 5. https://dod.defense.gov/Portals/1/Documents/pubs/2018-National-Defense-Strategy-Summary.pdf

[5] Office of the Secretary of Defense. *Summary of the 2018 National Defense Strategy*. Washington, D.C.: U.S. Department of Defense, 2018. Pg. 11. https://dod.defense.gov/Portals/1/Documents/pubs/2018-National-Defense-Strategy-Summary.pdf

[6] Office of the Secretary of Defense. *Summary of the 2018 National Defense Strategy*. Washington, D.C.: U.S. Department of Defense, 2018. Pg. 7. https://dod.defense.gov/Portals/1/Documents/pubs/2018-National-Defense-Strategy-Summary.pdf

3. Enhance Warfighter Innovation & Capability

AM allows tactical units to develop innovative solutions in theater. AM helps us shift the balance toward our greatest strength, the Warfighter. "The creativity and talent of the American Warfighter is our greatest enduring strength, and one we do not take for granted."[7] There are many examples already: U.S. Marine Corps innovating in the field printing a sensor housing to secure a gap in the perimeter of a base; Army field repair units printing a low cost cap to protect a million dollar lens on a tank, and the U.S. Air Force using AM to replace obsolete parts for the C-5 at five percent of the cost. Despite AM providing Warfighters with increased capabilities, it must be balanced with safety guidelines, training, and systems to support appropriate use.

A connected digital approach is a foundational element of this strategy. The digital thread provides digital process integration with complete, secure, and authoritative data required for the safe and effective use of AM. It enables the Warfighter by giving tactical units secure access to approved data; a way to share innovative solutions; and the ability to submit ideas back to engineering centers and life cycle managers.

III. Purpose

The purpose of this DoD AM strategy is to provide a shared set of guiding principles and a framework for AM technology development and transition to support modernization and Warfighter readiness within DoD, Military Services, and Agencies. It supports the Office of the Secretary of Defense (OSD), Military Services, and relevant DoD Agencies to build on current or planned activities, reduce redundancy, align funding opportunities, and improve the effectiveness of AM implementation/campaign efforts.

This strategy identifies pathways to overcome the remaining barriers to move AM into the realm of generally accepted technologies like machining and casting in order to take advantage of the capabilities of this technology. To mainstream AM across DoD, five primary needs must be addressed: (1) rapid and standardized approaches for qualification of materials and processes, and certification of AM parts, (2) new business models for contracting and acquisition of AM digital technical data, (3) logistics model for production of AM parts at forward operating locations, (4) standard AM technical data content, and (5) an interoperable secure AM digital thread for connectivity and data management.

Figure 2: 3D Printed Concrete Bridge.

[7] Office of the Secretary of Defense. *Summary of the 2018 National Defense Strategy*. Washington, D.C.: U.S. Department of Defense, 2018. Pg. 8. https://dod.defense.gov/Portals/1/Documents/pubs/2018-National-Defense-Strategy-Summary.pdf

DoD's Vision for the Use of Additive Manufacturing

Additive Manufacturing enables a more agile, adaptable and aligned defense supply base to outpace adversarial threats.

IV. Vision

In the future, AM will enable a more agile, adaptable and aligned defense supply base to outpace adversarial threats. AM will be a widely accepted manufacturing technology used across DoD and defense industrial base. It will be broadly applied for innovative designs, increasing lethality and reliability for weapons systems and the Warfighter. New technologies will transition more rapidly from research and development to fielded capabilities to support modernization and sustainment.

The digital thread, an ecosystem of interconnected systems, software and data will accelerate use of AM by connecting information to physical processes more effectively. The use of advanced technologies like modeling and simulation, artificial intelligence, and machine learning will improve development and production of new capabilities more effectively. DoD will implement new business models to access and license digital data rights to improve cost and maintenance using AM.

Standards, specifications, and data sets will be available to rapidly qualify AM machines and materials and certify AM parts. Personnel will be trained appropriately for their jobs. Service members will be proficient in using AM to solve field challenges. Engineers adequately trained to design for AM. Manufacturing operators will be certified to use AM machines. The acquisition and industry community will be educated on how to appropriately use AM for system development, production and sustainment.

V. Goal Summary

To achieve this vision, DoD will:

1. **Integrate AM into DoD and defense industrial base.**

   DoD will integrate and promote the use of additive manufacturing to modernize weapon systems, increase materiel readiness, and enhance Warfighter capabilities through policy, guidelines, and Service or Agency-level implementation plans.

2. **Align AM activities across DoD and with external partners.**

   DoD will continue to collaborate and bring together stakeholders from across the Services, defense industry, and academia to reduce barriers to the adoption of AM and to integrate AM into the supply chain through a variety of forums.

3. **Advance and Promote Agile Use of AM.**

   DoD will modify and adopt policies for AM across technical and business processes, including qualification and certification approaches that increase agility and incorporate new developments in AM machines, materials, and technologies.

4. **Expand proficiency in AM: learn, practice, and share knowledge.**

   The Services will educate and train the technical and business workforce necessary to integrate and use AM.

5. **Secure the AM workflow.**

   DoD will identify challenges, recommend solutions, and implement digital thread capabilities that integrate AM processes, secure and control AM systems, and provide access to authoritative AM digital data.

VI. Goals and Focus Areas

Goal 1: Integrate AM into DoD and the defense industrial base.

This goal focuses on allowing the Department to realize the benefits and far-reaching impact of AM across DoD operations and the industrial supply chain, from engineering and acquisition to maintenance and sustainment. To this end, the Department will develop internal policy and expand guidance for the appropriate use of AM by the defense industrial base. DoD will promote sharing of AM part life and performance data with original equipment manufacturers to support lifecycle analysis to further improve reliability and sustainability.

1.1 Develop policy and guidance that enable the use of AM to the widest extent practical.

Policy and guidance need to be refined to increase the supply chain's adoption of AM. As this manufacturing technology matures, the policy and guidance must provide the flexibility to allow not only near-term adoption to meet readiness needs but also long-term design enhancements to improve systems. Identifying critical readiness drivers across weapons systems will enable DoD to assess near term opportunities to address those needs through AM.

Policy and guidance need to focus on the technical aspects for AM and business practices and strategies to address concerns such as intellectual property and cyber protection that are paramount to this digital manufacturing application. Policy will address the acquisition process to ensure proper consideration of the necessary data rights to support maintenance, cost analysis and other considerations of balancing industry and government interests. Department-wide policy will provide the overarching guidance for the advancement of AM.

1.2 Revise Service or Agency-level AM implementation plans.

DoD Military Services and relevant Agencies will formally develop and update implementation plans to operationalize AM into their respective organizations and improve and augment the supply chain. The Services and relevant DoD Agencies have already started to develop initial AM frameworks and implementation/campaign plans to address the development and execution of AM throughout their organizations. At the core of these plans are the following basic tenets that align across DoD:

- Enhance proficiency through development of qualification and certification guides to ensure best-in-class AM capabilities within the Services and how we share information throughout government, industry, and academia
- Enable widespread exchange of ideas to foster innovation and new designs and deliver rapid capability
- Provide guidance to our expeditionary and point of need sources
- Develop a world-class workforce of practitioners, designers, technicians, and acquisition professionals
- Define business practices, logistics, cost modeling, and supply chain integration policies and guidance.

1.3 Develop the metrics and measures of success.

DoD will use metrics to evaluate the implementation of AM supported by digital tools (e.g., Joint Additive Manufacturing Model Exchange (JAMMEX), Repository of Additive Parts for Tactical and Operational Readiness (RAPTOR)). DoD will refine the current set of metrics to define the value of AM in terms of readiness and cost as AM technology matures. This includes how AM products can be consistently and accurately produced whether they involve small or large production lots. Measures of performance (i.e., number of parts produced, type, etc.) and measures of effectiveness (i.e. consistent quality, increased system readiness and reduced cost) will be agreed to and reported on in a consistent manner across

PROVIDING GUIDANCE

AM Acquisition Guide: The Department is developing responsive AM-related business practices and contracting guidance that consider Intellectual Property considerations with other legal and liability implications. Current conventional or industry business profit models may need to be modified for broad implementation and use of AM capabilities. AM may create opportunities and pathways to provide incentives for suppliers that also benefit DoD's cost and performance interests.

To meet this need, Office of the Under Secretary of Defense for Acquisition and Sustainment, in partnership with the Navy and industry, has developed an acquisition guide that outlines considerations in the procurement of AM parts and data rights.

DoD. It will be important to ensure that system level performance and reliability metrics are maintained with the use of AM.

1.4 Develop and share new business models for AM in contracting and acquisition.

While AM enables design flexibility and speed of fabrication of complex components incapable of being manufactured previously, there are many important considerations regarding the adoption of AM, including legal and contracting approaches. Developers need business models and contracting guidance to scale and incentivize the use of AM parts in DoD weapon systems where appropriate.

To be effective, guidelines or instructions need to address all phases of the acquisition cycle from initial design to sustainment. The proper configuration control for AM parts in systems need to be in place if there are design changes for example from suppliers. There are significant challenges and concerns regarding intellectual property rights and what opportunities are open with respect to reverse engineering end item parts for limited and rapid production. DoD will consider technical data access as part of the contracting process, to include alternative business models such as licensing rather than acquiring data. Aspects to be considered are scenarios for traditional government acquisition, parts obsolescence and material shortages, design improvements, contracted logistic support, and point of need printing on demand.

1.5 Employ sound risk management practices.

The Military Services are currently employing low-risk approaches to address readiness issues and to allow the scaling of technology capability and introduction through agile infrastructures. Risk management practices need to consider the consequences of failure for a tailorable qualification and certification process to improve the speed of AM application, address Service-unique elements, cybersecurity and operational use. Low-risk approaches should broadly consider non-critical part applications such as support equipment, vehicles, tooling/fixtures, and non-critical weapon system components/parts. As the technology matures, greater use of AM such as in metal and structural applications will expand through enhanced materials, processes, and risk assessments on the use of AM components for specific applications. DoD will continue to take a stepped approach to ensure risk and consequence of failure is considered appropriately in the use of AM using consistent approaches. DoD will also use part management best practices (configuration control and part identification) to protect against counterfeit parts and ensure quality.

Goal 2: Align AM activities across DoD and external partners.

This goal focuses on formally aligning leadership, resources, guidance, and processes for new and advanced designs as well as improved sustainment of our military systems across DoD in partnership with other Government partners and industry. Efficient deployment of AM technologies enabled by effective leadership, policies and resources will result in more lethal, responsive and effective DoD forces. Additionally, AM involves many digital engineering modalities that are under development as well; and require careful attention as they mature to utilize these to their fullest advantage.

2.1 Support and resource cross-Service collaboration.

The Joint Additive Manufacturing Working Group (JAMWG) was established to provide a forum to: share best practices; identify common challenges and key resource gaps; collaborate on joint projects; and recommend changes in policy or guidance. Forums such as the Naval AM Technology Interchange (NAMTI), the AM Workshops coordinated with JAMWG, the Air Force Technical Interchange Meeting (AFTIM), and the Army Community of Practice bring government leaders and industry participants together to address AM challenges. These are also opportunities to refine goals and common interests and to foster improved communication and insight into AM technology developments. Building upon the work of the community so far, the JAMWG will develop a communication and collaboration plan to ensure stakeholders engaged across the Department focus on high-value activities to jointly execute this strategy and engage with external collaborators.

COLLABORATING ON MANUFACTURING

In recognition of the impact of manufacturing across DoD enterprise, a formal cross-DoD collaboration framework is being established. The Joint Defense Manufacturing Council will allow Senior DoD leaders to align resources and share information to maximize the value of manufacturing to maintain DoD's strategic competitive advantage. The JDMC will align modernization priorities and manufacturing efforts to impact the readiness of the Department today and the future of the Nation's defense.

The JDMC will serve a central coordination role for internal working groups such as the Joint Additive Manufacturing Working Group, as well as external stakeholders – such as industry partners and DoD Manufacturing Innovation Institutes.

2.2 Revise joint roadmaps and align resources.

DoD will continue to develop and refine current AM roadmaps to best inform the Service implementation plans and evaluate resources. In 2016, the first DoD-wide AM Roadmap was published with four focus areas: design, material, process, and value chain.[8] The roadmap is being updated to incorporate advances in technology and current information from Service-level plans. DoD will align research and development, acquisition, logistics, and business process investments to gaps in the roadmap to meet DoD

[8] Fielding, Jennifer, et. al. *Department of Defense Additive Manufacturing Roadmap,* Report 88ABW-2016-5841. Washington, DC: Department of Defense, November 20, 2016. https://www.americamakes.us/wp-content/uploads/sites/2/2017/05/Final-Report-DoDRoadmapping-FINAL120216.pdf

AM objectives and improve the effectiveness of AM implementation efforts.

2.3 Partner across the Federal Government and with external stakeholders.

DoD will continue to strengthen partnerships across the Federal Government working with related agencies on the advancement of AM. National Aeronautics and Space Agency (NASA), Department of Energy (DOE), Federal Aviation Administration (FAA), Department of Commerce (DOC) and others all have active and robust AM programs and activities. DoD will leverage their work and where possible identify joint projects and programs.

To be effective in the sustained and broader use of AM, DoD must work with industry to take advantage of best-in-class knowledge, tools and private sector experience. Understanding industry needs when creating policy and guidance will inform more effective outcomes. The Department has established eight public-private partnerships shown in Figure 3, DoD Manufacturing Innovation Institutes (MIIs) are focused on key advanced manufacturing technologies. These MIIs are part of a larger national network and serve as national resources to bring together industry, academia and government partners to advance the state of the art and maintain U.S. manufacturing competitiveness. DoD will strategically and tactically engage in investments through these MIIs to advance AM and related technologies, like digital engineering.

As DoD Services continue to leverage each other's strengths in AM, DoD will also benefit from working with our allied and North Atlantic Treaty Organization (NATO) partners. In the future, coalitions will be critical to DoD success in future conflicts. Integrating AM technologies has already begun to be tested and proven, during two recent exercises. As part of the 2018 Coalition Warrior Interoperability Exercise (CWIX) in Poland, a U.S. Marine Corps Unmanned Autonomous Vehicle (UAV) was printed by Norway and flown at CWIX. This event leveraged the ability to securely transfer data between allied nations. During the 2018 Trident Juncture in Norway, U.S. Marines Corps trained with their Norwegian counterparts and conducted a personnel exchange with Norway's Defense Research Establishment. This bolstered

Figure 3: The DoD Manufacturing Innovation Institutes, national research and development assets.

sharing of lessons learned and discussions of engineering technical data, as well as demonstration of secure file transfer between nations. It is essential for events of this nature to continue as they are critical in our partnerships in the goal to fully leverage the capacity of AM technologies.

Goal 3: Advance and Promote Agile Use of AM.

This goal focuses on enabling DoD to be more responsive to Warfighter needs and maintain technological superiority through increased scientific understanding, innovative design and application of AM. Further, this goal looks to scale the adoption of AM within the Services as well as the industrial base. AM will afford a level of responsiveness that realigns American military might with an emerging industrial base that is innovative, bold, and agile. Through rapid prototyping, AM accelerates capability development to address urgent needs, drives innovation at the speed of battle, and delivers advanced warfighting capabilities. Use of AM for tooling, fixtures, jigs and job-aids are near term use cases that support traditional manufacturing and maintenance. The Department is beginning to see the how AM can support readiness. As one example, the Air Force is using AM to support the C-5 Galaxy Program as shown in Figure 4.

3.1 Develop and share new approaches to certification and qualification.

AM is currently well suited for low-volume, out-of-production or long lead time parts. However, the need to qualify and certify parts, including structural components, and their associated processes is a challenge and barrier to a broader use and ability to scale production of end use parts. AM process operations have influence over the final part quality, raw material, and part geometry. These contributing factors may add complexity to qualification and certification, potentially adding cost. A risk-based approach to qualification and certification will appropriately manage the level of rigor and cost for the highest risk parts and processes (e.g., critical safety items).

Researchers are studying the factors that contribute to performance of AM parts to develop

Figure 4: Expansion of the use of AM within the C-5 Galaxy Program. PA Case No . 78ABW-2020-0016(20-02391) Distribution A. Approved for public release.

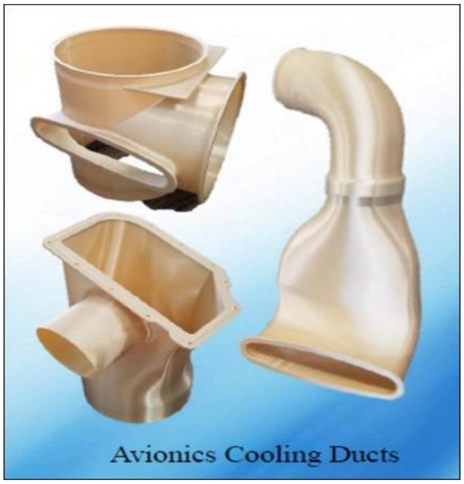


Figure 5: C-17 Galaxy avionics cooling duct family of parts approved for AM production. PA case number 88ABW-2018-1788. Distribution A. Approved for Public Release.

tools to accelerate qualification. DoD will leverage data, lessons learned and best practices already being developed from the Services and industry for qualification and certification of AM components in order to develop common definitions and standards to rapidly enable future improvements.

The Department is developing criteria to define the factors that allow the expansion of AM capabilities and incorporation into products (e.g., families of parts) such as avionics cooling ducts on the C-17 Galaxy, as shown in Figure 5. Readiness will drive the scale and opportunities for AM to meet warfighting needs.

3.2 Advanced technology to inform design.

The flexibility of AM calls for the development of new technological approaches to accelerate design, qualification and certification processes. The Services are currently evaluating Modeling and Simulation (M&S) tools to increase confidence that structural metallic parts are reliable and cost effective. Figure 6 summarizes the Quality Made program currently executed through the Office of Naval Research who will share the outcomes of this research DoD-wide. This is one example of an improved qualification approach enhanced by incorporating modeling and simulation with process controls and feedback mechanisms. DoD will continue research and development in these important areas as the technology remains in early stages of implementation.

3.3 Support forward deployment and application of AM in the field.

The use of virtual environments, creating a manufacturing "digital twin" to improve manufacturing operations and maintain appropriate databases as part of a model-based enterprise, will support materiel readiness going forward. It is imperative that the Services provide

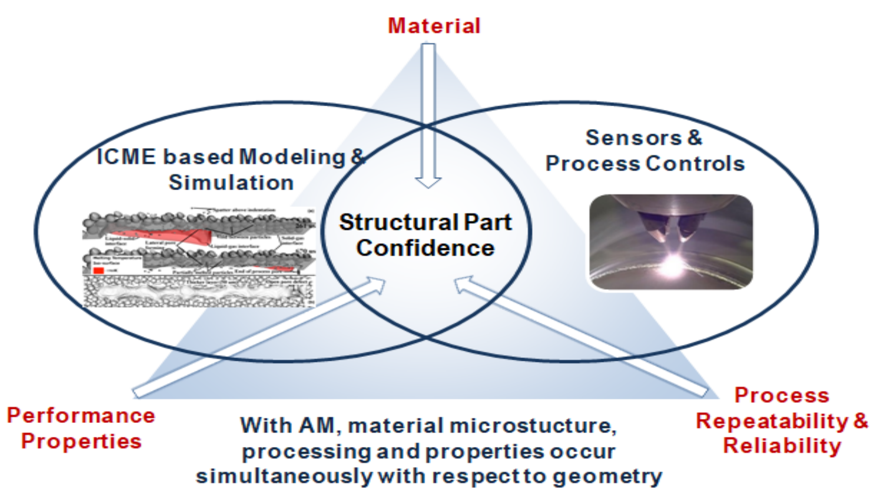


Figure 6: A summary of the Navy's Quality Made Program to improve qualification and increase confidence in AM through advanced technologies. (Distribution A. Approved for public release; DCN 43-2411-17)

their field/afloat units and Commanders with the guidance and streamlined ability to triage part requests, provide engineering approval and feedback for parts that require enhanced review, and minimize the risk that forward-deployed units assume in accepting 3D printed solutions. The expansion of the digital thread for complete, secure and authoritative data for safe and effective use of AM within the Services, across DoD and industry will support this process.

As the Services employ AM machines and applicable post-processing equipment, attention to facility; safety; and hazard risk assessment standards based on technical understanding will also require further development. Use of AM for temporary, life-limited parts needs to be appropriately managed with guidance and training. The expeditionary use of AM will take into consideration logistics for materials, machines, and personnel. These standards will include forward-deployed expeditionary and afloat locations. Figure 7 shows examples of expeditionary AM capabilities (clockwise) U.S. Marine Corp's X-Fab, Navy's USS Stennis AM Lab, and Army's Rapid Fabrication (R-FAB) via AM on the Battlefield.

Figure 7: Examples of DoD's expeditionary and afloat AM capabilities.

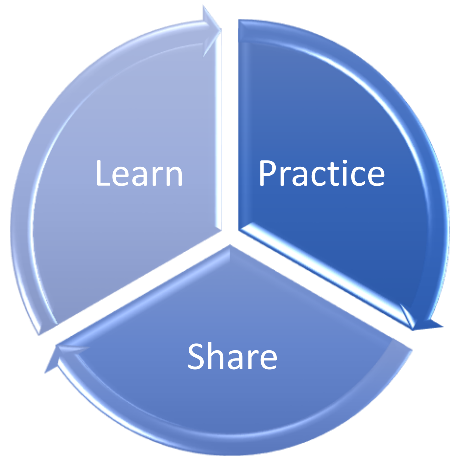
Goal 4: Expand proficiency in AM: learn, practice and share knowledge.

This goal aims to develop and maintain competency in the application of AM across the defense industrial base, which is central to realizing the value proposition offered by this new technology. Due to the broad range of AM applications and its relative immaturity in the realm of manufacturing of end use parts, there is very little difference between the skill sets needed to properly specify all material and process requirements and physically printing the part.

There are broad national trends in the need for more skilled labor in the manufacturing sector as advanced technologies become the foundation of the industry. DoD is developing an overarching strategy to address US manufacturing workforce challenges to support the nation's defense. DoD MIIs have a key role to play in educating and training the next generation manufacturing workforce which includes DoD personnel.

There are some specific challenges for workforce development within the Department that require additional consideration. The traditional make or buy decisions for out-of-production parts will be influenced by the use of AM and having sufficient internal knowledge and capability. The Department's flexibility and negotiating position is strengthened by maintaining a high-level of credibility and technical proficiency in AM.

Developing and maintaining AM competency will require enhanced support over the next 10 years to address skill set gaps, and a lack of accredited training programs and industry consensus on manufacturing standards. Three key tenets to developing and maintaining proficiency in AM are to: (1) **Learn** processes and best practices, (2) **Practice** the discipline of making parts, and (3) **Share** knowledge.



4.1 Learn processes and best practices

DoD's workforce needs additional technical and non-technical education to maintain internal AM expertise. Developing best practices to understand business implications of low lot size and long lead-time challenges, cost model and Cost Benefit Analysis development, and the impacts of Intellectual Property policy and practice are needed to deploy AM. While many lead time and availability challenges can be addressed with AM, much of the true value of the technique will come when adapting the part geometry to the capabilities of the processes. DoD will identify, define, and adopt best practices regarding Design for Additive Manufacturing (DFAM).

The Department must develop capability consensus for the enterprise-level knowledge of what AM is and how best to use it with baseline

"The creativity and talent of the American Warfighter is our greatest enduring strength, and one we do not take for granted."

-Summary of the 2018 National Defense Strategy

AM education development. The plan to develop subject matter experts (SMEs) must be supported by investments in maintaining and advancing technical knowledge in AM. Personnel need a combination of formal training, on-the-job training (OJT), and qualification prior to the operation and use of AM machines and processes appropriate to their roles. The acquired SMEs must be retained, with continuous training and technical development opportunities. The Military Services and Defense Agencies will leverage, develop and adopt technical accreditation and certification relevant to current job roles that is portable to employment in industry and academia. DoD will also incorporate AM relevant training into the acquisition workforce as part of existing training and development pathways.

4.2 Practice the discipline of making parts

To establish and maintain an organic capability baseline, the workforce must continually demonstrate, use, and reinforce AM competencies and proficiencies. The learning process for AM is grounded in the art of doing. Apprenticeship programs with hands-on training are being deployed across DoD. The Department will partner with industry to establish standards and best practices for training and certifying engineers and technicians in AM. Upskilling and reskilling will be important aspects to maintaining a ready workforce. A key element to overcome these challenges and fully embrace AM is to ensure depth of talent in any critical knowledge set.

Figure 8: Soldiers using the Army's R-Fab unit for AM.

4.3 Share knowledge

A key way to achieve proficiency faster and maintain core competency is to ensure that important information is connected to decision makers at all levels both within and external to DoD. DoD Services will share best practices and lessons learned internally and as appropriate with external partners. Additive processes rely heavily on a digital infrastructure, which affords access to large volumes of process and performance data.

The digital thread within each Service is critical in providing configuration control and management of approved AM data. The connection of data across DoD can be enabled by cross DoD tools, such as the Joint Additive Manufacturing Model Exchange (JAMMEX), which serves as a portal to AM digital data for operational users.

Key areas that will be focal points for sharing and maintaining AM information are:

- **Standards and Guidelines.** DoD will continue to support development and sharing of industry and military standards, technical work orders or instructions, and other practical guidelines across Services with encouragement to adopt and adapt as needed.
- **Digital data management.** Sharing data and having common standards will reduce the time required to develop and certify new materials and processes. Data retention guidance is another aspect of the overall digital data management that will be supported.
- **Connection to industry and academia.** DoD will engage in technical interchanges, share lessons learned and information with internal and external stakeholders to increase knowledge. Qualification and certification

data is a key gap and opportunity for collaboration.

Goal 5: Secure the AM workflow.

This goal is to ensure cyber security throughout the AM workflow, to secure the digital thread which includes the creation and transfer of data, as well as the protection of the AM production and testing processes.

To realize the value of AM we must expand the defense-industrial base to include non-traditional suppliers and operational users. As the AM manufacturing base expands the cybersecurity risks increase, including potential for data theft, alteration of data and machine tampering which could result in low quality parts.

Most AM machines are not connected to a network today due to these known cybersecurity risks. DoD organizations have implemented secure, access-controlled data systems to allow approved users to download and then manually upload data to the machine. While this process manages cybersecurity risk, it is slow and labor intensive.

To realize the value of AM across the Department and to maintain security, tools, guidelines, and standards must be enhanced to enable: (1) controlled access and use of up-to-date authoritative digital data to qualified machines and personnel (2) direct and secure connection of AM machines to the network with approved digital frameworks and protocols; and (3) quality assurance processes from raw materials management to final part validation.

5.1 Protect, control and manage data transfer and access.

The Department leverages existing cybersecurity policies and protocols to develop policy and guidance for secure transfer of AM data to authorized machines and personnel. DoD will establish processes to validate AM part data and use digital twins for validation and prevention of tamper to secure the digital supply chain.

DoD will use data management best practices and configuration control for AM technical data. Digital thread guidelines for connected AM machines will address the need to clear data after a print is completed to prevent data spillage between builds. Guidelines will also be provided for disconnected AM machines to consider expeditionary environments. The AM process generates a large amount of data and uses several file types during the design and build process. Best practices for managing and retaining this intermediate type of data will also be developed to ensure proprietary and sensitive data are appropriately handled.

5.2 Enable direct and secure network connection of AM machines

DoD will leverage existing cybersecurity frameworks to securely connect AM machines to the network. DoD will also establish best practices for contracting and work with manufacturers to consider the cyber-physical security requirements of AM related equipment. DoD will partner with industry to identify and implement best practices for Information Technology (computers, networks, software to manage digital data, digital twins and models) and Operational Technology (the hardware and software to manage physical devices, equipment or events) risk management approaches to enhance AM cyber-physical security.

Once machines are connected maintaining machine configuration and ensuring machines are qualified for the intended use is critical. The Department will develop digital thread capability guidelines to validate AM machine qualification and configuration for network connected machines.

5.3 Use quality assurance practices to validate parts.

AM components are sensitive to variations in equipment configuration, material, and process parameters. Securing the process parameters in a networked machine needs to be considered as part of cyber security. Material and machine management are essential elements to quality assurance of the final part. Quality assurance (QA) processes have been developed by DoD components and are tailored based on risk assessment of the part. QA data is a part of the

AM digital thread and must also be secured and properly managed. DoD will leverage Component processes to develop policy and guidance for AM machine and material qualification and material management.

Rapidly assessing AM produced parts to meet the design requirements is essential to confirming that design, production, cyber-physical security and shop floor practices are robust and ensure quality. As rapid machine and material validation approaches, including shop floor best practices, are developed in one Service, they will be shared, and adopted across the Department.

Approaches to address the inspection and validation of AM parts are described below.

- **Standardize inspection and metrology practices for AM.** The range of complex geometries, novel materials, and unique microstructures enabled by AM can challenge some of the conventional approaches to nondestructive inspection (NDI). Investment in standardization and development of NDI validation will be a continued priority for DoD to advance the state of the art in inspection techniques to match AM requirements.
- **Development of *in-situ* sensing for part security validation**. The layer by layer AM process lends itself to correction and enhanced control. AM machine activity can be monitored real time, called *in-situ* sensing. This information can be fed back to the control system of the machine to make corrections, called closed-loop control. Sensing and control can help increase confidence in quality and be used to verify proper manufacturing. DoD will continue research and development of sensors and control systems to improve the control of AM processes and will support transition of these technologies to commercial products.
- **Provide data and software to support validation**. Data management extends to quality assurance and validation steps. It will be essential to providing quality control engineers with the right data to assess AM-produced parts. DoD will identify opportunities to partner with industry and invest in evaluating the utility of information in the digital thread and technical data packages for the purpose of validating the quality of AM parts.

VII. Key Next Steps

The OSD and DoD Services will work together on the acceleration of adoption through the implementation of this AM Strategy. OSD will support the refinement of DoD Service-level implementation plans aligned to the Additive Manufacturing Strategy. Actions are discussed throughout this document and the key next steps include the following:

1) Collaborate on Joint AM Activities. The OSD will continue to collaborate with DoD Services and Agencies through the Joint Defense Manufacturing Council and Joint Additive Manufacturing Working Group (JAMWG). They will ensure the highest level of coordination across the Services, DoD, Defense Logistics Agency (DLA), and others, geared toward activities that implement this strategy collectively. The JAMWG will identify metrics for DoD Services and Agencies to adopt and track the use, management, and value of AM.

2) Refine DoD Implementation Plans. DoD Services and Agencies, in collaboration with OSD, will refine or create AM implementation/campaign plans and roadmaps as necessary to align with this AM Strategy.

3) Implement Programs and Work with Industry. The OSD and DoD Services and Agencies will address operational and business gaps by launching pilot programs. OSD and DoD Services and Agencies will work with industry and Standards Development Organizations to develop and implement common AM standards. DoD will assess and ensure sufficient resources are available to support this activity.

4) Sustain the AM Digital Workflow. DoD will implement AM policy, guidance, and training initiatives to transform AM to a widely accepted and well-understood manufacturing technique. DoD will implement AM policy and guidance to ensure the transition to full digital design for new hardware. OSD and DoD Services and Agencies will support research and development programs to integrate advanced technologies (e.g., artificial intelligence, machine learning, process monitoring, etc.) into the AM digital thread and digital manufacturing environment.

VIII. Conclusions

The expected benefits of widespread adoption of AM supported by this strategy are 1) more lethal systems powered by innovative designs, 2) increased materiel readiness, and 3) empowered Warfighters to solve problems in theater real-time. Investments in AM must be made DoD-wide in order to achieve these benefits. As with any new technology, there are barriers to implementation. The maturity of the technology, the level of expertise of people, and the availability of data, materials, and machines all will contribute to the ability to use the advantages of a new technology.

The goals identified in this strategy present a pathway for DoD to overcome these challenges and to realize the power of AM to modernize the Nation's defense and increase materiel readiness. The execution of this strategy requires multiple stakeholders to work together within the Department and in collaboration with other government agencies, industry, academia, and U.S. allies.

Appendix 1 – Summary of Additive Manufacturing Goals and Focus Areas

Goals	Focus Areas
Goal 1: Integrate AM into DoD and the defense industrial base.	1.1 Develop policy and guidance that enable the use of AM to the widest extent practical 1.2 Revise Service or Agency-level AM implementation plans 1.3 Develop the metrics and measures of success 1.4 Develop and share new business models for AM in contracting and acquisition 1.5 Employ sound risk management practices
Goal 2: Align AM activities across DoD and external partners.	2.1 Support and resource cross-Service collaboration 2.2 Revise joint roadmaps and align resources 2.3 Partner across the Federal Government and with external stakeholders
Goal 3: Advance and Promote Agile Use of AM.	3.1. Develop and share new approaches to certification and qualification 3.2 Advance technology to inform design 3.3 Support forward deployment and application of AM in the field
Goal 4: Expand proficiency in AM: learn, practice and share knowledge.	4.1 Learn processes and best practices 4.2 Practice the discipline of making parts 4.3 Share knowledge
Goal 5: Secure the AM workflow.	5.1 Protect, control and manage data transfer and access 5.2 Enable direct and secure network connection of AM machines 5.3 Use quality assurance practices to validate parts

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Acronyms

Acronym	**Term**
3D	Three-Dimensional
AFTIM	Air Force Technical Interchange Meeting
AM	Additive Manufacturing
ASTM International	American Society for Testing and Materials International
CWIX	Coalition Warrior Interoperability Exercise
DED	Directed Energy Deposition
DLA	Defense Logistics Agency
DMSMS	diminishing manufacturing sources and material shortages
DOC	Department of Commerce
DoD	Department of Defense
DOE	Department of Energy
FAA	Federal Aviation Administration
FDA	Food and Drug Administration
ICME	Integrated Computational Material Engineering
JAMMEX	Joint Additive Manufacturing Model Exchange
JAMWG	Joint Additive Manufacturing Working Group
JDMC	Joint Defense Manufacturing Council
M&S	Modeling and Simulation
MIIs	Manufacturing Innovation Institutes
NAMTI	Naval Additive Manufacturing Technology Interchange
NASA	National Aeronautics and Space Agency
NATO	North Atlantic Treaty Organization
NDI	Nondestructive Inspection
NDS	National Defense Strategy
ODASD(SE)	Office of the Deputy Assistant Secretary of Defense for Systems Engineering
OSD	Office of the Secretary of Defense
PBF	Powder Bed Fusion
R-FAB	Rapid Fabrication (ref. U.S. Army and AM on the Battlefield)
RAPTOR	Repository of Additive Parts for Tactical and Operational Readiness
UAV	Unmanned Autonomous Vehicle