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Feasibility of 3D Printing Applications for Highway Infrastructure Construction and Maintenance

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16. Abstract

In recent years there has been a significant increase of the interest in additive manufacturing (AM; also frequently referred to as 3D printing), yet AM is largely unexplored within infrastructure projects. By harnessing the new capabilities of AM, researchers have managed to access unprecedented new design capabilities and operational flexibility (e.g., on-demand, tool-free production). This revolutionary progress, however, has not been reflected in applications focused on transportation infrastructure. This project explores AM innovations and their capabilities related to transportation infrastructure and as a potential future resource to assist MassDOT Highway Division's ongoing rehabilitation of bridge, tunnel, and highway structures, as well as classic recurring maintenance activities. The project's main research objective is to connect the additive manufacturing research community with MassDOT to explore additive repair techniques as well as individual component manufacturing for the highway and construction sector purposes. The project also aims at drafting MassDOT business process recommendations for AM technologies.

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Feasibility of 3D Printing Applications for Highway Infrastructure Construction and Maintenance

Final Report

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The workshop organizing committee is grateful to MassDOT for the generous support for the organization of this workshop. The organizers gratefully thank Patty Leavenworth, Lily Oliver, Catherine Chen, and Paul Tykodi at MassDOT for their generous support of this workshop.

Disclaimer

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Executive Summary

This study of Feasibility of 3D Printing Applications for Highway Infrastructure Construction and Maintenance, was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

In recent years there has been a significant increase in interest in additive manufacturing (AM; also frequently referred to as 3D printing), yet AM is largely unexplored within infrastructure projects. By harnessing the new capabilities of AM, researchers have managed to access unprecedented new design capabilities and operational flexibility (e.g., on-demand, tool-free production). This revolutionary progress, however, has not been reflected in applications focused on transportation infrastructure. This study explores AM innovations and their capabilities related to transportation infrastructure and as a potential future resource to assist MassDOT Highway Division's ongoing rehabilitation of bridge, tunnel, and highway structures as well as classic recurring maintenance activities. The potential advantage of AM is that it could reduce road closure times for maintenance and enable prolonged longevity of existing infrastructure components by both proactive maintenance and faster urgent repairs.

The project's main research objective is to connect the additive manufacturing research community with MassDOT to explore additive repair techniques as well as individual component manufacturing for the highway and construction sector purposes. The project aims at drafting MassDOT business process recommendations for AM technologies. The recommendations focus on identifying the organizational processes that would be needed to support successful procurement services and the resulting quality assurance review of received AM products that have been created using the AM techniques.

The research effort focused on the following objectives:

O.1. Engage with MassDOT's six district maintenance and engineering sectors to build an exemplary inventory of possible candidate objects for test printing using AM technologies–based techniques. Discussions also considered the critical elements found to impact the feasibility of integrating AM techniques into future MassDOT projects (for example, constraints involving object size, material properties, and cost of production).

O.2. Survey colleagues in the transportation industry to learn more about their experience with AM. This review was not exhaustive, but it considered several different aspects for which AM can be potentially beneficial. Research also studied adapting or modifying AM technology to increase its feasibility for applications in the repair, maintenance, and construction of transportation infrastructure.

O.3. Perform appropriate research to assess the advantages, disadvantages, and cost efficiencies to compare using AM to produce actual replacement parts and using AM to produce models of needed replacement parts, which could then be used to drive acquisition through a standard procurement. In this effort, we explored the suitability of MassDOT's current standard procurement methods and processes for use with AM.

O.4. Conduct a test application of AM on additive repair technology applied to deteriorated steel bridge beams.

O.5. Based on the research outcomes, we studied an initial set of draft internal MassDOT business process recommendations for the procurement, installation, and quality assurance testing of objects produced via 3D printing additive manufacturing techniques.

The main outcomes of this research are the following:

D.1. Review literature on the current and potential use of additive manufacturing in highway, tunnel, and bridge maintenance.

D.2. Provide information to MassDOT highway, tunnel, bridge, and other sectionsregarding the potential application of AM technologies in the repair, maintenance, and construction of transportation infrastructure.

D.3. Explore the use of AM as an additive repair technology and develop solutions for deteriorated bridges.

D.4. Review the costs incurred in producing pilot objects via 3D printing.

Table of Contents

List of Tables

List of Figures

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List of Acronyms

Acronym	**Expansion**
3D	Three-dimensional
ABC	Activity-based costing
AM	Additive manufacturing
ASTM	American Society for Testing and Materials
BMD	Bound metal deposition
CAD	Computer-aided design
CNC	Computer numerical controlled
DED	Directed energy deposition
EBSD	Electron backscatter diffraction
EDM	Electrical discharge machining
EDS	Energy dispersive spectroscopy
FDM	Fused deposition modeling
FHWA	Federal Highway Administration
HAZ	Heat-affected zone
IPF	Inverse pole figure
ISO	International Standards Organization
LENS	Laser-engineering net shaping
LOM	Laminated object manufacturing
L-PBF	Laser powder bed fusion
MicroDLP	Micro digital light projection
MIT	Massachusetts Institute of Technology
MJF	Multi jet fusion
OIM	Orientation imaging microscopy
PBF	Powder bed fusion
SEM	Scanning electron microscope
SL	Sheet lamination
SLA	Stereolithography
SLM	Selective laser melting
SME	Subject matter expert
SPR	State Planning and Research
UMass Amherst	University of Massachusetts Amherst
WAAM	Wire and arc additive manufacturing

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1.0 Workshop on Opportunities and Challenges for 3D Printing in Highway Infrastructure Construction and Maintenance and Tour of 3D Printing Facilities

1.1 Introduction

The purpose of Task 1 was to familiarize DOT personnel with the basic principles, application space, and process capability for additive manufacturing technologies.

This task comprises two major activities. First, a two-day workshop was held on October 20 and 21, 2020. Workshop themes focused on process technology and application potential for additive manufacturing in the transportation infrastructure sector. During the workshop, a series of additive manufacturing technology providers, including large-format polymer and metal printing, computational engineering software providers, and additive manufacturing infrastructure developers, were featured. After each industry presentation, MassDOT personnel asked questions and discussed the materials presented. Following the conclusion of the industry presentation segment, a discussion was held between MassDOT staff, industry representatives, and the project research team.

The second major activity within this task is a tour of representative Boston-area printing facilities. The purpose of the tours was to demonstrate the processes described during the workshop to MassDOT personnel. Hands-on exposure to the technology provided a realistic understanding of the general process workflow and application space for AM. Beyond observation, the tours allowed MassDOT personnel to build relationships with AM companies and ask questions of industry technical experts.

The tours were originally intended to be held during the workshop. However, due to the COVID-19 pandemic, in-person travel was restricted at potential tour destinations. COVID-19 restrictions proved challenging in coordinating the tour visits during the earlier phase of the project.

However, the delays included by COVID-19 were inadvertently advantageous for coordinating the tour destinations. A key finding of the October Workshop and of the structural beam investigation performed in Task 2 is that AM for more typical infrastructural elements (including structural beams, pedestrian infrastructure, housing, and cementitious formwork) is promising. However, as is described later in this report, one important further finding from our interviews with the MassDOT districts is that there is a general incongruity in size and geometric complexity between typical high-value AM components (which are often small and complex) and durable infrastructure components (which are typically large and comparatively simple in shape). The process of evaluating components for printing was a challenging exercise due to these apparent incompatibilities. Thus, when selecting a tour destination, we had this prior experience in mind and were able to tailor our destination to processes and applications that are more feasible for an organization's first exploration in AM applications.

1.2 Background

Additive manufacturing (AM), also known as three-dimensional (3D) printing, is a process by which the 3D object is produced by adding material layer upon layer using a computer-controlled process *(1–5)*. The potential benefits of 3D printing, for example, on-site manufacturing *(6,7)* and production of complex geometries *(8,9)*, have attracted broad interests from automotive *(10)*, aerospace *(11)*, and medical *(12)* industries. During the last two decades, improvement in AM process and relative materials has resulted in successful commercial realizations *(7,13–15)*. For example, the global 3D printing market involving 3D printing system, design software, and materials, has been growing from about \$4.0 billion in 2014 to about \$12.1 billion in 2019 with a 25% annual growth rate since 2014 as shown in more detail in Figure 1.1 *(16)*.

Although this growth has been immense, the applications of AM in the construction industry and civil engineering in general only account for about 3% of total applications *(16)*. Although the investment of 3D printing applications in the construction industry is relatively limited compared to other manufacturing industries, the potentials of 3D printing are considered substantial *(17)*.

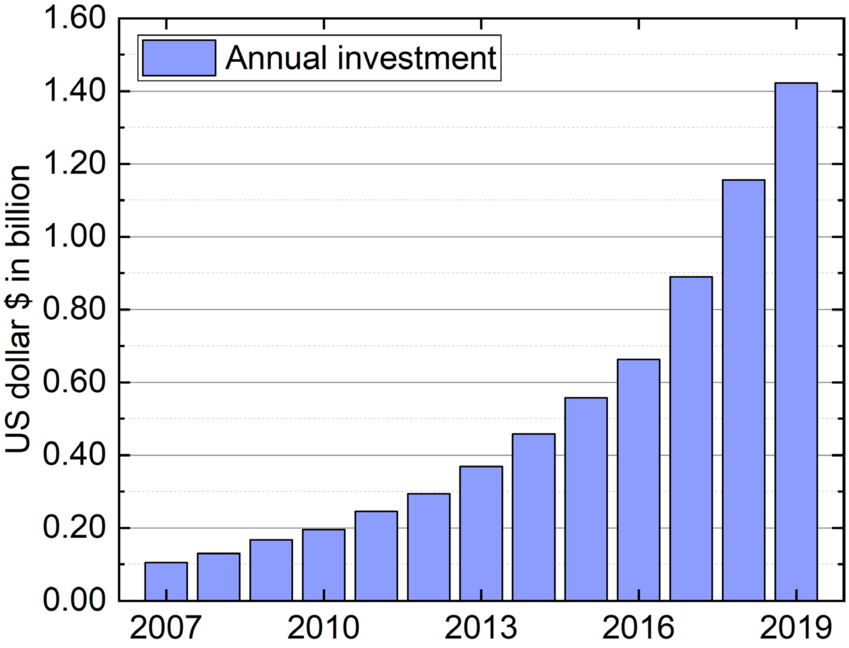


Figure 1.1: AM investments worldwide for all industries

There are a number of key requirements for improving construction processes: enhancement of structural efficiency and safety, reduction of construction time and cost, innovation of structural materials, and improvement of the repair process *(6)*. Taking into account the general advantages of 3D printing, the construction sector could benefit from potential novel solutions meeting these requirements. For instance, the number of steps involved in the supply chain could be reduced using AM in construction and thereby the reduction of construction cost because AM allows components to be printed on site. AM can also fabricate productions of complex geometries so that the part-specific tooling and assembling operations could be eliminated.

In particular, corrosion in joints of bridges is a critical issue in the transportation industry *(18–23)*. Extensive corrosion of bridge girders, which is deleterious for the bearing capacity of bridges, is commonly observed beneath deck joints. Current repair methods are generally expensive *(23–25)*, and conventional repair methods are also difficult to implement due to the elevation of the superstructure needed to provide a load-free condition during the repairing process *(25)*. Thus, to improve the efficiency of maintenance and further enhance the performance of transportation infrastructure, a cost-effective, time-effective, and easy-to-use technique is necessary for bridge maintenance. Recent developments in 3D printing could potentially allow agencies to adopt these technologies in repair *(26–31)*. Regarding the high process speed and low energy input, 3D printing enables the repairing process toward resource efficiency. In addition, a mobile system featuring automated robotic arms has been developed commercially so that repairing using in situ materials could be processed on site *(32,33)*. Therefore, the additive repair techniques could result in the reduction of closure time during the repairing process and the extension of the longevity of existing infrastructure components through both proactive maintenance and faster urgent repairs.

Specifically focusing on the feasibility of using 3D printing techniques for highway infrastructure construction and maintenance, a two-day online workshop, “Opportunities and Challenges for 3D Printing in Highway Infrastructure Construction and Maintenance,” was held on October 20 and 21, 2020, through Zoom due to the COVID-19 restrictions on travel. The workshop was organized by the University of Massachusetts Amherst (UMass Amherst) and the Massachusetts Institute of Technology (MIT). Four Zoom screenshots, that is, the introductory remarks delivered by Chief Engineer Patty Leavenworth, one of the presentation slides of Professor John Hart, the research plan regarding the additive repair innovation in transportation infrastructure, and the Q&A in the session of invited industrial presentations, are shown in Figure 1.2. Twenty-seven attendees had the opportunity to hear from both academics and industrial partners on interesing 3D printing applications.

A website (https://hoop0130.wixsite.com/online-workshop/) was also created to advertise the workshop to MassDOT personnel and provide the basic information of 3D printing technologies together with all the materials presented in the workshop. Basic information on UMass, the MIT laboratories, and the deteriorated bridges research program was documented as well (under the “More” tab). In addition, the workshop agenda and the videos of the presentations and discussions in the workshop are available on the website (under the “Watch Workshop Videos” tab). A screenshot presenting the website home page is presented in Figure 1.3. In accordance with the scopes of the research project, this website will be continuously used as a platform to share information with interested MassDOT personnel from all districts in the state of Massachusetts.

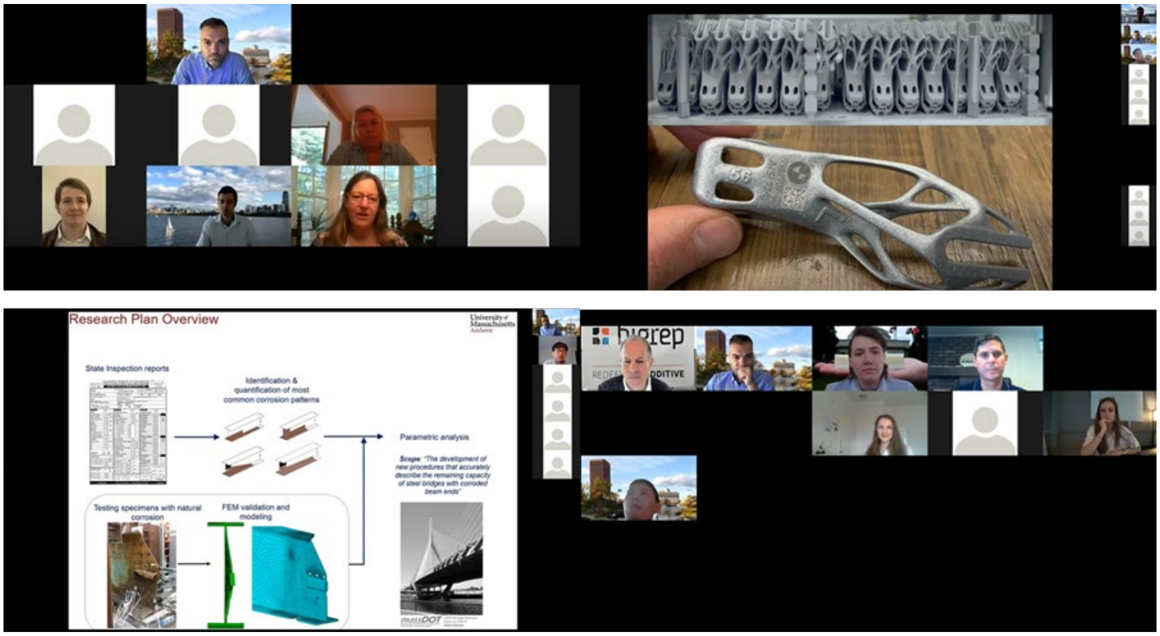
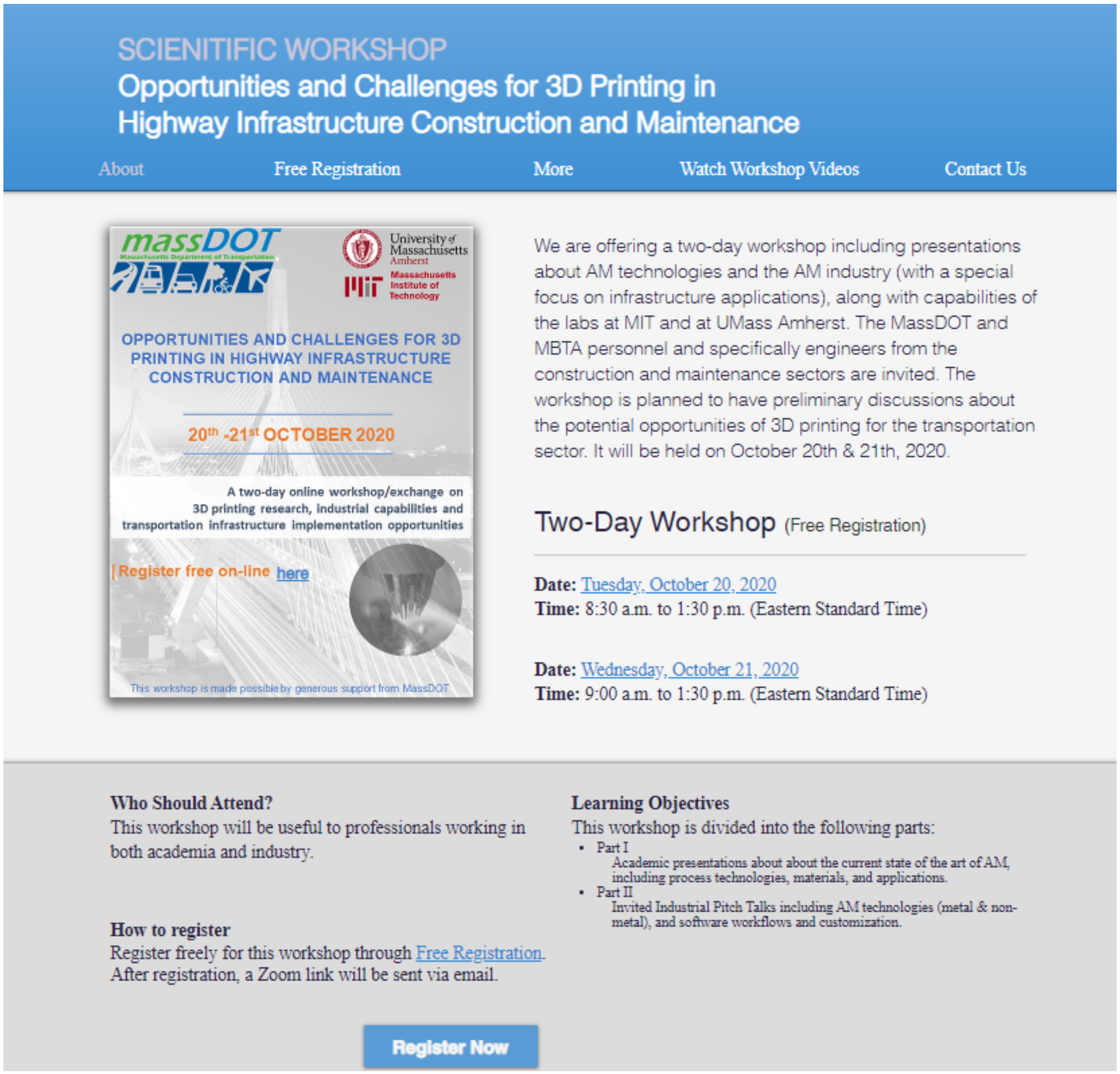


Figure 1.2: Screenshots of the Zoom meeting room

The goals and objectives of the two-day online workshop are summarized in the following:

I. Introduce the basic concepts of 3D printing and review advances in 3D printing technologies related to manufacturing and construction industries. Assess the potential opportunities of 3D printing on the establishment of scientific and regulatory approaches for the applications in highway infrastructure construction and specifically on the maintenance in transportation infrastructure.
II. Propose an appropriate research plan in evaluation of the advantages and disadvantages of 3D printing through the comparison between using AM to produce actual replacement parts and using AM to produce models of needed replacement parts, which will be used to assess the suitability of the current standard procurement methods in MassDOT in the applications of AM.
III. Survey colleagues and engage discussions about the feasibility of 3D printing on applications in the transportation industry and maintenance. Leverage the colleagues' experiences of 3D printing and identify the necessary tasks based on the research plan to establish scientific standards for applying 3D printing technology on the maintenance of highway bridges.



SCIENITIFIC WORKSHOP

Opportunities and Challenges for 3D Printing in Highway Infrastructure Construction and Maintenance

OPPORTUNITIES AND CHALLENGES FOR 3D PRINTING IN HIGHWAY INFRASTRUCTURE CONSTRUCTION AND MAINTENANCE

20th -21st OCTOBER 2020

A two-day online workshop/exchange on 3D printing research, industrial capabilities and transportation infrastructure implementation opportunities

|Register free on-line here

This workshop is made possible by generous support from MassDOT

We are offering a two-day workshop including presentations about AM technologies and the AM industry (with a special focus on infrastructure applications), along with capabilities of the labs at MIT and at UMass Amherst. The MassDOT and MBTA personnel and specifically engineers from the construction and maintenance sectors are invited. The workshop is planned to have preliminary discussions about the potential opportunities of 3D printing for the transportation sector. It will be held on October 20th & 21th, 2020.

Two-Day Workshop (Free Registration)

Date: Tuesday, October 20, 2020
Time: 8:30 a.m. to 1:30 p.m. (Eastern Standard Time)

Date: Wednesday, October 21, 2020
Time: 9:00 a.m. to 1:30 p.m. (Eastern Standard Time)

Who Should Attend?
This workshop will be useful to professionals working in both academia and industry.

How to register
Register freely for this workshop through Free Registration. After registration, a Zoom link will be sent via email.

Learning Objectives
This workshop is divided into the following parts:
- Part I
  Academic presentations about about the current state of the art of AM, including process technologies, materials, and applications.
- Part II
  Invited Industrial Pitch Talks including AM technologies (metal & non-metal), and software workflows and customization.

Figure 1.1: Screenshot of the website home page

The workshop consisted of two main sessions: (1) academic presentations about the state-of-the-art AM, including the processing technologies, materials used in AM, applications of AM, and the deteriorated bridges research program; and (2) invited industrial pitch presentations focusing on the commercial AM systems and software platforms. Also, two breakout session discussions were conducted that were related to the key issues of highway infrastructure and the potential solutions using 3D printing. In Appendix A, the presentation titles and names of presenters are documented. The brief introductions of each member in the workshop organizing committee are summarized in Appendix B. Appendix C consists of the contact information of the workshop participants.

1.3 Information Highlighted in the Session of Academic Presentations

Additive manufacturing processes with high-energy heat source, equivalently known as 3D printing, have been developed and applied in recent decades to build up the complex-shaped, multifunctional, and custom-designed components. The computer-based system involving digital 3D design tools is generally used to control the layer-by-layer fabrication processing using material deposition *(1–5)*. Currently, various types of AM techniques exist and specifically, according to ISO/ASTM 52900 standard *(34)*, metallic AM techniques are categorized into

1. directed energy deposition (DED) method,
2. power bed fusion (PBF) method, and
3. sheet lamination (SL) or laminated object manufacturing (LOM) method.

The schematics of the three AM techniques frequently applied for metallic components are depicted in Figures 1.4 through 1.6, respectively *(1,35)*.

DED is a group of AM processes that use metallic powders (Figure 1.4B) or deposited wires (Figure 1.4A) in the parallel position with the heat input to fabricate shaped components. An electron-beam, laser-beam, or plasma arc energy source is generally used to melt materials in DED-based processes. The environment of inert gas (in laser-beam or plasma arc systems) or vacuum (in an electron-beam system) is needed when the deposition is processing.

In contrast, PBF is another subset of AM processes in which the heat input is used to selectively melt or sinter the preplaced metallic powders instead of feeding directly into the melt pool (as in DED processes). The energy source used in a PBF-based method is either electron-beam or laser-beam. Figure 1.5 presents the schematic of a PBF-based process. The metallic component is fabricated layer by layer on a powder bed whose height is gradually decreasing as each layer is increasing during the PBF-based process. The near-full density and near-net components can be fabricated using DED-based or PBF-based processes. The properties of the metallic components can also be controlled and manipulated through the processing parameters, for example, heat energy, scan speed, layer thickness, and hatch spacing.

Unlike the DED-based and PBF-based processes, the SL process as one of AM processes uses metallic sheets as feedstocks. In general, the energy source used in the SL processes is ultrasonic or laser. The interfaces of stacked sheets can be boned using an energy source and mechanical pressure through diffusion during the SL process (Figure 1.6). In the ultrasonic AM process, the object is built up on a rigidly held base plate bolted onto a heated platen, with temperatures ranging from room temperature to approximately 200°C. A rotating sonotrode with compressive force travels along the length of the metallic sheet to build component layer by layer *(1)*. The SL processes are broadly used for composite materials along with the high processing speed and low cost compared to the DED-based and PBF-based processes.

These three AM processes have been developed for different applications and materials. A large number of general reviews and studies on the AM processes have emerged to evaluate the various types of AM techniques in the past two decades *(36–39)*. Different AM processes can be treated as alternative and complementary techniques through considering the specific scope which depends on some key factors *(2,3,35)*, for example, the production cost, the processing speed, and the tolerance of the final product.

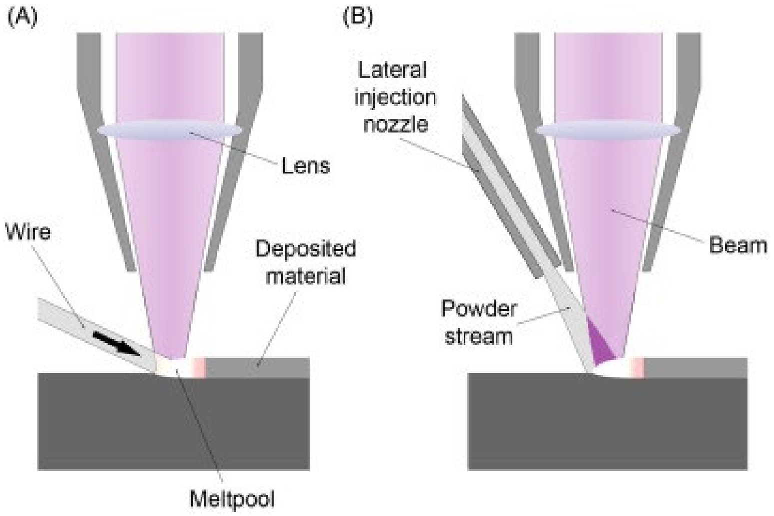


Figure 1.2: Directed energy deposition method

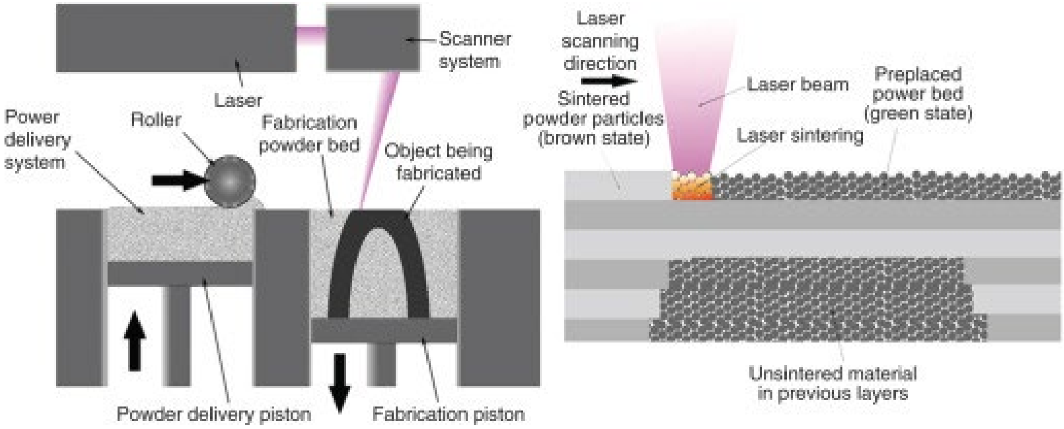


Figure 1.3: PBF-based selective laser melting process

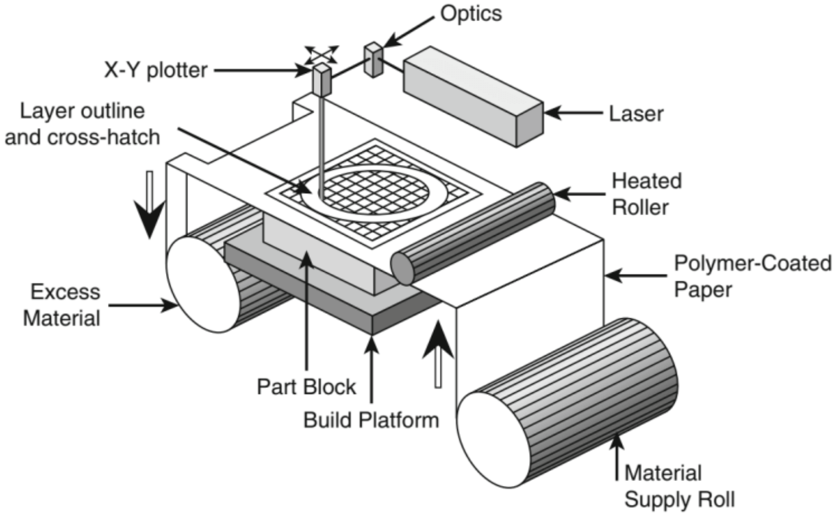


Figure 1.4: Ultrasonic AM process based on the sheet lamination method

AM has been identified as one of the strategic technologies which will play an important role in the manufacturing industries because AM provides several advantages and potential opportunities over traditional manufacturing methods *(7)*. The primary advantages of AM are fast prototyping, high structural freedom, increased functionality, elimination of assembly, efficient manufacturing system, and high-quality material.

Industries from the automotive, aerospace, and medical fields have explored the benefits of using AM in their businesses. For instance, AM has been used to reduce the production time by taking advantage of rapid prototyping *(1)*. Moreover, the complex geometries required to produce the final components have been achieved when AM was involved. Following the trend of using AM and taking the potential benefits, the construction and transportation industries have recently started the journey toward the use of AM technologies *(6,8)*. For example, geometrically complex structures, one component consisting of various materials, and the automation process are areas of potential impact from AM processes. Thus, the potential cost-based and innovation-based opportunities for construction and transportation industries offered by AM could be to reduce the construction time and materials and to enhance the structural efficiency.

In 2017, the first residential house with a 38 m^2 building area in Russia was 3D printed on site by Apis Cor company using the mobile concrete 3D printers (Figure 1.7). The automated and repeatable building process was done in 24 h, and the total cost was $10,134 *(40)*. This project demonstrated that the construction time required to transport and assemble components can be significantly reduced, suggesting an economical construction process. Under a demand for functional-optimized structures, the extended freedom of design and innovation allows the construction companies to tailor the structure approaching the desired function. Accordingly, as shown in Figure 1.8, a stainless steel bridge (12.5 m in length, 10.5 m in span, and 2.5 m in width) was designed to make the compressive stresses dominating in the structure, and it was printed by MX3D company using DED-based wire and arc additive manufacturing (WAAM). The bridge was built up in a series of layers of weld material in two nominal thicknesses (3.5 mm for the handrails and 8.0 mm for the substructure). The bridge has an overall mass of 7.8 tons, of which, approximately 4.6 tons was 3D printed. Almost 60 wt.% of the bridge (total weight of 7.8 tons) were manufactured through AM, and the printing was completed in 6 mo *(*41*)*. Although the larger scale and faster processing time may be needed for more general applications, this example has indicated that using AM enables designers to extend the range of opportunities for structural and functional designs.

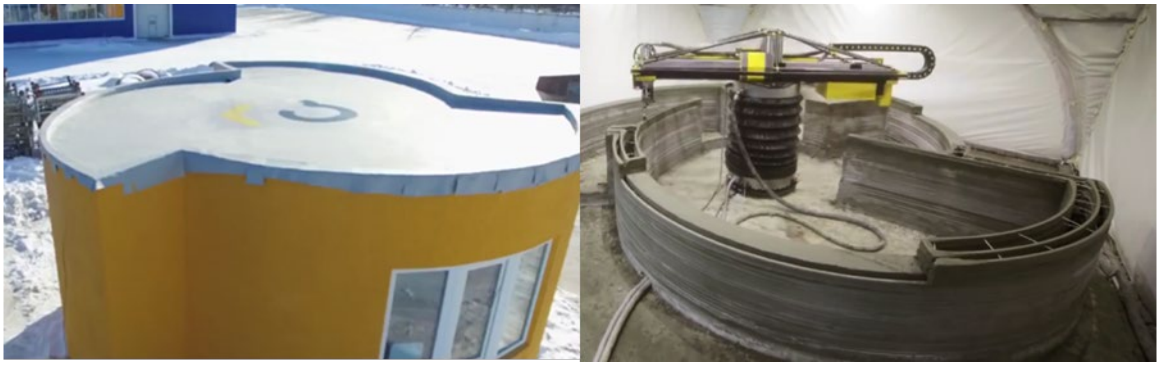


Figure 1.5: Residential house 3D-concrete printed on site by Apis Cor

Figure 1.6: MX3D 3D-printed stainless steel bridge

In the transportation industry, important parts of the bridge structure often suffer from corrosion mostly resulting from the wet environment *(42–44)* and leading to the reduction of the brudge structural capacity. To maintain the workability of the bridge, maintenance or replacement processes are usually required in the transportation industry *(45,46)*. Because replacement parts are expensive, repair methods are more favorable than replacement methods *(45)*. However, the current repair methods are costly and time-consuming because of the labor requirements and the multiple steps for operations during the repairing process. As a result, the consequences inherent in road closures are increased as maintenance time is increased.

AM offers significant potentials in maintenance applications compared to the conventional repair methods. The high production speed as one of the important benefits of AM for maintenance can essentially reduce the time during the repairing process so that the road closure time can be minimized. The development of mobile 3D-printing systems would allow for an on-site automated repair process, which can further reduce the repair time and enhance the repair efficiency *(32,47,48)*.

An AM repair system has been developed recently by RepAIR to automatically identify the dimensional and geometric deviations between the damaged part and the original part *(48)*. In addition, compared to conventional repair methods (e.g., tungsten inert gas welding and gas metal arc welding), the low heat input in AM can result in low material distortion and low thermal damage. The energy source (e.g., laser-beam in the DED-based process), controlled by a computer-aided design (CAD) model enables a precise and repeatable repair process. Therefore, an economic and automated repair process (we call it an "additive repair process") is promising for the transportation industry.

Recently, additive repairs for turbine blades have been explored in the aerospace and turbine industries due to the inherent advantages over conventional methods, for example, reducing processing time and multiple material deposition *(49–55)*. For instance, an erosion damaged T700 blisk was repaired using a DED-based laser-engineered net shaping (LENS) method by Optomec *(56)*. Figure 1.9A presents the additive repairing process, the T700 blisk after edge repair (Figure 1.9B), and the T700 blisk after finishing (Figure 1.9C). The results exhibited the minimal distortion. Moreover, Yu et al. *(57)* investigated the mechanical properties of additive repaired steel alloy and their results as shown in Figure 1.10 showed that the component repaired additively exhibited better uniform elongation and comparable tensile strength compared to the counterpart repaired using a conventional welding process. Figure 1.10 shows the tensile results on Von Mises stress and strain relations of the original material (no repairing), repaired (by welding), and repaired (by AM) with the same repaired depth of 3 mm. It demonstrated the promise of additive repair for the component quality. Although these examples are mostly in the aerospace industry rather than the transportation industry, the AM potentials regarding the repair process are revealed.

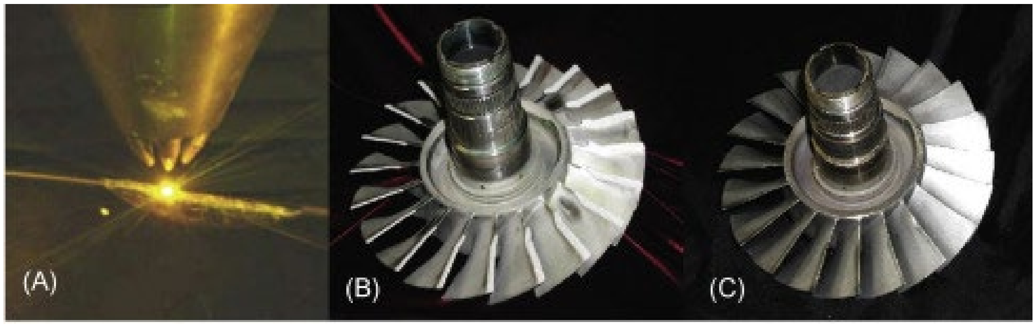


Figure 1.7: Airfoil repair using a DED-based LENS AM system

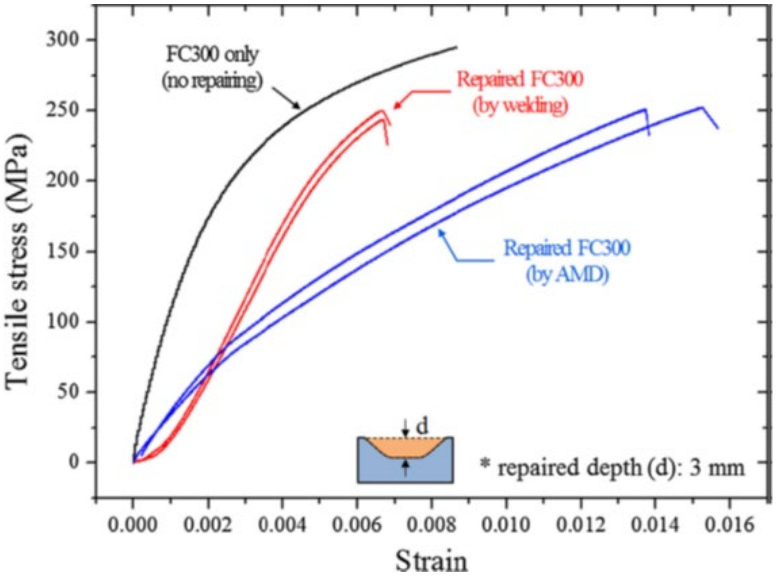


Figure 1.8: Tensile results on Von Mises stress and strain relations

In the workshop, we introduced the AM technologies and identified the potentials for using the additive repair techniques to enhance repair processes in the transportation industry, specifically, in the highway bridges in Massachusetts. In recent studies by the research team on the performance of highway bridges, corrosion was identified as the critical factor leading to the deterioration of steel bridges because aged joints allow water or deicing mixtures to penetrate the bearing area (Figure 1.11). This is considered a major problem in the northern part of the country. Figure 1.11 shows a 21WF73 girder with the characterizing feature of a combination of corrosion holes located along the studied end, extracted from a bridge in Massachusetts. Based on the inherent advantages of AM as already described, the additive repair of the damaged parts in highway bridges was investigated in the research laboratories at UMass Amherst and MIT and the results are shown in the next sections of this report.

1.4 Industrial Presentations of the Workshop

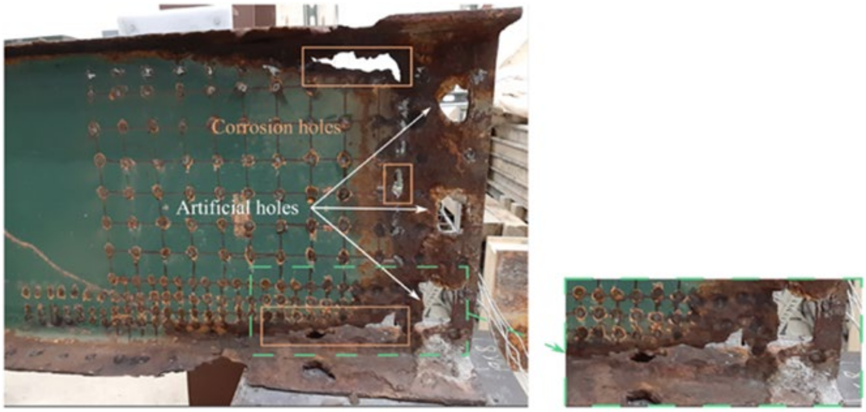
In this section, the highlights of the invited industrial presentations are summarized to introduce the current status of AM technologies and the relevant software developed in industrial companies. The successful cases of AM applications from the invited companies, the potential opportunities and the feasibility of AM in applications for infrastructure construction and transportation are illustrated.

1.4.1 AM for Construction and Infrastructure Applications

Peter J. Denmark, ExOne

ExOne as one of the successful 3D printing developers has used the binder jetting method to provide 3D printing systems in the markets since 1995. The commercially available materials used in their 3D printers include metal powders and sand powders. Currently, more than 20 different types of metallic powders are successfully transformed into metal, ceramic, and composite components. The metallic components with near-full density have been fabricated using commercial 316 stainless steels, 420 stainless steels, bronze, and Inconel 625. Moreover, sand 3D printing using the binder jetting method for large-scale sand molds, cores, and new tooling options has been developed by ExOne.

With the exception of large-scale components in the construction industry, the sand 3D printing can be a good candidate to produce 3D large-scale complex geometries without the use of temporary supports. As presented, the ExOne sand 3D printing process provides significant time and cost advantages over traditional manufacturing processes for delivering sand molds and cores for metal castings. For instance, an automaker applied the ExOne sand 3D printing to produce the 200L complete casting mold for the aluminum alloy 356, as shown in Figure 1.12. According to the study by ExOne, the cost per part was reduced to $1,800 and the production time was 4 h when the sand binder jetting method was used.



(a) Web

(b) Bottom flange (c) Top flange

Figure 1.9: 21WF73 girder with corrosion holes from a Massachusetts bridge

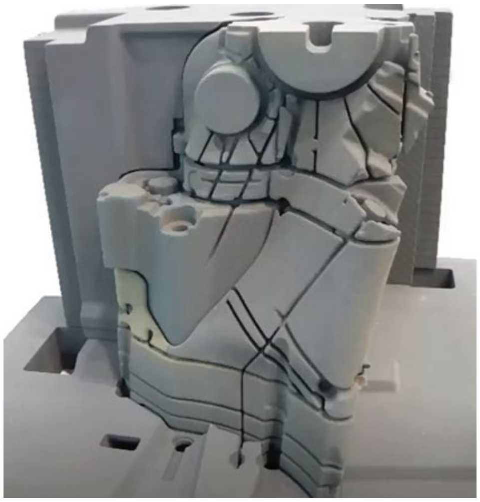


Figure 1.10: Compact utility tractor components

1.4.2 How EOS Supports Your Success in Additive Manufacturing

Maryna Ienina, EOS

EOS is one of the successful 3D printing technology suppliers in the field of industrial 3D printing of metals and polymers. Binder jetting methods have been used in EOS for the development of 3D printing systems since 1989. In general, the binder jetting methods as one of the AM processes have been mostly used in metallic, polymer composite, and ceramic components. The advantages of binder jetting methods include the high scalability of the process and the high efficiency of linewise patterning owing to the adjustable number of ejection nozzles. As the development of the binder jetting technology in EOS has evolved, there are various types of alloys (aluminum alloys, cobalt chrome alloys, nickel-based alloys, refractive metals, stainless steels, tool steels, and titanium alloys) and polymers (polyamides, polystyrenes, thermoplastic elastomers, polypropylene, and polyaryletherketone) produced using EOS 3D printing systems.

One successful case of a 3D printing application presented by EOS is an injector head for rocket engines with complex geometries that was manufactured additively using the EOS M 400-4 3D printer (Figure 1.13). The additively manufactured baseplate of the injector head of a rocket engine with 122 injection elements was made from EOS IN718. The number of components composed for one injector head was significantly reduced from 248 to 1 when 3D printing was used instead of a conventional method. As a result, the total cost and production time were reduced by 30% and 80%, respectively.

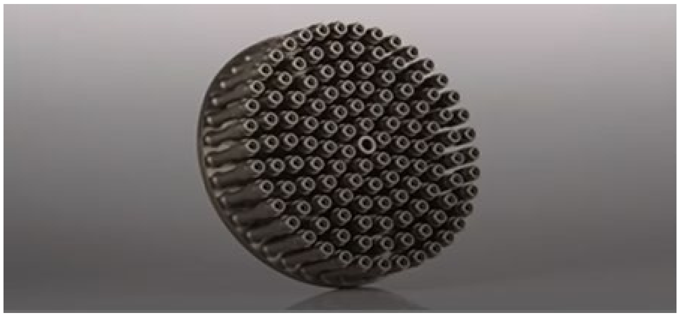


Figure 1.11: Manufactured baseplate of the injector head of a rocket engine

1.4.3 BigRep Construction Projects

Frank Marangell, BigRep

BigRep is a 3D printing developer for the large-format designation in industrial manufacturing environments. It provides engineers and manufacturers with a highly scalable solution, able to efficiently manufacture end-use parts and products or factory tooling. In particular, because the capacity in reaching a larger scale in components is one of critical factors influencing the applications of 3D printing in the construction industry, the BigRep ONE 3D printer features a build volume of 1,005 mm × 1,005 mm × 1,005 mm allowing large-scale components that are suitable for concrete construction.

For instance, a concrete wall (Figure 1.14a) designed with functional application and complex geometry was additive manufactured in BigRep in collaboration with CCC. This process was demonstrated as the cost- and material-efficiency process because the remaining concrete can be recycled during the 3D printing process. Figure 1.14b shows the Deutsches Museum façade developed using 3F studio with BASF and Sculpteo, another example of a large-scale façade that was fabricated at BigRep by eight 3D printers. It was completed in 2 mo.

Figure 1.12: (a) A smart concrete wall; and (b) the Deutsches Musem façade

1.4.4 AM in Infrastructure Applications

Patrick Duis, and Greg Constantino, DSM

DSM is a global science-based company in nutrition, health, and sustainable living. DSM Additive Manufacturing has focused on 3D printing technologies, the performance of materials, and the applications of 3D printing in different industries. The materials include engineering thermoplastics, resins, high performance fibers, and coatings which appear in products essential to the applications in these industries.

In particular, in the field of structural applications using 3D printing, DSM developed a large-scale component for the transportation industry. Motivated by the fact that the improvements of duration, weight efficiency, and cost efficiency of maintenance are necessarily needed in bridge decks to further develop the infrastructure transportation sector, DSM is planning to use thermoplastic composites fabricated by 3D printing to replace heavy concrete bridge decks. The lifetime of 3D-printed thermoplastic composites is expected to be extended to 30–50 years, meanwhile the weight would be reduced by 10 times as compared with concrete bridge decks. Therefore, cost of maintenance in bridges could be reduced when the 3D-printed composites are used. Figure 1.15 shows the 3D printing process generating the specimens of thermoplastic composites and the load testing in a current project in DSM. In this project, the DSM 3D printer features a build volume of 10 m × 4 m × 2 m, and it will enable the large-scale components for applications of bridges.

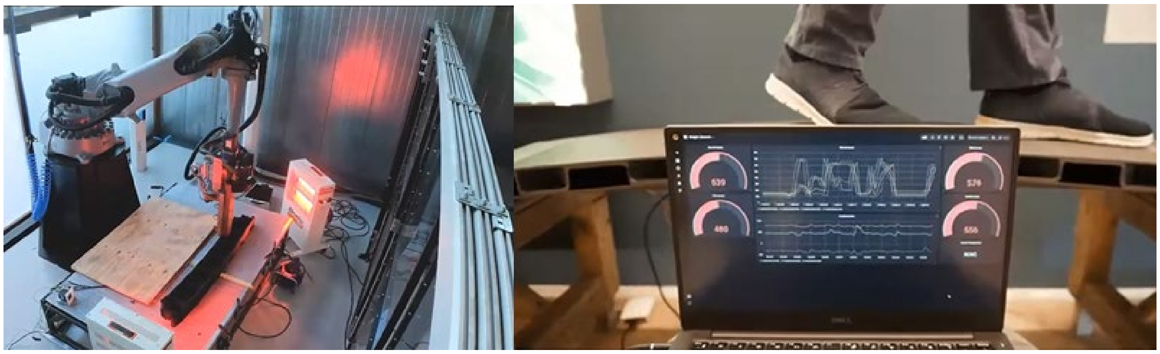


Figure 1.13: (Left) 3D printing process, and (right) load testing

1.4.5 The Introduction of Autodesk

Louisa Holland, Autodesk

Autodesk is a multinational software corporation that makes software products and services for the architecture, engineering, construction, manufacturing, and media industries. Because 3D printing requires the computer systems for controlling processes and AM designation depends on the inputs from CAD software, the capacity, quality, reliability, and efficiency of CAD software is essential to design AM components and for subsequent applications.

Considering the AM applications in the transportation industry, Autodesk presented the InfraWorks software, which shows potential for improving road design. Figure 1.16 shows a visual example of the Autodesk InfraWorks software in which the details of landform are available so that the design could be easily correlated to the specific landform. In addition, the visualization of a 3D environment in the software allows designers to efficiently perform the designation and thus enhance the design process.

Start Station: 1640.17 ft Length: 423.63 ft End Station: 20+63.80 ft

Figure 1.14: Civil 3D Autodesk software for road and highway design

1.4.6 The Introduction of nTopology

Gabby Hayes, nToplogy

nTopology is a software company developing the engineering design tools using the topology/structural optimization methods. Because AM offers high structural freedom, the complex external and internal geometries can be designed using nTopology software to improve the functionality and the appearance of a building component.

Figure 1.17 shows the nTopology design work platform on which the topology optimization method was used to design the lightweight structure with complex geometries. In addition, materials with complex structures, for example, cellular materials and forms, can be designed to realize the various functionalities using the nTopology software. It is of technical and fundamental importance to enhance the performance of materials and structures and meanwhile reduce material waste.

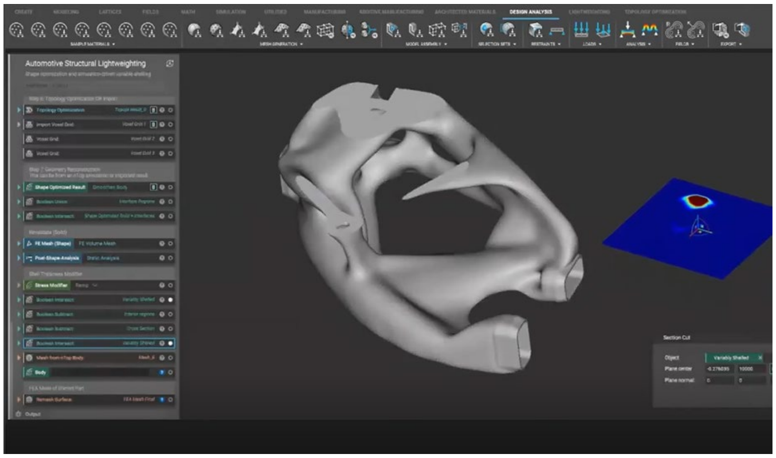


Figure 1.15: 3D nTopology software for topology optimization design

1.4.7 The Introduction of Twikit

Stephanie Seghers, Twikit

Twikit is a software company developing software solutions that cover the entire process from customer order to production in the field of 3D printing technology. The Twikit's proprietary software allows customers to design and interact with products according to their own needs, bringing mass customization to the factory floor. Moreover, Twikit provides the parametric configuration allowing the correlation of visual modifications to direct technical output and thus 3D printing on demand.

For instance, mass customization service using 3D printing has been used by BMW in collaboration with Twikit (Figure 1.18). The customization is among the benefits that 3D printing brings to the manufacturing industry. Considering the customization in the construction and transportation industries, the applications of AM in the improvement of workplace safety and employee health through customization based on the person-specific data could be realized.

Figure 1.16: Personalized 3D printed BMW MINI scuttle collaborated with Twikit

Overall, the capacities including scalability, complexity, materials, and methods of commercial AM facilities were demonstrated in the representative instances provided by ExOne, EOS, BigRep, and DSM. Moreover, CAD software coupled with visualization, topology optimization, and customization presented by Autodesk, nTopology, and Twikit allow us to further enhance the performance of components or structures fabricated using AM techniques and to reinforce the applications of AM in the construction and transportation industries.

1.5 Information Highlighted in the Breakout Sessions

Several general topics were discussed following the academic and industrial presentations:

- General cost and production time of using 3D printing techniques for maintenance in the transportation industry;
- Scalability and the associated limitations of current 3D printing systems; and
- Feasibility of AM maintenance on damaged joints in bridges.

The main takeaways from the general topics are summarized as follows:

- The current studies on 3D printing show that AM processes are generally cost effective. Moreover, AM is offering high flexibility of both structure and manufacturing, which could enhance the supply chain efficiency, for example, by reducing the inventory and transportation costs, and thus leading to a reduction of the overall cost of the entire process of production.
- The material cost is a considerable factor contributing to the total cost of AM processes. However, the cost of raw materials for 3D printing is believed to be decreasing as the adoption of 3D printing is expanding.
- The scale limitations differ with various AM techniques. For example, WAAM can be used to print large-scale components, whereas PBF is suitable for small components. As shown in the example of the MX3D stainless steel bridge (Figure 1.8), the large part with 10.5 m in length was fabricated using a robotic 3D printer. As the AM techniques continuously develop, the larger scalability and lower cost of AM systems is expected to occur in the future.
- AM techniques, such as LENS, provide capabilities for repairing damaged components and even for repairing components that have been considered nonrepairable by conventional methods. For instance, the bearing, seal, and coupler surfaces on shafts are typically considered nonrepairable by conventional welding techniques due to the material deposition, which is hard to be precisely controlled. However, LENS repair could be used to repair these components that require high accuracy in geometry. AM maintenance has been investigated and successfully adopted in aerospace industries. However, AM repair is rarely used in construction

industries and there are limited data available. Studies of AM maintenance for construction industries are needed.

According to the discussions, the high-penetration sources, for example, X-ray computed tomography, may be necessary for repairing components to detect the location and the topology of damage. Also, it was acknowledged that the AM techniques as new technologies need to be further developed to meet the requirements, for example, enhancement of cost- and time-efficiencies, of broad applications in infrastructure transportation and maintenance.

1.6 Tours of 3D Printing Facilities

The first tour took place in December, 2021, at the Empire Group, a 3D printing service provider located at 217 East Street, Attleboro, MA. The Empire Group is one of a small number of 3D printing contract manufacturers located within eastern Massachusetts. The Empire Group primarily works with polymeric and polymer-composite components (Figure 1.19).

Figure 1.17: Empire Group AM Equipment (Empire Group)

The tour of Empire Group's facilities began with a presentation from Empire Group staff on their history, technology capabilities, and infrastructure-relevant applications for each of their in-house technologies. This presentation was followed by a detailed walk-through of their design engineering, production, and finishing facilities. Following the walk-through, the project team and MassDOT and Empire Group staff had a thorough discussion on AM's possibilities for transportation infrastructure.

The technologies featured included those presented at the October Workshop. The Empire Group includes the following technologies:

- **Stereolithography** (SLA) printing. This process uses a laser to selectively cure photopolymer resin. SLA is suitable for short-run injection mold tooling, high-precision polymer components, detailed demonstration parts, and fine-tolerance prototypes.

- **Multi Jet Fusion** (MJF) printing. This process uses inkjet-based chemical deposition and thermal treatment to selectively bond and polymerize a bed of polymer powder. The MJF process is relatively high-speed and low-cost, making it suitable for prototyping or short-run production applications of nonstructural components. MJF is also often used for nondurable tooling such as drill jigs or alignment fixtures.
- **Fused Deposition Modeling** (FDM) printing. This process selectively extrudes a heated polymer filament onto a substrate. This process is the most common printing process by machine-type, is accessible at a wide variety of price points (from several hundred dollar equipment to several hundred thousand dollars), and is generally inexpensive compared to other printing methods. Printing filaments can incorporate continuous fiber reinforcement or other additive materials to improve mechanical properties. FDM is used in a wide range of applications from prototyping to concrete mold tooling to end-use parts.
- **Micro Digital Light Projection** (MicroDLP) printing. MicroDLP printing uses a projector to display structured light onto a photopolymer resin layer-by-layer. This process is suitable for high-precision components with features as small as several microns.
- **PolyJet** printing. PolyJet uses selective inkjet deposition of a UV-curable photopolymer resin, followed by a pass of UV light, to selectively deposit and cure material to form parts. The large number of inkjet heads allows Polyjet parts to feature different materials, which most often vary in color and durometer. High color saturation and soft, realistic material properties mean that polyjet is most often used for photorealistic demonstration parts. There are other uses of polyjet including in short-run tooling and functional prototyping.

The Empire Group's other capabilities include room-temperature vulcanization, CNC machining, painting, and other miscellaneous polymer and metal forming and finishing processes. During the presentation and tour, several key themes emerged that are worth highlighting in this report.

- AM processes do not exist in a vacuum. As the Empire Group's facilities showed, printing is only one stage of production for printed components. Printed components may be finished for dimensional accuracy (e.g., by machining or manual finishing) or mechanical properties (via thermal tempering, coating, or using fiber-reinforced materials). As is discussed later in this report, any consideration of printing for MassDOT use must also consider subsequent processing steps. In many cases, the subsequent processing of printed components after the initial printing stage substantially influences their performance in-use. During procurement discussions of potentially printed components, MassDOT should be cognizant of the implications of subsequent processing steps on the cost and lead-time of printed parts. Moreover, implementation of AM on site for MassDOT fabrication facilities should consider secondary operations that may be necessary to produce components of the requisite quality and appearance.

- AM excels at low-quantity, high-complexity parts. AM offers nearly unlimited geometric complexity within given size and material constraints. Empire Group's portfolio of work therefore largely features parts at the tail ends of their lifecycle: either demonstration parts and functional prototypes during initial product development or spare and replacement parts that are difficult to acquire traditionally. When considering potential uses of AM in MassDOT activities, emphasis should be placed on cases at these extremes. On the early end of a project's lifecycle, AM can, for example, be used for planning and demonstration. Engineers at Boeing use AM for printing scale miniatures of future planned major facility projects. These miniatures enable real-time planning of facility layout and process flow, and they also can be used as a tool to present projects to key stakeholders or senior management. A scale miniature of MIT's campus (Figure 1.20), used to demonstrate a major planned construction, is on display at the MIT Atlas Service Center.

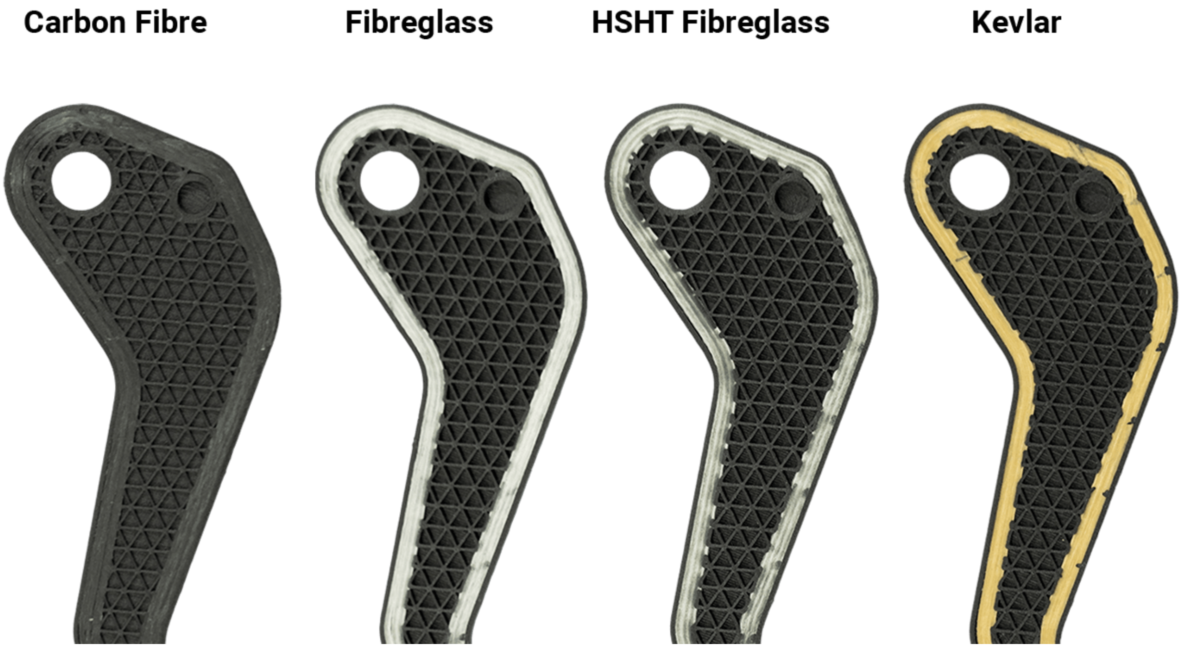
Figure 1.20: 3D printed scale model of MIT's campus (MIT)

Conversely, the use of AM for replacement parts has numerous advantages, especially for difficult-to-replace parts, worker tools and aids, or customized components. One application evaluated during this project are the metal keys used to open manholes. Depending on the locking mechanism design, manhole keys in some industrial settings can be difficult to replace and/or are manhole-specific. For a part with these characteristics, AM can be an excellent quick-turn replacement. During the Empire Group tour, we viewed the Markforged continuous-fiber reinforced FDM extrusion process (Figure 1.21). For applications with similar traits to the manhole key example, this process produces low-cost, high-strength parts comparatively quickly. The continuous-fiber reinforcement, when applied in parallel to the load vector on the part, can add strength comparable to material. The equipment's form factor is small and could be used at parts warehouses to augment physical inventory, especially for temporary or nonstructural parts.

- Organizations often start small when first applying AM. Many of the uses of AM shown at the Empire Group were for prototype or intermediate components. The advantages of AM lend themselves to these early-stage models without the risk associated with material qualification for end-use. For this reason, the Empire Group, like the AM industry, began as a rapid prototyping service, and many of the applications of AM industrially are similar today. Consequently, as the MassDOT seeks to adopt and integrate AM into its design, engineering, and procurement activities, it should target low-cost, low-risk uses, or uses that clearly solve a problem that AM is well-suited to address. For example, fused deposition modeling (or extrusion AM) is a low-cost AM process that can be easily integrated into engineering offices, parts and service depots, and fabrication facilities. For parts with greater mechanical or dimensional requirements that require more complex AM processes, utilizing service providers is an accessible way to explore printing uses.

In addition to the Empire Group tour, an additional visit of other area printing locations, including MIT, Desktop Metal, and its subsidiary companies is being planned for May 2022 to complement the polymer equipment housed at the Empire Group. This visit, originally planned for February 2022 was postponed upon request by Desktop Metal, which restricted third-party tours during the COVID-19 winter surge.

These tours are an important contrast to the processes, materials, and workflows demonstrated previously. Desktop Metal, and its companies ExOne and Envisiontec, have three metal printing processes relevant to MassDOT.


Carbon Fibre

Fibreglass

HSHT Fibreglass

Kevlar

Figure 1.21: Cross-sectional view of printed parts using Markforged process (Qualified3D)

- **Bound metal deposition** (BMD) printing involves the extrusion of molten metal-composite onto a substrate, followed by a series of thermal and chemical treatments that densify the printed component and concentrate the source metal. The process is suitable for functional metal prototype parts. A low form-factor and entry cost (compared to other metal AM processes) make it an accessible early-stage metal AM process.

- **Binder jet** printing involves the selective inkjet deposition of a chemical binder into a bed of metal powder, followed by a series of treatment stages to consolidate the material into a dense form. Binder jetting is a high-speed printing process and is markedly lower cost than other printing processes (such as laser powder bed fusion) due to reduced material and equipment costs. However, because material consolidation is done during a heat treatment stage, which occurs post-printing, material densities and performance are lower than bulk formed (e.g., wrought) materials. Binder jetting is therefore used predominantly for volume production of low-duty metal parts, temporary components, and prototypes.
- **Sand binder jetting** uses the same selective inkjet deposition process to selectively bind sand to create complex molds for metal casting. This process is used predominantly for cast prototypes, replacement parts, and high-complexity components that require the complex molds that printing enables. The casting process is conducive to heavy-duty and end-use structural parts, and it could be an accessible avenue for the MassDOT to approach printing for cast components.

1.7 Conclusions

The topics regarding opportunities and challenges for 3D printing in highway infrastructure construction and maintenance were addressed and discussed in the online two-day workshop. It consisted of two main sessions, that is, academic presentations and industrial presentations. Breakout discussions following each main session were also included in the workshop.
In the session of academic presentations, the fundamentals and potential advantages of AM were addressed. In particular, the AM opportunities of applications in the construction, structural, and civil industry were illustrated by considering the potential advantages of AM technology, for example, on-site manufacturing and production of complex geometries. By applying 3D printing to the construction industry, some of the challenges consisting of improving structural efficiency and safety, optimizing the process of maintenance and repair, enhancing properties of structural materials, and reducing time and cost, could be overcome in the future.

Furthermore, the innovative repair methods are necessarily needed to enhance the repair process in the transportation industry. AM offers considerable potentials in repair applications and also enables the extensive possibilities for automation. In the 3D printing process, the high process speed and low energy input would lead to a cost- and time-efficient repair process. Recent development of the mobile 3D printer featuring automated robotic arms enables performing the maintenance using in situ materials and on site. As a result, road closures could be minimized, and the longevity of existing infrastructure components through both proactive maintenance and faster urgent repairs would be extended.

In the session of industrial presentations, commercial AM techniques and relevant design software were introduced, and the successful cases of AM applications in industries were demonstrated. To assess the feasibility of 3D printing applications in the construction and transportation industries, the representative cases regarding the capacities of scalability, complexity, materials, and methods of commercial AM systems were presented by ExOne, EOS, BigRep, and DSM. The design software related to 3D printing applications were introduced by Autodesk, nTopology, and Twikit. The development of design software will further enhance 3D printing applications and improve the performances of material and structure.

In the breakout discussions, three general topics regarding AM applications in the transportation industry—the general cost and production time of using 3D printing for real-world application, scalability of 3D printing, and feasibility of additive repair—were discussed. According to the breakout discussions, efforts on research and technology are required to further improve the time- and cost-efficiency and scalability of AM techniques suitable for the transportation industry and thus broaden the applications of 3D printing, specifically on highway infrastructure construction and maintenance.

2.0 Exploring Opportunities of AM within MassDOT

2.1 Collecting Information on MassDOT Needs and Opportunities

Over the course of the 2-year project, dozens of interviews were held with personnel from various MassDOT districts. Originally intended to be on-site interviews, again the travel restrictions imposed by COVID-19 limited the project's ability to interview staff and visit MassDOT districts and job sites. Each interview was instead coordinated digitally and conducted using a web conferencing application.

The interviews involved detailed discussions between MassDOT staff and the project team. Staff interviewed did not necessarily have a foundational understanding of AM and, as a result, the first portion of each interview was typically dedicated to a brief presentation and discussion of AM's application potential in transportation infrastructure. Many of the applications already discussed in this report were addressed as suitable candidates for AM. In particular, the following part characteristics were suggested for candidate geometries:

1. Parts that are hard to procure or replace. For reasons already discussed, AM is well-suited to rapid replacement of hard-to-acquire maintenance parts and worker tools. AM is used both to print direct replacement parts and to print one-off tools used to manufacture replacements conventionally. For example, custom facades or other concrete components can be cast inside on printed formwork.

2. Parts that are of a size suitable to industrially mature printing processes. The size of industrially capable printing processes is a major barrier to their potential utility in the transportation infrastructure sector. Most machines are capable of printing components with dimensions no greater than a foot in their longest axis; large-format machines exist and are capable of printing parts of a yard, or in limited cases, several yards in scale. However, the number of providers of equipment of the large-format type, and their relatively few applications, limits their development and therefore readiness for use in MassDOT activities. Parts that already fit within the constrained build volumes of industrially proven machinery will be best suited to candidate exploration.

3. Parts with limited service lifetimes or reduced duties. As is discussed during the Task 3 segment of this report, the current standards, qualification, and regulatory regimes for printed components are relatively nascent. Expansive qualification needs across materials and processes limit the pace of developing these standards. As a result, many standards are temporary standards that reference standard practice from similar manufacturing processes or adjacent industries. For example, AM-specific post-

processing standards for common metal alloys may reference generic aerospace association standards. The lack of detailed AM and industry-specific AM standards is an impediment to their broader exploration. The MassDOT should consider candidate parts that do not have rigorous duties or lengthy service lifetimes as initial candidates for AM. Selecting lower-performance parts is advantageous insofar as it minimizes the risks associated with a developing qualification environment while still allowing the MassDOT to gain familiarity with AM processes.

4. Parts that benefit from custom or complex geometries that would be too difficult or cost prohibitive to produce otherwise. The design flexibility afforded by AM is best captured when applications would be difficult or impossible to manufacture using conventional manufacturing methods.

Dozens of concepts, parts, and uses of AM were discussed during the project. As MassDOT engineers will be aware after reading the list of criteria above, there are few parts that perfectly meet these conditions. Although it is certainly possible to print parts that do not meet each criterion, every complication adds technical uncertainty and may require further research and development to mature. The MassDOT and project team agreed on practicality as the driving consideration for part selection.

However, this does not mean that parts that may be technically unfeasible or cost-prohibitive in the status quo were not discussed. Instead, each prospective candidate part offered the opportunity for the project team and MassDOT staff to engage in a detailed discussion regarding the capabilities and limitations of AM. Moreover, each part evaluation was an opportunity to reinforce the principles of part selection identified previously. Through reviewing these parts in detail and ultimately identifying many of them as technically infeasible or cost prohibitive, the MassDOT staff engaged in a valuable learning process and acquired meaningful capability to evaluate future candidate components for AM suitability.

Two of the candidate parts discussed in depth with MassDOT personnel are highlighted in this report. Each candidate was identified by the MassDOT and project team for different reasons and, if pursued, had various production approaches discussed as means for fulfillment.

Manhole Key

As mentioned previously, during an interview with MassDOT staff, when describing the use of AM to fulfill hard-to-replace, job-specific maintenance parts, the concept of site-specific or legacy design manhole keys was discussed. During the discussion, the MassDOT staff were not certain of the exact geometric and mechanical requirements for these keys. Subsequent research by the project team in other industries showed surprising diversity of shape and function for manhole keys (Figure 2.1).

Figure 2.1: Manhole key configurations (Bass & Hays, Faithfull Tools, Ehle)

Although the MassDOT staff were not perfectly familiar with these components, the strong potential for AM prompted the MassDOT team to investigate the application further. This application was identified as strongly suitable for several reasons. Although ultimately unselected for reasons described later, the assessment of this concept as promising is useful to describe here as guidance for further AM development within MassDOT.

1. Custom (i.e., site-specific) or hard-to-replace (i.e., legacy design) components are strong candidates for AM. AM does not require geometry-specific tooling to be designed to order the printing process. It is therefore adequate for printing diverse geometries without substantially greater cost. For legacy or custom components, the AM process can be digitally and quickly adjusted to print different geometries.

2. Tools, especially task-specific aids, are strong candidates for AM. They do not have the same rigorous performance requirements as end-use parts and can often be customized to the individual worker or task. In addition, the geometric flexibility of AM may allow for marginal improvements over conventionally manufactured alternatives, especially for worker ergonomics.

3. The part could be manufactured using a high-strength, fiber-reinforced polymer process. This process is low-cost and can be performed using comparatively low form-factor equipment, making it a preferred process for an early candidate part. In the context of polymer extrusion, a single directional load vector is advantageous. The extrusion process typically results in parts that are anisotropic, and thus parts can be purpose-designed to maintain sufficient strength while performing their designated duty, but they may fail under complex multidirectional loading conditions. The manhole key application presented a simplified loading case for which low-cost polymer extrusion would provide adequate mechanical performance.

On final review, the MassDOT team was able to identify a manhole key used in MassDOT District One (Figure 2.2).

Figure 2.2: District One manhole key (MassDOT)

This particular key geometry is not an ideal geometry for replacement via AM. The part is clearly formed by a simplified forging process involving the forging of a tapered end and bending the eye of the key. The simple geometry and manufacturing process likely means that this part is already inexpensive to procure and would be simple to replace using existing vendors. Even if reverse engineering and rapid replacement were required, the straightforward geometry could be quickly reproduced using conventional manufacturing methods. Moreover, the durability of the manhole key likely far exceeds the durability of a printed alternative. For these reasons, the manhole key was not selected for further investigation.

Bridge Bearing

The next component investigated in detail was a steel bridge beam bearing. This bearing is used to secure structural beams to the bridge foundation (Figure 2.3).

Figure 2.3: Bridge bearing in use (MassDOT)

The part was identified as being potentially suitable for AM due to the requirement for site-specific customization. The bearing interfaces with beams at different, varying angles. Consequently, the geometry and location of the bearing pad differ from site-to-site. Additionally, to secure the bearing in place, welds are required between the bearing and the beam. One potential advantage of AM previously unaddressed in this report is the ability to consolidate complex geometries into single prints. For complex components, it is often the case that limitations in manufacturing processes require that those components be produced as separate pieces and then assembled thereafter. The geometric flexibility of AM allows for parts to instead be printed as single components. Examples of part consolidation were discussed during the October workshop. A participant of the October workshop, familiar with this value proposition of AM, suggested the bearing pad as a candidate to potentially minimize the number of welds required during installation.

A detailed feasibility assessment was conducted for the bearing to assess its suitability for AM. First, MassDOT provided schematic drawings (Figure 2.4) of the bearing to the project team. The drawings provide general dimensional requirements rather than detailed dimensions for each feature. From these drawings, a representative CAD model was generated (Figure 2.5). This CAD model was then used to index the technical feasibility of printing the component using different AM processes.

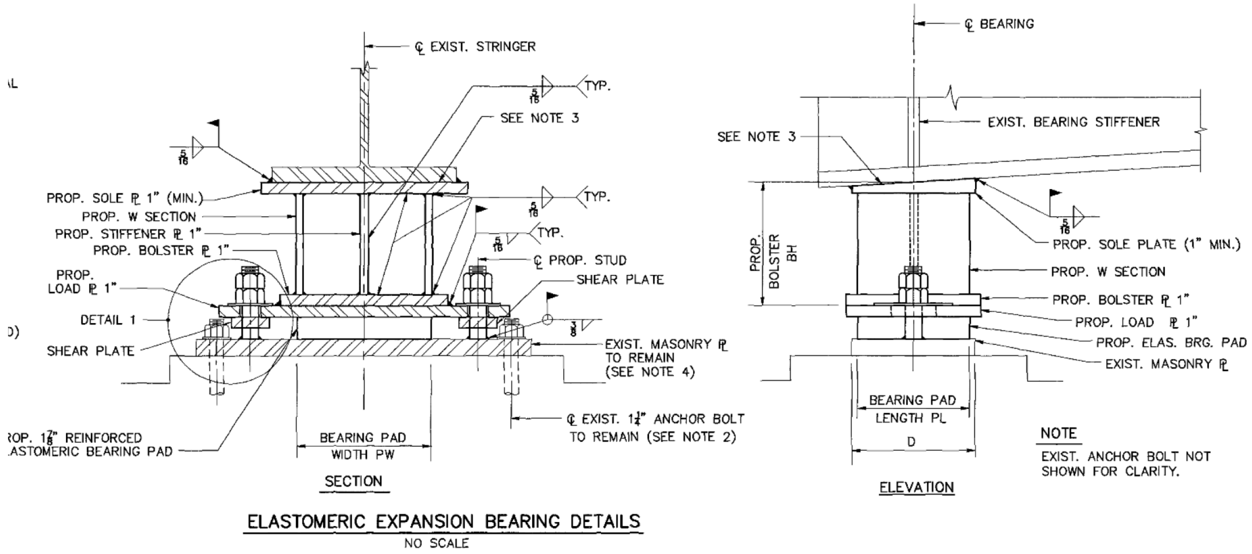


Figure 2.4: Bridge bearing schematic drawing (MassDOT)

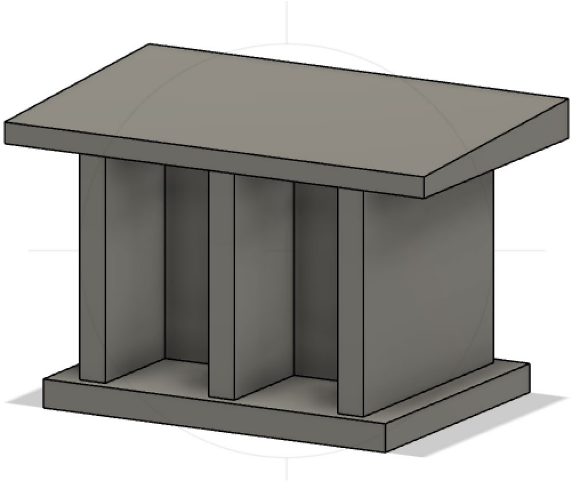


Figure 2.5: Bridge bearing CAD representation (MIT)

For the purposes of our initial evaluation, two AM processes were identified as candidates for printing the bearing. Directed energy deposition (DED) deposits material in powder or wire format along a substrate by direct application of energy at the deposition point. Among metal printing processes, DED is arguably the fastest process by volume of material deposited per time increment. What DED benefits from in speed, it lacks in accuracy; the process generally deposits tracks of material as large as several millimeters in width and height, and printed parts must be substantially finished after printing for dimensional accuracy.

For large-sized metal AM components, DED is a preferred process, because the chamber size in much DED equipment is substantially larger than other AM processes. For complex geometries, DED processes are subject to the same constraints as the processes used to finish them (e.g., CNC machining), because these processes are often a required component of the DED workflow.

Direct production of the bearing using DED was considered. Direct production would entail printing of the entire bearing geometry. However, upon inspection, it is not considered to be a suitable production method. In particular, the bearing has considerable negative space inside two cavities within the bearing body. To improve the mechanical properties of the bearing, including fatigue and creep properties, machining of the coarse, as-printed surface would be required. The depth of the two cavities within the bearing would pose difficulties using conventional machining methods, because the tool required to surface the bearings would need to penetrate the full depth of the cavity. This machining task would likely require several tool changes, and the additional cost and process step were expected to add cost and process complexity beyond the status quo choice of bearing.

As mentioned, the exact angle of the slope along the top of the bearing is semicustom to the specific beam interface where the bearing is installed. One idea suggested by MassDOT was to use DED to print only this slope on top of an existing, mostly finished bearing. This option would eliminate the costly machining task described previously. This suggestion demonstrates an evolution of thinking over the course of the project. Where AM may pose challenges when implemented as the exclusive fabrication method, its combination with conventional forming approaches can create unique value by reducing design constraints and simplifying last-mile customization or finishing of components.

In the specific case of the bearing, the use of DED to form the slope would not add considerable value; the slope is already manufactured when the part is made conventionally, thus DED would add processing work that is not required. Additionally, the recommendation to use AM for the bearing was in an attempt to eliminate the number of welds when installing the bearing; it was unclear how the use of DED would meaningfully reduce this number. We conclude that DED would not be a suitable printing process for either the bearing in its entirety or for the sloped top piece.

The second metal AM process considered for printing the bearing is the laser powder bed fusion (L-PBF) process. L-PBF uses a scanning laser to selectively fuse metal powder inside of a powder bed. This process is the most widely adopted in the industry for printing metal end-use parts, including in health care, energy, and aerospace. Due to its relevance, L-PBF is arguably also the most mature metal printing technology. The ASTM/ISO F42 Committee on Additive Manufacturing Standards has produced standard procedures for L-PBF materials and processing conditions. For these reasons, L-PBF is a reliable benchmark process when evaluating any prospective metal AM component for production.

In the case of the bearing, specifically, L-PBF is suitable for producing parts with a relatively smooth surface finish when compared to DED. Although L-PBF parts often require surface finishing, the degree of material removal is substantially less than in DED, and machining is often not required. In this regard, the cavities in the bearing that restricted the applicability of DED for its production did not pose the same degree of challenge for L-PBF.

For these reasons, the L-PBF process was selected for further feasibility study. In this analysis, we consider both the component's manufacturability using the L-PBF process, and estimated production costs using an analytical model of L-PBF cost. To assess manufacturability, the CAD model was imported using Materialise MAGICS "build preparation software" into a virtual printer environment for an EOS M400-4 L-PBF system. The EOS M400-4 can produce among the largest L-PBF parts and is a capable benchmark system for the state-of-the-art in L-PBF technology. In the virtual build preparation environment, the model can be configured for printing and compared against constraints including part size, part orientation during printing, and other aspects of the printing strategy.

A high-level assessment of manufacturability seeks first to evaluate if the geometry proposed for printing is compatible with the L-PBF printing process. We define three high-level, easily-answered questions for assessing manufacturability. Asking and answering these questions can be done quickly, with readily obtained information, and can quickly screen parts for their suitability for printing.

1. Is the part size compatible with printing? If not, can the part be printed in an assembly and still retain its full function? Parts that are too large to be printed and cannot be sectioned into components of an assembly should not be considered for printing.

2. Would the part's orientation when printing unreasonably raise the cost of production? When using the L-PBF process, "support material" is required to provide support against gravity for overhanging elements of the printed component inside of the powder bed. These supports must be removed after printing. Orientations during printing that cause excess support can add substantial material and labor costs such that AM is not suitable for production.

3. Would the part's orientation when printing add unreasonable risk of the print failing? When choosing a printing orientation for L-PBF parts, machine operators must consider both the thermal histories of the part as they are being printed and the mechanical interaction between the printed part and moving components of the printer itself. In general, the L-PBF process creates highest-quality parts when there are not large continuous masses of formed material (e.g., plates) being printed. Dense low surface-to-volume ratio features require substantial deposited energy to form and can create strong thermal gradients and stress concentrations that cause warping or cracking of printed components. In addition, it is advantageous to align the edge of printed features orthogonal to the direction of the moving recoater blade inside the printer. The recoater blade spreads powder across the powder bed after each printed layer. The reason to align the edge of part features orthogonally is to minimize the potential contact area between the recoater blade and the printed part. When the edge is aligned in parallel to the recoater, the greater the risk of the recoater catching on the printed part. This can either damage the recoater, causing the job to fail, or damage the part, causing the job to fail. In either case, the consequence is catastrophic and the job must be restarted anew.

With these three criteria in mind, we evaluate the bearing for production using the L-PBF printing method.

The bearing was not recommended for AM during the initial manufacturability assessment. It is important to note, if current trends hold, limitations in equipment size and capability may quickly be overcome. Challenges arising from geometry and available print orientations may be partially overcome by technological advances. As Table 2.1 demonstrates, the problems themselves are in part a function of the geometric constraints imposed by the limited build volume in available equipment.

For several reasons—that the technology may be capable in the future to produce parts of this size, that this part was elected as a good candidate by informed, AM-familiar staff, a relative absence of suitable candidate alternatives, and that the L-PBF process is an industrially relevant and mature metal AM process—this part was nonetheless further evaluated for economic feasibility.

The economic feasibility assessment uses an activity-based costing (ABC) method developed at MIT. The ABC methods decompose larger processes into their granular constituent costs. Individual cost elements are then assigned per activity, and the share of cost per activity assigned to each part is then a function of the number of parts processed during a given activity. For a simplified representation of this model, consider the cost of producing metal bushings.

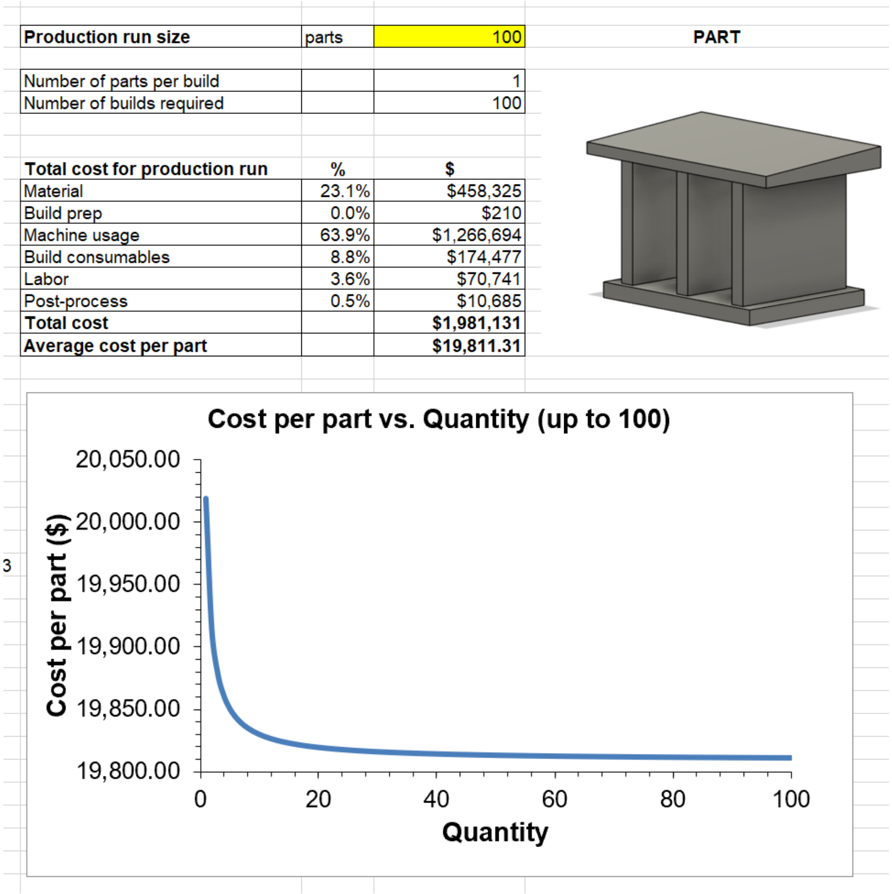
Consider first the individual part costs. Bushings might be turned individually from stock material on a lathe. The cycle time for each individual bushing corresponds to the amount of machine time required per bushing. If a lathe costs \$60/h to use and each bushing takes 1 minute to manufacture, then the machine usage cost per bushing would be \$1. Next, we consider bulk costs. A lot size of 100 bushings might be tumble finished in a single tumbling operation. The tumble-finishing operation may have a fixed cost per cycle. This cost would then be divided by the number of parts finished in a given cycle.

The model details costs that are associated with material, build preparation activities, machine usage, consumables, and post-processing activities. Using benchmark parameters from industrial equipment, the model simulates the number of printing jobs, printing time, labor hours, and material required to complete a full production run. For the bearing example, representative data was used from industry sources for material and equipment costs.

Table 2.1: Bearing evaluation for production using L-PBF

Feature	Yes/No	Notes
Size	No	The bearing was evaluated against the largest print-size L-PBF system that is industrially available. At no orientation would the part fully fit within the L-PBF system. The difference in size was not substantial, and an increase in 4–6 in. in any dimension from present capabilities would be sufficient. Sectioning the part would allow it to be printed in multiple pieces using L-PBF. However, once sectioned, the part would need to be welded together before installation. This would increase, not decrease, the number of total welds required for the bearing. Given that the purpose of investigating this part for printing would be to reduce the number of welds required, this would be an unsuitable outcome. The pace of technologic growth in AM is strong, and it is likely that new L-PBF equipment, with an expanded build volume, will be available in the near future. Although currently not feasible, it would be of value to the MassDOT to continue to monitor the growth of state-of-the-art L-PBF hardware systems for potential application in MassDOT operations.
Orientation (cost)	Risky	The two deep cavities would require support material extending from the bottom-to-top plate of the part; this would add considerable material consumption and cost during printing. In addition, the top-plate overhangs beyond the side-walls of the bearing. These overhangs would also require additional support material. The height of this support material would be nearly the full height of the part itself, as they would directly interface from substrate to the overhanging feature on the top plate. The amount of support required to print this part would represent a significant amount of mass. A visualization was prepared to demonstrate the excess support required for this part. Shown in light blue is support material. Shown in yellow is the actual part geometry.
Orientation (printability)	Risky	The large size of the bearing reduces the available orientations for printing it. The part can only be oriented in such a way that it will fully be printed inside the available build chamber. Because both the build chamber and the bearing are fundamentally symmetrical and cubic in their design, it becomes increasingly difficult, or

		impossible, to orient the part inside the build chamber outside of aligning it in parallel to the walls of the chamber. This alignment leads to two potential issues with printing. When orienting the part, it is advantageous to rotate the part horizontally at a 5-degree or greater angle, such that edge features of the part are not perfectly parallel with the edges of the build chamber. This is done so that when the recoater blade passes over an individual layer, the potential contact area between the recoater blade and the part geometry is minimized. The size of the part presents difficulties in orienting the geometry at an angle. In addition to horizontal rotation, vertical rotation of several degrees is also advantageous. In general, the L-PBF process is more likely to fail when large concentrations of energy are required in a relatively constrained area or volume to form material. Thermal stress concentrations are more likely to occur when forming large-area layers. As a result, the orientation of L-PBF parts should be optimized to minimize the cross-sectional area of a given layer during printing. The larger the part is relative to the available build chamber size, the more constrained the orientation must be. Because the bearing would only fit within the largest conceivable L-PBF systems, it is assumed that the printable orientation would be aligned normally to the substrate. For the thick top and bottom plate features of the bearing, this would require printed layers with a large cross-sectional area, making them more prone to stress-concentration and warping or cracking during or after the printing process.



Production run size	parts	100

PART

Number of parts per build		1
Number of builds required		100

Total cost for production run	**%**	**$**
Material	23.1%	$458,325
Build prep	0.0%	$210
Machine usage	63.9%	$1,266,694
Build consumables	8.8%	$174,477
Labor	3.6%	$70,741
Post-process	0.5%	$10,685
Total cost		**$1,981,131**
Average cost per part		**$19,811.31**

Figure 2.6: Bearing cost analysis results (MIT)

Total cost estimated is $19,811.31 per piece when produced in a unit quantity of 100. The largest cost drivers are associated with machine usage and material usage; these two cost elements taken together compose almost 90% of total cost for the component. The third largest cost element are build consumables (i.e., the inert gas and other consumable items required for printing the part).

Importantly, the cost model does not account for costs associated with failed prints and understates the cost of post-processing by simplifying the post-processing steps calculated within the model. Therefore, the approximately $20,000 cost per part is likely an understatement.

The cost analysis is informative, and deviates somewhat from a typical cost breakdown for L-PBF parts. We review each of the cost drivers identified in the model, and comment on several exemplary findings from the analysis.

Material Costs

The L-PBF process uses gas-atomized metal powders; the production process for these materials adds considerable cost, and thus powder materials for metal printing may be an order of magnitude more expensive than the bulk formed alternatives used in conventional processes. Typically, the cost of material therefore dominates the cost structure for printed parts.

In the bearing case, material cost is considerable; for 100 parts, a greater than $450,000 investment in material is required. Discounting all other costs, material cost alone would assign a greater than $4,500 cost per part; roughly four times the total cost of production for the status quo bearing.

Machine Usage

The marginal cost of using the machine is by far the greatest cost associated with the part. For the 100-part production run modeled, machine usage costs exceed $1,260,000. If only machine costs were calculated, each part would cost at least $12,600 in machine usage fees alone.

This cost composition is atypical; AM part costs often reflect a majority cost share attributed to material costs, with a minority cost share associated with machine usage costs. In particular, as described previously, the cost model assumes equipment is "non-dedicated," and that machine costs are assigned marginally based on print time required, rather than amortized fully over a fixed number of parts. This approach accommodates typical industry usage scenarios for AM, where equipment is stored in job shops and used to create a variety of parts across different products and projects. It is therefore not only atypical that machine costs should dominate the cost structure for a printed part, but the cost model specifically biases against this outcome by only assigning marginal costs during the machine's fractional utilization by the production scenario being modeled.

There are two reasons why machine usage costs are substantially greater than expected for this part. They both are related to the geometry of the part, in particular, its size and mass.

First, the large size of the part poses problems, as we have reviewed during the manufacturability assessment. For the cost model, we scaled the simulated machine build volume so that it could fit the bearing inside of a single job. With this expanded build volume, a single bearing could be printed per printing job. In other words, 100 printing jobs are necessary for the production of 100 parts.

This setup is imperfect from a cost perspective. The time required for a given print job has both fixed and variable time increments associated with it. Fixed time increments include the time required to heat and cool the machine before and after the printing stage has occurred. Variable time increments are associated with the actual physical forming of material during printing, which is a function of the geometry to be produced. Jobs that are comparatively unproductive—that is, that print one to a few parts per print cycle—are inefficient in the allocation of fixed time allotments. In the case of the bearing, each part must account not just for the cost of printing, but for the fixed costs of heating and cooling the equipment during printing. Heating and cooling add hours to each print job and thus drive the cost up considerably.

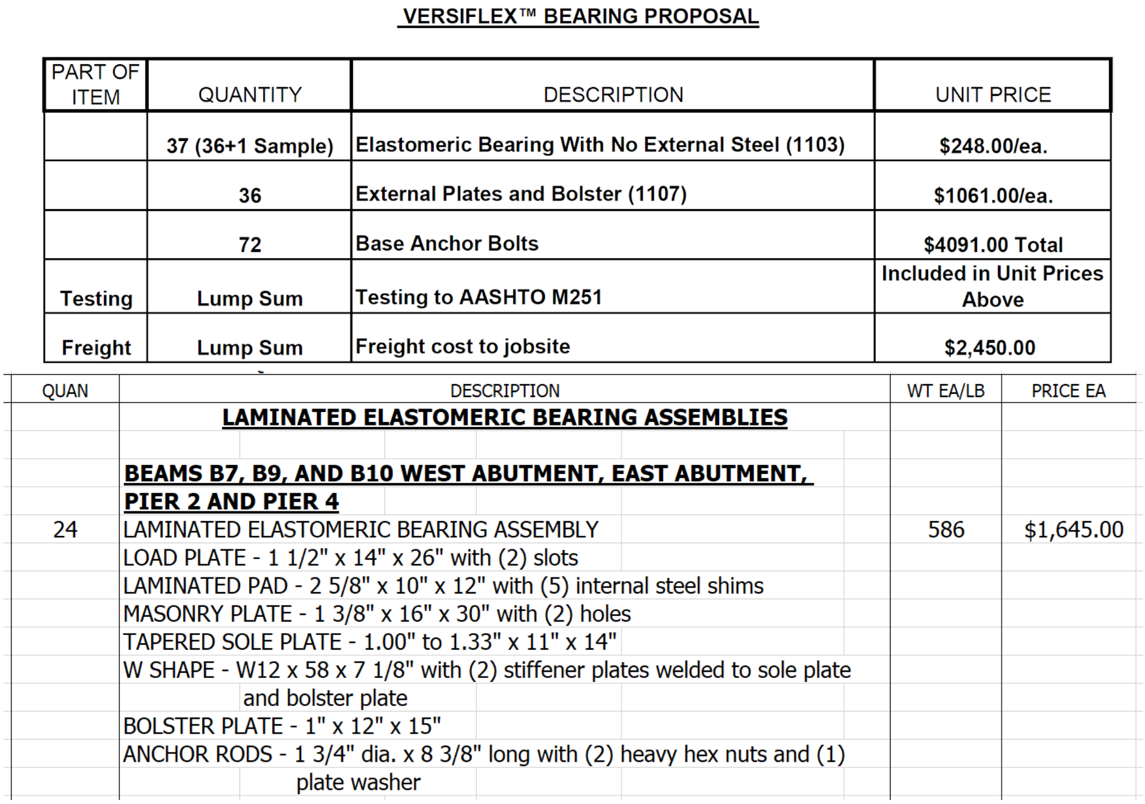
Second, the mass of the part poses further problems. The risks of this part causing failure during the printing process have been discussed during the manufacturability assessment. These risks are directly derivative of the large amount of formed mass in the part, specifically for the top and bottom plate features. These features require substantial machine time to form. The L-PBF process is a precision rather than a bulk forming process. A small-diameter laser selectively scans a pattern layer by layer. Parts that have thick large-area planar features (i.e., the top and bottom plates) will require a considerable amount of machine time to process. In other words, the simpler and bulkier the geometry, the greater the amount of machine time required to form it. The costs associated with machine usage for the part are substantially driven by the significant amount of printing time required to form these features.

Build Consumables

Build consumables account for 8.8% of cost, or almost $175,000 for 100 parts. A $1,750 cost per part for build consumables is an order of magnitude higher than what would be typically expected for a L-PBF part. The cost of build consumables scales as a function of print time and build volume utilization (i.e., the number of parts printed within a single job). There are two primary cost elements within the consumables category. The first element is the cost of inert gas, which must be continuously supplied to the L-PBF during operation. Gas is used to inert the build chamber and prevent oxidation of powders. The longer the print time, the more gas is consumed during this process. The second consumable is the cost of build plates. The build plate is the initial substrate upon which the part is formed. In between each job, the build plate must be removed and resurfaced for flatness; an uneven build surface would cause parts to fail. Insofar as only one piece can be printed per job, the full cost of resurfacing a build plate is loaded onto each part, further escalating the costs for this component.

Cost Analysis Results

In total, the cost of printing the bearing using L-PBF is more than an order of magnitude greater than the conventional cost of the part. The nominal cost of the bearing, when procured from a third party supplier, is around $1,600. For AM to be cost competitive, the cost of printing would need to be reduced to below 8% of its expected production costs; such a dramatic reduction in costs is unrealistic, even given the fast pace of technologic development described elsewhere in this report.



VERSIFLEX™ BEARING PROPOSAL

PART OF ITEM	QUANTITY	DESCRIPTION	UNIT PRICE
	37 (36+1 Sample)	Elastomeric Bearing With No External Steel (1103)	$248.00/ea.
	36	External Plates and Bolster (1107)	$1061.00/ea.
	72	Base Anchor Bolts	$4091.00 Total
Testing	Lump Sum	Testing to AASHTO M251	Included in Unit Prices Above
Freight	Lump Sum	Freight cost to jobsite	$2,450.00

QUAN	DESCRIPTION	WT EA/LB	PRICE EA
	LAMINATED ELASTOMERIC BEARING ASSEMBLIES		
	BEAMS B7, B9, AND B10 WEST ABUTMENT, EAST ABUTMENT, PIER 2 AND PIER 4		
24	LAMINATED ELASTOMERIC BEARING ASSEMBLY	586	$1,645.00
	LOAD PLATE - 1 1/2" x 14" x 26" with (2) slots		
	LAMINATED PAD - 2 5/8" x 10" x 12" with (5) internal steel shims		
	MASONRY PLATE - 1 3/8" x 16" x 30" with (2) holes		
	TAPERED SOLE PLATE - 1.00" to 1.33" x 11" x 14"		
	W SHAPE - W12 x 58 x 7 1/8" with (2) stiffener plates welded to sole plate and bolster plate		
	BOLSTER PLATE - 1" x 12" x 15"		
	ANCHOR RODS - 1 3/4" dia. x 8 3/8" long with (2) heavy hex nuts and (1) plate washer		

Figure 2.7: Prior bearing quotes (MassDOT)

This cost investigation, although it is not favorable for recommending the bearing for further printing, is not a fruitless endeavor. As with previous part investigations, the evaluation and discussion of the bearing example provides useful feedback for MassDOT future planning in AM. In particular, we highlight the following recommendations for further AM investigation:

1. The economics of AM scale proportionately to the volume of formed material inside the build chamber. Smaller parts, or parts with high surface-to-volume ratios, will result in more favorable economics as they minimize costs associated with production time. The more productive an individual job is (i.e., the greater number of parts that can be printed within a given cycle), the more favorable the cost of AM. When evaluating prospective candidate parts, preference should be given to parts that can comfortably fit inside the existing equipment and that are designed to minimize the time required to print them.

2. Many of the parts used by MassDOT are simple geometries and formed using established manufacturing methods. Thus, the cost of procuring these standard components is both affordable and reliable using established vendors. Even assuming the most favorable conditions for printing, the cost of printing, when compared to high-volume, low-cost conventional processes, will likely always be greater than the conventional production cost. At minimum, it should be expected that there is a cost

> premium of at least 5 to 10 times greater when using L-PBF printing compared to machining or casting. Parts under investigation for printing should be those where this cost premium is acceptable.

Taken in total, both recommendations support a broader, but critical, consideration in application identification. There are many prospective value propositions of AM: consolidating geometries, reducing waste, increasing performance, enabling customization, and so on. The strongest applications of AM, from an economic perspective, will be those where the value induced by converting to AM offsets increased production costs. We did not, for example, model the cost savings that may be associated with decreased labor time used to weld the bearing in place. Recall, our original thesis for this component was that AM could allow for site-specific customization and reduce downstream labor welding the bearing to the beam it supports. In this specific case, it was not clear how AM would minimize these tasks. However, when exploring future uses of AM in MassDOT, it is imperative that engineers consider the full implications of AM on their cost structures. In cases for which AM is only marginally more expensive than a conventionally supplied component, the cost savings or value created from converting to AM may partially or wholly offset increased costs associated with switching to AM as a production method.

Task 2.1 Conclusion

Task 2.1 consumed the greatest amount of time among any task on the project. This is due to the inherent challenges associated with part selection with AM. There are barriers associated with information exchange—MassDOT staff are unfamiliar with AM, and the project team is not aware of the full catalog of parts that may be suitable. Moreover, as the research revealed, more typical transportation infrastructure components do not lend themselves (from a technical or economic perspective) to ready conversion to AM. In some cases, as with the manhole key, assumptions between the project team and MassDOT were challenged by the reality within the district setting. The depth of information asymmetry is an impediment to any organization seeking to adopt AM, and prior research demonstrates that this challenge is difficult to overcome. It is unsurprising that candidate part selection was a lengthy process that involved detailed discussions between the project team and MassDOT.

To provide the most immediately useful deliverable to MassDOT, the project team proposed, in addition to further exploration of candidate components, that a segment of this report include decision-making tools that can be used asynchronously by MassDOT to explore applications of AM. These tools are described at length in section 4.3.

3.0 Additive Repair for Corroded Bridge Steel

3.1 Additive Bridge Repair Technology for Deteriorated/Damaged Steel Beams with Plasma Arc or Laser-Engineered Net Shaping

This task focused on the technical feasibility study of using additive repair technology in maintenance of construction materials and structures. We have pursued a preliminary experimental study on additive repair of damaged construction materials and structures. In this work, laser-based directed energy deposition (DED) is leveraged to repair a damaged low-carbon A36 steel transportation structural beam using 316L stainless steel powders. The microstructure, constituent phases, crystallographic texture, and tensile properties of the repaired interfaces are systematically investigated.

3.2 Laser DED Repair Processing and Tensile Testing of As-Repaired Specimens

Figure 3.1 shows three corroded W-shaped beam ends from real bridges. Corrosion can be observed in the web (concentrating with larger thickness losses at the bottom part of it) as well as in the flanges. In some locations, corrosion has caused holes in the steel plates. One of the damaged ASTM A36 low-carbon steel beam ends (Figure 3.1) was cut and carefully polished to remove the surface rust and oxide layer. Three different surface groove shapes (namely, R1, V1, and U1) were prepared on the A36 steel plate (i.e., base metal) to simulate different damage and surface profiles (Figure 3.2). The laser DED repair was conducted on an Optomec laser-engineered net shaping (LENS) 450 system under protective argon atmosphere (Figure 3.2a, b). 316L stainless steel powders with a particle size ranging from 45 to 105 μm were used as repair filler material. The printing parameters are the following: laser power P = 300 W with 0.25-mm layer thickness and 0.3-mm hatch spacing. After AM repair, flat dog-bone tensile samples involving the repaired groove in the gauge section were cut from the plate by electrical discharge machining (EDM) (Figure 3.2c). The tensile properties of the AM repaired specimens were examined at a quasi-static strain rate of 10–4/s to assess the surface profile effect. The gauge length, width, and thickness of tensile specimens were 6.5 mm, 2.0 mm, and 1.2 mm, respectively, and a servo hydraulic Instron load was used to perform tensile testing. An Instron noncontact AVE2 video extensometer with a displacement resolution of 0.5 μm was applied to measure the axial strain. Figure 3.2b shows the laser powder repairing process on the low-carbon steel plate. Figure 3.2c shows a schematic of groove shapes (i.e., rectangular, tripodal, and U-shape) prepared on the low-carbon steel plate, and Figure 3.2d shows the as-received low-carbon steel plate with U-shape grooves cut from a bridge beam in Massachusetts.

Figure 3.1: Corroded W-shaped bridge beam ends

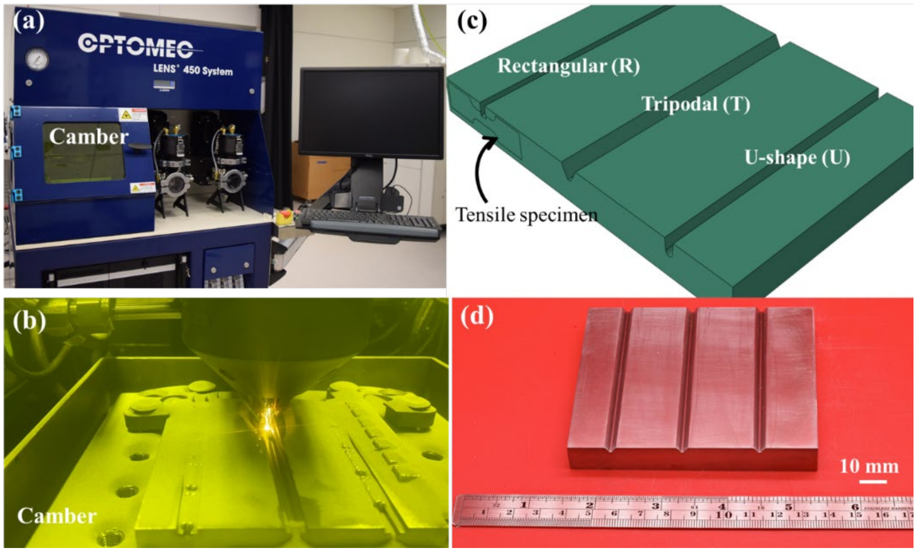


Figure 3.2: OPTOMEC LENS 450 System instrument

Table 3.1 summarizes the tensile properties of all repaired specimens. As shown in Table 3.1, the U1 specimen shows better tensile properties in terms of tensile strength and tensile elongation as compared to R1 and V1 specimens; thus, the surface profile of the U shape was used in the following study to optimize the laser DED printing parameters and the resultant mechanical properties of the repaired component. To this end, a wide range of laser powders and scan speeds were used, and the mechanical properties are summarized in Table 3.2.

Table 3.1: Macroscopic tensile properties of different repair geometries

Specimen	Groove shape	Power (W)	Scan speed (mm/min)	Yield strength (MPa)	Tensile strength (MPa)	Tensile elongation (%)
As-received A36	—	—	—	238	406	21.6
R1	Rectangular	230	800	174	280	6.5
T1	Tripodal	230	800	148	242	5.1
U1	U-shape	230	800	214	348	6.5

Table 3.2: Macroscopic tensile properties of U-shape welds with different energy densities

Specimen	Groove shape	Power (W)	Scan speed (mm/min)	Linear energy density (J/mm)
U29	U-shape	240	500	28.8
U24	U-shape	240	600	24.0
U30	U-shape	250	500	30.0
U25	U-shape	250	600	25.0
U26	U-shape	260	600	26.0
U20	U-shape	260	800	19.5

In the current study, two specimens with a U-shaped groove repaired using energy densities of 24 J/mm and 26 J/mm (denoted as U24 and U26, respectively) are used as examples to assess the quality of AM-repaired specimens. Figure 3.3 shows the tensile stress-strain curves of as-repaired U24 and U26 specimens along with the as-received base metal that was directly cut from the corroded steel bridge beam. The U24 specimen shows an elastic modulus of ~200 GPa, yield strength of ~230 MPa, tensile strength of ~400 MPa, and uniform elongation of ~15%. The U26 specimen exhibits a similar yield strength as U24 specimen but a higher tensile strength of ~420 MPa and a lower uniform elongation of ~12%.

Compared to the tensile properties of the as-received base metal, the as-repaired specimens show a comparable yield strength while exhibiting even higher tensile strength yet a reduced uniform elongation. Aiming at the remaining tensile strength, which is the governing factor for the residual capacity of deteriorated steel beam ends, these results suggest that the laser DED-base AM method is promising for repairing a damaged structural steel alloy by using stainless steel powders. In the next section, the microstructure characterization will be presented, and the correlation of mechanical properties and microstructure will be discussed.

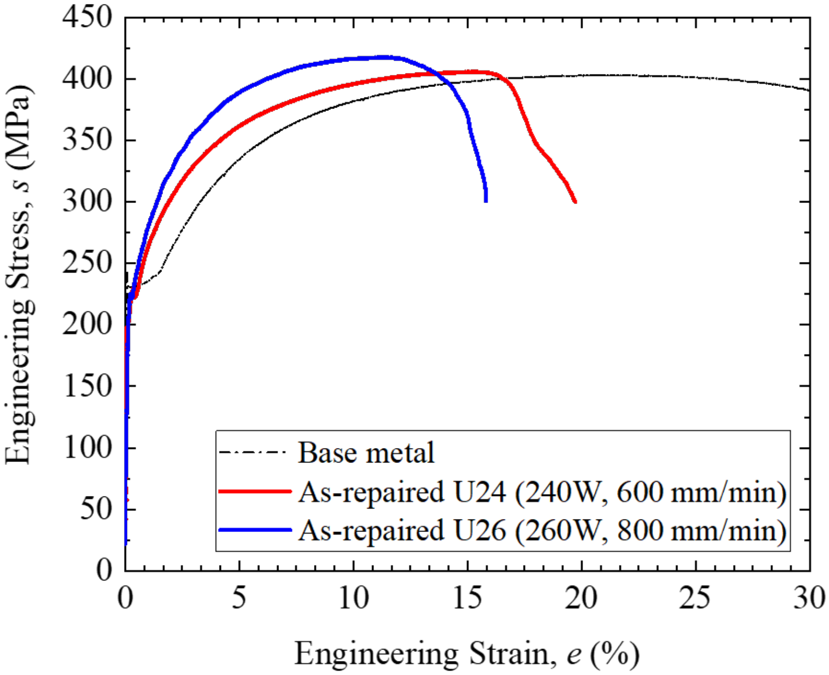


Figure 3.3: Tensile stress-strain curves of the A36 base metal and the as-repaired specimens

3.2.1 Microstructural Characterization

The grain morphology, grain size, constituent phases, and crystallographic orientations of a representative specimen (U24) were carefully analyzed by an Olympus BX51 optical microscope and a Tescan Mira3 scanning electron microscope (SEM) equipped with an electron backscatter diffraction (EBSD) detector and an energy dispersive spectroscopy (EDS) detector. An acceleration voltage of 20 kV and two resolutions (i.e., 40 and 110 nm step sizes) were used to collect EBSD data, which were post-processed to obtain the inverse pole figure (IPF) maps and phase maps using an orientation imaging microscopy (OIM) analysis software. Pole figures representing crystallographic textures in base metal and 316L stainless steel deposition were generated using MTEX software. Moreover, the chemical composition of the as-repaired U24 specimen at the interface between base metal and 316L stainless steel was analyzed using EDS for elements of Iron (Fe), Nickel (Ni), Chromium (Cr), and Molybdenum (Mo) to examine elemental diffusion behavior after the AM repair.

Figure 3.4 presents the optical micrograph of the as-repaired U24 specimen. In the as-printed 316L stainless steel of the repaired region, a semicircular melt pool boundary trace is clearly observed. The as-printed stainless steel shows highly heterogeneous grain geometries with subgrain cell structures due to rapid solidification (Figure 3.4a). Cellular structures with a high dislocation density enabled by rapid cooling during AM can contribute to a high strength in 3D-printed components. Furthermore, in the current study, the melt pool shape is shallow, and the ratio of melt pool width to height is about 9:10 (Figure 3.4a). Generally, the melt pool geometry influences the thermal gradients and solidification behavior.

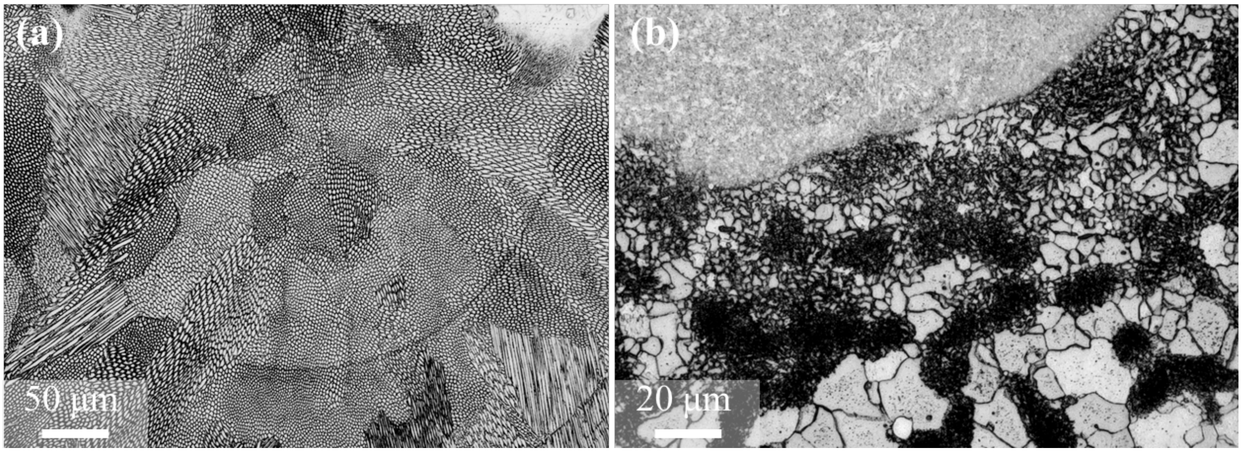


Figure 3.4: Optical micrographs of the as-repaired specimen U24

A prominent feature of the repaired specimen is that the grain size of the base metal becomes significantly smaller at the dissimilar A36/316L joint region of the heat-affected zone (HAZ). This trend is likely due to in situ thermal cycling–induced recrystallization during the AM process.

To provide a more detailed understanding of the changes in microstructure of base metal after the repair process, the microstructure of the HAZ in U24 specimen is carefully studied by EBSD. Similarly, we observed much more refined grains at the HAZ, and a large proportion of those grains developed a needle-like morphology (Figure 3.5a). In some welding studies, the fine-grain structures are sometimes formed in the HAZ due to the high temperature–induced local recrystallization as well as phase transformation. It should be noted that remarkable grain growth and coarse grain structures are more often formed during conventional welding process due to its high energy input. However, in the current study, the microstructure in the HAZ does not develop the coarse grains, and it is mostly because of the low energy input and high scan speed in the laser-based AM process that help suppress the grain growth kinetics. The refined grains in the HAZ is of significance to the high strength of the repaired specimen because the strength would be lower with the increase in grain size. The highly localized heating and rapid cooling during the laser DED repair process could suppress the grain coarsening and result in large thermal gradients. Thus, a high density of dislocation is believed to form within the non-equilibrium microstructure in this HAZ. Therefore, the smaller grain size and higher amount of dislocation density would contribute to the higher yield strength in the as-repaired U24 specimen.

The constituent phases in the HAZ are illustrated in the EBSD phase map (Figure 3.5b). The base metal consists of almost single BCC ferrite phase and the stainless steel deposition mostly contains FCC austenite phase. Such a clear separation of phase suggests that there is not significant elemental diffusion at the interface, likely caused by the rapid solidification rate. Also, the columnar austenitic grains in the HAZ almost aligned vertically toward the normal direction of melt pool boundaries, which has been reported to be governed by the maximum temperature gradient and sonification rate along the building direction during AM.

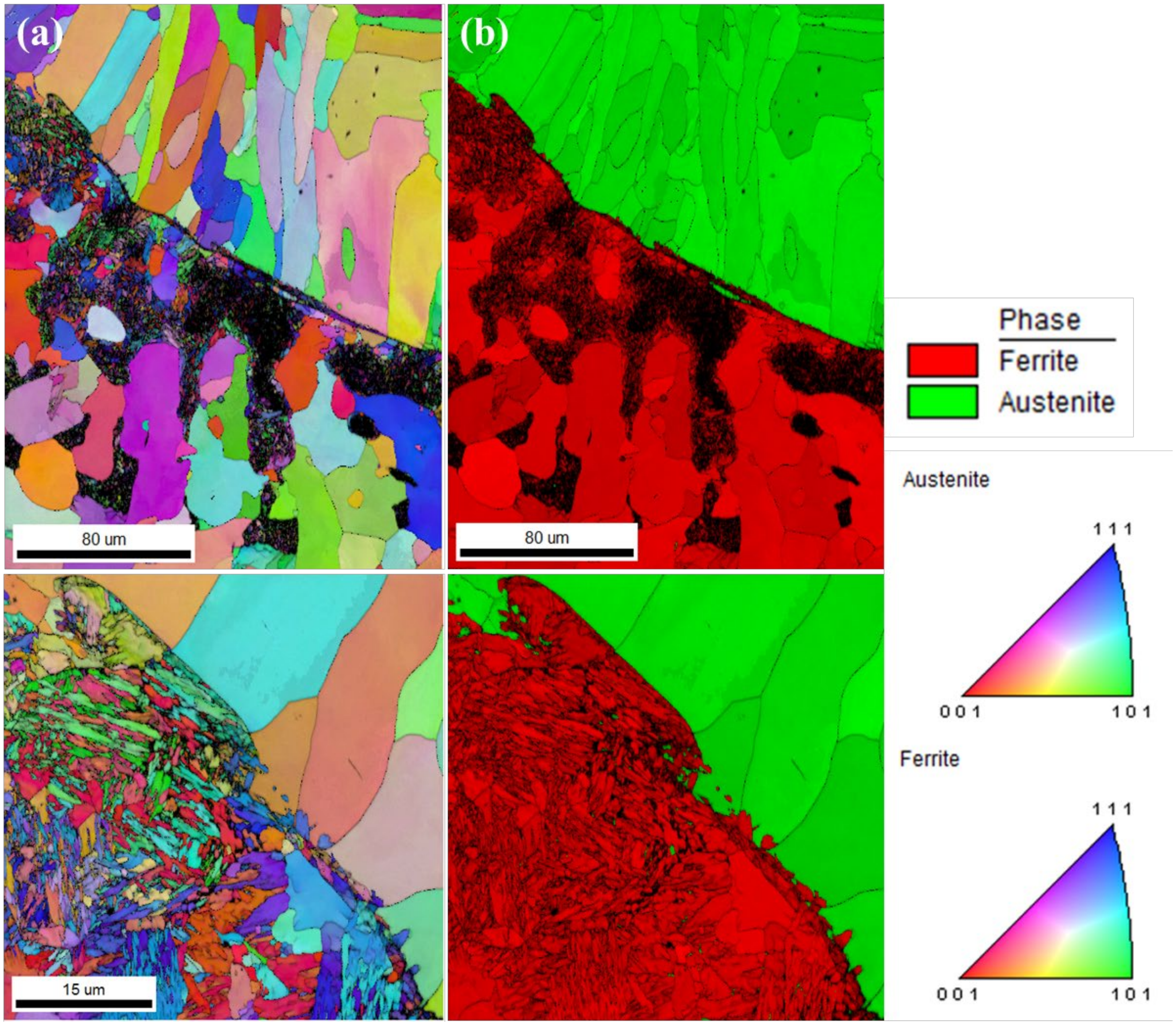


Figure 3.5: U24 (a) EBSD IPF maps and (b) EBSD corresponding phase maps

3.2.2 Microhardness Testing

The microhardness across the interface of the base metal and the as-repaired deposition of a representative sample (U24) was also examined. Figure 3.6 (top) is a SEM micrograph showing the path of microhardness measurement in the repaired metal using 260 W power and 800 mm/min scanning speed. Figure 3.6 (bottom) shows the Vickers hardness of the repaired metal from the repaired region to base metal. In general, the microhardness of the stainless steel side is higher compared to the base metal side of the as-repaired sample. Moreover, the microhardness in the base metal is significantly higher at the HAZ in the vicinity of the interfacial layer. This is believed to be attributed to the refined grain structures therein due to dynamic recrystallization. However, the microhardness in the stainless steel deposition is lower at the interfacial layer. The decrease in microhardness is likely related to the reduction in dislocation density, which is often induced by the repeated heat treatment during the laser repairing process.

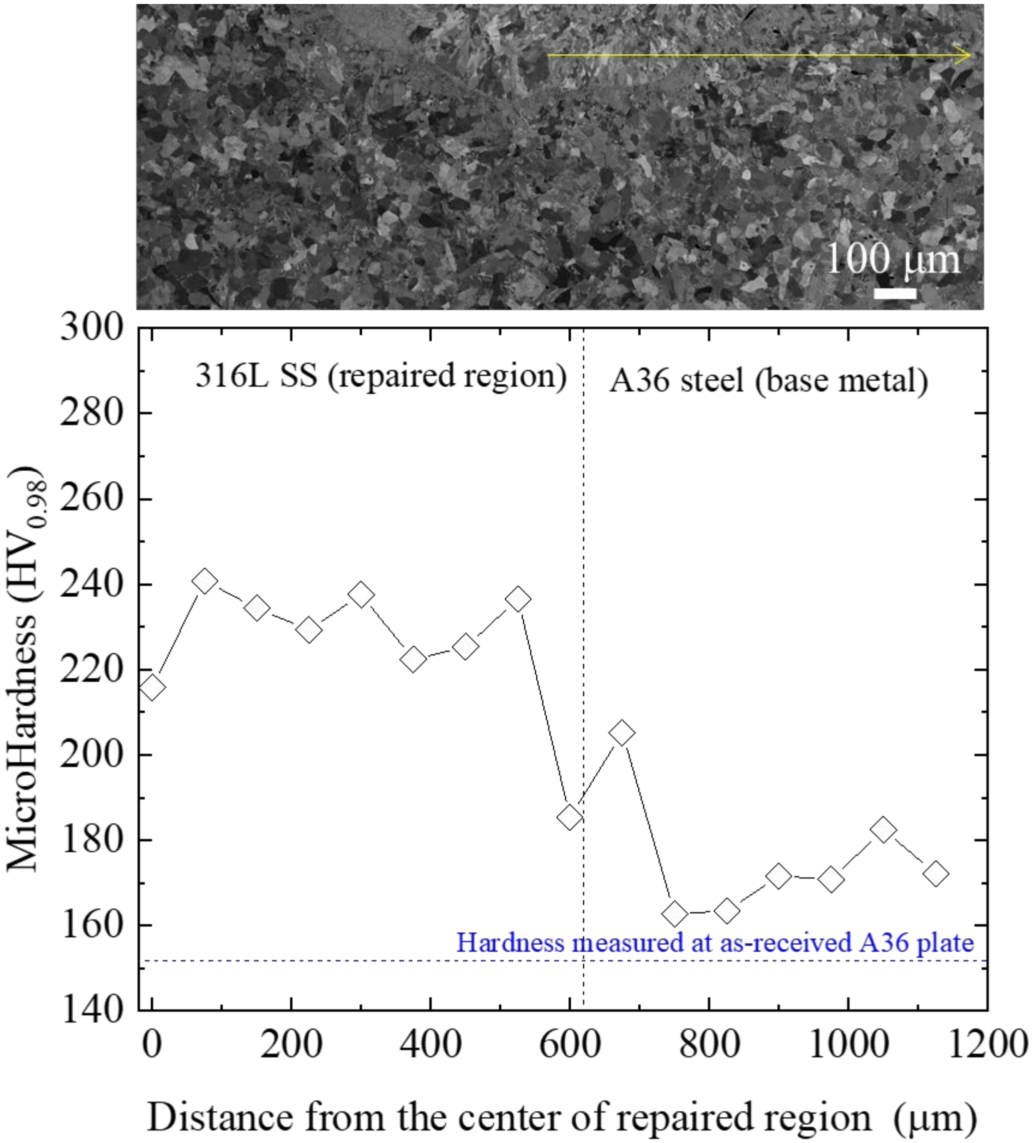


Figure 3.6: SEM micrograph (top) and Vickers hardness of the repaired metal (bottom)

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4.0 AM Decision-Making Tools for MassDOT

4.1 Introduction

Throughout the project, and in this report, we have attempted to elucidate the key findings from the project on the application potential of AM for MassDOT. These findings are useful on their own in clarifying the activities conducted during the project but can also be used to inform future MassDOT operational practice. To ensure that the findings from this project can be productively used to guide future practice, we proposed to create easy-to-use decision-making tools for MassDOT to screen parts for AM.

This slight pivot in approach was chosen to ensure that the project's work has measurable and lasting impact within MassDOT and to enable the results of the project to be disseminated and used by individuals and roles outside of the MassDOT staff directly working on the project. In this section, we summarize the key findings of the project and then present two tools that can be used by MassDOT in further part evaluation for AM. The tools are developed based on the findings of the project and resonate with themes presented previously in this report.

4.2 Principles of Part Selection for AM

We identify five guiding principles for identifying potential applications of AM within an organization. These principles include subtopics and can be assessed both qualitatively and quantitatively. The principles below are presented in loose sequential order, from easiest to assess to most difficult to assess. This framing is meant to provide a high-level sequence of evaluation, in which a prospective part's failure to meet any one principle is a disqualifying factor in moving to the next assessment tier. This framing is clarified via a decision-tree tool presented later in this section.

Principle 1. Identify applications where the economics of AM are likely to be favorable. MassDOT typically works with components that are not economically favorable for printing. Bulky large parts, and especially those that require large equipment and have lengthy printing times, are not likely to be economically affordable compared to conventional alternatives. Conversely, small parts or those with high surface-to-volume ratios are more likely to be economically advantageous. In cases where parts can absorb a higher cost premium, AM is more likely to be favorable than parts on a tight procurement budget.

Principle 2. Index printing applications against the capabilities of AM equipment. Parts that are too large to fit within the machine, or that would cause irrecoverable defects during the printing process, should not be considered for printing. If a part appears to be economically desirable as a printing candidate, it must also be checked against potential processes for producing it. Size compatibility is a quick heuristic assessment. For a more technical assessment that evaluates whether the part geometry is compatible with the chosen printing process, dedicated AM subject matter experts (cultivated in-house) could be consulted for part selection. Alternatively, applications could be discussed with service providers and contract manufacturers, who can quickly assess the likelihood of a given geometry printing successfully using a chosen process.

Principle 3. Tap into the unique value of AM. There are many value propositions of AM that are used to justify its production costs in industry. These propositions include the ability to consolidate complex assemblies, rapid fulfillment of hard-to-replace components, and performance advantages associated with the complex geometries AM is capable of forming. When candidate parts directly solve an existing problem by leveraging these unique value propositions of AM, their value is more likely to offset increased production costs. In general, replacing conventionally made parts with AM-produced parts is not likely to add value; there must be an overarching reason for selecting AM, and the cost and complexity associated with it, over a conventional process. As a result, parts that are currently being designed or undergoing a redesign process are more suitable for AM than those with readily established geometries. If parts can be optimized for the printing process, then it is more likely that they are economically favorable and leverage the unique value propositions afforded by AM production methods.

Principle 4. Consider parts where value is yet unexplored. In industrial settings, AM is often used to fabricate parts that would otherwise not be manufactured. There is an intrinsic disconnect between fabrication personnel and engineering, procurement, and managerial personnel. The day-to-day difficulties associated with assembling or installing equipment may not be disseminated in detail to designers in office environments. The degree of back-and-forth during the interview process revealed that isolation of engineering and production functions can create viscosities and asymmetries of information, which delay the identification of new candidate parts. Low-cost entries in AM (e.g., using office-friendly desktop extrusion equipment) especially among hands-on operators and fabricators can be used to generate AM applications with reduced risk. Volkswagen, for example, uses low-cost extrusion printers in their assembly lines to create alignment aids during final vehicle assembly. These parts are inexpensive (likely <$40 each) and were produced upon request of assembly technicians to minimize variation during a routine alignment task. We argue that industrial experience demonstrates that hands-on technicians are familiar with the regular problems within their work and are eager to identify potential solutions to minimize variation and waste.

Figure 4.1: Volkswagen/Ultimaker 3D printed alignment fixture (Ultimaker)

Principle 5. Applications of AM must be considered across design, engineering, procurement, and managerial functions. Given the complexities associated with AM described elsewhere in this report, the incorporation of AM into MassDOT operations will require the synchronization of different functional roles. In particular, as we discuss in Task 3, the qualification regime for printed components is limited and will require further development to enable mature applications of AM. This observation is corroborated by prior industrial research, where a major industrial user of AM required greater structural integration between design, production, and testing groups during AM product development. MassDOT should be cognizant of this complexity up-front when identifying new applications of AM. Applications should be considered for their mechanical performance, their cost, and within the greater context of procurement and regulatory structures used by MassDOT. It was often the case when evaluating parts during this project that consultation with various MassDOT staff and district personnel was required to capture the full range of considerations (e.g., engineering drawings, quotations, qualification standards, and so forth) necessary to assess the application in detail. Future processes and tools adopted to screen candidate parts for AM should incorporate these different roles and perspectives up-front to simplify the screening process and reduce the number of unique evaluations required per part screened.

With these principles in mind, we developed two tools that can be used by MassDOT staff to screen candidate parts for printing. Keeping in line with Principle 5 articulated above, the goal is to create tools that can be used quickly by staff members with only a basic familiarity with AM. The easier to use the tool, the more broadly it can be productively used by a variety of functional roles within MassDOT.

The first tool is a simple scorecard (Table 4.1). This can be used to compare clusters of parts using a semi-quantitative method. The exact score weights are arbitrary; the intent is to use the scorecard to compare parts against one another. Higher scoring parts are more suitable for further investigation using AM, and lower scoring parts are less likely to be promising AM candidates.

The second tool is a decision tree (Figure 4.2). This decision tree demonstrates a sequential decision-making logic that can be used to assess a single part. Decision trees are used across industrial settings, for example, in the aerospace industry, to assess components for printing. The decision tree presented in this section is a high-level screening mechanism that identifies key considerations when selecting parts for AM and proposes direct actions to address potential concerns during application identification.

In reviewing both tools, the reader should be familiar with the project experience and arguments underlying each consideration. The criteria identified in the tools were directly identified using the feedback collected during the research project.

Table 4.1: AM feasibility scorecard

Application Characteristics		
TRAIT	SCORING NOTES	SCORE
Prototype or intermediate part (e.g., jig or fixture), spare part, or end-use (production) part?	• Prototype or intermediate part: score 3 • Spare part: score 2 • End-use or production part: score 1	
Is the part heavy-duty, medium-duty, or low-to-no duty?	• Low-to-no duty: score 3 • Medium-duty: score 2 • Heavy-duty: score 1	
Are you willing to pay a cost premium to: save lead time or customize the part?	• Yes, a substantial premium: score 3 • Yes, a slight premium: score 2 • No, no premium: score 1	
Is it difficult to replace the part using current manufacturing methods?	• Yes, it is very difficult: score 3 • Yes, it is slightly difficult: score 2 • No, it is not difficult: score 1	
	Total "Application Characteristics" Score	
Manufacturability Assessment		
Are the part's dimensions and features compatible with existing AM equipment?	• Yes, they are fully compatible: score 3 • No, but they are close to current equipment capabilities: score 2 • No, they are not compatible: score 1	
Does the part have a high or low surface-to-volume ratio?	• High surface-to-volume ratio: score 3 • Unsure: score 2 • Low surface-to-volume ratio: score 1	
Does the part have bulky, simple geometries, such as thick plates or walls?	• No, the geometry is complex: score 3 • Some simple or bulky features, but some of the geometry is complex: score 2	

	• Yes, the geometry is simple: score 1	
Is or can the part be redesigned?	• Yes, the part can be modified for the AM process: score 3 • Unsure: score 2 • No, the part’s geometry cannot be modified: score 1	
Total “Manufacturability Assessment” Score		
Economic Assessment		
Is it acceptable to produce the part at a five-times cost increase?	• Yes, a 500% cost increase is acceptable: score 3 • A cost increase of <500% is acceptable: score 2 • No cost increase is acceptable: score 1	
Would the value created by using AM offset a potential cost premium?	• Yes, the value created would offset a 500% cost premium: score 3 • AM would add value, but it is not clear if this would offset increased cost: score 2 • AM’s value created would not offset increased cost: score 1	
Total “Economic Assessment” Score		
Total Score		
Notes:		

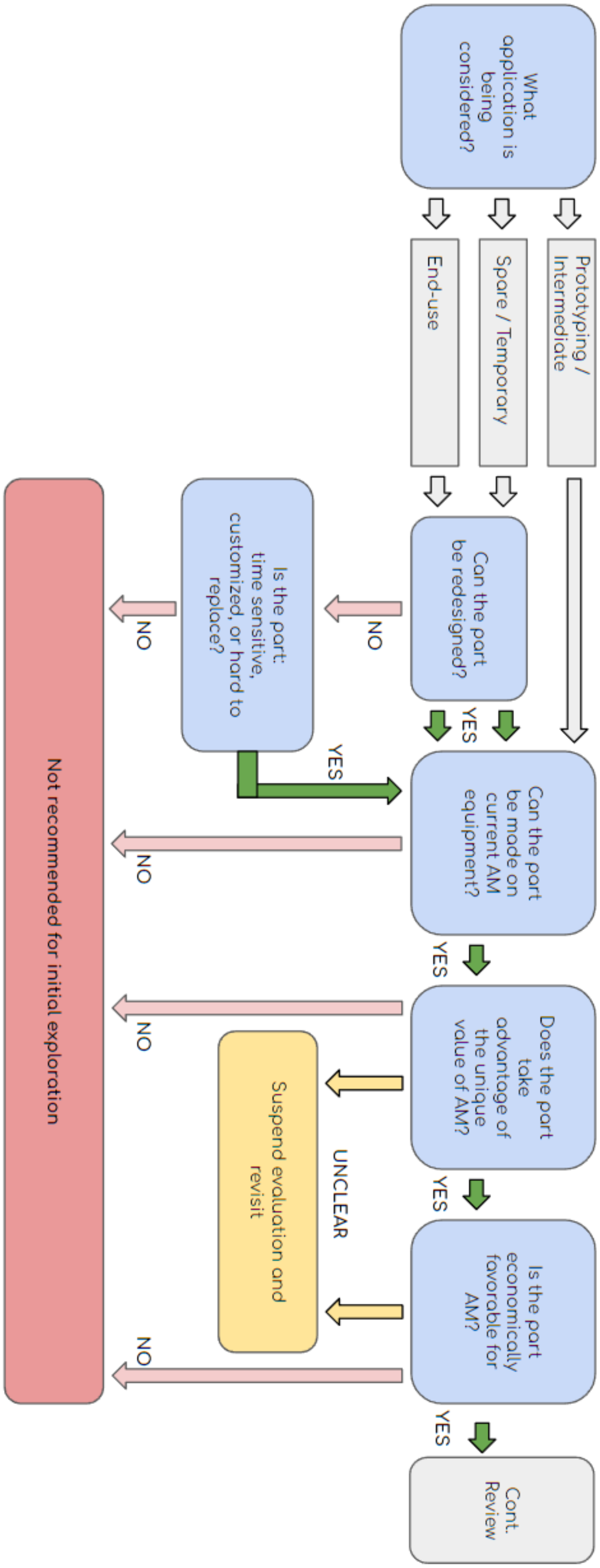

Figure 4.2: AM part screening decision tree

4.3 Using the Tools

In using the tools, a basic familiarity with AM processes and its value propositions is helpful. We propose two nonexclusive scenarios for tool use within MassDOT.

In the first scenario, MassDOT could elect to establish designated AM subject matter experts (SMEs). These experts could be selected from MassDOT staff who participated in this project. The SMEs could use these tools in consultation with other MassDOT district personnel to screen candidate components for printing. The SMEs would be tasked with translating the specific requirements of the parts provided by the district into AM process evaluations using the tools provided.

In the alternative scenario, the tools could be used as an accompaniment to a short workshop or training for MassDOT staff. A brief (4-h) training program could be developed and deployed digitally or in person for a large number of MassDOT staff. The training program could focus on the most important aspects of AM for part selection as identified in this report. In particular, it could emphasize AM's value propositions and its manufacturing and economic constraints. After the training is completed, these tools could be used by MassDOT staff to augment the training materials and screen candidate parts for further inquiry.

After the tools have been used to assess parts for suitability for AM production, further review is necessarily required before the parts can be adequately evaluated. In particular, activity-based cost models, as were used in this project, could be used to further predict the order-of-magnitude cost for printed components. Additionally, an evaluation of possible material and mechanical properties of printed parts must be performed against their requirements. The specific methods for performing this comparison are expanded upon in Task 3.

4.4 Prototyping Work

In addition to the preceding tools, a final candidate part was selected for prototyping. This part is a lead-core seismic isolation bearing. Seismic isolation bearings are used to isolate structures from vibration induced by seismic activity; they are installed underneath bridges, buildings, and other standing structures.

Seismic isolation bearings are an interesting candidate for a full-scale redesign using AM. In particular, during operation the isolation bearing must be able to shear independently of the structure the bearing supports. The project team is excited by the prospect of advanced cellular lattice structures and, in particular, pentamodal lattice geometries. These complex lattices can only be fabricated via AM, and they have geometric characteristics that are favorable for their economics. Pentamodal lattice structures, in particular, demonstrate high directional shear properties and can be engineered with predictable deformation mechanics under premodeled loading conditions. The lattice could be used to substitute the lead core element. This approach has been discussed in civil engineering literature, but empirical demonstrations are few.

The project team is interested in this concept and is developing a physical demonstration model for further discussion.

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5.0 Initial Framework of Standard Operating Procedures for AM in MassDOT

5.1 Overview

Task 3 describes recommendations on procuring, installing, and quality testing printed components using different techniques. Task 3 aims to offer an initial framework of standard operating procedures for the incorporation of AM-produced components into MassDOT's operations.

AM in the transportation infrastructure sector is relatively immature. As a result, there are few existing standards, especially for the secure management of digital data, that are directly applicable to MassDOT. For example, development of standardized design documentation is an ongoing research project at the ASTM Additive Manufacturing Center for Excellence (https://amcoe.org/project/Process-qualification-lbpbf). As a result, during discussions with MassDOT, it was emphasized that successful completion of this task would offer an initial framework for evaluation of printed components from a qualification perspective. Standards for processing and qualifying printed components, in general, are comparatively more mature and available than for data management or for specific applications in the transportation sector. Therefore, Task 3 includes two primary sections. In Section 5.2, we will review the current standardization approaches for AM components. This discussion will highlight key elements of the AM workflow that must be managed and reference exemplary standards documents for each. In Section 5.3, we will review standards provided by MassDOT to the project team and reflect on how these standard approaches could be adopted to evaluate an AM-produced component.

Standards for AM are developed by a joint standardization committee. The International Standards Organization (ISO) and the American Society for Testing and Materials (ASTM) created the "ISO/ASTM F42 Committee on Additive Manufacturing Standards." In addition to the AM-specific standards developed by the ISO/ASTM F42 Committee, there are many other industry or material-specific standards used to qualify components. These qualification requirements are not superseded by the ISO/ASTM F42 standards. Instead, ISO/ASTM F42 standards attempt to standardize key inputs and actions during the AM production workflow. Printed parts must still conform to industry- or company-stated regulatory requirements.

5.2 Additive Manufacturing Standards

AM standards are compartmentalized into the following categories:

- **General standards** that are applicable across AM technologies, materials, and applications. Examples include ISO/ASTM 52900:2015, "Additive Manufacturing –

General Principles – Terminology," which standardizes process terminology for each AM process.

- **Category AM standards** are applicable only to specific subject categories. These include standards that characterize feedstock materials (e.g., metal powders), standards that characterize processes (e.g., L-PBF), and standards that describe finishing methods (e.g., heat treatment). ISO/ASTM 52911-2:2019, "Additive Manufacturing – Design – Part 2: Laser-Based Powder Bed Fusion of Polymers," is an example of a category standard, because it describes a single printing process (L-PBF) but does not describe a specific chemical composition of material to be printed.
- **Specialized AM standards** are standards describing specific combinations of material, process, application, and industry. A specialized standard, for example, would be ASTM F2924-14, "Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion." This standard addresses both a specific alloy composition and a manufacturing process.

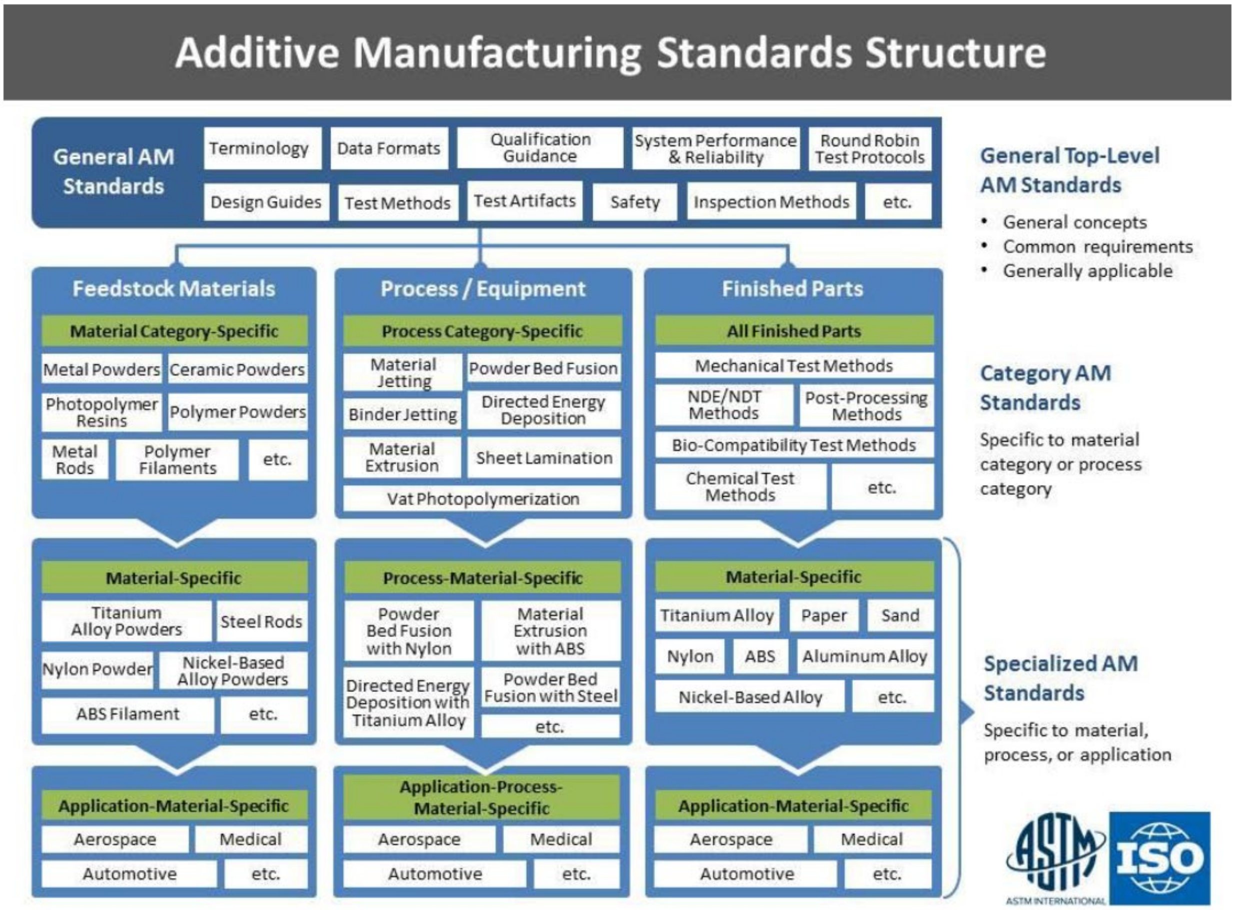

Figure 5.1: Additive manufacturing standards structure (AmericaMakes/NIST)

These standards (Figure 5.1) are far from complete for each material, process, application, and industry segment in AM. The incorporation of these standards within MassDOT will therefore remain a function of how and when these standards are developed for broader use.

When considering procurement of AM-produced components, MassDOT staff should request vendors conform with available standards.

For example, were MassDOT to consider manufacturing an AM component using L-PBF of metals, the following must be considered:

- **Material standards.** The specific alloy composition, particle size distribution, and atomization method of metal powders, among other considerations, will have consequences on the physical forming process and resulting outcomes of a print job. Standards such as ISO/ASTM 52907:2019 “Additive Manufacturing – Feedstock Materials – Methods to Characterize Metal Powders,” include standard procedures for characterizing the suitability of metal powders for use in AM.
- **Process standards.** Process standards describe standard methods for installing, operating, calibrating, and maintaining machinery. These process standards remain underdeveloped. In 2020, the ISO/ASTM F42 Committee announced the development of a general standard for L-PBF processes, but this standard has not yet been released.
- **Finishing Standards.** Printed parts, in most cases, require specific post-processing to ensure required dimensional and mechanical performance. ASTM F3301-18a, “Standard for Additive Manufacturing – Post Processing Methods – Standard Specification for Thermal Post-Processing Metal Parts Made Via Powder Bed Fusion” describes specific requirements and methods for thermal treatment of printed parts.

The exact combination of material, process, and post-processing (or finishing) used to produce a given part can have significant implications on the component’s mechanical properties. Therefore, these standards that regulate the production process are required to minimize variation during production. Once a material, process, and finishing method have been standardized, their repeat execution should result in subsequent parts with the same levels of expected performance. Standardizing these aspects does not guarantee that the part adequately performs for the given application. Instead, these standards are used to ensure a reliable and predictable outcome during the manufacturing process. A part’s conformance with required mechanical, chemical, or other properties would be assessed using extant standard test procedures.

Industry can and does print qualified components for which standards do not currently exist. In these cases, qualification is done ad hoc and in consultation between the manufacturing entity and the appropriate regulatory or qualifying agency. For example, the Federal Aviation Authority created a “National Team” composed of industry stakeholders and regulatory agents. The National Team performs ad hoc qualification of printed aerospace components using test regimens and processing conditions they devise for the specific component in consultation with the manufacturing entity.

There are therefore two approaches to adopting qualified AM components. In the first approach, parts are only considered if the appropriate processing standards exist for the selected material, process, and post-processing actions. Suppliers of printed parts should be able to demonstrate conformance with these standard practices. This approach is the most risk-averse approach, but it limits the utility of AM in the near-term. An alternative approach, in which parts are considered to be printed even if they lack comprehensive standardization, would require that MassDOT and relevant regulatory agencies and working groups devise application-specific qualification regimes. This latter approach is most common in industry, especially in the energy, health care, and aviation sectors, where the cost of developing both novel applications and the standard procedures for realizing those applications is justified due to first-mover advantages gained by private sector firms.

5.3 Example Standards for MassDOT

MassDOT published its construction specifications for 2022 earlier this year, including supplemental specifications released on March 31, 2022 *(58–65)*. For material components, we reference standards provided in subsection M8 "Metals and Related Materials."

The standards provided within this section describe mechanical conformance specifications against ANSI, AASHTO, and AWS standards. The document provides flexibility depending on the application selected. For example, "Testing will be done in accordance with latest standard procedures of ASTM and/or AASHTO."

Section M8 of the Standard Specification reveals both challenges and opportunities with the adoption of AM for MassDOT uses. For example, subsection "M8.01.0: Reinforcing Bars," specifies that reinforcing bars "shall consist of deformed bars rolled from new billet steel," which would automatically disqualify AM. When MassDOT standard specifications reference specific manufacturing processes and feedstock compositions, alternative packages of standards referenced from, for example, the ISO/ASTM F42 Committee, must be identified.

On the other hand, there is substantial opportunity for AM to be used to replace components for which MassDOT's standard specification does not specify a required manufacturing method. Subsections "M8.01.5: Anchor Bolts, Nuts and Washers" and "M8.04.3: High Strength Bolts" describe performance requirements for fasteners, including minimum hardness, load capacity, dimensions, and ASTM material grades. The fabrication method for these parts is not specified; thus, the use of AM as a production method is possible within the current Standard Specification as long as printed parts conform to the mechanical and dimensional requirements. There is therefore no need for MassDOT to develop commensurate standards to what is already provided in the Standard Specification; standards such as ASTM F3125/F3125M, for example, can continue to be used for grading the performance of printed components.

5.4 Standards Recommendations

Available standards for additive manufacturing materials, processes, and parts remain immature and piecemeal. As MassDOT seeks to incorporate AM into its operations, awareness of standard practice will be critical to ensuring parts conform with their required properties. We provide the following recommendations for MassDOT in evaluating standard practices for AM:

- Where possible, leverage existing standards for evaluating component performance. The material, process, and post-processing standards described at the beginning of this section of the report are used to qualify a printing process to reliably produce the same quality of parts during each successive print. These standards are therefore not necessary where MassDOT is only concerned with finished part performance. As long as printed parts are demonstrated to conform to required levels, there is no need for MassDOT to invest time in evaluating the standardization of the production process through which the parts are fabricated.

- If MassDOT is developing applications using AM that require MassDOT to qualify the production process, applications should preference those where existing standards produced by the ISO/ASTM F42 Committee are available. If such standards are not yet available, MassDOT should consider collaborative process standardization in consultation with the appropriate regulatory agencies.

- In general, MassDOT would benefit from participation in standardization bodies and professional associations focused on standardization in AM. In particular, the AmericaMakes national manufacturing institute dedicated to AM is the leading public–private partnership in developing new standards for AM. Participation in AmericaMakes events and research programs could align MassDOT thinking with the current state of the art.

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6.0 Conclusions and Future Work

The main goals of this project were to explore the feasibility of 3D printing application for the construction and maintenance in the framework of MassDOT. AM technologies have progressed immensely in the last decades, but this progress has not really been reflected in processes regarding infrastructure and the transportation sector.

Within these research goals, we achieved to first connect the MassDOT community with AM in terms of the technology. During the project, we held several discussions with MassDOT personnel in addition to the 2-day workshop, which brought together the MassDOT engineers with the researchers and industrial 3D printing companies. From that point of view, the project accomplished one of the most important initial goals. All stakeholders not only identified and realized the limitations of the technology as it stands today but also found the ground for highly promising applications to be explored further. One of these applications was the additive repair concept for deteriorated steel bridges, which was identified after the presented preliminary experimental results. This is a direction for an extension of this research that is going to be pursued by the researchers in the coming years.

In addition, high-level assessment of manufacturability were presented and followed for proposed objects such as the bearing of bridges using L-PBF. Although the part was deemed not suitable for printing, following a process such as this one was considered very helpful for future similar studies. Cost estimates about materials, machine usage, and build consumables were also accounted for in the decision-making process for manufacturability, thus establishing a roadmap for potential studies of other candidate objects for printing. Last, an initial framework of standard operating procedures for AM within MassDOT was presented.

This project demonstrated the new opportunities that have opened up for the usage of AM in the transportation and infrastructure sector in general. Although the path for successful application of AM is not linear, all participants in the project have concluded that there is a future where AM can play a significant role in improving the construction and maintenance of our transportation infrastructure. One of the immediate next steps in this research effort will focus on additive repair of deteriorated steel bridges.

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8.0 Appendices

8.1. Appendix A: Workshop Agenda

- **DAY 1 9:00 a.m. to 1:30 p.m. Part I: Academic Presentations**

9:00 a.m. to 9:45 a.m.	The status and trajectory of additive manufacturing technology *by **John Hart**, **Haden Quinlan** (MIT)*
9:45 a.m. to 10:15 a.m.	Current 3D printing capabilities *by **Wen Chen** (UMass Amherst)*
10:30 a.m. to 11:00 a.m.	Transportation infrastructure and 3D printing opportunities *by **Peijun Hou** (UMass Amherst)*
11:00 a.m. to 11:30 a.m.	The UMass new england bridge program *by **S. Gerasimidis**, **G. Tzortzinis*** (*UMass Amherst*)
11:30 a.m. to 1:30 p.m.	Open discussion

- **DAY 2 9:00 a.m. to 1:15 p.m. Part II: Invited Industrial Pitch Presentations**

9:05 a.m. to 9:15 a.m.	AM for construction and infrastructure applications *by **Peter J. Denmark** (ExOne)*
9:15 a.m. to 9:25 a.m.	How EOS supports success in AM *by **Maryna Lenina** (EOS)*
9:25 a.m. to 9:35 a.m.	Metal AM Q&A
9:35 a.m. to 9:45 a.m.	BigRep construction projects *by **Frank Marangell** (BigRep)*
9:45 a.m. to 9:55 a.m.	AM in infrastructure applications *by **P. Duis, P. Duis, and G. Constantino** (DSM)*
9:55 a.m. to 10:10 a.m.	Polymer AM Q&A
10:10 a.m. to 10:20 a.m.	Autodesk *by **Louisa Holland** (Autodesk)*
10:20 a.m. to 10:30 a.m.	nTopology *by **Gabby Hayes** (nTopology)*
10:30 a.m. to 10:40 a.m.	Twikit *by **Stephanie Seghers** (Twikit)*
10:30 a.m. to 10:55 a.m.	Software Q&A
11:15 a.m. to 1:15 p.m.	Open discussion
1:15 p.m.	Adjourn

8.2. Appendix B: Workshop Organizing Committee

The workshop organizing committee was responsible for the workshop and dissemination of workshop results. It consisted of the following people at UMass Amherst and MIT:

Simos Gerasimidis, Assistant Professor in Department of Civil and Environmental Engineering, UMass Amherst.

John Hart, Professor of Mechanical Engineering, MIT; Director, Center for Additive and Digital Advanced Production Technologies (APT); Director, Laboratory for Manufacturing and Productivity.

Wen Chen, Assistant Professor in Department of Mechanical and Industrial Engineering, UMass Amherst.

Haden Quinlan, SRS Program Manager, MIT.

Peijun Hou, Postdoctoral Research Associate in Departments of Civil and Environmental Engineering and Mechanical and Industrial Engineering, UMass Amherst.

Simos Gerasimidis received his Ph.D. (2011) from the Aristotle University of Thessaloniki in Greece. He then worked as a postdoctoral research scientist at Columbia University in the Department of Civil Engineering and Engineering Mechanics (2011–2015). In September 2015, he started his academic career by joining the University of Massachusetts, Amherst, as Assistant Professor at the Department of Civil and Environmental Engineering. His primary research interests lie in the areas of infrastructure resilience, architected metamaterials, shell buckling, structural response of critical infrastructure systems subjected to extreme-loading events in urban regions, resilient-oriented structural design approaches, damage propagation and structural response of damaged structures covering a broad spectrum of structural behavior.

John Hart received his Ph.D. (2006) from MIT in Mechanical Engineering. Prior to joining the MIT faculty in July 2013, he was assistant professor of Mechanical Engineering, Chemical Engineering and Art/Design, at the University of Michigan. At MIT, he leads the Mechanosynthesis Group, which creates new machines, materials, and design principles for advanced manufacturing, including carbon nanomaterials, additive manufacturing processes, and origami-inspired materials design. He interests within the scope of the center include design and manufacturing of customized agricultural tools and medical devices, and empowering creativity using rapid prototyping and additive manufacturing technologies.

Wen Chen received his Ph.D. (2015) in Mechanical Engineering and Materials Science at Yale University. After his Ph.D., he worked as a postdoctoral research scientist at Lawrence Livermore National Laboratory, where he developed direct ink writing–based technology for additive manufacturing of metals. In July 2018, he joined the University of Massachusetts, Amherst, as assistant professor at the Department of Mechanical and Industrial Engineering. His research interests primarily lie in mechanical behavior of materials, materials design, and additive manufacturing.

Haden Quinlan received his B.A. (2015) in Political Science and International Affairs from Northeastern University. After his B.A., he joined in MIT as the program manager.

Peijun Hou received his Ph.D. (2020) in Materials Science and Engineering from the University of Tennessee, Knoxville. In September 2020, he joined the research teams of Prof. Gerasimidis and Prof. Chen in the Departments of Civil and Environmental Engineering and Mechanical and Industrial Engineering, UMass Amherst.

Table 8.1: Information of participants

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