Direct Digital Manufacturing of Metallic Components: Vision and Roadmap

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Abstract

This paper reports on the results of the Navy Workshop entitled "Direct Digital Manufacturing of Metallic Components: Affordable, Durable, and Structurally Efficient Airframes" held 11-12 May 2010 at the Holiday Inn, Solomons Island, MD. DDM has the potential to enhance operational readiness, reduce total-ownership-cost, reduce energy consumption, and enable parts-on-demand manufacturing. The seventy-two participants from academia, industry, DoD, and the Navy were asked to help to identify the key technical challenges and needed R&D approaches required to implement DDM. Working groups were established in a) Innovative Structural Design, b) Maintenance and Repair, c) Qualification and Certification Methodology, and d) DDM Science & Technology. The results of the working groups' deliberations, as well as the insights of the plenary speakers are discussed. The R&D roadmaps generated for the near, mid, and far term timeframes are discussed.

Introduction

Accelerating the introduction of new technologies into the maintenance environment has been a priority, as has the reduction of sustainment cost [1]. The problem has been that conventional engineering solutions used to address repair, durability, and weight, typically result in increased acquisition costs and, consequently, are untenable to the program managers. Further, it has become abundantly clear that the cost, weight, and durability of naval air weapons systems must be improved. For example, $3B per year is spent on corrosion-related maintenance of Navy aircraft, curtailing our ability to acquire new weapons systems and decreasing the availability of operational assets [2].

Direct digital manufacturing (DDM) is an innovative part fabrication and repair technology that represents a game changing advance in the way airframes are designed, built, and maintained. DDM technology was identified in a prior Navy workshop as a means of effecting a 30% cost reduction and a 30% increase in through put [3].

High value, difficult to machine, and process alloy components materials favor the use of DDM. These types of alloys are typically used in demanding, fatigue-critical applications. Consequently, producing DDM parts with fatigue properties comparable to wrought products is an important objective. In situ and post fabrication techniques were identified as a means of enhancing fatigue performance. Control of surface roughness was also considered important.

Executive Guidance

Direct Digital Manufacturing (DDM) aligns well with and supports executive level guidance. The CNO [4] and the Quadrennial Defense Review Report [5] have emphasized reducing the Total Ownership Cost (TOC) of our weapon systems. The NAE S&T Strategic Plan [6] and NAE S&T Objective document [7] include incorporating affordability into platform design and construction; and responsive and visible logistics to enable distributed forces. The President has provided guidance to pursue transformational solutions and support visionary thinkers proposing high-risk, high-payoff research [8].

Vision State

The vision for DDM is illustrated in Figure 1 [9]. Its implementation would enhance operational readiness, reduce energy consumption, and reduce total ownership cost by exploiting advanced metallic direct digital manufacturing technologies. Metallic parts would be fabricated on-demand at a location in proximity to their end use.

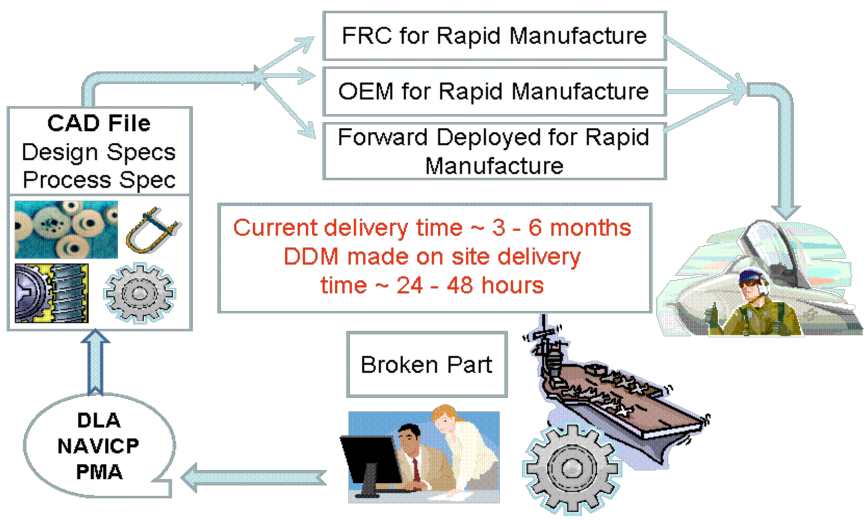

Figure 1 DDM Vision State: Parts-on-Demand – “Ship Electrons not Parts”

Conceptually, a broken or worn part is identified by a maintainer. The maintainer uses a computer terminal to access a parts database. The part’s DDM build package is sent to a fabrication site (e.g., the Navy’s Fleet Readiness Centers) near where it is needed. The metallic part is fabricated to net shape using direct digital manufacturing equipment, finished, machined and assembled.

In the event a build package is not available, the part may be reverse engineered. The needed part could be laser scanned and imported into a digital cloud map. This information could then be transferred to any number of engineering design CAD/CAM programs, e.g., Pro-E. Once the design configuration is established, a DDM build package would be developed and archived for future use.

Workshop Purpose

The workshop was held in order to assist ONR and NAVAIR develop a robust research and development program in the area of DDM, e.g., an ONR Future Navy Capabilities Program. The workshop was structured to help identify research opportunities and to address the technical challenges associated with using DDM of metallic components. The technical obstacles to DDM implementation were examined and approaches to overcoming the identified barriers formulated. The workshop explored (i) innovative design concepts which reduce weight, (ii) maintenance and repair concepts, (iii) life-cycle-costs reductions, and (iv) qualification and certification methodology. Further, the overarching goal is to enhance operational readiness, reduce energy consumption, and enable parts-on-demand manufacturing

Workshop Concept of Operation

The workshop provided an opportunity for seventy-two invited experts from Navy, DoD, industry, academia, and leading research institutes to share their views and make strategic recommendations. Figure 2 provides a list of represented organizations at the workshop.

Government	Industry	Industry	Academia
• NAVAIR (4.1, 4.3, 4.4, 4.5, 4.7, 4.8, 5.2, 6.7) • FRC • NASA • Air Force • OPNAV • OSD • ONR • PEOs	• Bell Helicopter • Boeing • CalRam • CTC • GE Aviation • Lockheed Martin •Morris Technology • NAVMAR • Navy Metalworking Center	•Northrop Grumman •Sikorsky •Stratasys •TRI •Wyle •Honeywell •Sciaky •Innovati •Pratt & Whitney	• University of Texas, Austin • North Carolina State University • University of Michigan • California Institute of Technology • Penn State University • National Center for Manufacturing Science

Figure 2 Organizations Participating in the May 2010 Navy DDM Workshop.

Plenary

A plenary session was held on the morning of the first day of the workshop. Table 1 lists the plenary speakers representing executives and technical leaders from the government, industry, and academia. This was followed by parallel working group breakout sessions in four topic areas: DDM Science & Technology, Qualification & Certification Methodology, Innovative Structural Design, and Maintenance & Repair. Workshop participants were asked to validate the goals and objectives of the working group and to identify technical challenges and approaches for achieving the goals.

Table 1 Plenary Speakers and their Affiliation	
Mr. Garry Newton	Deputy Commander Fleet Readiness Centers, NAVAIR
Mr. Richard Gilpin	Director, Air Vehicle Engineering Department, NAVAIR
Mr. Greg Kilchenstein	Senior Sustainment Technology Policy Analyst, OSD (AT&L) delivered by Constance Philips, National Center for Manufacturing Sciences
Mr. Mike Deitchman	Deputy Chief of Naval Research, Naval Air Warfare and Weapons Science and Technology Department ONR
Ms. Karen Taminger	Senior Materials Research Engineer, PI for Materials and Structures for the Subsonic Fixed Wing Aircraft, NASA Langley Research Center
Dr. Thomas Donnellan	Associate Director for Materials and Manufacturing, ARL Penn State.
Mr. Blake Slaughter	Metallic Processing Group, Boeing Research and Technology.
Prof. Dave Bourell	University of Texas Austin delivered in the workshop brief-out session.

GOTChA Process

The GOTChA (Goals, Objectives, Technical Challenges, and Approaches) approach was used as a tool to develop the products of the workshop. Figure 3 graphically illustrates the GOTChA process. The Navy defined the goals and objectives of the workshop. The overarching goal of the workshop was to enhance operational readiness, reduce total ownership cost, and reduce energy consumption by exploiting advanced metallic direct digital manufacturing technologies.

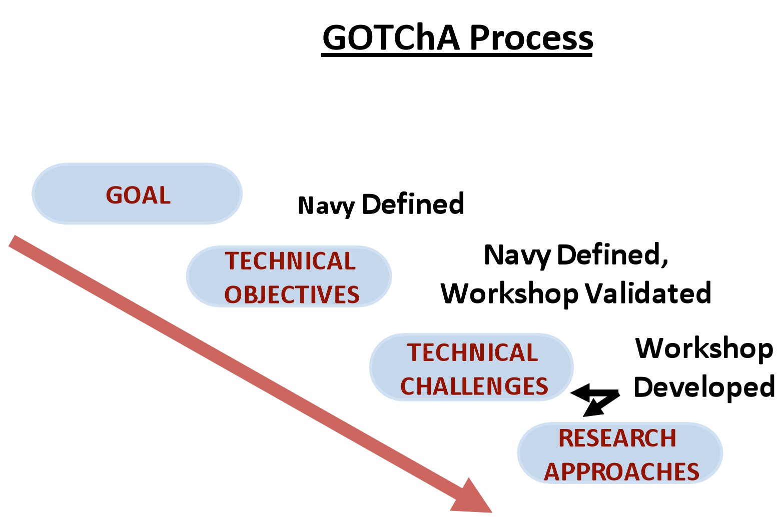

Figure 3 Methodology: Goals, Objective, Technical Challenges & Approaches (GOTChA)

The working groups met for approximately 8 hours. Their first task was to validate and, if necessary, amend the three working group objectives. The working group then identified and prioritized the technical challenges associated with achieving the objectives. The balance of their time was used to develop viable approaches to solve the challenges identified. These approaches were broadly grouped into three time frames: near (< 5yrs), mid (5-10yrs), and far (>10yrs). The workgroup results were briefed-out in a plenary forum prior to concluding the workshop. A post workshop analysis was performed in which the salient information was summarized and packaged in a format suitable for dissemination.

Workshop Results

The results of the workshop are divided into three parts: (i) Plenary, (ii) Working Groups, and (iii) Summary.

Plenary Summary

The plenary session provided a forum for leaders from the Government, Academia, and Industry to discuss DDM in terms of warfighter needs. There was overwhelming agreement that DDM is an agile and viable source of manufacturing and repair and its exploitation would help address pressing naval aviation needs.

DoD-Navy's Environment: The Navy's current and, likely, future environment was discussed. The Country is at war and naval aviation must respond quickly and effectively to warfighter needs. There are several key factors which will drive naval aviation to use direct digital manufacturing. There is an increased emphasis on reducing the cost of Defense Department's Operation: acquisition and sustainment. The average age of our Navy's aircraft is 19.18 years . This is putting an increased strain on the Navy's supply chain. As aircraft age, parts that were never expected to break or fail do [10]. Supply chain does not have the ability to repair or produce new parts. Aircraft are grounded while we spend precious time researching vendors who can repair or replace the parts.

Naval Aviation Needs: In order to respond to the Country's wartime footing and aging fleet of aircraft, there has been an increased demand for one-off parts, crash damage repair, and rapid solutions to Red Stripes [10]. An Agile and Viable Source of Manufacturing and Repair (e.g., DDM) is required. DDM may be especially useful addressing the issues which arise in the Sun Down/Disposal phase of a weapon systems life cycle.

The technical barriers associated with inserting DDM were discussed. Some of the more salient research and development needs are listed in Table 2. In order to achieve the vision state of parts-on-demand, the need to accelerate part qualification and certification tops the list. The value of having the capability of producing an aircraft parts in a matter of hours is of little value if it takes weeks or months of testing and evaluation to certify it for use. An accelerated qualification process is closely linked to a number of factors including (i) an understanding of machine-to-machine variability and repeatability, (ii) accurate, predictive process models for microstructure and properties, and (iii) computationally guided processes and closed loop process controls.

Table 2 Research and Development Needs: Plenary Session
• Accelerated qualification and certification methods • Accurate, predictive process models for microstructure and properties • Fatigue properties comparable to wrought materials, Post fabrication processes to enhance fatigue properties. Methods to reduce surface roughness of parts • Part-to-part and machine-to-machine variability and repeatability • Computationally guided processes and closed loop control. Integration of sensors into process control systems to enable real-time NDE during processing • Technology fusion, i.e., laser scanning, database, design tools, and database • New structural design & analysis tools, e.g., stiffeners that follow load paths • Alloys designed for DDM fabrication

Working Group Products

DDM Science and Technology: The Navy's S&T Objectives for DDM are listed in Table 3. Associated with each objective, the Working Group identified three technical challenges which must be addressed. For example, to obtain fatigue properties equivalent to wrought alloys, the Working Group felt that the top two technical challenges were the control of microstructure and the elimination of defects.

Table 3 DDM S&T Objectives and Technical Challenges
Goal: Enhance operational readiness, reduce energy consumption, and reduce total ownership cost by exploiting advanced metallic direct digital manufacturing technologies.
Objectives and Challenges
Objective 1: Static and fatigue performance equivalent to wrought 1. Controlling Microstructure 2. Elimination of Defects 3. Material Challenges **Objective 2: Achieve Statistically Repeatable and Predictable Processes** 1. Monitoring and Controlling the Process 2. Need to model the process 3. Need NDE for DDM materials **Objective 3: Surface Finish / Minimize Assembly and Post Deposition Processing** 1. Maintain acceptable deposition rates while achieving good surface finish 2. Need controlled position of DDM machine 3. Lack of scientific/technical info on post treatments of DDM surfaces

Maturation of technologies at the TRL 3-4 to TRL6 and above are of significant interest. Analysis of the DDM S&T Roadmap, Figure 4, suggests that the following research areas should be explored. In order to enhance the fatigue performance of DDM parts, develop in situ DDM processes to improve part surface finish and to mechanically work the DDM part during deposition, e.g., by using laser shock peening. The development of physics based models for structure-property-processing are also essential in order to be able to consistently and accurately produce DDM parts of diverse configurations.

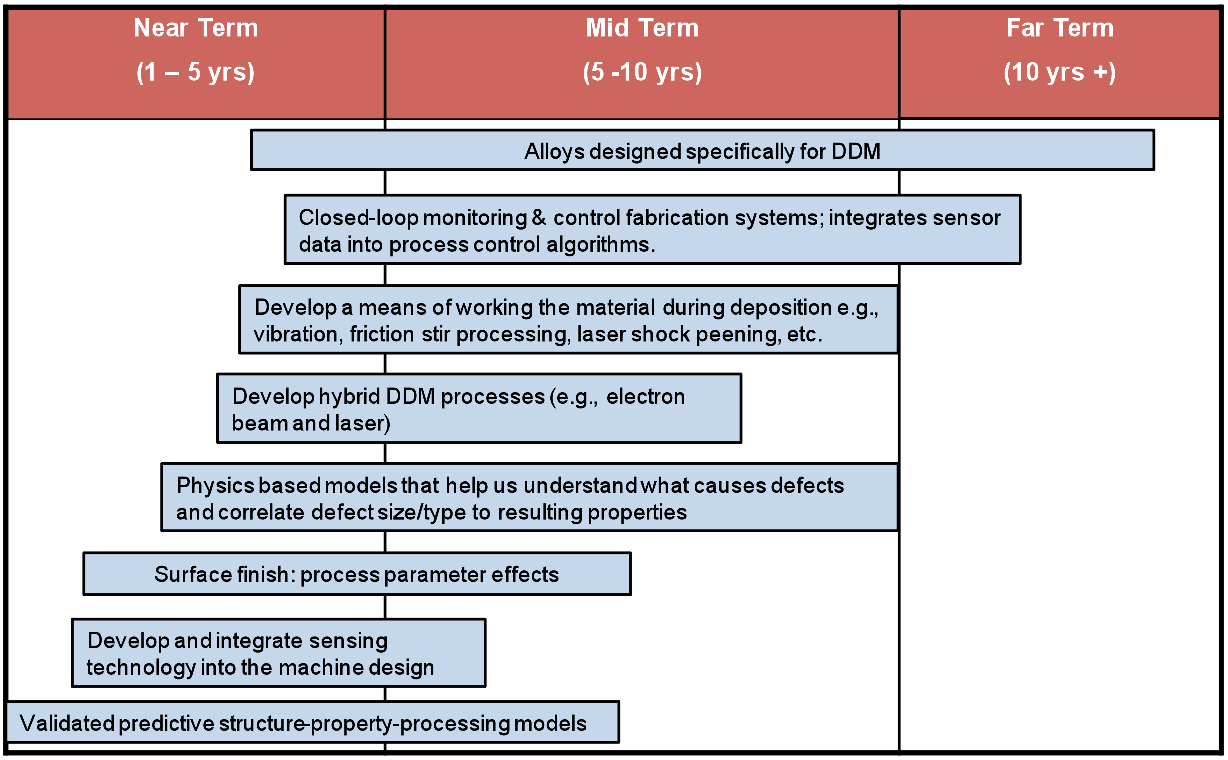

Figure 4 DDM S&T Roadmap

Qualification and Certification: The three Navy objectives associated with the qualification and certification of DDM metallic components are presented in Table 4, along with the list of technical challenges developed by the Working Group. For example, the Working Group felt that a DDM database of material properties was necessary. Importantly, the database must represent the pedigree of the data and come from a stabilized DDM process.

Table 4 Qualification and Certification Objectives and Technical Challenges
Goal: Enhance operational readiness, reduce energy consumption, and reduce total ownership cost by exploiting advanced metallic direct digital manufacturing technologies.
Objectives and Challenges
Objective 1: Qualification of DDM fabrication processes 1. Definition of methods required for verifying control of the key process variables 2. Definition of qualification requirements for each of the three phases of product life cycle - new design/prototype, repair/replacement, and production part 3. Demonstrate repeatability **Objective 2: Eliminate the need to qualify each part individually** 1. Need materials properties database developed under a "stable" process 2. Determine necessary steps to avoid repeating generation of materials properties database for different DDM technologies **Objective 3: Reduce the time & cost of qualification by 90%** 1. Definition of acceptance requirements for repair/replacement of fielded parts and prototype 2. Prioritization of action items associated with qualification process

Analysis of the Qualification and Certification Roadmap, Figure 5, suggests that the following research areas should be explored. Maturation of technologies at the TRL 3-4 to TRL6 and above are of significant interest. In order to secure the vision of parts-on-demand, accelerated part qualification methods need to be developed. Research should be focused on the development of heuristic, and probabilistic, qualification methods. The development of industry specifications and standards are necessary as is a robust materials database. However, it is unlikely that S&T funding can be used to directly support their development.

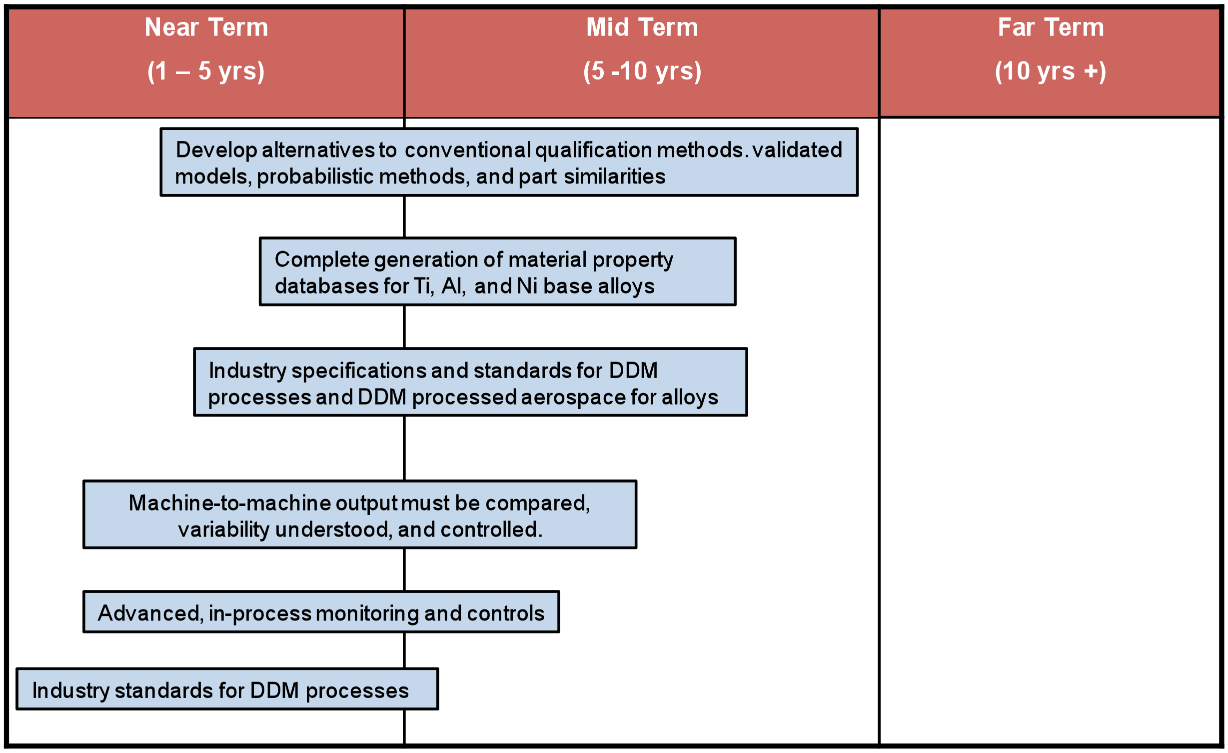

Figure 5 Qualification and Certification Roadmap

Innovative Structural Design: The objectives and the technical challenges associated with Innovative Structural Design are presented in Table 5. In order to reduce structural weight, better, integrated structural & DDM fabrication design tools are needed. Similarly, to reduce cost, true net-shape fabrication methods are needed which eliminate the need for secondary (post fabrication) processing.

Table 5 Innovative Structural Design Objectives and Technical Challenges
Goal : Enhance operational readiness, reduce energy consumption, and reduce total ownership cost by exploiting advanced metallic direct digital manufacturing technologies.
Objectives and Challenges
Objective 1: Reduce structural weight by 25% with no increase in acquisition cost. (freeform technologies, Ti-6-4, apply to entire air vehicle vs. piece part) 1. Better structural optimization including multifunctional design 2. Integrated design while allowing for maintainability 3. Introduce/integrate new alloy composition "sweet spots" for the design 4. Design community to accept paradigm shift to adopt new design rules **Objectives 2: Enable complex part fabrication with a 50% reduction in cost.** 1. Near-net shape manufacturing (reduce buy:fly ratio, reduce labor cost, reduce # of secondary operations) 2. Use of lower cost starting materials 3. Develop more innovative techniques to develop/finish near-net shape parts with the goal using the part as-built **Objectives 3: Reduce the design, engineering, build, test & qualification time cycle by 60%.** 1. No recognized standards exist 2. Streamline design process 3. DDM design with minimal tooling & facilities 4. Risk tolerance by approving authorities & designers

The examination of the Innovative Structural Design Roadmap, Figure 6, reveals two significant features. 1. There is a need for integrated structural and materials design optimization tools to support the design and certification of non-traditional design concepts. 2. In line with what the Qualification and Certification working group reported, there is a need for a shared materials property database; and industry specification and standards.

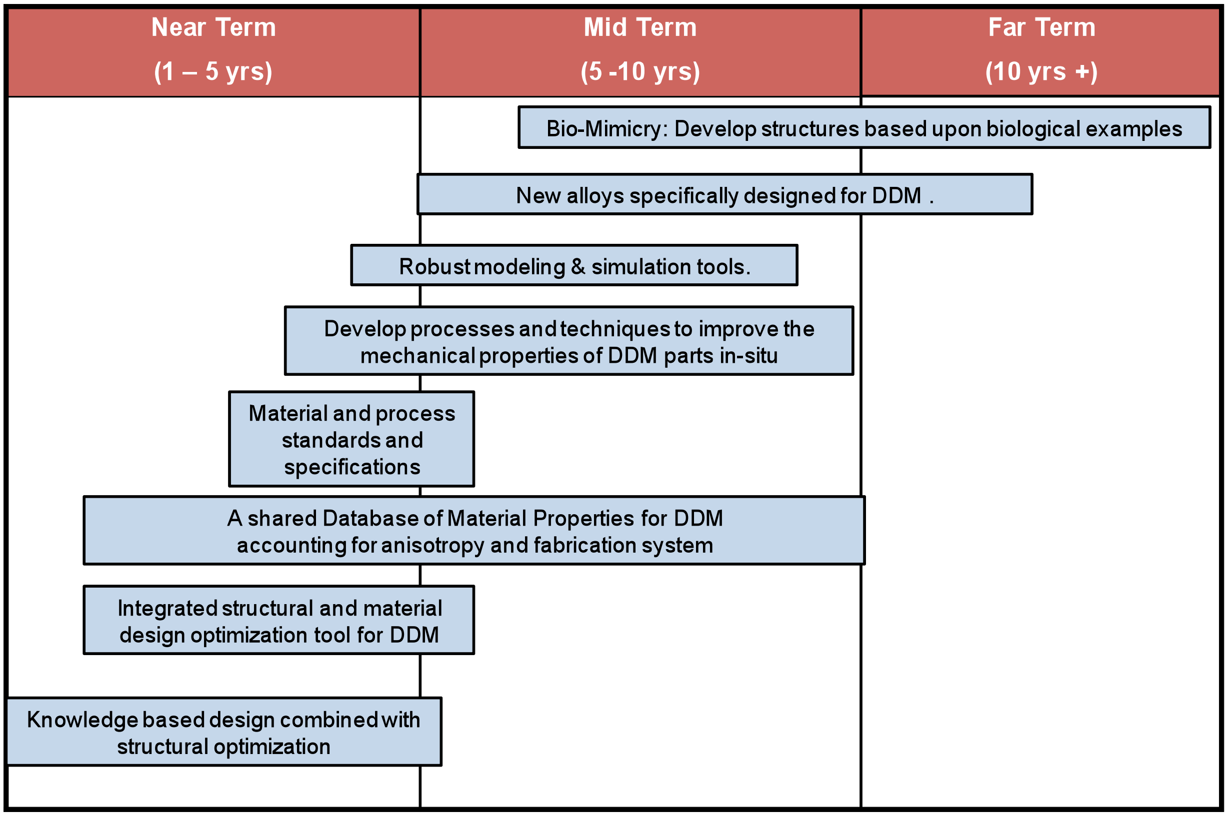

Figure 6 Innovative Structural Design Roadmap

<u>Maintenance and Repair</u>: The objectives and the technical challenges associated with Maintenance and Repair are presented in Table 6. In order to reduce the time required to acquire out-of-production parts by 90%, the need for an improved and accelerated means of qualifying and certifying DDM parts is needed. The objective of reducing part energy content was associated with the need to reduce or eliminate post fabrication processing. Further to effect a reduction in logistics foot print, DDM equipment versatility is needed.

Table 6 Maintenance and Repair Objectives and Technical Challenges
Goal: Enhance operational readiness, reduce energy consumption, and reduce total ownership cost by exploiting advanced metallic direct digital manufacturing technologies.
Objectives and Challenges
Objective 1: Reduce time to acquireout-of-production parts by 90% 1. Certification and approval 2. Merging existing technology & material capabilities with actual parts that are needed. 3. Quality control – parts feedstock and process **Objective 2: Reduce total energy content by 60%** 1. Post processing: Surface finish requirements & dimensions. Residual stress/heat treatment 2. Equipment efficiency increases 3. Raw material cost/deposition efficiency. **Objective 3: Reduce logistic footprint by 20%** 1. Equipment versatility 2. Additional post processing/NDI/HIP 3. Raw materials storage

The Innovative Maintenance and Repair Roadmap is presented in, Figure 7. The Working Group identified qualification-by-similarity as a needed research area as well as improved surface finish and dimensional accuracy. These two areas were also identified by other working groups as important areas to pursue. The development of alternatives to hot isostatic processing (HIP) of DDM parts to achieve wrought fatigue properties was identified as a critical need. The use of HIP is capital intensive and would increase part cost and fabrication time.

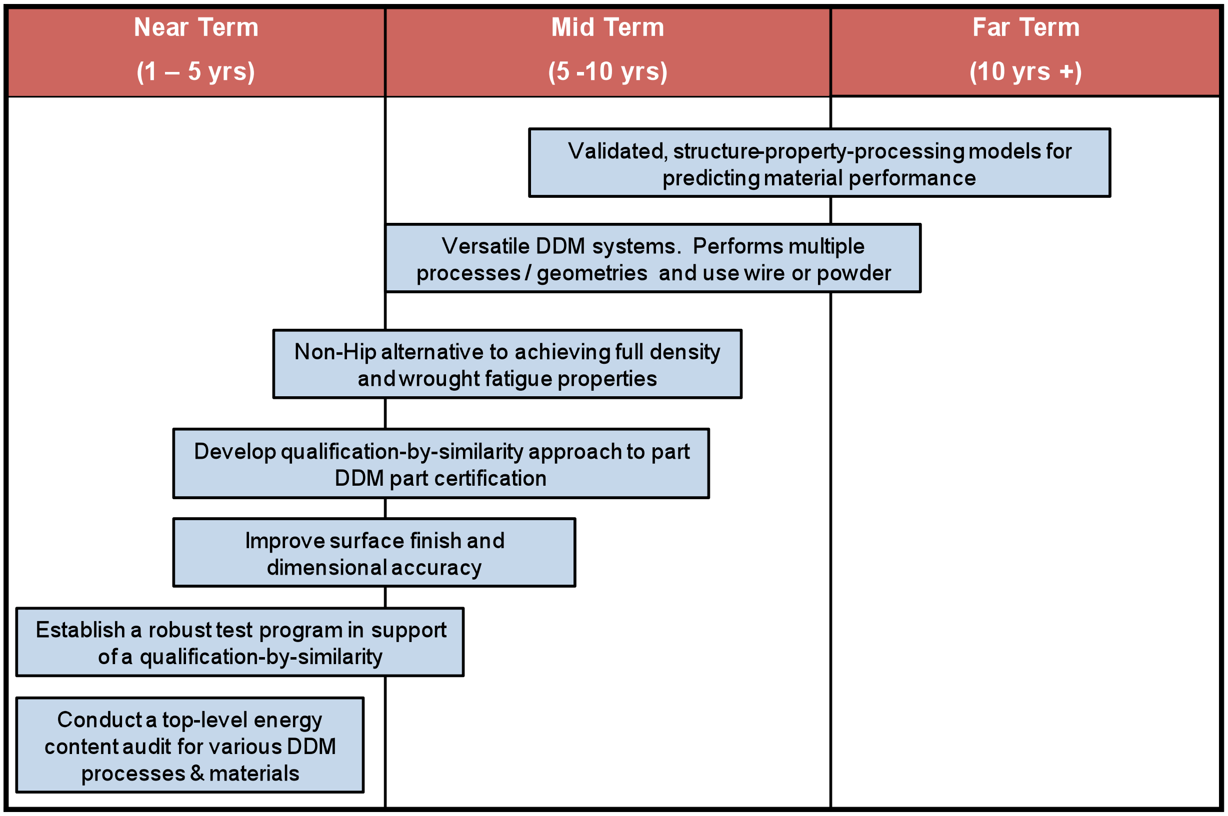

Figure 7 Maintenance and Repair Roadmap

Critical Research Areas Summary

The critical areas of needed research may be divided as follows: (i) Underlying DDM Science, (ii) Process Control, (iii) Qualification, and (iv) Innovative Structural Design.

Underlying DDM Science

A robust understanding of the underlying science of DDM is essential to the widespread implementation of DDM. New alloys must be developed that lend themselves to DDM. A priority is the development of physics based models relating microstructure, properties, and process to performance. This represents the foundation upon which process control, part qualification, and innovative designs concepts can be built. Innovative in situ processes (e.g., hybrid laser and electron beam systems) and an improved understanding of structure-property-processing relationships are required in order to enhance fatigue properties. This includes an understanding of how to reduce surface roughness. Lastly, technology integration and fusion is required to achieve the desired "Vision State." The various component technologies associated with DDM fabrication, reverse engineering, qualification, and design must be made to work together seamlessly.

Process Control
The ability to achieve the vision state of parts-on-demand requires accurate and predictable control of the DDM fabrication process. Machine-to-machine variability must be understood and controlled. Industry specifications and standards for the processing of aerospace alloy components must be developed and inculcated throughout the industry. The highest priority should be given to developing integrated in-process, sensing, monitoring, and control technologies.

Qualification
The ability to produce a wide variety of parts-on-demand is essential to harnessing the full potential of DDM. Part-by-part certification is costly and time consuming and is antithetical to achieving the Navy's vision. Therefore, alternatives to conventional qualification methods must be found; these are likely based upon validated models, probabilistic methods, and part similarities. Likewise, industry specifications and standards for DDM and DDM processed aerospace alloys are needed. These standards and specifications form the foundation for rapid part certification. Similarly, advanced NDE techniques capable of detecting critical flaws and defects with a high degree of certainty are needed.

Innovative Structural Design
The introduction of new and innovative structural designs requires that the design community be knowledgeable of DDM. A priority should be given to the development of integrated structural and materials design tools. A robust DDM database accessible to these communities must be developed in order to provide pedigree data which integrate structural and materials.

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